Oil-Free Transportation

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My prior talk "Reinventing Fire" in this Symposium[1] summarized how to achieve greatly expanded 2050 U.S. mobility without oil by first getting superefficient—including tripled-efficiency trucks and planes—then switching fuels to any mix of hydrogen, electricity, and advanced biofuels.

AUTOMOTIVE PHYSICS

The basic physics of automobiles was elegantly summarized[2] by Professor Marc Ross at the University of Michigan, paraphrased and slightly updated here:

- Powertrain efficiency, measured from fuel tank to wheels, is the product of three efficiencies: engine thermodynamics (fuel to work, nominally ~0.38 with Otto or ~0.45 with Diesel engines), engine mechanicals (work to output torque, ~0.53), and driveline (engine to wheels, ~0.85). This product, nominally ~0.17, is doubled by modern hybrid powertrains, *e.g.* to ~0.33–0.37 in the 2004 Toyota *Prius*, because partly or wholly electric coupling from engine to wheels enables the engine to operate at or near its "bull's-eye" of peak efficiency much or most of the time, and because deceleration energy can be electrically stored by regenerative braking for later reuse.
- Vehicle load is the sum of tractive load (power required to move the vehicle) plus accessory loads (nominally ~2–3%, often engine-driven with conversion losses, but increasingly electrically driven to facilitate better control and variable-speed drive of cube-law fans and pumps).
- Tractive load, in approximate instantaneous mechanical kW, is the sum of four terms:
  - Inertial load = $0.5M \times [\Delta v^2/\Delta t]$ (M^* $1.03M$ to include rotating intertias, M in kg, $[\Delta v^2/\Delta t]$ in m^2/s^3); with regenerative braking, multiply by $(1 - \eta_{regen})$
  - Rolling resistance = $C_R Mgv$ (M in tonnes, v in m/s)
  - Aerodynamic drag = $0.5\rho_{air} C_D A v^3/1000$ (sea-level $\rho \approx 1.2$ kg/m^3, frontal area A in m^2)
  - Grade = $mgv \cdot \sin\theta$ (grade = $\tan\theta$, neglected in most comparisons)

  Inertial and grade loads can be negative and $\eta_{regen} \approx 0.7$ to ≥ 0.8 recovered, wheel-to-wheel, by very efficient regenerative braking with battery or ultracapacitor storage.

Tractive load is surprisingly small—for the fleet-typical 1995 Ford *Taurus*, just 6.3 kW on the then-standard EPA test (55% city / 45% highway driving). This corresponds to 1.6 L/100 km or ~149 miles per U.S. gallon of gasoline. But the reality is 6-fold worse because of the ~0.17 powertrain efficiency, which no technology can improve beyond 1.0. *However, tractive load can be reduced almost without limit*, constrained only by safety, comfort, styling, and cost. Today's cars and light trucks, averaging roughly 8 L/100 km, can thus be cost-effectively improved by ~4–8-fold in practice by artfully optimizing mass, drag, rolling resistance, accessory loads, and then a severalfold smaller (hence cheaper) powertrain.

A typical midsize U.S. car in standard U.S. driving cycles uses each day about 100 times its weight in ancient plants, and emits each year about its own mass in CO_2. As Fig. 1 shows, this is mainly because ~86% of the fuel energy never reaches the wheels: it's lost first in engine losses, idling, driveline losses, and accessory loads. The ~14% of fuel that meets tractive load is caused roughly one-third by heating displaced air (aerodynamic drag varies as the cube of speed) and two-thirds by the vehicle's own gross mass, which linearly contributes to both rolling resistance (heating the tires and road) and inertial load (accelerating the car and then heating the brakes). Only ~6% of the fuel energy accelerates the car—which weighs ~20 times as much as the driver, so only ~0.3–0.5% of the fuel energy actually moves the driver! After ~120 years of devoted engineering effort, this is not very gratifying. But now a heady blend of corporate, academic, government, military, and nonprofit-group research is starting to get designing and making cars unstuck from the bad physics behind this inadequate fuel efficiency.

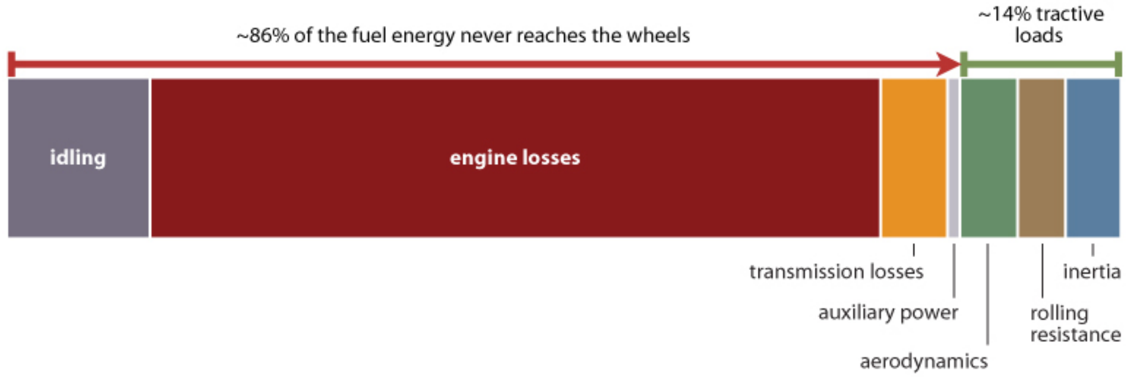

Fig. 1. Energy flow through a typical U.S. internal-combustion-engine automotive powertrain. Reducing tractive load—two-thirds of it proportional to mass—leverages far greater powertrain savings upstream.

LIGHTWEIGHTING FIRST

Automakers have long focused mainly on wringing losses out of the powertrain, using the same logic as Willie Sutton, a famous bank robber who was once asked, "Why do you rob banks?" and replied, "Because that's where the money is!" Similarly, we focus immense effort on getting another tenth of a percent out of the engine or transmission because that's where most of the losses are. But saving one unit of energy in the powertrain saves only *one* unit of energy in the fuel tank. In contrast, saving one unit of energy at the wheels saves *seven* units of fuel (or about half that much in a full hybrid) by avoiding the losses in *delivering* fuel energy to the wheels. Thus we should begin by reducing tractive load, especially via lightweighting, and only later consider the powertrain. Indeed, we can then make the powertrain smaller to get the same acceleration, and use its lower cost to help pay for the lightweighting. Electric powertrain often wins: it's very efficient, modular, high-torque, reliable, compact, quiet, controllable, clean, fairly cheap, and far richer in design flexibility and rapid evolutionary potential than the mature Victorian mechanical arts epitomized by today's sophisticated internal-combustion engines.

Empirical data (Fig. 2) show weak or no correlations between the market price of U.S. new cars in Model Year 2010 and their curb weight (measured with normal equipment and consumables, full fuel tank, and no people), aerodynamic drag coefficient C_D, and coefficient of tire rolling resistance C_R. There is also a huge scatter in each of these parameters between different makes and models at a broadly similar market segment and price. Yet only in the past few years has lightweighting, coupled with other reductions in tractive load, become key to many automakers' competitive strategy. On the contrary, average U.S. autos just suffered a quarter-century epidemic of obesity, gaining weight twice as fast as their drivers.

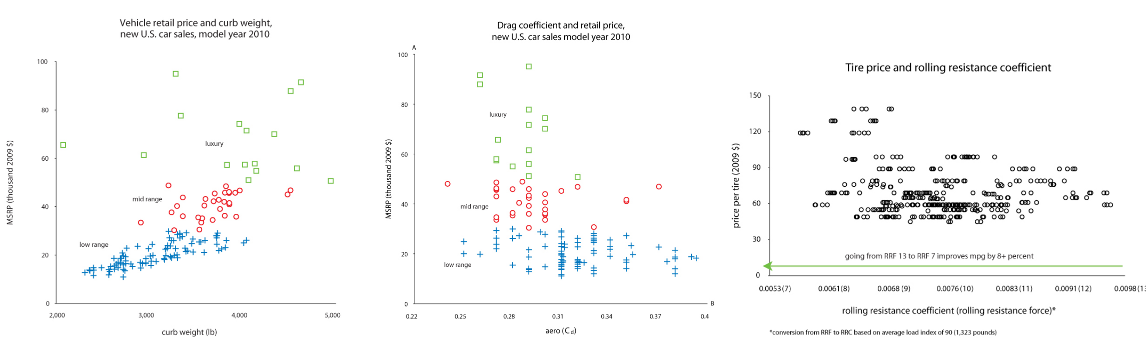

Fig. 2. U.S. Model Year 2010 auto sales' physics parameters that largely determine tractive load are poorly correlated with Manufacturers' Recommended Retail Price (sticker price), with strong price scatter at almost any value on the abscissa (RMI analysis).

Powertrain-centric automakers also began to introduce partly or wholly battery-electric propulsion, and many offered some alternative fuels or conversion systems such as compressed natural gas engines or hydrogen fuel cells. But these were often awkward and costly because they were put into heavy, inefficient autos. Government policy, too, sought to make batteries and fuel cells cheaper, but inefficient autos made them numerous (many kW per vehicle) and hence costly, reducing marketability.

A general solution to this dilemma was proposed in 1991[3], refined through the 1990s, illustrated by a 3.56 L/100 km (gasoline) or 2.06 L/100 km (hydrogen) midsize SUV virtual design in 2000[4] and by a 420-kg *Prius*-size plug-in hybrid in 2007 (Toyota's *1/X*), and brought to market in 2013–14 by BMW (*i3* followed by *i8*) and VW (the low-volume two-seat 1 L/100 km *XL1*) (Fig. 3). This solution combines the two hottest trends in the industry—ultralighting and electrification—*in that sequence*.

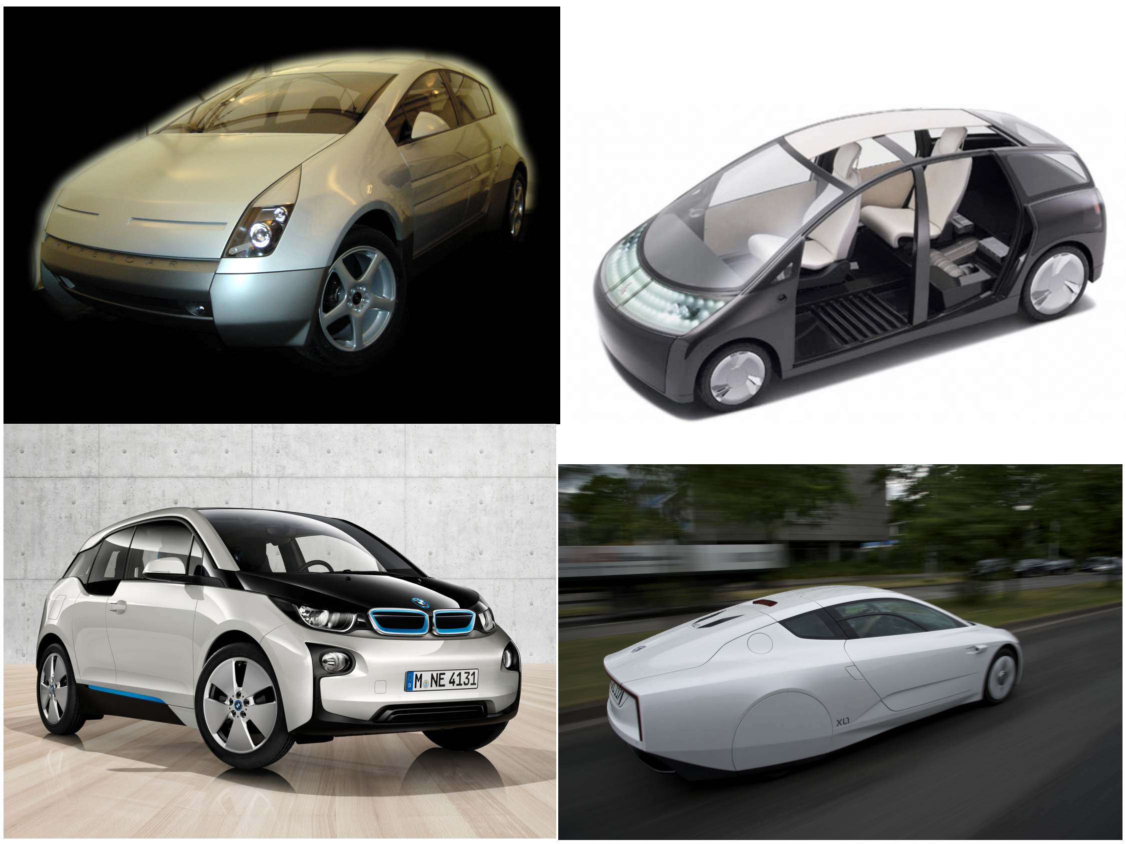

Fig. 3. Clockwise from upper left: Hypercar Revolution *(2000) full-scale "pusher" mockup of virtual design, Toyota* 1/X *concept car (2007), BMW midvolume-production* i3 *(2013), and VW* XL1 *(2013).*[5]

Ultralighting *first* makes electrification affordable because such an efficient vehicle needs 2–3-fold *fewer* of the costly batteries or fuel cells. Such marketable vehicles—optionally aided by a temporary size- and revenue-neutral "feebate"[6] to arbitrage the spread in discount rate between auto-buyers and society—can achieve high volumes at comparable prices, achieving the same ultimate goal of cheap batteries and fuel cells, but with far less time, cost, and risk. Federal policymakers began adopting this approach in 2013.

By spring 2014, global industry was offering ~17 competing manufacturing processes to mass-produce ultralight but ultrastrong carbon-fiber structures. At least one process[7], whose customers have been using it to produce midvolume parts in several sectors since the late 1990s, can now make complex 2 × 2-m parts in 1–2 minutes, consistent with normal high-volume automotive requirements, and with considerably greater versatility and lower scrap than competing processes. It can also produce anisotropic parts with different strength and stiffness in different directions so as to match load paths, saving even more weight and cost. The molded parts, made with ~90–95% fewer body parts (Fig. 4) and ~98–99% lower tooling cost than today's steel autobodies, can snap precisely together for bonding with no robotic body shop and little or no paint shop. Such dramatically simplified automaking (with up to ~80% less capital investment) and severalfold smaller powertrain can approximately pay for the higher costs of carbon-fiber composites, making the ultralighting approximately free.[8]

Such uncompromised 1–2 L-equivalent/100 km (~125–240 mi/USgal) autos promise breakthrough competitive advantage, higher profitability at lower industrial risk, and improved safety (since properly shaped carbon-fiber-composite structures can absorb ~6–12 times more crash energy/kg than steel, up to 250 kJ/kg, and do so more smoothly, using the crush stroke up to twice as effectively). U.S. automakers' adoption of such designs could ultimately save ~1.5 Saudi Arabias' or half an OPEC's worth of oil at an average cost around $18/bbl. Those "negabarrels" are domestic, secure, carbon-free, and inexhaustible.

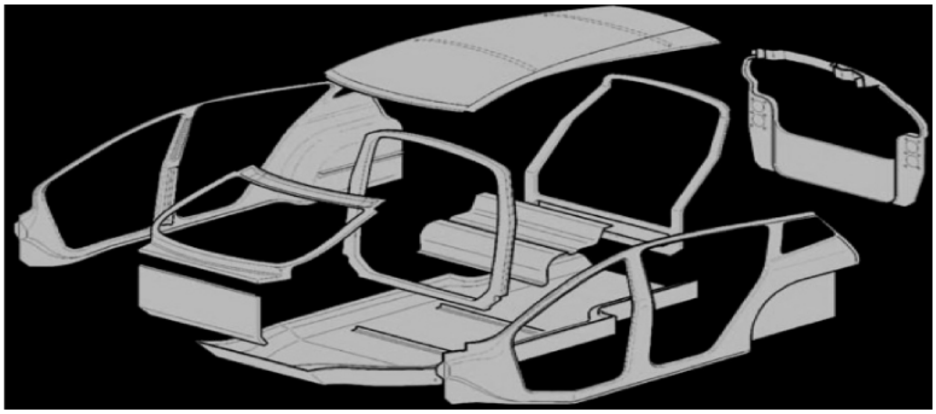

Fig. 4. How to make a carbon-fiber-composite, airframe-like autobody (for Hypercar's 2000 Revolution *midsize-SUV virtual design) with snap-together parts (each made with a single low-pressure dieset—~90–95% fewer than in an equivalent steel SUV body—yet with far greater strength and stiffness.*[4]

AUTOMOTIVE CHALLENGES AND OPPORTUNITIES

Designing such ultralight vehicles requires rigorous attention to mass decompounding (the less mass you have, the less mass you need) and radical simplification (*e.g.*, a good series hybrid design can eliminate transmission, clutch, flywheel, axles, differentials, driveshaft, universal joints, starter, and alternator—triggering with each elimination a new recursive round of further mass savings and simplifications). Thorough design integration[9] is also required to achieve multiple benefits from single expenditures. These changes in design method require in turn a very different design culture, plus formidable changes at each step of manufacturing and marketing.[10] These changes are now gradually underway on several continents, including in Detroit (where Rocky Mountain Institute is assembling a supply chain for volume production of carbon-fiber automotive structures). Approximately 4–7 automakers are in various stages of adopting RMI's ultralighting-then-electrification strategy, with BMW the most explicit. That firm has stated that the *i3*'s carbon fiber is paid for by requiring fewer batteries, and its CEO, echoing an RMI remark, has said: "We do not intend to be a typewriter-maker"; he can look across München to where Olympia, until 1992, made excellent typewriters. Signs are also emerging of a potential China-led, RMI-catalyzed, industry-supported leapfrog that, if adopted, could transform the global competitive landscape.

Less dramatic but still important progress can also be made with conventional light metals. For example, making Ford's 2015 flagship *F150* pickup truck—America's most popular vehicle—all-aluminum shrank its weight by ~318 kg and its powertrain by 19–54%, saving more weight and presumably helping to pay for the costlier aluminum. A 1997 proprietary study by RMI and a major automaker found that this approach could make a high-volume aluminum-intensive production car more efficient than a *Prius* hybrid but without the hybrid powertrain, improving fuel efficiency by three-fifths with a two-year retail payback and much higher profit margins. And RMI spinoff Bright Automotive's aluminum-intensive 2009 *IDEA* commercial fleet van's driving prototype (with strong market interest, but not produced after a government loan program took 3.2 years to make no decision) saved a ton of weight and half its batteries through lightweighting and drag reduction, making this plug-in hybrid (1.5–3.4 L/100 km depending on driving cycle, *vs.* a U.S. norm of 17–19) attractive to fleet buyers *with no subsidy.*

However, advanced polymer composites, though less familiar, offer major further gains in performance and in simpler manufacturing.

Radical "vehicle fitness"—obesity removal—enables all advanced powertrains. For example, the midsize fuel-cell SUV design mentioned above needed only 3.4 kg of 345-bar H_2, in 137 L of carbon-fiber tanks, to drive 530 km. Its two-thirds smaller tanks were readily packageable (Fig. 5) without interfering with passenger or cargo volumes and without needing a breakthrough in storage (such as the difficult 700-bar tanks being introduced by several major automakers for heavy steel platforms). The fuel cell too shrank by two-thirds, justifying three times higher cost per kW. A typical 80% experience curve—so a doubling of cumulative production volume cuts real cost 20%—would then need ~32 times less production to reach a competitive pricepoint, cutting a decade or two off deployment times. The key in both cases is to make the vehicle so efficient that it can cruise at 89 km/h with the same power to the wheels that a normal SUV uses on a hot afternoon to run its air conditioner.[11] Prior findings of poor prospects for fuel-cell vehicles flowed from the common but unwarranted assumption of inefficient vehicle physics.[12]

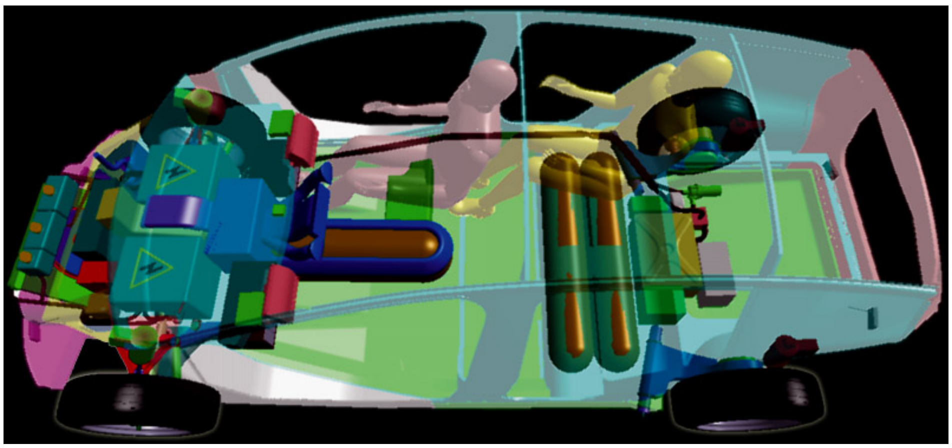

Fig. 5. Packaging of the Hypercar Revolution *SUV fuel-cell powertrain (ref. 4) using off-the-shelf 1990s filament-wound cylindrical carbon-fiber tanks for analytic convenience. This 3.6×-more-efficient virtual design was simulated to cruise at 89 km/h with the same power to the wheels that a normal SUV uses on a hot afternoon to run its air conditioner. The hydrogen tanks can thus store a normal 530-km range's worth of fuel (137 L, 3.4 kg) at 345 bar, and the fuel cell too (with "X," just aft of the paired fuel tanks) becomes three times smaller than often assumed, yielding 2.06 L-equivalent/100 km onroad at attractive cost.*

In short, incremental improvement, chiefly in powertrain efficiency, is not the only way to make automobiles several- to manyfold more fuel-efficient. Every official study has pursued that well-trodden path, usually assuming only small improvements in platform fitness—the basic physical parameters that drive efficiency, most importantly mass. However, a disruptive design and manufacturing strategy tightly integrating ultralighting, excellent aerodynamics and tires, superefficient accessories, and electric traction can improve efficiency by nearly an order of magnitude without compromising safety, handling, acoustics, acceleration, cost, styling, or other driver and market parameters. Twenty-three years into this design-led revolution, its technical basis is now looking wholly feasible, its competitive advantage ever more striking, and its market success ever more plausible. Further developments that could make electrification cheap even before ultralighting, or could radically decrease automotive mass[13] even without using more-exotic materials than carbon fiber, are also possible, though the synergies between ultralighting and electrification make both worthwhile no matter which happens first.

This automotive revolution is not only about technology but also, centrally, about *design* (the way technologies are combined). It also engages innovative public policies and competitive strategies. The innovations in design and in business models can even be more important than those in technologies. For example, David Moskovitz of the Regulatory Assistance Project has proposed that automakers can sell electrified vehicles at a large discount if the buyer agrees that when plugged in and parked, the vehicle can be used for automaker/utility electrical transactions. The automaker can then aggregate many vehicles to provide numerous energy and ancillary services to the grid, negotiate good prices for them, and settle their accounts without hassle for the owner. The owner gets a guaranteed-uncompromised driving capability and experience at a lower up-front price. The automaker hopes to earn a profit on the electrical transactions, and will surely sell more vehicles at the big purchase discount. Even more disruptive business models now emerging in the provision of mobility and access will be mentioned below. These are starting to shift some automakers from selling cars to leasing mobility and access services, aligning interests with customers'.

HEAVY TRUCKS

The second-biggest user of U.S. mobility fuel, heavy (Class 7 and 8) trucks like the ubiquitous 18-wheelers, have analogous physics on a much larger scale. About two-thirds of the over-the-road tractive load is due to aerodynamic drag, one-third to rolling resistance. The engine is typically a large and very efficient Diesel, with torque transmitted through an elaborate many-speed transmission that may be largely automated. Some truckmakers are beginning to offer hybrid-electric drive, and many, plus a swarm of aftermarket firms, offer important innovations in aerodynamics and tires. As with autos, the biggest immediate gains are in platform fitness, and they suffice to roughly triple today's typical cargo-hauling efficiencies of about 36 L/100 km (6.5 miles per U.S. gallon) or 50 T-km/L (130 ston-mi/USgal), raising them to about 129 T-km/L (335 ton-mi/USgal), as summarized in Fig. 6.[14]

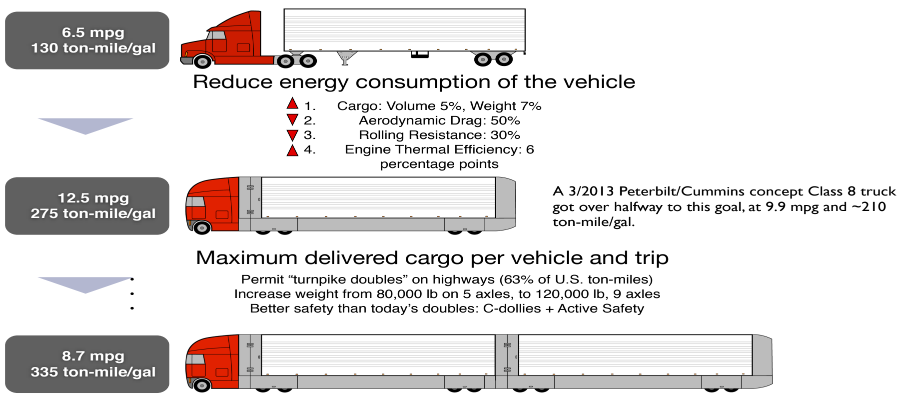

Fig. 6. RMI's 2008 Transformational Truck Study (ref. 14) sought the proven boundaries of efficiency and productivity in Class 7 and 8 trucks, and found a 2.3–2.7× potential improvement without counting some further savings that would raise the total potential to at least 3×.

Efficiency can first be doubled by systematic refinements that provide ~5% greater cargo volume with 7% less weight, halve aerodynamic drag, cut rolling resistance ~30%, and improve engine thermal efficiency by ~6 percentage points. All these methods are already demonstrated and in or entering the market. Together they can double efficiency to ~18.8 L/100 km (12.5 mi/USgal) or ~106 T-km/L (275 ston-mile/USgal). Permitting "turnpike doubles" (two or even three trailers per tractor) on highways, which carry ~63% of U.S. freight-hauling, can decrease weight per axle because gross vehicle weight rises from 36.3 to 54.4 T but the number of axles rises more, from 5 to 9. Using a Canadian coupling innovation called a C-dolly, plus active safety controls, can improve stability and road safety. The result, at 27 L/100 km (8.7 mi/USgal), uses more fuel per haul but halves the hauls, raising freight-hauling efficiency to about 129 T-L/km (335 ston-mile/US gal) or 2.6 times the initial value. This can rise further to tripled efficiency with further improved auxiliaries, accessories, and refrigeration where present; hybridization and regenerative braking; idle elimination by using an auxiliary power unit when parked rather than idling the large Diesel engine; and optimizing driver training and operating speed (remember that aerodynamic drag rises as the cube of speed). If lighter, smaller, cheaper, fully digital Diesels developed by a Colorado firm called Sturman Industries fulfill their initial lab- and road-test promise, it may also become possible to raise engine efficiencies from ~45–50% to ≥60% while eliminating NO_x emissions, nearly eliminating particulate emissions, and becoming able to burn any fuel cleanly on the fly.

Despite the efforts of vendors, buyers, third-party add-on vendors, and the federal Supertruck program, there are substantial challenges from institutional inertia, traditional purchasing practices, conflicting business models, limited market power to ensure "demand pull," and dis-integrated tractor and trailer design. But the prize is so great that in time it seems highly likely these will be overcome. RMI's spinoff, the North American Council for Freight Efficiency, is among the groups driving this agenda.

As with car, plane, and ship efficiency, truck innovations will be sped by the military revolution in fuel efficiency, much as military R&D created the Internet, GPS, and the jet-engine and microchip industries that transformed the civilian economy. The difference is that this time the prize is getting the civilian sector—which uses over 50 times as much oil as the U.S. military—off oil faster, so American warfighters can have negamissions in the Persian Gulf—Mission Unnecessary.[15] They really like that idea.

AIRPLANES

Airplanes, the third-biggest user of mobility fuel, are supported by wings rather than wheels, so light weight and low drag have received stronger attention and innovation. U.S. fuel use per seat-km fell 82% during 1958–2010, but even greater gains are in store. Boeing, MIT, and NASA, among others, have designed tube-and-wing airplanes with truss-braced wings, or blended-wing-body configurations with boundary-layer ingestion, with improved engines, aerodynamics, and advanced-composite structures (*vs.* the ~50% in Boeing's *787* and Airbus's *A350*; taking 1 kg out of a typical plane is worth about $2,000). Such innovations may reduce manufacturing cost, as in the Lockheed-Martin Skunk Works' ~1994 Joint Strike Fighter variant that was 95%-carbon-composite, one-third lighter, yet two-thirds cheaper (at the hundredth copy) than its 72%-metal base-case. Continued advances may mean that doubling efficiency with tube-and-wing or tripling it with blended-wing-body may be outdated targets: NASA's chief scientist even thought quadrupled-efficiency tube-and-wing designs may be possible. In all, innovations on many fronts offer roughly 3–5-fold long-term efficiency gains from today's commercial jet fleet. Liquid-H_2 "cryoplanes" to exploit hydrogen's very low density (more important than its greater bulk) via unducted-turbofan or fuel-cell-fan propulsion may ultimately, with new infrastructure, increase these savings to ~6–7-fold with similar economics and improved safety.

OTHER VEHICLES

From motorcycles to trains and buses to ships, similar integration of advanced materials, powertrains, hydrodynamic surfaces and controls, and other components can dramatically reduce energy use and improve safety and performance. This is true not just of propulsion but also of important onboard loads. For example, Rocky Mountain Institute found that both a new luxury yacht (*S/Y Ethereal*) and a potential retrofit of "hotel loads" on a U.S. Navy *Aegis* cruiser (*USS Princeton*, CG-59) offered an economically attractive potential for doubled electrical efficiency—very valuable because the onboard generators burn oil, not very efficiently (especially in Naval vessels with part-loaded gas turbines). Similar opportunities recently emerged on a new cruise ship.

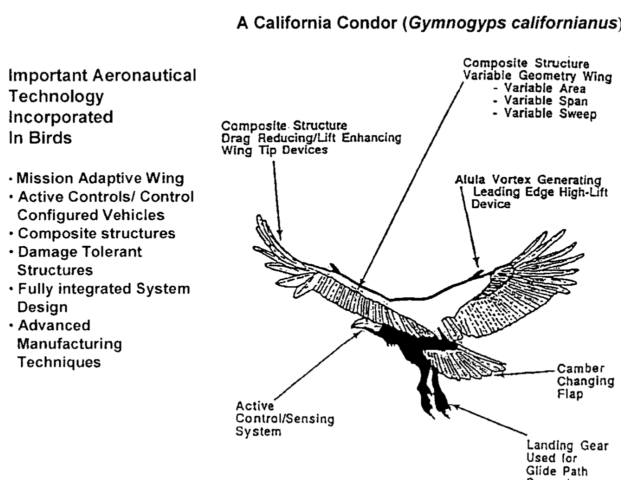

Fig. 7. Aerodynamic innovations of a gliding California Condor, courtesy of Dr. Paul MacCready (1925–2007), founder and chairman of AeroVironment, Inc.

Biomimetic innovations, especially novel uses of laminar vortex flow[16], promise further efficiency breakthroughs in all sorts of vehicles. Humans have yet to design an airplane as efficient as an albatross, or as the winged seed of the tropical Asian climbing gourd *Alsomitra macrocarpa*, which glides for hundreds of meters. The late great aerodynamicist Professor Paul MacCready noted that the California Condor's innovative design features (Fig. 7) push to or beyond the limits of today's most sophisticated airplanes.

VEHICLE PRODUCTIVITY, MOBILITY, AND ACCESS

Walmart's giant fleet of heavy trucks used 46% less fuel to move a case of merchandise in 2013 than in 2005, thanks to systematic improvements in both truck technologies and logistics. Yet comparable or larger savings remain to be captured by using all kinds of vehicles far more productively. This is not just about driving empty backhauls out of freight or doing road/rail piggybacks and intermodality. If the peaks of fuel-wasting road congestion in morning and evening rush hours were an electricity loadshape, we would throw a lot of IT-enabled pricing, demand response, and smart grid at it to try and flatten out those peaks. But by not yet doing this for road traffic, we are wasting many billions of dollars a year in idle people, idle vehicles, and idle roads. *Reinventing Fire* found that the proven performance of four innovations—charging drivers for road infrastructure by the km not the L, IT-enhanced transit and car- or ride-sharing (nowadays integrated through smartphones), New Urbanist land-use and development models (so more people are already where they want to be and needn't go elsewhere so much), and IT-smoothed traffic flow—could cut U.S. driving by 46–84% for the same access. (Some analysts also believe that autonomous autos, if sensibly used, may save even more fuel.) More fundamentally, making markets in "negakilometers" and "negatrips" so they can compete fully and fairly with physical mobility could help provide greater, cheaper, easier, and fairer access for all, yet with less movement of mass. Increasingly, too, Moore's Law will improve virtual mobility—moving just electrons and leaving the heavy nuclei at home.

FUELS

As shown in *Reinventing Fire*, these levels of efficiency (Fig. 8, modestly reinforced by more-productive use) can enable a 2050 U.S. economy with 158% higher GDP, 90% more automobility, 118% more trucking, and 61% more flying than in 2010—yet using *no oil*. The 1–2 L-equivalent/100 km ultralight electrified autos can use any mixture of hydrogen fuel cells, electricity, and advanced biofuels. Heavy trucks and airplanes can realistically use advanced biofuels or hydrogen; trucks could even burn natural gas; but no vehicles will need oil. Any biofuels the U.S. might need, at most 3 Mbbl/d, could be made two-thirds from wastes, without displacing cropland or harming climate or soil. The land-use and other issues that arise with very-large-scale use of biofuel feedstocks would be avoided by superefficiency, leaving a very diverse portfolio of competitive options whose long-term mix cannot and need not be known in advance. As for economics, advanced-biofuel contracts for 2014 and 2015 delivery to the U.S. Navy and 2014 delivery to United Airlines are reportedly cost-competitive with the petroleum fuels for which they completely substitute as tested, certified, and miscible drop-in replacements. Hydrogen economics (chiefly using forecourt reformers except where cheap windpower supports electrolysis) also look sound, as shown in *Winning the Oil Endgame*, and practical hydrogen infrastructure solutions were worked out in 1999.[17]

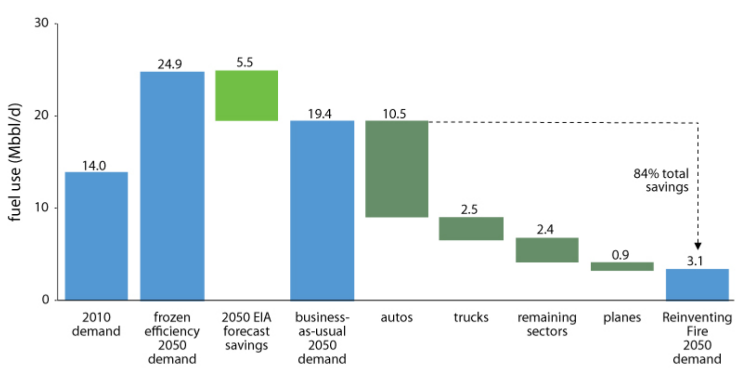

Fig. 8. U.S. transportation fuel-saving potential, 2010–2050 (RMI analysis, ref. 1).

Reinventing Fire found a 17% internal rate of return for getting U.S. mobility completely off oil by 2050 (Fig. 9), assuming that carbon emissions and all other hidden or external costs are worth zero—a conservatively low estimate. The required technologies all provide a ≥15%/y real return in trucking or a ≤3-y simple payback to the autobuyer. The average cost of saving or displacing oil for U.S. mobility is roughly $25/bbl (2009 $ levelized at a 3%/y real discount rate)—a small fraction of today's oil price or of marginal oil-based fuel production and delivery costs. This implies, as *Reinventing Fire* showed, a $4-trillion net-present-value U.S. saving potential. If this number had included just the economic and military costs of U.S. oil dependence, that would be about $12 trillion—not counting any harm to health, safety, environment, climate, global stability and development or the United States' independence and reputation.

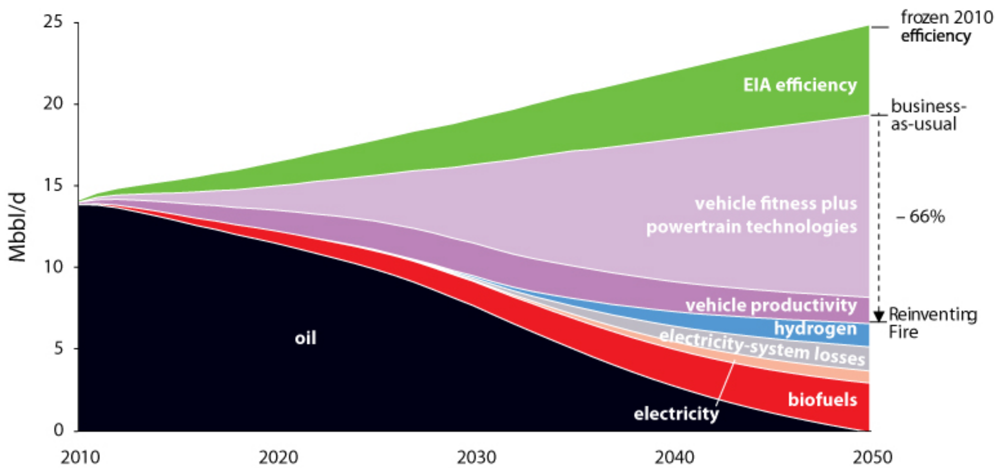

Fig. 9. Projected path to U.S. oil-free transportation, 2010–2050 (ref. 1). Only the "EIA efficiency" is baked into the January 2010 Energy Information Administration forecast used as RMI's base case.

IMPLICATIONS

Basic physics reveals a surprisingly attractive pathway for several- to manyfold more efficient vehicles. Using these in more productive ways that make sense and make money can further reduce their fuel use. These innovations all have a compelling business case, so many of them are already beginning to be adopted by alert market actors around the world. Since burning oil, mainly for transportation and about one-half in autos, releases two-fifths of global fossil-fuel carbon emissions, this implies that a similar fraction of those emissions can be abated not at a cost but at a profit, because efficiency costs less than fuel. (The same turns out to be true for virtually all the other emissions too.) The policy innovations needed to enable and speed these developments can all be done in the U.S. administratively or at a state or local level. The only policy needing an Act of Congress—harmonizing Federal highway standards to modernize size, weight, and multitrailer rules—could be omitted with only 0.26 Mbbl/d foregone savings by 2050.

For these and other reasons, many related to national and international security, many analysts began around 1999 to forecast "peak oil" not in supply but in *demand*, with global oil demand peaking as early as this decade, then declining. (U.S. gasoline use peaked in 2007.) Like whale oil in the 1850s, oil is becoming uncompetitive even at low prices *before* it becomes unavailable even at high prices. This has profound implications for the immensely powerful and capable industry that supplies the oil. Reapplying its skills and assets to thrive in the emerging new energy world will require wrenching transformation. That transition too is beginning to emerge from the oil industry's unpromising fundamentals—perhaps in time. As *The Economist* recently commented on the plausibility of peak oil on the demand side, "Rather than push towards ever more esoteric frontiers, the supermajors might do better to slim down and turn away from the oil that they prize so highly but that the world may no longer want ever more of…."[18]

ACKNOWLEDGMENTS

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Fiberforge, and Bright Automotive spinoffs, and innumerable other organizations. Many key contributors are cited in the Acknowledgments of the two books in ref. 1. The views expressed here are solely the author's. Preparation of this paper was supported by a grant to RMI from Fred and Alice Stanback.

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1 Details are documented in A.B. Lovins *et al.*, *Reinventing Fire* (Chelsea Green, White River Junction VT, 2011), and in backup materials at www.rmi.org/reinventingfire. See also A.B. Lovins *et al.*, *Winning the Oil Endgame*, Snowmass, Colorado: Rocky Mountain Institute, 2004, www.oilendgame.com. Graphics accompanying the lecture summarized in this paper are posted at **TK URL**. Graphics in this article are copyright © 2011 by Rocky Mountain Institute and used by permission; for more information, see www.rmi.org/reinventingfire.

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