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Topic Paper #7

Mass-Market Adoption of Ultralightweight Automobiles

On August 1, 2012, The National Petroleum Council (NPC) in approving its report, *Advancing Technology for America's Transportation Future*, also approved the making available of certain materials used in the study process, including detailed, specific subject matter papers prepared or used by the study's Task Groups and/or Subgroups. These Topic Papers were working documents that were part of the analyses that led to development of the summary results presented in the report's Executive Summary and Chapters.

These Topic Papers represent the views and conclusions of the authors. The National Petroleum Council has not endorsed or approved the statements and conclusions contained in these documents, but approved the publication of these materials as part of the study process.

The NPC believes that these papers will be of interest to the readers of the report and will help them better understand the results. These materials are being made available in the interest of transparency.

Mass-market adoption of ultralightweight automobiles
Step Out Technology Essay for NPC Transportation Fuel Study
Draft 4 by Amory B. Lovins, 22 April 2012 ("TK" = to come from NPC)

America's two-ton automobiles must reverse the epidemic obesity that in the past quarter-century has raised their weight twice as fast as their drivers'. Weight causes two-thirds of the energy needed to move a typical car. That energy at the wheels is multiplied sevenfold at the fuel tank, since delivering one unit of fuel energy to the wheels loses six more in the engine and driveline—and needs an even bigger engine to accelerate it, further increasing weight. But how light should and can autos get? Could new lightweight materials even transform automotive manufacturing and economics today, much as vanadium steel enabled the *Model T*?

This report assumes that automobiles sold in the United States during 2012–**TK** will be no more than 30% lighter in curb mass than the basecase vehicles in the 20**TK** EIA Reference Case. Yet this familiar and comfortable assumption—less ambitious than the 1994 PNGV program's 40%-lighter goal[i]—falls far short of what is now technically possible, economically interesting, and strategically compelling.[ii]

A 2010 review described 19 industry projects—five production, four prototype, ten concept—that had saved ≥30% of curb mass using light metals or even lightweight steels.[iii] A 1988 review[iv] described more than a dozen additional mid-1980s industry designs weighing 44–68% less[v] than the 1,403-kg average U.S. 1990 production car and getting 67–138 mpg; at least two automakers said they'd be producible at about normal cost. Thus this 2012 study's confining its weight savings to 30% is decades behind the fast-moving state of the art.

Today, advanced composites[vi], rarely considered in the 1980s but entering automotive mass production in 2013, are the most effective weight-saver. Three concept cars confirm that uncompromised advanced-composite autos could far eclipse the ~40% mass saving Ford's aluminum-intensive *P2000* achieved in 1998:

- GM's 1991 *Ultralite* 4-seat roadster (similar to a Japanese concept car built a few years earlier but never announced) weighed 635 kg.[vii] With a 79-kg, 111-hp two-stroke engine—smaller than a Honda *Civic*'s—but no hybridization, it could accelerate 0–60 mph in 7.9 s (like a 12-cylinder BMW *750iL*), average 62 mpg, and cruise at 100 mpg at 50 mph using only 4.3 hp at the wheels—71% less than an Audi *100*. Its efficient packaging combined the wheelbase of a Lexus *LS-400*, the exterior volume of a Mazda *Miata*, and the interior spaciousness of a Chevrolet *Corsica*, which was twice as heavy and half as efficient. For a 100-day project whose haste at least doubled the mass of its 6-piece, 191-kg carbon-fiber monocoque[viii] body, not yet optimized nor engineered for production, that's impressive.
- Hypercar, Inc.'s 2000 *Revolution* midsize crossover upmarket SUV was virtually designed with two Tier One firms to weigh just 857 kg—52% less than its steel market comparable (2000 Audi *Allroad 2.7T with Tiptronic*).[ix] Midvolume production costing, based on supply-chain cost-pack responses for a 499-line-item Bill of Materials, indicated a <2-y U.S. retail payback at $3/gal for a gasoline-

hybrid AWD variant. A nonhybrid gasoline powertrain like the steel *Allroad*'s was found to offer a 54% weight and 59% fuel saving at a pretax retail price premium of just 1.6%, implying a four-month payback—nearly free ultralighting.[x]

- In 2007, Toyota unveiled the *1/X,* a carbon-fiber plug-in hybrid concept car with the same interior volume as a 2007 *Prius* but half its fuel use and 67% less curb mass, or 70% less if it had a comparable powertrain.[xi] Follow-on plans have not been revealed, but one day earlier, Toray, the world's largest maker of carbon fiber, had announced a $0.3b plant to "mass-produce carbon-fiber car parts for Toyota," then added Honda, Nissan, Subaru, and Daimler—later its joint-venture partner in producing carbon-fiber parts in Stuttgart. There are ample indications of Japanese ambitions to mass-produce ultralight carbon-fiber autos.

GM *Ultralite*, 1991

Hypercar *Revolution*, 2000

Toyota *1/X*, 2007

Such >50% to 70% curb-mass reductions remain rare due to ten[xii] main barriers—less technological and economic than cultural and organizational—that have thus far delayed widespread structural adoption of carbon-fiber composites:[xiii]

1. Ultralight autos can't be achieved within the same mindset and design space that created heavy autos, any more than Kelly Johnson could have designed the *Blackbird* in the same way that he'd created the *U-2* spy plane. He understood that design is like a rubber band: the more you try to stretch it from current norms, the more resistance you feel, and eventually it breaks. To achieve a very different result, you must jump into a whole new design space with its own brand-new rubber band. If some needed elements aren't yet ripe, you can stretch the rubber band back toward today's norms, but as the technologies mature, the rubber band will relax toward your goal and pull you into the future.
2. Ultralighting cannot be achieved by today's ultra-complex, siloed, dis-integrated design process. When David Taggart was leading the 1992–94 Lockheed-Martin Skunk Works'® design of a 95%-carbon-composite tactical-fighter airframe—one-third lighter but two-thirds *cheaper* than its 72%-metal predecessor—he used Kelly Johnson's novel ways of organizing the designers. He then reapplied them when he led the *Revolution* design team in 2000. For example, the seven engineers each responsible for one major vehicle system had no requirements for those systems—*only for the entire vehicle,* so no system could be optimized at the expense of another, and all must be optimized together as a whole system around the same table. This highly integrative, compact, agile design process is still novel to automakers, though Toyota reportedly used it to design the *1/X*.

3. Ultralighting comes only from optimizing the whole vehicle, not just its parts, and from the wheels back (fitness first, powertrain last). GM's *EV-1* was a rare example of such clean-sheet design. In 2000, functional integration saved not only 57% of mass in *Revolution*'s structure, but also 72% in trim and interior[xiv], 54% in electrical, 38% in propulsion, and 34% in chassis. Astonishingly, the first serious effort by a major U.S. automaker to answer a very simple question—how much lightweighting (even with metals) could be paid for by shrinking the powertrain to get the same acceleration—was only in 2007. Automakers' siloed organization is traditionally ill-suited to asking such questions, though their superb engineers and analytic tools can certainly answer them—an important start, though still many complex steps away from production intent.
4. Ultralighting must exploit mass decompounding—snowballing mass savings—through recursive design that shrinks and even eliminates components and subsystems. Lightness multiplies. This aerospace practice[xv] is also rather new to automakers, who prefer picking standard parts out of the bin to redesigning them for just the needed size and strength. Designers seldom exploit the potential to *eliminate* big parts or subsystems: *e.g.*, wheelmotors can eliminate transmission, clutch, flywheel, axles, differentials, driveshaft, and U-joints.
5. For best results, ultralighting should exploit anisotropic structures—with different strength and stiffness in different directions. Modern advanced-composite manufacturing techniques could scale to produce these cost-effectively, indeed at no extra cost but with considerable weight and cost *savings*—but most metal-car experts don't yet know how to design anisotropically.[xvi] Most or all carbon-fiber cars slated for 2013 volume production conservatively use biaxial carbon-fiber cloth, limiting anisotropy's weight and cost savings. Aerospace composites pioneer Burt Rutan doesn't hire people from metal-airplane companies because, he says, they have too much to unlearn, but many could use a mental retread.
6. Ultralighting needs wider adoption of modern virtual tools for structural analysis and crash simulation. Some practitioners believe those tools already suffice, while others think they need further refinement, which DOE is helping to fund. There are similarly divergent views about post-crash diagnosis and reparability, recycling, and other key enableing technologies.
7. For the sake of familiarity, comfortable rates of cultural change, and comity with suppliers, most automakers switch materials part-by-part. However, the resulting mixed-materials structural solutions, especially for autobodies, tend to incur more problems (incompatible coefficients of thermal expansion, joining issues, paint mismatches, etc.) than switching from metal-dominated to more-coherent composite-dominated solutions and using metal only where necessary.
8. Ultralighting must overcome a host of other challenges, including immature supply chains (metal producers fiercely defend their arena with well-organized technical programs, while polymer producers have long lagged in comparable support for automakers' R&D); obsolete metrics (counting cost by the part or pound, not by the auto); and the old Detroit habit of counting sunk costs as unamortized assets (thus basing strategic choices on accounting, not economics). New leadership in Detroit is starting to recognize and overcome these obstacles.

9. Automakers' cost comparisons usually overlook the opportunity for radically simpler manufacturing. For example, *Revolution*'s SUV body[xvii] had just 14 parts —~90–95% fewer than a steel SUV body—and each part is formed by one low-pressure dieset, not an average of four high-pressure progressive steel-stamping diesets. This saves ~98–99% of the ~$0.3b tooling cost. Each part is liftable by one hand with no hoist; I can briefly lift the biggest part with one *finger*. The parts' clevis joints snap precisely together for bonding, self-aligning and detoleranced in two dimensions, so they need no robotic body shop. Any of several color-in-the-mold techniques can eliminate most or all of the ~$0.5b paint shop. There go the two hardest and costliest steps in automaking. Add the 2–3x downsizing of the powertrain, and together all these changes pay for the carbon fiber, making the ultralighting free and the total capital intensity ~80% lower. But all this is invisible to incremental thinkers focused on parts, rather than integrative thinkers who view the whole vehicle within its production and market context.
10. Hardest of all, a switch to advanced composites must survive the immune system of a metal-centric industry that is extraordinarily skilled at making metal autos, has very little (before 1996 in the U.S., no) manufacturing experience with advanced composites, has persistent and deeply held misconceptions about them[xviii], and has felt little competitive need to change. Even today, there are often major divergences of opinion and knowledge about advanced composites within the same automaker, and even more between internal and public views.

Yet many independent observers, including some senior advisors to this study, believe that succumbing to these challenges is no longer necessary or sustainable, so basic structural materials choice is ripe for transformational change. Lightweighting was the key theme of the 2011 Frankfurt Auto Show, a timely fit with oil jitters and climate concerns. But the broader strategic context could now drive far more dramatic change. Automakers' strategic imperative is "systematic derisking by cutting capital intensity, lead times, oil dependence, borrowing needs, complexity, inflexibility, and societal impacts (especially carbon emissions)."[xix] Ultralight electrified vehicles, once mature, could potentially do *all* these things; incrementally improved heavy oil-fueled vehicles cannot. Just as U.S. autobodies switched from 85% wood in 1920 to over 70% steel in 1926, or composites rapidly displaced wood and metal in the 1960s in boatbuilding and in recent years in aerospace, synthetic net-shape structures could transform automaking over the next two decades into an agile, short-cycle competitor that manages all its existential risks. The 5–7 Dec 2011 *CompositesWorld* annual Carbon Fiber 2011 conference found[xx] carbon fiber is being rapidly adopted "in a huge range" of industrial applications, and reported: "Forget the *What's a composite?* question; it's now *Is there enough fiber to sustain growth*?" Carbon fiber is "evolving into high-volume processing" in many applications. Automakers currently lag some other sectors, but not for long.

Safety is another motive for advanced composites: their crush structures can absorb 6–12 times as much crash energy per pound as steel, and their smoother crushing (nearly a square-wave response) can use the crush stroke up to twice as efficiently.[xxi] Exploiting these attributes can make autos large (hence comfortable and safe) without making them heavy (hence hostile and inefficient). U.S. rules that regulate efficiency by size, not weight, now decouple these parameters. Also, advanced composites don't rust or fatigue, fenderbenders can become fenderbouncers, raw materials choices are diverse, and complete recycling is straightforward.

Carbon fiber is probably about to become much cheaper as supply catches up with demand, processes mature and scale, and new, far less expensive raw materials and manufacturing processes for carbon fiber move to market. DOE already expects high-volume carbon-fiber prices to fall below the $6/lb assumed in ref. 2, and is starting to shift its R&D strategy to support lightweighting, though its emphasis is still on cheaper carbon fiber, not on busting barriers to its wide adoption. Michigan's Center for Automotive Research has also just launched the Coalition for Automotive Lightweighting Materials to advance agendas common to all lightweight materials.

At least 17 firms now offer process equipment for manufacturing advanced-composite structures with near-aerospace performance. Some processes are scalable to cycle times of 1–3 minutes per part and offer variable thickness, molded-in holes, overmolding, anisotropy, and arbitrary fiber mixtures (*e.g.*, combining carbon with far cheaper glass fiber to achieve near-carbon properties at nearer-glass cost). One especially rapid and versatile U.S. process (see posted videos) robotically lays up thermoplastic/carbon-fiber prepreg tape to form a multilayered flat tailored blank, warms it to soften the thermoplastic, then thermoforms the consolidated blank onto a hot die, quenches the die, and about a minute after thermoforming, trims off ~7% typical scrap to yield the finished net shape.[xxii] Current German resin-transfer-molding processes reportedly have severalfold longer cycle times, manyfold higher scrap rates, and often much higher pressures and capital costs.

Adhesive, ultrasonic, and induction bonding (all more durable than spot-welding steel), reparability, and Class A finish show gratifying progress. Major carbon-fiber makers like Toray, Teijin (partnered with GM), and Zoltek have established advanced-composite automotive centers. So has the Japanese Government, with Germany in hot pursuit. Together, these advances could help make composite autos' total manufacturing costs comparable to those of today's steel autos, especially if traditional emphasis on thermosets, like those favored by Dow (now partnered with Ford), is widened to include potentially advantageous thermoplastics.

Mass-produced carbon-fiber cars began in 2011 to move from wishlists toward assembly lines. BMW's *i3* electric car, combining carbon fiber with an aluminum structure, is slated for 2013 midvolume production. Volkswagen and Audi have also announced volume production of carbon-fiber electrified autos by 2013; VW's, a 2-seat plug-in hybrid[xxiii], is rated at a gamechanging 230 mpg gasoline-equivalent. Combining this imminent production intent and the strategies behind it with indications of similar ambitions elsewhere strongly suggests that carbon-fiber autos could become a significant market force not in decades but in *this* decade.

Lightweighting improves autos with any powertrain using any fuel, but is especially advantageous in electrified vehicles. Indeed, it can trigger an electrification revolution by saving half to two-thirds of the costly batteries or fuel cells otherwise needed. (BMW has said the *i3*'s carbon fiber's marginal cost is offset by needing fewer batteries.) Exploiting three steep and strongly synergistic learning curves—in carbon fiber, its structural manufacturing, and electric powertrain—can create strong competitive advantage. Rivals today find it hard to catch up with Toyota's 15-

year lead in hybrids, but hybrids have just one learning curve, not three. This automotive strategy built on vehicle fitness also reverses today's electrification strategy. Making batteries or fuel cells *fewer first* can greatly accelerate electrification, boosting sales that then make these costly components cheap later—thus achieving the goals of DOE's cheaper-first strategy but with less time, risk, and cost.

Based on my work in the industry, I believe that by 1Q12, between three and seven automakers worldwide had adopted or were moving to adopt this breakthrough strategy. If it became pervasive across U.S. automaking and auto markets, it would double the normally expected oil savings over the next 40 years through vehicle fitness, then enable electrification that saves the other half of the oil[xxiv]—an outcome far outside the limited range that this study considers. Carbon-fiber autos could thus represent, in 2050 U.S. potential, 1.5 Saudi Arabias or half an OPEC, costing $18/bbl and found by drilling in the Detroit Formation—America's most prospective oil play. Those "negabarrels" are domestic, secure, carbon-free, and inexhaustible. And capturing them opens up new, high-value petrochemical markets.

Ref. 2 analyzes the implications of this contingency, plus well-established efficiency potentials in other vehicles and other sectors. and in the renewable supply transition they permit. It finds that a 2.6-fold larger U.S. economy in 2050 could need no oil, no coal, no nuclear energy, and one-third less natural gas; have a $5-trillion lower net-present-value private internal cost than business-as-usual; require no new inventions and no Acts of Congress; and be led by business for profit. In due course, readers will discover in the marketplace whether this NPC study, rather than being constrained by traditional automakers' old conventional wisdom, should have analyzed the vehicular part of this new potential, as some of us advised at the time.

—Amory B. Lovins, SAE (NPC member and L1 advisor)
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[i] T.C. Moore & A.B. Lovins, "Vehicle Design Strategies to Meet and Exceed PNGV Goals," 19 Aug 1995, SAE 951906, Society of Automotive Engineers.

[ii] A.B. Lovins and Rocky Mountain Institute, *Reinventing Fire: Bold Business Solutions for the New Energy Era*, Chelsea Green (White River Junction VT), Oct 2011, esp. Ch. 2, and full documentation at www.reinventingfire.com. Nontechnical summaries are in *Foreign Affairs* **91**(2):131–146 (Mar/Apr 2012), www.rmi.org/Knowledge-Center/Library/2012-01_FarewellToFossilFuels, and a May 2012 talk at ted.com.

[iii] N. Lutsey, "Review of technical literature and trends related to automobile mass-reduction technology," UCD-ITS-RR-10-10, Institute of Transportation Studies, U.Ca./Davis, May 2010, pubs.its.ucdavis.edu/publication_detail.php?id=1390.

[iv] D.L. Bleviss, *The New Oil Crisis and Fuel Economy Technologies: Preparing the Light Transportation Industry for the 1990s*, Quorum Books (NY). For comparison, GM's 2-seat *EV-1* weighed 1,400 kg with lead-acid or 1,319 kg with NiMH batteries.

[v] These designs included VW's 5-seat *Auto 2000* (779 kg), Peugeot's 5-seat *205XL* (767 kg), Volvo's 5-seat *LCP 2000* (707 kg), VW's 5-seat *E80* diesel (699 kg), British Leyland's 4-seat *ECV-3* (664 kg), Toyota's 5-seat *AXV* diesel (649 kg), Renault's 4-seat *VESTA II* (475 kg), and Peugeot's 4-seat *ECO 2000* (449 kg).

[vi] This means polymer composites whose reinforcing fibers are significantly stronger than glass fiber, such as carbon fiber or aramid. However, mixtures of various fibers are often advantageous for improving toughness, fracture masking, cost, etc.

[vii] J. Keebler, "GM Builds 100-mpg 'Ultralite' car," *Automotive News*, pp. 1 & 31, 31 Dec 1991; D. Sherman, "Using Carbon Fibers to Conserve Hydrocarbons: GM Ultralite," *Motor Trend*, pp 74–76, Feb 1992.

[viii] A monocoque's shell *is* the structure—like a lobster shell—with no separate frame.

[ix] Described briefly in refs. 1 and 2 and more fully in A.B. Lovins & D.R. Cramer, *Int. J. Vehicle Design* **35**:50–85, www.rmi.org/Knowledge-Center/Library/T04-01_HypercarsHydrogenAutomotiveTransition. (See also D.R. Cramer & D.F. Taggart, "Design and Manufacture of an Affordable Advanced-Composite Automotive Body Structure," *Procs. 19th Intl. Battery, Hybrid & Fuel Cell El. Veh. Sympos. & Exh. (EVS-19), 2002*, www.rmi.org/Knowledge-Center/Library/T02-10_AdvancedCompositeAutomotiveBody.) Today's powertrain and structural components (which would permit a true monocoque) could now raise *Revolution's* mass saving to the high 50s of %. But just its original *5*-seat SUV carbon-fiber design had the same curb weight as the 2001 Honda *Insight 2*-seat aluminum hatchback I drive.

[x] These further results are from a DoD-sponsored 2004 reanalysis: A.B. Lovins, E.K. Datta, O.-E. Bustnes, J.G. Koomey, & N.J. Glasgow, *Winning the Oil Endgame*, RMI, www.oilendgame.com, pp. 61–72.

[xi] According to its lead designer, the 420-kg curb mass of Toyota's *1/X* would have been 400 kg—70% lighter than a 2004 *Prius*—without the extra 20 kg of batteries that made it a plug-in hybrid, but including the half-liter engine under the rear seat.

[xii] An industry survey in 1995 elicited an astounding 324 barriers—12 per interviewee (M. Flynn & B. Belzowski, "Barriers to Automotive Composites: Concerns, Competition, and Competence," *Adv. Compos. Conf. & Expos.* **11**:517–535 (6 Nov 1995). Solutions were surveyed in M.M. Brylawski & A.B. Lovins, "Ultralight-Hybrid Vehicle Design: Overcoming the Barriers to Using Advanced Composites in the Automotive Industry," *41st Intl. Soc. Advancement Mater. Proc. Eng. (SAMPE) Sympos. & Exhib.*, 25–28 Mar 1996, www.rmi.org/Knowledge-Center/Library/T95-39_UltralightHVDesignBarriers, and elaborated in —, "Advanced Composites: The Car Is At the Crossroads," *43rd SAMPE Sympos. & Exhib.*, 31 May – 4 June 1998, rmi.org/Knowledge-Center/Library/T98-01_CarAtCrossroads.

[xiii] Rocky Mountain Institute has a project underway to help vault these barriers.

[xiv] Ref 2, p 23: "…by exposing the body structures to the interior and making their components simultaneously vibration-damping, crash-absorbing, heat-insulating, good-looking, and therefore fewer." Each part does many jobs. A 7.5-kg composite Lotus *Elise* front-end structure provides structural integrity (mountings for optional headlamps, radiator, and "clamshell" one-piece front body), sealed ductwork for the radiator and the HVAC intake, and a crush structure that can absorb the entire energy of a 30-mph fixed-barrier crash, leaving the aluminum chassis undamaged.

[xv] G. Rucks (RMI), 2012, http://blog.rmi.org/blog_what_automakers_can_learn_from_boeings_culture_of_weight_reduction.

[xvi] BMW's *i3*, though impressive, is made by a resin-transfer-molding process based on woven carbon-fiber cloth. This saves 24% of curb weight and improves mechanical performance but can scarcely exploit anisotropy. Alternative materials formats and processes can save far more mass and cost while eliminating the metal frame.

[xvii] See ref. 2, p 23. Boeman & Johnson (ORNL Publ. #$2002-01-1905) found an 18-part carbon autobody could cut body-in-black weight 60%, *vs. Revolution*'s 57%.

[xviii] For example, that making structures must be costly (hand layup) and costly (autoclaving thermoset resins like epoxy), like handmade racecars. No longer.

[xix] Ref. 2, pp 41–42.

[xx] S. Black, *Composites World*, March 2012, posted 29 Feb 2012, www.compositesworld.com/articles/carbon-fiber-market-gathering-momentum. However, some automotive analysts rightly note that aerospace leadership in carbon-fiber demand emphasizes higher performance—*e.g.*, ~3,600 Mpa strength and 225 GPa modulus even for commodity fiber—than most automotive structural applications would require (roughly 1,700 and 170 respectively).

[xxi] Handling can also improve due to greater stiffness: ref. 9, p 63, n 330.

[xxii] Www.fiberforge.com. I am this firm's Chairman Emeritus and a small shareholder.

[xxiii] This 795-kg 2-seat *XL-1* is only 23% ferrous, and like GM's 1991 *Ultralite* concept car, boasts superlative aerodynamics (C_d = 0.186) and excellent tires.

[xxiv] Ref. 2, Chapter 2. Full analytic assumptions and models with supporting data were made available in late 2011 to this study's lead integrator but were not adopted as an alternative to or sensitivity test of this study's findings.