Re: DEPARTMENT OF TRANSPORTATION
National Highway Traffic Safety Administration
49 CFR Part 533
[Docket No. 2003-16128]
RIN 2127-AJ17
Reforming the Automobile Fuel Economy Standards Program

26 April 2004, by Fedex

Docket Management Facility
U.S. Department of Transportation
400 Seventh Street, SW., Nassif Building, Room PL-401
Washington, DC 20590-001

Dear NHTSA:

On 27 April 2003, I wrote to NHTSA Administrator Dr. Jeffrey Runge, marked "personal," some comments of the kind whose solicitation is described on p. 18 of your Notice of Rulemaking in this proceeding (hereinafter NR:page). While I didn't link those comments numerically to a docket or RIN number, I did expect them to be delivered to Dr. Runge, as they contained the kinds of basic technical and policy suggestions provided in these comments. Unfortunately, as I later discovered (too late to help inform the agency in framing this proceeding), NHTSA did not deliver my comments to him, but instead filed them unread by any policymaker and with no action taken. Hence the need for me to resubmit these expanded and updated comments more formally.

This proceeding brings NHTSA to a critical juncture. Setting the wrong policy here will not only lastingly harm the national interest in saving lives, oil, and emissions. It will also degrade the competitive prospects of U.S. automakers by encouraging them to make vehicles that increasingly are unsaleable abroad. Many policymakers in Europe, Japan, China, and Canada don't share—for reasons described below—the view that light vehicles, except perhaps the heaviest, must stay heavy for safety (or that CO_2 isn't important). As U.S. OEMs struggle with eroding market share and strive to globalize their operations, further perverse U.S. regulatory incentives are the last thing they need.

The conceptual basis of this proposed rulemaking is technically incorrect in three fundamental respects:

- NHTSA's historic correlations between weight and crash risk are being taken as predictive, when in fact they have no predictive validity or value. Extrapolating from past to future is wrong in principle.
- It's also wrong in practice, because the assumed linear "relationship between weight and size" (NR:56) can be radically altered by modern materials and manufacturing technologies without harming cost-competitiveness. The weight/size relationship can't be inferred from historic statistics and assumed fixed; it's a major technical and policy *variable* which policy should be designed to *influence*—strongly.
- Specifically, neither NHTSA nor the NAS/NRC report on which this rulemaking relies has substantively considered new technical solutions, using either high-strength steels or advanced polymer composites, that can decouple size from mass. NHTSA's proposed policy framework therefore overlooks the potential for such solutions to eliminate the safety/fuel-economy/cost tradeoffs that this rulemaking is meant to grapple with. It seeks to solve a problem that can be readily and advantageously avoided.

These views are explained below in terms of three key technical points seemingly missing from NHTSA's views:

- the pervasive and dangerous confusion between vehicle size, vehicle mass, fuel economy, and safety;
- the rapidly emerging potential to make vehicles ultralight but ultrasafe and cost-competitive; and
- the criteria that should govern public policy in order to reduce the public health risk of vehicle accidents.

Public policy criteria

Starting with the third of those points, and seeking to make my philosophical as well as technical framework clear at the start: I think that good science, the rapidly emerging ultralight vehicular structural options described below, the need to take market economics seriously, and common sense would all suggest that any CAFE modifications should:

- be performance-based, not prescriptive
- be at least neutral as to vehicle mass, rigorously avoiding any incentives for a further “mass arms race”
- if they *do* influence mass, favor its *downward* rather than upward harmonization
- if fuel-economy choices are desired to be decoupled from vehicle-size-class choices, then do so by normalizing to *size*—*e.g.*, to gal/mi per interior ft^3—*not* to mass, so as to encourage size/mass decoupling
- be technology-neutral but preferably (in the national interest) technology-forcing

I also think other public-policy instruments, superior to CAFE, would be better ways to drive automotive innovation, especially on the lines of the feebates[1] and accelerated scrappage I’ve proposed for the past few decades. These are further analyzed in a major DoD-cosponsored study my RMI team will publish in July.[2] Nonetheless, I’ll frame these comments as if the CAFE regime must continue indefinitely (as perhaps it should to discourage recidivism).

A note on my background

> Amory B. Lovins, 57, is CEO of Rocky Mountain Institute (www.rmi.org), an independent, nonpartisan, nonprofit, entrepreneurial applied research center he cofounded in 1982 in Snowmass, Colorado. RMI’s ~50 staff foster the efficient and restorative use of resources to create a secure, prosperous, and life-sustaining world. Mr. Lovins founded two of RMI’s four for-profit spinoffs.
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> A consultant experimental physicist educated at Harvard and Oxford, he has received an Oxford MA (by virtue of being a don), eight honorary doctorates, a MacArthur Fellowship, the Heinz, Lindbergh, and *Time* Hero for the Planet Awards, the Happold Medal, and the Lindbergh, Mitchell, “Alternative Nobel,” Shingo, and Onassis Prizes; held visiting academic chairs; briefed 18 heads of state; published 28 books and several hundred papers; and consulted for scores of major corporations and governments worldwide. *The Wall Street Journal*’s Centennial Issue named him among 39 people in the world most likely to change the course of business in the 1990s, and *Car*, the 22nd most powerful person in the global automotive industry. A former member of DOE’s Energy Research Advisory Board and of a Defense Science Board panel on military platform efficiency, he is a member of SAE and a Fellow of AAAS and WAAS.
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> Mr. Lovins’s 1990–91 invention of a highly integrated ultralight-hybrid car concept, now known as the hypercar® approach, received the 1993 Nissan Prize at the main European car-technology conference, ISATA, and the 1999 World Technology Award in association with Booz Allen & Hamilton and *The Economist*. He and his colleagues have advised senior executives and development engineers at several dozen automakers and suppliers, which have collectively committed ~$10 billion to this general line of development since he put the hypercar concept in the public domain in 1993 and maximized competition in exploiting its market and manufacturing advantages. In 1999, he spun off RMI’s Hypercar Center into an independent for-profit technology development firm, Hypercar, Inc., which he chairs and which in 2003 won its own World Technology Award. In eight months of 2000, for a few million dollars, the firm developed a production-costed and manufacturable virtual design for an uncompromised, cost-competitive, quintupled-efficiency midsize SUV described below. Hypercar, Inc. has raised $10 million of private equity and is currently completing the validation of its patented Fiberforge™ process for manufacturing ultralight carbon-composite autobodies meeting all requirements at mid-volume at competitive production cost. To declare an interest, Mr. Lovins holds minor shares and options in Hypercar, Inc., and in two publicly traded fuel-cell companies.

This background enables me to offer NHTSA some uniquely independent views as an innovation- and market-oriented technologist and designer, a long-time industry observer (at senior including CEO level), a supporter of the industry’s transition, from a nonaligned nonprofit group that doesn’t lobby or litigate, working in over 50 countries, and covering (within the bounds of discretion) topics that OEMs can’t discuss because of their competitive constraints on proprietary information. Now, from that perspective, I’ll explain the conclusions above.

Size/mass confusion

Most light-vehicle collision-safety discussions, including this rulemaking, confuse vehicle size, mass, fuel economy, and design. Neither NHTSA nor NAS adequately distinguishes these attributes, nor emphasizes that differences in

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[1] D.L. Greene, P.D. Patterson, M. Singh, & J. Li, “Feebates, rebates and gas-guzzler taxes: a study of incentives for increased fuel economy,” *En. Pol.*, in press, 2004.
[2] A.B. Lovins *et al.*, *Winning the Oil Endgame*, Rocky Mountain Institute, www.rmi.org, in preparation, July 2004.

design and materials can decisively decouple variables assumed to be inextricably and inexorably linked, such as size and mass, mass and safety, or size and fuel intensity. Let me start with some contextual remarks:[3]

- There is no causal relationship between present cars' fuel economy and their on-the-road fatality rate.
- Statistical correlation never proves causality. Regression analysis is the last analytic resort (if one cannot directly test a causal hypothesis by scientific experiment) and is notoriously prone to mislead.
- Historical fleet behavior reflects the relative homogeneity of vehicles built of similar structural materials (nearly all steel) and in broadly similar ways (unibody or framerail). It can never support an inference about the safety, mass, or other attributes of future vehicles built of other materials or using other designs.
- The most important finding of NHTSA's historic-fleet regression analysis[4] is the very large spread in crash safety between different models of comparable weight. Unfortunately, NHTSA has never seen fit to fund a serious exploration of why some cars at a given weight are far safer than others of similar weight, so that details of design and materials conducive to safety, especially if lightweight, can be encouraged while those harmful to safety can be discouraged. This serious gap in NHTSA's analysis is far more important to the success of its core safety mission than the great attention it has paid to spurious mass/safety correlations based on aggregate regression-line behavior within a highly scattered data set for broadly similar vehicles. It seems especially important to understand the links between design quality and safety in light of Wenzel and Ross's striking 2003 claims that foreign cars are less crash-risky than domestic ones with the same weight, and that the domestic fleet's risk is better predicted by price (or *Consumer's Report* quality ratings) than by vehicle weight—indeed, that the apparent statistical link between weight and risk disappears if the regression includes a variable for resale value.[5] If correct, these conclusions would shake Dr. Kahane's thesis to its roots, and suggest that by emphasizing weight, NHTSA is looking for safety in the wrong places.
- Better control of risky driver behavior is crucial: behavior may be 10^3 times more risk-determining than the vehicle. Dr. Leonard Evans, when he led GM's safety research, pointed out that only ~1/20^th^ of crashes don't involve driver factors.[6] Car attributes can be very difficult to sort out from driver factors, just as it's nearly impossible to distinguish mass from size effects in the steel-light-vehicle fleet.
- About the only unambiguous correlation that emerges from the historic data is between risk and acceleration—a fact unmentioned since the marketing of more muscular vehicles intensified in the mid-1980s.
- All vehicles should be made safer without putting the adjustment burden (if any) on the lighter-weight ones. Heavier vehicles have a special need to be made less aggressive[7]—softer, less angular, more absorptive, more compatible, with bigger ridedown distances—and the on-the-road fleet's mass dispersion should be narrowed.[8] It may be worthwhile to equip heavy trucks with highly energy-absorbing front structures—perhaps even external airbags.
- The laws of physics require that collisions between two cars *identical* except in mass will tend to damage the lighter car more. This also means heavier vehicles, other things being equal, are riskier for those they hit. It's gratifying to see NHTSA's recent attention to this issue. But it's regrettable that NHTSA pays less (if any) attention to new ways, described below, to make the "other things" as *un*equal as possible, taking advantage of two key engineering facts: *new materials and protective designs can be far more important to safety than is mere mass, and the structures and systems needed to protect people weigh very little.*[9]

The majority in the NAS/NRC report[10] on which this rulemaking rests implicitly assumed that autobodies will continue to be welded from stamped steel in today's common designs (unibody or framerail), so future cars, like past ones, will become less protective if they're made lighter *and*—importantly—if nothing else changes, as NHTSA's interpretation of its historic-fleet regressions implicitly assumes. But as Henry Ford put it, "I cannot imagine where the delusion that weight means strength came from." Cars' weight does *not* necessarily determine their size or

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[3] These are largely based on my automotive article in the 1995 Wiley *Encyclopedia of Energy and the Environment*.
[4] C.J. Kahane, *Vehicle weight, fatality risk and crash compatibility of model year 1991–99 passengers cars and light trucks*, NHTSA, DOE HS 809 662, October 2003, www.nhtsa.dot.gov/cars/rules/regrev/evaluate/pdf/809662.pdf.
[5] T. Wenzel (LBNL) & M. Ross (U. Michigan), "Are SUVs Safer than Cars? An Analysis of Risk by Vehicle Type and Model," 15 Jan. 2003 brief to Transportation Research Board 82^nd^ Meeting, Washington DC. The vertical scatter in their slide 9 also shows large differences in risk to other drivers depending on which of several outwardly similar (same-class) vehicles hits theirs.
[6] L. Evans, *Traffic Safety and the Driver*, Van Nostrand Reinhold (NY), 1991.
[7] R. Käser, "Safety potential of urban electric vehicles in collisions," *Procs. Urban Electric Vehicle Conf.* (25 May 1992), OECD/NUTEK/IEA, Stockholm; T.C. Moore & A.B. Lovins, "Vehicle Design Strategies to Meet and Exceed PNGV Goals," SAE 951906, 1995, www.rmi.org/images/other/T95-27_VehicleDsnStategies.pdf.
[8] I concur with the line of findings by NHTSA's Hans Joksch (DOT/HS 808 802, 809 194, 808 679) that if properly done, this should improve overall safety.
[9] Moore & Lovins (ref. 7).
[10] National Research Council, *Effectiveness and Impact of Corporate Average Fuel Economy (CAFE) Standards*, 30 July 2001, National Academy Press (Washington, DC), http://books.nap.edu/catalog/10172.html, slightly revised 2002 at …/10284.html.

crashworthiness as those historic correlations might suggest.[11] Of course, physics requires that, other things being equal, a heavier car is safer to be in but more dangerous to be struck by.[12] *But other things aren't equal*. Vehicle *size*—"the most important safety parameter that doesn't inherently conflict with greater fuel efficiency"[13]—doesn't shift risk from the projectile to the target vehicle. Rather, a car that's bigger but not heavier is safer for people in *both* vehicles, because extra crush length absorbs crash energy without adding the aggressivity of weight. *Since weight is hostile but size is protective*[14]*, adding size without weight provides protection without hostility. Lighter but stronger materials can thus decouple size from both weight and safety: bigger needn't mean heavier, lighter needn't mean smaller, and light but strong materials can improve both safety and fuel economy without tradeoff, offsetting ultralight vehicles' mass disadvantage when colliding with heavier vehicles.* That engineering fact falsifies all of NHTSA's basic assumptions underlying this rulemaking. Sorry, but the agency really needs to start over.

New ways to make vehicles simultaneously large, lightweight, safe, and cost-competitive

Two broad classes of new materials now permit light vehicles' mass and size to be substantially decoupled at attractive or zero marginal manufacturing cost while improving crash safety: new steels, and advanced polymer composites. I'll focus on composites because they're less familiar, more important, and have two unique safety advantages:

- Properly shaped crush structures made of advanced polymer composites, typically reinforced with carbon fiber[15], can far more than offset advanced-composite (or other light) vehicles' lighter mass by absorbing up to ~110 kJ/kg with a thermoset matrix—4–5 times as much energy per kg as steel can absorb—or an astounding ~250 kJ/kg, 10–12 times what steel can absorb, with a thermoplastic matrix.[16] The corresponding figure for ordinary steel crush structures is ~20 kJ/kg. For example, the front end of a 2004 Mercedes *SLR McLaren* supercar (1,768 kg curb weight) contains two 3.8-kg thermoset crush cones, two feet long, reinforced mainly with woven carbon fiber. Their cross-section varies over their length to provide constant deceleration. Those two cones can absorb the entire crash energy of a fixed-barrier frontal crash at ~66 mph at the nominal 120 kJ/kg shown by Mercedes.[17] However, data from Dr. Evans graphed by Ross and Wenzel[18] suggest that >99% of U.S. vehicle crashes, and 75% of belted-driver deaths, involve a velocity change <35 mph: "Some crashes are at too high a speed for effective protection, but those crashes are fairly rare."
- By crushing smoothly ("square-wave response") instead of jerkily as metal does when it accordion-folds, well-designed composite crush structures can use their crush stroke ~1.5[19]to 2 times as efficiently as metal. This ratio and the deceleration profile can be optimized by appropriate fiber mixtures and geometries.

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[11] Within NHTSA, confusion persists not only at a political but also at the bureaucratic level: *e.g.*, NHTSA's *2020 Report* (Sept. 1997, www.nhtsa.dot.gov/nhtsa/whatis/planning/2020Report/2020report.html) states: "Lighter vehicles built with aluminum and plastic may create additional safety problems due to the basic physics of a heavy object crashing into a lighter object. These lighter vehicles will also have engines with higher power output due to improved efficiency and lower weight thereby maintaining present day performance with increased fuel economy." The first sentence ignores many light materials' greater strength and energy absorption per pound, and the second sentence gets the engine's power output backwards (less would be needed).

[12] L. Evans & M.C. Frick state in *Accid. Anal. & Prev.* **25**(2):213–224 (1993) two "laws" fitting their data for vehicles of various types and sizes but similar materials and design: that "when other factors are equal, (1) the lighter the vehicle, the less risk to other road users, and (2) the heavier the vehicle, the less risk to its occupants."

[13] B. O'Neill, *The Physics of Car Crashes and the Role of Vehicle Size and Weight in Occupant Protection*, Insurance Institute for Highway Safety (Arlington VA), 1995, *Phys. Med. & Rehabil.: State of the Art Revs.* **12**(1):23 (1998). The quotation refers specifically to crush length, which O'Neill agrees can improve safety in both striking and struck vehicle if added without increasing weight, *i.e.*, by using light-but-strong materials. (His article also correctly criticizes a decade-old journalistic misstatement of some safety principles of ultralight cars.) Ironically, NR:34 states that "the empirical relationships between size and safety are less well known than the relationships between weight and safety." Actually, even if the two could be statistically disentangled, in terms of energy-management physics the reverse is more nearly true, because size clearly enhances safety for both collision partners (as well as in stationary-object crashes) whileweight does not.

[14] B. O'Neill, W. Haddon, & H. Joksch, "Relationship Between Car Size, Car Weight, and Crash Injuries in Car-to-Car Crashes," *3rd Intl. Congr. Automotive Safety*, July 1974.

[15] I'll use this generic description as shorthand, but in fact a mixture of fibers may be used in composite autobodies and crush structures, including *e.g.* glass for toughness, polyaramid or Spectra or polyethylene for fracture control and cohesion, etc.

[16] H.-G. Herrmann, C. Mohrdieck, & R. Bjekovic, "Materials for the Automotive Lightweight Design," DaimlerChrysler Research & Technology (Research Center Ulm) presentation to FKA/IKA conferences *New Advances in Body Engineering*, Aachen, 28 Nov. 2002, program at www.ika.rwth-aachen.de/aktuell/veranst/euro11-02.

[17] *Id.*

[18] M. Ross & T. Wenzel, "Losing Weight to Save Lives: A Review of the Role of Automobile Weight and Size in Traffic Fatalities," ACEEE-T013, LBL-48009, 2001, www.aceee.org/pubs/t013.htm, with emphasis removed from quotation. I concur with their recommendation that weight should be reduced not only through light materials, which I emphasize here, but also through improved body design (unibody, spaceframe, monocoque,…), styles (perhaps crossover), and high-efficiency powertrains.

[19] M. Norr & D. Imbsweiler (DaimlerChrysler), "Experience in Crash Simulation of Composite Materials," Workshop on Composite Material Modeling, 22 Feb. 2001, Institut für Verbundwerkstoffe (Kaiserslautern), gives a simple empirical example.

The now well-accepted combination of up to twofold more efficient crush stroke with up to 10–12-fold greater specific energy absorption means *that ultralight vehicles made of advanced polymer composites*, or using energy-absorbing structures made of them, *can offset (or more) their mass disadvantage in collisions with heavy steel vehicles, thereby combining very light weight with superior crashworthiness and fuel economy.* It is even possible for relatively *small* lightweight vehicles to do well with heavy collision partners by extending their crush length (using packaging space freed up by the light platform's smaller powertrain), and to make their crush structure progressively stiffer as the crushing approaches the passenger compartment, thereby "borrowing" some crush length from the collision partner. (The crash performance of Honda's small, light, metal vehicles today is an impressive starting-point.)

The ability of ultralight polymer-composite vehicles to withstand collisions with heavy steel vehicles has been amply demonstrated in European tests—to the extent that the Féderation Internationale de l'Automobile (Brussels), the governing body of motorsport, gave strong video-illustrated testimony to the E.U. in the mid-1990s on how this approach can readily and radically decouple vehicle size from mass without compromising safety. Today's techniques and materials are considerably better. European best practice carefully coordinates safe lightweight energy-management structures with sophisticated occupant protection by other means.[20] This well-established[21] combination is effective enough that a 2.5-m-long *Smart* microcar's crash dummies reportedly "survived" a 31-mph, 50%-offset frontal crash with a Mercedes *S*-class ~2.5× times its weight.[22] EU acceptance of this approach underlies leading European automakers' conclusion that "Lightweight design is a must for future vehicle concepts (in Europe)"[23] to meet fuel and emissions commitments. Any U.S. regulatory approach that penalizes safe lightweighting will be correctly attacked as a nontariff trade barrier, and will boomerang on U.S. OEMs by inhibiting sale of their heavy products to Europe and its policy emulators worldwide. The correct view (EU's) ultimately wins.

Another instructive reason for reflection comes from Formula One racing. Its drivers are seldom killed nowadays even by 200+-mph crashes in their ultralight carbon-fiber cars. Kinetic energy rises as the square of speed—it's 13 times as great at 220 mph as at 60—so just the drivers' special padding can't save them. But in 2003, Swedish race-driver Kenny Brack survived a horrific ~220-mph crash in his carbon-fiber racecar—hit from behind, pinwheeled into the air and into a steel-and-concrete barrier, and smashed to bits. Brack suffered five fractures, recovered in six months, and expects to return to racing in time for the 2004 Indy 500.[24] His comment: "Obviously, this shows that the [ultralight carbon-fiber Formula One] cars are very safe."[25]

Just two days after Brack's crash, apparently without noticing any inconsistency, nearly all major media misreported that NHTSA's statistical study had found (as the *New York Times* put it) that "reducing vehicle weights would have a deadly effect over all." It found nothing of the sort: since it examined only old steel cars, it couldn't predict anything about *future* cars using different materials and designs, as the forward-looking "would" implies. If safety required weight, Brack would be dead and bicycle helmets would be made of steel. Brack is alive, and bicycle helmets are made of carbon-fiber composites, because they're such a great crash-absorber. If you doubt the strength of ultralight structures, just try eating an Atlantic lobster in its shell without tools. Carbon composites are even stronger.

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[20] *E.g.,* P. Frei, R. Käser, R. Hafner, M. Schmid, A. Dragan, L. Wingeier, M.H. Muser, P.F. Niederer, & F.H. Walz, "Crashworthiness and Compatibility of Low Mass Vehicles in Collisions," SAE 970122; P. Frei, R. Käser, M.H. Muser, P.F. Niederer, & F.H. Walz, "Vehicle Structural Crashworthiness with respect to Compatibility in Collisions," Oct. 1999, www.agu.ch/pds/Compatibility.pdf; M. Muser, G. Krabbel, V. Prescher, A. Dragan, F. Walz, & P. Niederer, "Advanced Energy Absorbing Components for Improved Effectiveness of Low Mass Vehicle Restraint Systems," *Intl. Conf. On the Biomechanics of Impact*, Dublin, 11–13 Sept. 1996 (www.ircobi.org); R. Käser, M. Muser, O.Spieß, P. Frei, J.M. Guenat, & L. Wingeler, "Passive Safety Potential of Low Mass Vehicles," *Procs. IRCOBI Conf.* 337 (1995). See also the extensive efforts and publications of the EU's Composit network, www.compositn.net.

[21] For example, after quoting a 91% weight saving for a carbon-composite square-section axial tube compared with an equally energy-absorbing steel one, the Academy's Commission on Engineering and Technical Systems concluded: "Based on these test results, the committee believes that structural concepts and analytical tools are available to design lightweight PNGV concept cars that will perform safely in collisions with heavier cars because of the excellent energy absorption characteristics of the alternate materials." *Review of the Research Program of the Partnership for a New Generation of Vehicles: Fifth Report* (1999), at p. 67, http://books.nap.edu/books/0309064430/html/67.html#pagetop.

[22] *Auto-Motor-Sport Journal* 19/1999, p. 42ff, summarized at www.bics.be.schule.de/son/verkehr/presse/2000_2/v4002_47.htm and www.threepointmotors.com/smart/index.asp. An offset-crash video is at www.off-road.com/mbenz/videos/Sclass_Smart.avi, with a >2:1 mass ratio corresponding to a velocity far over 70 km/h; an offset-crash still photo with an *E*-class is at www.whnet.com/4x4/Smart_crashtest.html; and a head-on at www.pistonheads.com/gassing/topic.asp?f=23&h=0&t=90655.

[23] H.-G. Herrmann (DaimlerChrysler), "Lightweighting in Automotive Industry," 14 March 2003, EADS-CRC (Ottobrunn), www.compositn.net/Downloads/Presentation%20-%20Lightweighting%20-%20DaimlerChrysler%20-%201pp.pdf.

[24] C. Cavin, "Brack continues recovery with his return to stage," *IndyStar*, 7 April 2004, www.indystar.com/articles/6/135805-5186-037.html.

[25] T. Savage, "Brack Gives First Interview Since Crash at Texas," 4 Nov. 2003, www.indyracing.com/indycar/news/story.php?story_id=2115.

Impressively safe ultralight composite family vehicles have already been designed. Some show promise of cost-competitiveness; I'll give an example below. National policy should encourage such decoupling of size from weight and safety, reverse the spiraling (and unsubtly marketed) "arms race" in vehicle weight,[26] and save both lives *and* oil. Nothing in the backward-looking NHTSA study, nor in science or engineering, refutes such innovations. To make its light-vehicle fleet safer, the U.S. needs to:

> …resolve the incompatibility of light trucks with cars [in weight, frontal stiffness, and height] and it needs to continue development and adoption of powerful crash mitigation and avoidance technologies. Making heavy vehicles lighter (but not smaller) and making lighter cars larger (but not heavier) would not only increase safety but also increase fuel economy…[by] over 50%….[27]

Or as Dr. Evans correctly confirmed just last month:[28]

> Increasing the amount of light-weight materials in a vehicle can lead to lighter, larger vehicles [possessing]…all of the following concurrent characteristics: reduced risk to its occupant in two-vehicle crashes; reduced risk to occupants in other vehicles into which it crashes; reduced risk to its occupants in single-vehicle crashes; reduced fuel consumption; reduced emissions of [CO_2]….

Advanced polymer composites are especially attractive for this role, because not only do they have exceptional crash energy absorption, stiffness, and durability, but they also hold promise of simpler and cheaper manufacturing with dramatically reduced capital intensity, operating costs, and plant scale, thereby strongly favoring early adopters.

My main point about Dr. Kahane's latest study is not that his correlations were defective (though they do appear to be[29]), but rather that his report was artfully framed to invite exactly the misinterpretation that occurred, apparently even by his own agency—namely, that historic correlations about similarly designed steel cars determine what is possible and what public policy should assume and influence for all future cars, made of any material, using any design. As noted above, the big lesson of his analysis is the wide variation in safety observed between different models of similar weight. That's an encouraging sign that empirically road-validated, empirically cost-effective *design* improvements are staring NHTSA in the face, but aren't yet being analyzed or applied to the vehicle fleet.

Thus ultralight advanced materials and design can in principle yield a far lighter but more crashworthy vehicle that is less mass-aggressive toward other vehicles, yet protects its occupants better even if its collision partner is far heavier. This win-win for public health is now becoming technically and economically possible, and needs to inform fuel-economy/safety conversations before ill-advised policy changes in this rulemaking discourage or prohibit it.

Basic weaknesses in the NAS/NRC study

Unfortunately, NHTSA appears to place heavy reliance on the 2001 NAS/NRC study, whose flawed process and logic greatly reduce its usefulness. All but two of its panelists didn't understand that it's both feasible and profitable to make vehicles lighter *and* safer simultaneously. And just as its predecessor did in 1991, the panel gravely underestimated the dynamism of the private market. It refused, for example, to consider hybrid propulsion among "emerging" technologies during ~2001–2017, let alone among technologies with "production intent," even though upwards of 85,000 hybrid light vehicles had already been sold by the time NAS reported in 2001 (and over 200,000 through 2003; U.S. hybrid sales have grown at an average rate of 89%/y during 2000–03). That's embarrassing.

It gets worse. Thirty-four weeks after the NAS report was formally published, Toyota's 2004 *Prius* came on the U.S. market, beating midsize sedans' efficiency (27.1 mpg) by not NAS's projected 20 but 28 mpg, not in 2012–17 but in 2003, all at the predicted price increase of $2,000–4,000 but shaved from the manufacturer's margin, not added to the sticker price.[30] Nor was this the Academy's first such embarrassment by the market: its 1992 study of this sub-

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[26] P. Roberts, "Bad Sports," *Harper's*, April 2001, www.stayfreemagazine.org/suv/harpers.html; K. Bradsher, *High and Mighty: SUVs—The World's Most Dangerous Vehicles and How They Got That Way*, Public Affairs (NY), 2002.

[27] M. Ross & T. Wenzel, ref. 18 above. For a useful lay commentary, see M. Gladwell, "Big and Bad," *The New Yorker*, 12 Jan. 2004, pp. 28–33, which notes, for example, that the subcompact VW *Jetta* has half the total fatality rate (per million car-miles driven) of popular SUVs nearly twice its weight, and protects its occupants similarly or better.

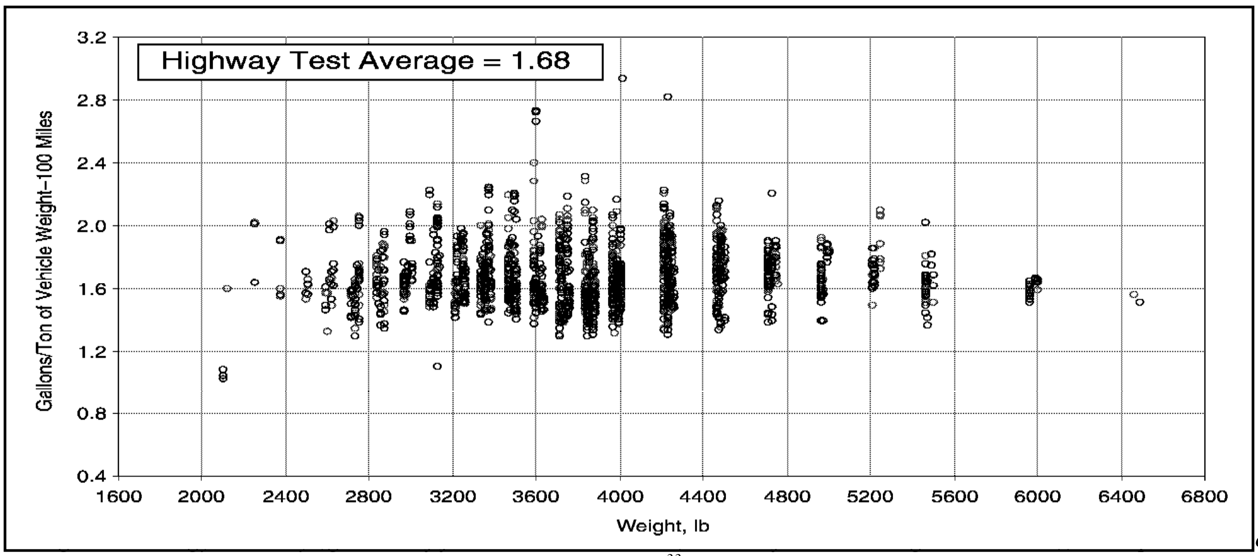
[28] L. Evans, "How to Make a Car Lighter and Safer," SAE 2004-01-1172 (10 March 2004, SAE World Congress), converting his bullets into semicolons.

[29] *E.g.*, see ref. 5 above, and further criticisms in "Key Deficiencies in the 1997 and 2003 Weight/Fatality NHTSA Studies: Initial Review," 15 Oct. 2003, www.citizen.org/documents/kahane2_guide.pdf.

[30] Public data don't permit a comparison of differences in manufacturer's margin between the 2004 *Prius* and such benchmark vehicles as the 2004 *Camry* or *Corolla*, but the *Prius* is rumored to earn a ~$1,100 manufacturer's margin and is authoritatively stated to incur a marginal production cost (over a similar nonhybrid) corresponding to ~$4,000 of MSRP, expected to fall to ~$2,000 over the next few years. In features, size, and price, it's between *Camry* and *Corolla*, but more value-loaded.

ject was published only weeks before the 51-mpg 1992 Honda *VX* subcompact hatchback entered the U.S. market. It was 16% more efficient, and its 56%-in-one-year mpg gain was 32–73% cheaper, than the Academy had deemed feasible with "lower confidence" for 14 years later (model year 2006).[31] In a 1991 Academy symposium I'd co-keynoted to inform its study, the Big Three had claimed that cars could be made only about 10% more efficient without making them undriveable or unmarketable—a vision framed by dividing the future into "too soon to change anything" and "too far off to speculate about," with nothing in between. Fortunately, Honda in 1992 and Toyota in 2003 felt uninhibited by this cramped vision. Today, whatever exists is possible. NHTSA should take care not to be similarly embarrassed, or expose itself to litigation for arbitrarily and capriciously basing its CAFE decision on outmoded technological assumptions. Rather, it should craft policies that recognize today's overwhelming dominance by standard steel autobodies and the challenges to major manufacturing shifts, yet that accommodate, encourage, and reward innovative materials, to widen and hasten their safety, fuel-economy, emissions, and industry benefits.

In short, NHTSA must get to grips with modern materials, design, and manufacturing alternatives for light-but-strong-and-cost-competitive autobodies and crush structures. This is especially true in view of the National Energy Plan's call for business-driven major gains in energy productivity. After all, two-thirds of a typical midsize sedan's fuel use is weight-related[32], and every unit of tractive load saved by reduced mass (or drag) will save ~7–8 units of fuel (or ~3–5 in a hybrid) by avoiding the compounding tank-to-wheels losses in the powertrain. Nothing in physics, vehicle technology or economics, or the safety literature denies this potential. Yet nothing in NHTSA's publications for this proceeding indicates any awareness of it. This rulemaking seems stuck in a 1980s time warp, as if the industry's striking advances in light-but-strong materials had never occurred and were unimaginable. That Dr. Evans, a severe critic of the Greene and Keller NAS/NRC dissent, should have titled his 2004 SAE World Congress talk "How to Make a Car Lighter and Safer" bespeaks how mainstream this overlooked opportunity has now become. (That he didn't highlight the advanced-composite approach to achieving the lighter-and-safer design philosophy he correctly espoused isn't surprising—he's an eminent expert on crash safety, not composites—but I doubt that any serious student of advanced-composite crush structures will quarrel with my characterization of their capabilities.)



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vehicle model in the MY2000–01U.S. new-light-vehicle fleet.[33] *Note the large vertical scatter at a given weight.*

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[31] National Research Council, *Automotive Fuel Economy: How Far Should We Go?*, National Academy Press (Washington DC), 1992, at p. 152, www.nap.edu/catalog/1806.html (projecting as "technically achievable" a 44-mpg subcompact at a marginal retail price of $1,000–2,500 in 1990 $; average MY1990 subcompacts were EPA-rated 31.4 mpg). *Cf.* J.G. Koomey, D.E. Schechter, & D. Gordon, "Cost-Effectiveness of Fuel Economy Improvements in 1992 Honda Civic Hatchbacks," LBL-32683, Lawrence Berkeley [National] Laboratory (Berkeley, CA), 1992, http://enduse.lbl.gov/Info/Honda.pdf. LBL found the 1992 *VX*'s adjusted EPA composite rating of 50.9 mpg incurred a marginal retail price, adjusted for other model differences, of $726 in 1992 $ (equivalent to $684 in 1990 $ or $845 in 2000 $), consistent with engineering estimates of the added production cost. This retail price was equivalent, at a 7%/y real discount rate, to $0.77/gal in 1992 $, or 45% less than the 1992 average taxed gasoline price). Less than one-tenth of the 56 percentage points' increase in the mpg of the 1992 *VX* (*vs.* the 1991 *DX*) came from reduced weight and drag, the rest from powertrain improvements.

[32] F. An & D. Santini, "Mass Impacts on Fuel Economies of Conventional *vs.* Hybrid Electric Vehicles," SAE 2004 World Congress (Detroit), 8–11 March 2004, SAE #2004-01-0572, SP-1833, Table 5, for a 2000 *Taurus* on the CAFE combined city/highway cycle, augmented to break out 8% of fuel consumption due to accessory loads; without these, 73% of fuel use would be weight-related.

[33] National Research Council, *Effectiveness and Impact of Corporate Average Fuel Economy (CAFE) Standards*, 30 July 2001, National Academy Press (Washington, DC), 2003, p. 34, http://books.nap.edu/books/0309076013/html/34.html.

The NAS/NRC graph above illustrates another aspect of the diversity of the historic fleet. It spans roughly threefold ranges in both weight and efficiency. Yet *at a given weight*, the models varied in efficiency by typically ~1.6× and up to ~2.3×—suggesting, consistent with the Academy panel's findings, that fleet efficiency could be about doubled by adopting in all cars the incremental powertrain and drag-reducing improvements now used in some, but without materially increasing their weight. By squashing similar safety-*vs.*-mass diversity into the averages of his regression analysis, Dr. Kahane left the impression of relationships far less varied and design-sensitive than they actually are. Moreover, we've just assumed constant weigh. The potential to achieve major efficiency gains over such a wide range of vehicles still doesn't count potential weight *reduction*, which the NAS brushed off in two sentences.[34]

Evolution in automotive structural materials

Most automakers' experience of lightweighting was historically limited to such light metals as aluminum and magnesium—a tradition that pervaded the NAS panel's approach and still seems to dominate NHTSA's thinking. Saving a pound of weight through light metals costs ~$1–3, but saves only about a gallon of gasoline every 12 years,[35] so light metals have long been barely cost-effective against U.S. gasoline, though they're widely used in Europe and Japan where taxes make gasoline prices ~2–4× higher.[36] European automakers typically tolerate weight savings costing up to €5/kg (~$3/lb) in light vehicles, and up to six times that in some truck applications.[37] In the mid-1980s, many European and Japanese automakers even built light-metal-dominated 4–5-seat concept cars weighing as little as 1,000 pounds, using internal-combustion engines but with 2–4× normal overall platform efficiencies.[38] Since then, light-metal manufacturing has become cheaper, so it's creeping into Detroit part by part. New processes might even halve the cost of superstrong titanium, bringing it nearer to practicality. But light metals remain costly.

The belief that light weight can mean only light metals and hence high cost is deeply embedded, yet increasingly unsupportable. Now it's unraveling at both ends: steels are getting lighter, while light metals are becoming just one of several weight-saving options, and often a less cost-effective one. Firstly, driven by competition from lighter materials and by automakers' need for lighter, strong, more formable, lower-cost materials, steelmakers continue to develop new products: half the steel alloys in today's GM vehicles didn't exist a decade ago. In 2002, a global consortium of 33 steel companies reported that extra-strong steel alloys and innovative body designs *could double automotive fuel economy and improve safety at no additional cost.*[39] NHTSA's analysis seems surprisingly uninformed by this major steel-industry effort, which OEMs, while not agreeing with every detail, have generally found invaluable. Secondly, an even bigger automotive gamechanger is emerging—advanced polymer composites, mainly reinforced with carbon fiber, of which 11 million lb/y is used in worldwide sporting goods. Carbon composites are now starting to transition from fancy concept cars and Formula One racecars to serious market platforms.

Of course, carbon composites have long been used in aerospace because they're stronger and tougher than steel but one-fourth as dense (one-third in a finished resin-plus-fibers composite with ~50–60% fiber content). Boeing plans

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[34] *Id.*, at p. 39. The Academy's analysis included only trivial weight and drag reductions of a few percent (pp. 3-20–3-22). All were assumed to bear a higher cost, as if weight were reducible only by the traditional means of substituting light metals for steel in a modest number of components. Its 2002 update added a third qualitative and inconclusive sentence saying the panel might have understated potential for mass and drag reductions, but offering no correction; they simply chose not to address the issue.

[35] D. L. Greene & J. DeCicco, "Engineering-Economic Analysis of Automotive Fuel Economy Potential in the United States," *Ann. Rev. En. Envt.* **25**:477–536 (2000), quoting EEA data at p. 500, state that gal/mi in a typical 1,400-kg 1998 car is reduced by 0.54% (0.64% with engine downsizing for constant acceleration) for each 1% decrease in vehicle mass. The corresponding elasticities are –0.22 for reductions in C_d and –0.23 in rolling resistance.

[36] Many production and prototype platforms in the 1980s weighed only about half as much as the U.S. MY2003 compact-car average of 1,430 kg: *e.g.*, VW's 5-seat *Auto 2000* (779 kg), Peugeot's 5-seat *205XL* (767 kg), Volvo's 4-seat *LCP 2000* (707 kg), VW's 4-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), among others, had all been reported by 1988. See D. Bleviss, *The New Oil Crisis and Fuel Economy Technologies: Preparing the Light Transportation Industry for the 1990s*, Quorum Books (NY), 1988.

[37] "The Future Use of Composites in Transport: Research Cluster: Lightweighting of Composite Structures for Transportation Systems: State-of-the-Art," ~2003, www.compositn.net/Clusters/Cluster%20-%20Lightweighting%20-%20State-of-the-Art%20-%20Comparison.htm.

[38] Bleviss, *op. cit. supra*.

[39] Assuming a high production volume of 225,000/y. The 5-seat midsize sedan's virtual design, with C_d 0.25 and m_c 998 kg (gasoline) or 1031 kg (Diesel), was predicted to achieve respective EPA combined city/highway ratings of 52 and 68 mpg and to have a production cost of $9,538 and $10,328. The body would weigh 52 kg less than normal, cost $7 less, and have 81 rather than 135 parts. American Iron and Steel Institute (Southfield, Michigan), "New Steels Can Help Vehicles Achieve Five-Star Crash Rating, Double Fuel Economy at No Additional Cost," 30 Jan. 2002, www.autosteel.org/press_room/2002_avc_short.htm; Porsche Engineering, *ULSAB-AVC Final Engineering Report*, 2002, www.autosteel.org/ulsab_avc/avc_eng_rpt_index.htm summarized at www.autosteel.org/ulsab_avc/index.htm.

~25 tonnes of advanced composites, over half the total structural mass, in its *7E7*; Airbus, ~30 tonnes in its *A380*.[40] The main issue is cost. Civilian aircraft can justify paying more than $100 to save a pound; some space missions, over $10,000. Aerospace composites, laid up by hand like fine couture, are made of carbon tape and cloth costing up to $100 a pound, while steel costs ~40–60¢ a pound. But nobody buys cars by the pound, and the dollars-per-pound-of-materials metric is profoundly misleading. Only ~15% of the cost of a finished steel car part is the steel, and composites can save much of the rest through simpler shaping, assembly, and finishing. As VW notes, low-cost carbon-composite automotive structures could cut the weight of a car by 40% and the number of body parts by 70%, making this approach "cost effective even if the manufacturing costs per part are still expected to be higher"[41]—partly because fewer pounds of carbon fiber are used and lighter cars need smaller, cheaper powertrains. But so vast was the cost-per-pound gulf that automakers—who still largely think of cost per pound, not per car, and whose steel body-making skills are exquisitely evolved—long denied carbon any serious attention. Until the mid-1990s, Detroit had only a few dozen people exploring advanced composites, probably none with manufacturing experience. The industry's few high-profile experiments, like Ford's 1979 1,200-pound-lighter *LTD* sedan and GM's 1991 *Ultralite*, were interpreted mainly as proving carbon cost far too much to compete, so it wasn't worth learning more about.

Reflecting this old thinking, the NAS panel did not consider weight reductions greater than 5%, based on a technically unfounded assumption that reducing weight by more than that would unduly compromise safety. Thus the most important fuel- and emission-reduction technology was arbitrarily taken off the table. Now NHTSA has compounded this error by stating at NR:32 that NAS "did not find the substitution of lightweight materials to be one of the more cost-effective strategies," implying that it can be ignored (supposedly benefiting safety) without compromising other key national goals. An accurate statement would be that the NAS panel devoted no serious analysis to the technology and economics of cost-effective lightweighting, declined to consider the technical materials that I supplied timely to its staff on this subject[42], and dismissed lightweighting without really considering its merits, including the important potential safety *advantages* described above. Thus the flawed NAS report cannot be considered a sound basis for NHTSA's decision about lightweighting in this proceeding, on grounds of either economics or safety. NHTSA cannot fulfill its obligations in this rulemaking without building a new, thorough, and balanced technical record on the safe lightweighting options described here.

Ultralight but ultrasafe design: an SUV/crossover case-study

To illustrate what's possible, a small private technology development firm, Hypercar, Inc. (p. 2), privately developed in 2000 a full virtual design for a 99-on-road-mpg-equivalent or 114-adjusted-EPA-mpg-equivalent, uncompromised, sporty, spacious, cost-competitive midsize crossover vehicle. (That design used a 35-kW direct-hydrogen fuel cell and 35-kW NiMH buffer; with a gasoline hybrid powertrain as efficient as that of a 2004 *Prius*, appropriately mass-corrected, its adjusted EPA rating would be ~66 mpg.) Comparable in features and performance to a loaded 2004 Audi *Allroad 2.7T*, this *Revolution* concept car is described in an invited review paper (Attachment One).[43] It combines packaging comparable to the 2000 Lexus *RX-300* (five adults in comfort, and up to 69 ft^3 of cargo with the rear seats folded flat), ability to haul a half-ton up a 44% grade, and brisk acceleration (0–60 mph in 8.2 seconds). Its 52%-lighter curb weight (857 kg), low rolling resistance (r_0 0.0078), and low simulated aerodynamic drag (C_d 0.26, A 2.38 m^2) together reduce its tractive load by about threefold, augmented by major reductions in accessory loads. The design team systematically strove to maximize nonlinear "mass decompounding"—the snowballing of weight savings—by downsizing and, where possible, even eliminating components and subsystems.

Revolution's direct-hydrogen fuel-cell system was simulated to achieve a 330-mile average range on 7.5 lb of safely stored compressed hydrogen in U.S.-approved 5,000-psi carbon-fiber tanks; newer German-approved tanks field-tested by GM operate at twice that pressure, which would extend the range beyond 500 miles, and by 2003 had become the new industry design norm. *Revolution* combines a body much stiffer than a good sports sedan's[44] with fast all-wheel digital traction control, 13–20-cm variable ride height, and smart semiactive suspension, so it should be

[40] *High-Performance Composites: Sourcebook 2004*, "Industry Overview: Sports and Aerospace Applications," www.compositesworld.com/sb/ov-hightech.

[41] VW *et al.*, "TECABS (Technologies for carbon fibre reinforced modular automotive structures)" 16 April 2003, www.bbw.admin.ch/html/pages/abstracts/html/fp/fp5/5gr99.0286-2.html. Carbon fiber also has a marketing value prized in cosmetic trim: P. Patton, "Low-fat car springs from a diet high in fiber," *N.Y. Times*, 9 Feb. 2004, www.globalcomposites.com/news/news_fiche.asp?id=1083&.

[42] In addition, respected ACEEE analysts submitted more mass-conscious calculations to the NAS panel, but I understand these were given very little weight—solely because of their source, not their technical merits. That was inappropriate as a matter of process, and was not adequately corrected by the 2002 follow-up discussions. I am glad to see NHTSA is not following suit.

[43] A.B. Lovins & D.R. Cramer, *Intl. J. Veh. Design* **35**(1/2):50–85 (2004), www.rmi.org/sitepages/pid175.php#T0401.

[44] Static analyses showed a bending stiffness of 14,470 N/mm, a torsional stiffness of 38,490 N•m/deg, first bending mode of 93 Hz, and first torsion mode of 62 Hz—nearly twice as stiff as a nominal BMW steel autobody. The large-area adhesive bonding would maintain stiffness throughout the very long life of the vehicle, *vs.* metal autobodies' rapid degradation of spot-welds.

very sporty. *Revolution* was probably the first car designed from scratch to be all-digital, all-networked, with all functionality in software—a highly robust computer with wheels, not a car with chips. Since its body wouldn't fatigue, rust, nor dent in a 6-mph collision, and the rest of the car is radically simplified, the design was consistent with a 200,000-mile warranty. The "pusher" show car and technology exhibit may be viewed by arrangement at Hypercar, Inc.'s headquarters in Basalt, Colorado, ~24 miles west of Aspen, 970 927 4556, www.hypercar.com.

Revolution was designed for manufacturing at a competitive cost at midvolume (~50,000/y), using innovative manufacturing methods that would eliminate the conventional body shop and make the paint shop optional.[45] Its ultra-strong carbon-composite passenger cell, with a drop-in aluminum front subframe, has only 14 parts, each hand-liftable by a small worker with no hoist. The self-fixturing body parts are detoleranced in two dimensions and designed for quick and inexpensive assembly. The capital, time, parts count, assembly effort and space, and optimal plant scale required for manufacturing would be many times smaller than for today's comparable platforms.

The prime contractor in this internally funded development project was TWR Engineering, a Tier One supplier of engineering services near Oxford, UK, which was widely considered the industry leader in virtual design; the TWR family also included an automaker (running the best Volvo/Renault plant) and a Formula One shop with long experience in advanced composites. Collaborating firms included Michelin, Sun Microsystems, and Forschungsgesellschaft Kraftfahrwesen Aachen mbH (FKA). Hypercar's team leader at TWR had previously led the Lockheed Martin Skunk Works® team that in the mid-1990s designed the 95%-carbon advanced-tactical-fighter airframe—one-third lighter but two-thirds cheaper than its 72%-metal predecessor, due to its clean-sheet design-for-manufacturing.

This project's goal was to demonstrate the technical feasibility and the driver, societal, and automaker benefits of holistic vehicle design focused on efficiency and lightweight composite structures. It was designed to have breakthrough (5–6×) efficiency, meet U.S. and European safety standards, and satisfy a rigorous and complete set of product requirements for a sporty and spacious five-passenger SUV crossover vehicle segment with technologies that could be in volume production at competitive cost within five years. The team developed a CAD model of the concept vehicle and performed industry-standard static bending and torsion, frontal-crash, powertrain-performance, aerodynamic, thermal, and electrical analyses to validate the conceptual design. Hypercar, Inc. also analyzed detailed costs for hypothetical 2005 production of such a vehicle at a greenfield plant making 50,000 vehicles per year—about the volume of the aluminum Audi *A2*. A 499-line-item Bill of Materials, developed in close collaboration with TWR Engineering, FKA, and suppliers, accounted for 94% of manufacturing cost. It supported cost estimates based 83% on unnegotiated[46] quotations by the supply chain in response to anonymous TWR cost-pack requests, 7% on standard parts-bin costs, and the rest on in-house and consultant analyses of proprietary production processes for composite components. The results confirmed the scope for cost-competitiveness at midvolume. My RMI team's recent reexamination of the proprietary manufacturing cost analysis confirmed its likely conservatism.

TWR's computer crash simulations of the Revolution *design indicated that this 52%-lighter (1,889-lb-curb-weight) vehicle could collide head-on with a fixed barrier at 35 mph without damaging its passenger compartment, and could collide head-on with a steel car twice its mass, each going 30 mph (60 mph closing speed), yet still meet FMVSS criteria for a 30-mph fixed-barrier collision.* This simulated crash performance, which to my knowledge is unprecedented, is made possible by a highly integrated design using a 57%-lighter (187-kg) long-discontinuous-carbon-fiber-reinforced thermoplastic composite "Body-in-Black"™ with aerospace-inspired ring-based design. The platform should also have exceptional handling qualities, and I believe its improved driver ergonomics and by-wire sidestick control would also significantly improve accident avoidance. Hypercar, Inc.'s budget has not yet permitted simulation of other crash modes, let alone physical crash tests, but due attention was given to designing for both regulatory-required and other realistic crash conditions, and good all-around crash performance is expected. I expect the firm would welcome NHTSA's help in scrutinizing and expanding these preliminary safety studies.

Recent market developments in advanced-composite automotive structural applications

There is considerable interest among and discussion with automakers worldwide about this approach: all would like to make autobodies from carbon composites, and just need a cost-competitive way to do it, so they say that if Hypercar, Inc. has cracked that code (as its August 2003 manufacturing process patent suggest), they're very interested. The barriers to adopting this completely different way of designing and building cars seem more cultural than economic or technical, and are expected to decrease as Hypercar, Inc. becomes able to provide testable carbon-composite structural components made with its proprietary Fiberforge™ volume-production process. Such samples are already being provided to OEMs. The firm is currently making briefcase-sized parts and expects within weeks to

[45] D.R. Cramer & D.F. Taggart, "Design and Manufacture of an Affordable Advanced-Composite Automotive Body Structure," EVS-19 (Seoul), 2002, www.hypercar.com/pdf/Hypercar_EVS19.pdf.
[46] Probably therefore overstated; ULSAB-AVC, for example, assumed in its cost analysis that "virtual negotiation" would reduce suppliers' bids by 10%.

be making 1×1-meter parts. The Fiberforge process automatically and rapidly lays carbon and/or other fibers in the desired positions and orientations (but not elsewhere, nearly eliminating scrap) to form a flat "tailored blank," compacting and binding the fiber layers in place until the blank is thermoformed into its final three-dimensional shape. Long discontinuous carbon fibers can flow into complex shapes and very deep draws while retaining high strength and uniform orientation. The goal is 85–90% of the strength of hand-layup aerospace composites at 15% of their cost—enough to beat aluminum in cost per part and steel in cost per car, unlocking advanced composites' full manufacturing potential for ultralight autobodies. Results to date are encouraging. My RMI team has recently deepened the manufacturing cost analysis[47], and found that the ~66-mpg hybrid variant of the original 2000 *Revolution* design would compete with today's comparable market platforms. In essence, *Revolution*'s halved curb weight and improved safety are *free side-benefits* of the design, materials, and manufacturing innovations that yield its efficiency.

I suspect this approach has not yet informed NHTSA's policymaking process. Despite the considerable interest among OEMs and Tier One and Two suppliers, DOT has so far shown no interest in this development and seems largely unaware of it. NRC's PNGV review panel had never heard of it until I told them a few years ago. The NAS/NRC fuel-economy study in 2001, as mentioned above, declined to consider all information on ultralighting or fuel cells, on the incorrect assumption that these couldn't make a difference in their time horizon (to ~2017). In January 2002, soon after FreedomCAR was announced, I told a senior DOE official about it, since DOE had just announced an intention to spend the next 10–20 years developing the car that Hypercar, Inc. had already developed 14 months earlier. His immediate reply was: "Well, then, we'd better not try to help you, because we'd just slow you down." That might be true, but it shouldn't be true, and it had better not be true if we want a healthy U.S. automobile industry, because foreign competitors, from within and outside the auto industry, won't wait.[48]

For example, in autumn 2002, *Ward's Automotive Weekly* reported that BMW "is planning to do what virtually every other major auto maker on the planet has dreamed about: mass producing significant numbers of carbon-fiber-intensive vehicles that are not only light and fast, but also fuel efficient."[49] BMW "…in the last two years…has shown several concept vehicles using considerable amounts of carbon fiber, and two projects are now in development for serial production. A major introduction with volumes as high as 100 cars per day is expected in 2005," based on the Z22 concept car shown to journalists in 2000 (Fig. 13c) and using over 200 pounds of carbon fiber. BMW's *M3 CSL*'s five-layer carbon-fiber roof weighs only 13 pounds, lowering the center of gravity to improve road-holding, and is automatically produced 5× faster than hand layup.[50] BMW has built "the world's first highly automated production process for carbon-fiber-reinforced plastic" and with 60 full-time composites manufacturing specialists, is "going 'all out' to develop the skills…to expand use of the material from its primary domain in motorsports…to regular vehicle production."[51] Meanwhile, MG is selling a *X-Power SV* carbon-fiber roadster: although made from costly "prepreg" carbon-fiber cloth, it has solved several key manufacturing problems while reportedly cutting body-panel weight and cost by three-fourths.[52] And carbon-fiber parts are showing up in 2004 hoods, roofs, and other parts from automakers on three continents (including BMW, Chevy, Dodge, Ford, Mazda, and Nissan), as well as in numerous aftermarket products. This rapid uptake will accelerate as the virtues of ultralight weight, near-zero fatigue and corrosion, and unprecedented crash energy management combine with competitive production cost.

Implications for this proceeding

NR:31 states baldly, and correctly, that "a weight-based standard…would reduce or eliminate the incentive for manufacturers to comply by…downweighting…." This is presented (except for the heaviest vehicles—NR:46) as a good thing for safety, which NHTSA seems to believe results from weight (NR:31, 45) except in the case of the heaviest vehicles (NR:45) whose mass-aggressivity is so clearly a threat to the rest of the fleet. NHTSA's E-CAFE proposal (N:48) *specifically disincentivizes* downweighting for light trucks already below 5,000 lb. But for the reasons explained above, this is all 180˚ off course, based on a misreading of materials science and safety technology. With proper materials and design, maintaining high weight for vehicles below ~5,000 lb curb weight is actually *bad* on all counts (as in all vehicles)—bad for safety, OEMs' competitiveness, fuel economy, and emissions.

My further tentative conclusions and recommendations based on the analysis above include:

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[47] See ref. 2 above.

[48] A.B. Lovins, "FreedomCAR, Hypercar®, and Hydrogen," 26 June 2002 invited testimony leading an industry panel, USHR Science Committee (Energy Subcommittee), www.rmi.org/sitepages/pid175.php.

[49] W. Diem, "BMW Races into Carbon Fiber," *Ward's Auto World*, 1 Sept. 2002, www.wardsauto.com/ar/auto_bmw_races_carbon_2/.

[50] A. Kochan, "BMW slashes cost of carbon-fiber panels," *Automobilwoche*, 8 Sept. 2003.

[51] Including the world's largest Resin Transfer Molding press (1800 tonnes): "BMW takes carbon-fiber technology to next level," *AEI*, p. 54, Nov. 2003, www.sae.org/automag/material/11-2003/1-111-11-54.pdf.

[52] "Weighing up the advantages," 2003, www.globalcomposites.com/news/news_fiche.asp?id=991&.

- I agree that the current CAFE program contributes to compatibility and rollover problems (NR:70), but believe this can be corrected by specific safety requirements without compromising the size, safety, cost, or fuel economy of any vehicle. I warmly applaud Dr. Runge's leadership on these important issues.
- The different CAFE treatment of light trucks and cars, and the 8,500-lb ceiling, are both inappropriate on grounds of technology, safety, public health, fuel economy, and emissions. Both rules should be abolished. Rather than distinguishing big passenger vehicles meant for private use from commercial trucks, vans, etc. of Classes 2–4, I'd prefer to bring the latter into the fuel-economy regime (*at least* up to the 10,000-lb GVR contemplated on p. 30), because essentially the same technical opportunities apply to them at similar costs. Even without significant reductions in mass, drag, or rolling resistance, Toyota's 7-seat 2005 *Highlander* SUV, using a scaled *Prius* powertrain, will achieve the fuel economy of a compact car, and doubtless Toyota expects to sell it at a profit. There's no reason commercial trucks of comparable size can't do the same thing—all the more so with safe-and-light materials. To the extent the current CAFE regime is sustained, therefore, I'd favor at least its extension to large vehicles described at NR:69–70.
- I emphatically share ACEEE's, Toyota's, and Honda's concern (NR:19–21) that a weight-class-based system would lead to upweighting, defeating public policy goals for safety, fuel economy, and environment. *Any* attribute-based system will be gamed (as is the current CAFE regime), but a size-based system, preferably based on some metric for interior volume (or equivalent cargo volume for *e.g.* pickup trucks), is much sounder than one based on weight. On no account should weight be rewarded, in any way, for any vehicle. The regulatory system should instead seek to reward safety, fuel economy, and low emissions while reducing weight.
- Though a fan of market mechanisms, I partly share ACEEE's reservations about a credit trading system. Since NHTSA is mindful of effects on automakers' markets, it should observe that China's nearly completed fuel-economy standards apply to *every* vehicle, not to a fleet average, and that Japan's Top-Runner program, as I understand it, still requires all vehicles in a given class to approach over time the fuel economy of the most efficient vehicle in that class. I agree with Japan's policy of discounting the recently allowed averaging between classes, but respectfully disagree with basing those classes on weight; they should instead be based on some size metric. (I also expect that if, as some evidence suggests, Toyota and Honda have significant black programs in advanced composites, the initial weight-class-based policy could well change to a size-based one once the resultant products enter the Japanese market.)
- Shadow size is probably not a good metric because it creates a perverse incentive for tall vehicles (decreasing compatibility and increasing rollover risk), especially in a country like Japan with astronomically costly parking per m^2. By linearly linking mass with size (NR:38, 42), NHTSA risks turning an ill-conceived mass-based standard (discouraging lightweight solutions) into an ill-conceived incentive to reduce size (the one vehicle parameter that definitely improves protection for occupants of both struck and striking vehicles, as well as in stationary-object collisions). Size also seems to me more likely than weight to be rationally related to customer function or utility, and hence to serve as a proxy for diverse customer preferences. And apart from concerns of urban space-use and visibility, I have no objection to large vehicles—only to heavy ones. Advanced composites can profitably decouple these two variables.
- The mixed-attribute system is based on the same misconceptions and yields the same perverse incentives already discussed, especially if "safety adjustment factors" (NR:56) further reward weight.
- The "two-fleet rule" is increasingly a dead letter; Nissan, for example, has just been exempted from it for the alleged reason of preserving U.S. jobs. Since NHTSA apparently doesn't intend to enforce this rule, there's little point debating it.
- The "flat floor" criterion (NR:64ff) is an historic artifact that should no longer influence fuel-economy regulation. The rise of alternative, notably hybrid and fuel-cell, powertrains will make powertrain packaging so flexible that it'll become increasingly attractive to offer flat floors in a wide range of light vehicles regardless of their size and functionality. I see no reason to deter or favor this development, whether in crossover vehicles or otherwise, nor to discourage manufacturers from providing removable seats and flexible interior design and packaging to meet evolving customer value needs. But since I don't think the car/light-truck distinction should be maintained—both should meet the same mpgs—this shouldn't matter.
- Similarly, there is no reason to discriminate between 2WD, 4WD, and AWD vehicles (NR:67ff), especially since the latter two options will increasingly be associated with series- or parallel-hybrid traction arrangements that should be encouraged for reasons of fuel economy and emissions, regardless of vehicle size, design, or intended purpose. This too won't matter because high fuel economy is available for and should apply to all light- and light-medium vehicles regardless of their traction arrangements.

Miscellaneous comments and corrections

At NR:57, "The agency reviewed the legislative history and concluded that Congress intended that passenger automobiles be defined as those used primarily for the transport of individuals and that all other vehicles would fall within the category of non-passenger automobiles" appears to intend "ostensibly designed" rather than "used." Some

90–95% of SUVs and pickup trucks are said to be actually *used* as car substitutes that do not haul bulky objects, go offroad, tow heavy loads, or do any of the non-passenger-carrying tasks for which they were supposedly *meant*.

The EIA macroeconomic analysis summarized at NR:12–13 is fundamentally unsound. NEMS is structurally incapable of validly generating the kinds of outputs described; the assumption (not prediction as stated) of increased vehicle cost has no valid technical basis and is almost certainly incorrect in both magnitude and sign; and the whole exercise is simply garbage-in/garbage-out. (Applying similar techniques to many existing NHTSA rules would give similarly misleading answers.) NHTSA should give it no weight in policymaking. In general, EIA is quite good at keeping historical energy statistics, but lacks the kinds of expertise in sophisticated energy-economic modeling and vehicle engineering (and lately, it seems, probably the political independence) to be the appropriate place to go to if NHTSA needed analysis of the kind described; but I don't understand why NHTSA would have such a need. To the limited extent automotive economics is critical to a NHTSA safety-and-fuel-economy decision, a straightforward, traditional, empirically grounded microeconomic analysis of vehicle costs and benefits should suffice.

Conclusions

In order to "enhance fuel economy, protect occupant safety, advance fuel-efficient technologies, and obtain the benefits of market-based approaches" (NR:8), I think NHTSA must fundamentally reshape its technical basis for this proceeding, because its foundations are unsound. In particular, having correctly stated that its historic regression analysis (most recently by Dr. Kahane) "is retrospective, and not necessarily predictive of the future, since it examines a specific group of model year 1991–99 vehicles, often in relation to the other vehicles on the road, in calendar years 1995–2000" (NR:11), NHTSA merrily proceeds—implicitly but unmistakably—to interpret those retrospective data as predictive, *i.e.*, as a proper basis for shaping policy to affect all future light vehicles. That's clearly wrong: NHTSA has succeeded in concealing the meaning of this analysis even from itself.

Dr. Kahane's regression did *not* find, as NR:9 states, that "downweighting of the light truck fleet, especially those trucks in the low and medium weight ranges, creates more safety risk for occupants of light trucks and all motorists combined"—least of all for any *future* fleet. (Wenzel and Ross, among others, have even raised serious questions about whether his finding is valid even for the historic fleet, or a mere artifact of omitting key explanatory variables.) Even if his analysis were perfect and complete, historic-fleet regressions can in principle say *nothing whatever* about the future vehicles that this rulemaking seeks to influence. Having discussed this point with Dr. Kahane, I know he appreciates this. Unfortunately, this rulemaking is misusing his report as if it were predictive. The distinction between "did" and "would" or "will" may seem small, but it's critically important to sound policymaking. Dr. Kahane's study is a rear-view mirror—not a windshield we can look through to drive America safely ahead.

National light-vehicle policy is poised for a fateful turn. It would be a tragedy for public health and safety, oil security, and other key goals if new Federal policies sought to reduce the fleet's mass dispersion by penalizing lighter or encouraging heavier vehicles, rather than by stimulating innovation in making all and particularly large vehicles both light *and* crashworthy. If the aggressivity and compatibility issues witnessed in recent years are any indication, that way lies an even more absurd mass arms race in which you drive a Hummer, she drives an 18-wheeler, and he drives a locomotive. Some of the less strategic thinkers and lobbyists in the industry would unfortunately welcome such an outcome, even though it would ensure the isolation and failure of such offerings within more discriminating global markets, and hence would damage OEMs' long-term competitive prospects and the Administration's broader economic objectives.

I hope NHTSA will strenuously resist outcomes so clearly counter to public health and the national interest. This will take serious intra-governmental and public education about how lighter need not mean smaller or riskier—if we properly harness modern technologies. A hidden advantage of mass/size decoupling, too, would be a strategically advantageous method of automaking that can reduce the required capital, space, assembly effort, parts count, and product cycle time by many-fold—thus ensuring the primacy of American automaking, if and only if we do it first. A creative CAFE rule that encourages size/mass decoupling can be a big first step toward revitalizing the nation's largest industry and all—as many as one in seven American workers, and everyone who drives—who depend on it.

I would be pleased to discuss these comments with appropriate NHTSA officials if desired.

Sincerely,

Amory B. Lovins
Chief Executive Officer

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