Public Lectures in Advanced Energy Efficiency:

3. Transportation

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The world consumes a cubic mile of oil per year—85 million barrels per day
[courtesy of CAPT Scott Pugh, USN Ret., RMI Military Principal]

85,000,000 x 30 inches
(12 inches/foot)(6,000 feet/nautical mile) = 35,416 nautical miles

20-inch pipeline

1 barrel of crude oil = 42 U.S. gallons

35,416 nm = 1,475 knots ≈ Mach 2

21,600 nm circumference

Image © 2006 Teledyne Motion
Image © 2006 NASA
Unlikely Allies Fight U.S. Oil Dependence

Bipartisan Network to Press for Reduced Consumption, Quicker Development of New Fuels
Whalers ran out of customers before they ran out of whales...

...even before Drake struck oil in 1859!
Some recent wildcat discoveries

- 8.3 million bbl/d play in the Detroit Formation
- 1.6 million bbl/d play in heavy trucks
- 1.2 million bbl/d play in industrial fuels/feeds
- 1.1 million bbl/d play in buildings
- 0.9 million bbl/d play in aircraft
- 1.6 million bbl/d play in other oil end-uses
- > 5 million bbl/d play in robustly competitive biofuels, chiefly cellulosic ethanol, and in biomaterials and biolubricants
- 12 TCF/y play in electricity and gas end-uses

Shouldn’t we drill the most prospective plays first?
20 Sept 2004 detailed study
Independent, peer-reviewed
Transparent, uncontested
OSD- and ONR-cosponsored
For business & mil. leaders, built around competitive strategy for cars, trucks, planes, fuels, and military
329-page book & complete technical details are free downloads from:
www.oilendgame.com

Over the next few decades, the U.S. can eliminate its use of oil and revitalize its economy, all led by business for profit

This work was cosponsored by OSD and ONR. The views expressed are those of the authors alone, not of the sponsors.
A profitable US transition beyond oil (with best 2004 technologies)

U.S. oil use and imports, 1950–2035

- government projection (extrapolated after 2025)
- end-use efficiency @ $12/bbl
- plus supply substitution @$26/bbl (av. $18/bbl)
- plus optional hydrogen from leftover saved natural gas and/or renewables (illustrating 10% substitution; 100%+ is feasible)

$180b investments saves $155b/y gross, $70b/y net, vs $26/bbl oil, cuts CO2 26%; 1M new + 1M saved jobs

Practice run 1977–85: GDP +27%, oil use −17%, oil imports −50%, Persian Gulf imports −87%

OPEC’s exports fell 48%, breaking its pricing power for a decade; U.S. is Saudi Arabia of negabarrels

...and all implementable without new fuel taxes, subsidies, mandates, or national laws
Vehicles use 70% of US oil, but integrating low mass & drag with advanced propulsion saves ~2/3 very cheaply

**CARS:** save 69% at $0.15/L

**PLANES:** save 20% free, 45–65% @ ≤$0.12/L

**BLDGS/IND:** big, cheap savings; often lower capex

**TRUCKS:** save 25% free, 65% @ $0.07/L

Technology is improving faster for efficient end-use than for energy supply
Light and heavy trucks = 70% of projected 2000–25 rise in total U.S. consumption of petroleum products (by volume)

Basic automotive physics

◊ **Powertrain efficiency** (tank-to-wheels) ≡
  - engine thermodynamic \( \eta \) (fuel-to-work) \( \times \) engine mechanical \( \eta \) (work-to-output-torque) \( \times \) driveline \( \eta \) (engine-to-wheels)
  \( \approx 0.38 \times 0.53 \times 0.85 = 0.17 \) (vs. 2004 *Prius* 0.33–0.37)

◊ **Vehicle load** = tractive load + accessory loads
  (~2–3%, often engine-driven with different conversion losses)

◊ **Tractive load** in approx. instantaneous kW \( \text{mech} \) =
  - **Inertia** = \( 0.5M^*[\Delta v^2/\Delta t] \) \( (M^* \approx 1.03M, [\Delta v^2/\Delta t] \text{ in } m^2/s^3) \)
  - + **rolling resistance** = \( C_R M g v \) \( (M \text{ in tonnes, } v \text{ in m/s}) \)
  - + **aero drag** = \( 0.5 \rho_{\text{air}} C_D A v^3/1000 \) \( (\rho \approx 1.2 \text{ kg/m}^3, A \text{ in } m^2) \)
  - + **grade** = \( m g v \text{•sin}\theta \) \( (\text{grade} = \tan\theta; \neglected \text{ in next chart}) \)
  - Inertial and grade loads can be negative; 2004 *Prius* hybrid recovers them with average wheel-to-wheel efficiency 0.66
  - 1995 *Taurus* tractive load is only 6.3 kW, equivalent to 1.6 L/100 km or 0.67 US gal/100 mi...but divide by powertrain \( \eta \)!

◊ **Powertrain** \( \eta \) can’t exceed 1.0, **but tractive load can be reduced almost without limit**
Current and projected new-car efficiency or CO$_2$ stds. (in US CAFE g CO$_2$/km-NEDC)


*Prius*
Challenging a basic assumption in Detroit and Washington

- Efficiency assumed to be a tradeoff—makes cars small, unsafe, sluggish, costly, ugly,...
- Hence policy intervention needed to induce customers to buy the compromised vehicles
How many people still buy phonograph records...

...or cathode-ray-tube TVs instead of big flat-panel TVs?

◊ An engineering end-run around tax/CAFE gridlock
◊ A robust business model based solely on value to customer and competitive advantage to suppliers
Where does a car’s gasoline go?

- 6% accelerates the car, 0.3% moves the driver
- Three-fourths of the fuel use is weight-related
- Each unit of energy saved at the wheels saves ~7–8 units of gasoline in the tank (or ~3–4 with a hybrid)
- **So first make the car radically lighter-weight!**
"I had been experimenting principally upon the cutting down of weight. Excess weight kills any self-propelled vehicle....Weight may be desirable in a steam roller but nowhere else.

The most beautiful things in the world are those from which all excess weight has been eliminated ....Whenever any one suggests to me that I might increase weight or add a part, I look into decreasing weight and eliminating a part!"

— Henry Ford, My Life and Work
Average new U.S. light-duty vehicle now weighs more than 2 short tons

For industry average:

\[ y = 47.5x - 91,240 \]

\[ r^2 = 0.99 \]

29% increase 1987–2006
U.S.-sold cars & vans are getting denser, compromising both safety and efficiency

**Weight**

\[ y = 24x - 44,676 \]

17.9% increase since 1987
(3,035 lb to 3,555 lb)

**Density**

\[ y = 0.16x - 287 \]

13% increase since 1987
(29 lb/ft\(^3\) to 32 lb/ft\(^3\))

70% of the increase in weight is due to design and materials, 30% to changes in size & mix.
Three technology paths: aluminum, light steels, carbon composites (the strongest & lightest)

- **SLR McLaren** suffers immaterial damage in side impact by *Golf*
- 7 kg of woven carbon crush cones (0.4% of car’s mass) can absorb all frontal crash energy at 105 km/h with thermoset (better w/thermoplastic)

- Carbon-composite crush structures can absorb 6–12\(\times\) as much energy per kg as steel—and more smoothly
- Size is protective, weight hostile; so adding size without weight adds protection and comfort without aggressivity or fuel inefficiency ...saving both oil *and* lives (and $)

Graphics courtesy of DaimlerChrysler AG
Confirmed by light-composite-car crash experience

Katherine Legge’s 290 km/h walk-away ChampCar wall crash on 29 September 2006
Tough stuff (≥250 kJ/kg)

From Tom Friedman’s 24 Jun 06 feature *Addicted to Oil* on The Discovery Channel...

*Revolution’s* most highly loaded and complex body part...

and Tom’s futile efforts to damage a 2-mm-thick x 200-mm-diameter thermoplastic carbon-fiber hemispherical shell for a military helmet
The nationwide crash data confirm: *size* confers safety; *weight* doesn’t.

When Kahane (NHTSA) found 100 lb lighter would kill 414–1,314 more people, he assumed size and weight were equivalent metrics—but they’re not.

Results from Van Auken and Zellner (DRI) 2003, *separating size from weight* in NHTSA/Kahane’s FARS database.

Effects are due to crashworthiness, crash avoidance, and compatibility. All light vehicles on U.S. roads, and all road users, are included.
Migrating innovation from military aerospace to civilian cars

◊ At the Lockheed Martin Skunk Works®, engineer David Taggart led a ‘94–96 team* that designed an advanced tactical fighter-plane airframe...

- made 95% of carbon-fiber composites
- 1/3 lighter than its 72%-metal predecessor
- *but 2/3 cheaper...
- because it was designed for optimal manufacturing from composites, not from metal

*Integrated Technology for Affordability (IATA)

◊ Finding no military customer for something so radical, he left. I soon hired him to lead the 2000 design of a halved-weight SUV (*Intl. J. Veh. Design 35*(1/2):50–85 [2004])...
An uncompromised, competitive, 3.6–6.2x-more-efficient midsize SUV

...in a thorough virtual design, done in eight months in 2000, for ~$3 million, by a small team led by Hypercar, Inc. in collaboration with two European Tier Ones...

### Performance Comparison

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Hypercar</th>
<th>Lexus RX350</th>
<th>Ford Explorer</th>
<th>GM Trio</th>
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<tr>
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<td>11.9</td>
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<td>Start off grade</td>
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1: includes 460kg payload. 2: Constrained by wheel diameter. 3: Hwy = 44.2 mpg City = 119.5. 4: 120 km/h speed limit. 5: 150 km/h speed limit. 6: 150 mph speed limit. 7: 150 mph speed limit.
Midsize 5-seat Revolution concept crossover SUV
Ultralight (857 kg = steel −53%) but ultrasafe
0–100 km/h in 8.3 s, 2.06 L/100 km = 114 mpg (H₂)...
or 0–100 in 7.2 s, 3.56 L/100 km
= 67 mpg (gasoline hybrid)
with +$2,511 MSRP (2-y US payback)
68% of the hybrid’s fuel saving comes from lightweighting

“We’ll take two.”
— Automobile magazine
World Technology Award, 2003

Uncompromised, production-costed, manufacturable, via strong design innovation & integration
In the United States, like finding a Saudi Arabia under Detroit
In ultimate worldwide full-scale production, a nega-OPEC
In highway driving, efficiency *falls* because there is far more irrecoverable loss to air drag (which rises as $v^3$) and less recoverable loss to braking.
Decompounding mass and complexity also decompounds cost

Only ~40–80 kg C, 20–45 kW, no paint?, little assembly, radical simplification as significant components/systems go away

Exotic materials, low-volume special propulsion components, innovative design

New design strategy, materials, and technologies
857-kg Revolution crossover SUV simulated frontal barrier crash (2000)

- 56 km/h fixed barrier crash causes no structural damage to passenger compartment; replaceable front end crushes instead

- FMVSS criteria also met in a frontal non-offset collision with a steel SUV twice its weight, each going 48 km/h (combined speed 96 km/h)
Ultralight autobody materials

Vehicle designed for 320,000-km warranty—no dent or rust, bounces off 10 km/h collision

aluminum front subframe

advanced-composite passenger safety cell

186.5-kg (~57%) body-in-black™: bending stiffness 14,470 N/mm, torsional stiffness 38,490 N•m/°, first bending/torsion mode 93/62 Hz—>50% stiffer than a steel premium sports sedan
Radically simplified manufacturing

◊ Mass customization
  o *Revolution* designed for 50k/year production volume
  o Integration, modular design, and low-cost assembly
  o Low tooling and equipment cost

  o 14 major structural parts, no hoists
  o 14 low-pressure diesets (not $10^3$)
  o Self-fixturing, detoleranced in 2 dim.
  o No body shop, optional paint shop
  o 2/5 less capital than leanest, 2/3 smaller
Rapid progress with midvolume cost-competitive advanced composites

◊ BMW: 60 specialists at Landshut, world’s biggest RTM press, series production 2000+5...
  o Already making >1k/y carbon roofs, hoods,...
  o Website strongly praises carbon composites

◊ Honda and Toyota: carbon-fiber airplanes

◊ Fiberforge®: 1999 RMI spinoff (W. Colo.)
  o Patented digital automated fiber placement process
  o Thermoform to net shape with ≤1-minute cycle time
  o ≥80% of hand-layup aerospace performance @ 20% of cost
  o Mature process at scale beats Al in $/part, steel in $/body at midvolume, and steel in $/car at any volume
  o Sample & development customers include OEMs and Tier 1s, e.g. JCI Genus seat (NAIAS 05)
  o World Techn. Award ’03, Davos Tech Pioneer ’07
Automated volume mfg. of continuous-fiber-reinforced thermoplastic structures
See www.fiberforge.com for technical details and papers

1. Digitally controlled automated fiber placement to create a flat preform (tailored blank™)
   ◦ Fast (1.35 m/s and rising), precise, CAD-driven
   ◦ Variable thickness, fiber mix/alignment/location
   ◦ Ideal for anisotropic parts optimized to load paths

This video is Fiberforge proprietary

Carbon/PEEK 200-mm hemisphere

SOME DIVERSE MATERIALS SYSTEMS & APPLICATIONS

Carbon/nylon-6 seat-back frame (NAIAS ’05)
Automated volume mfg. of continuous-fiber-reinforced thermoplastic structures

2. Thermoform on hot die to net shape, cool, trim

High material efficiency, low cost (can start with creel fiber and thermoplastic pellets), very low scrap

And carbon composites don’t rust or fatigue
Car design: six kō-ans (公案)

- Big fuel savings cost less than small fuel savings
- To leap forward, think backwards
- By not saving fuel, more fuel is saved
- To make cars inexpensive, use costly materials
- To make cars safer, make them much lighter
- To get the cleanest and most efficient cars, don’t mandate them—just let the customer demand and get superior design

Result: an automotive *hiyaku* (飛躍, leapfrog)
Crossover concept SUV designed with two Tier I’s in 2000; combination of unique public & proprietary data

Three powertrain variants resimulated by consultants

Production cost independently analyzed at 499-line-item level of detail, largely by industry bids @ 50,000/y

Scaled to all light vehicles by well-validated methods
Ultralight-but-safe light vehicles open a new doubled-efficiency design space at no extra cost

All Vehicles Shown in Green are Adjusted to EIA’s 2025 Acceleration Capability for That Class of Vehicle
RMI’s 2004 Average Vehicles are for EIA’s 2025 Sales Mix

Price Increase (MSRP 2000 $)

Absolute Liters per 100 Kilometers (EPA Adjusted, Combined City/Highway)

*33 steel firms + Porsche Eng.: 2,200-lb Taurus-class, 52 mpg, 5☆ safety, $9,538 production cost; BIW –52 kg, –$7
Emerging German innovation:
Loremo 2+2 sports car (2009)

German startup (München 2004)

Light steel structure (95 kg) with side and center longitudinal beams

Doorless; rearward rear seats/trunk

450 or 470 kg, $C_w$ 0.20, $C_wA$ 0.22 m$^2$

Nonhybrid 2- or 3-cylinder turbo-diesel, 15 or 36 kW (20 or 50 hp), 5-speed manual transmission

LS model: 1.5 L/100 km (157 mpg), 160 km/h, 0–100 km/h in 20 s

GT model: 2.7 L/100 km (87 mpg), 220 km/h, 0–100 km/h in 9 s

€10,990 or €14,990 in 2009
Stages of the emerging automotive [r]evolution

◊ An excellent hybrid, properly driven, doubles efficiency
  ○ Considerably more if new diesels can meet ratcheting air regs

◊ Ultralighting (+ better aero and tires) redoubles eff’y.

◊ Cellulosic-ethanol E85 quadruples oil efficiency again
  ○ Biofuels can make driving a way to protect, not harm, the climate

◊ A good plug-in hybrid (such as Toyota is rumored to plan for initial release MY08) redoubles fuel efficiency again, and could be attractive if the power grid buys its electric storage function
  ○ Precursor of “vehicle-to-grid” fuel-cell play—power plant on wheels
  ○ So far, these stages can save 97% of the oil/km used today

◊ Hydrogen fuel cells also compete via cheaper $/km and 2–6× less CO₂/km (or zero CO₂ if renewable)
857-kg curb mass (÷2), low drag, load ÷3, so 89 km/h on same power as normal a/c, so ready now for direct hydrogen fuel cells

137-liter 345-bar H₂ storage (small enough to package): 3.4 kg for 532-km range

35-kW fuel cell (small enough to afford early: ~32x less cumulative production needed to reach needed price)

Identical logic for HEVs, PHEVs, BEVs
Lightweighting cuts powertrain costs and enables advanced powertrains early

Example: fuel-cell vehicles with equivalent performance; same story for hybrids

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>Power (kW)</th>
<th>Type</th>
<th>Cost @ $100/kW</th>
<th>Range (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hypercar Revolution</td>
<td>35</td>
<td>hybrid</td>
<td>$3,500</td>
<td>531</td>
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<tr>
<td>Jeep Commander 2</td>
<td>50</td>
<td>hybrid</td>
<td>$5,000</td>
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<td>Hyundai Santa Fe FCV</td>
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<tr>
<td>Honda FCX-V4</td>
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<td>Toyota FCHV-4</td>
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<td>hybrid</td>
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<tr>
<td>GM HydroGen III</td>
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<tr>
<td>GM Hy-Wire</td>
<td>94</td>
<td>fuel cell</td>
<td>$9,400</td>
<td>129</td>
</tr>
</tbody>
</table>

Example: fuel-cell vehicles with equivalent performance; same story for hybrids.
Platform physics is more important than powertrain—and is vital to its economics

- Cars can run clean IC engines on gasoline or NG ($\equiv 1\eta$)
- Better ones using hydrogen in IC engines ($\leq 1.5\eta$)
- Still better ones using H$_2$ in IC-engine hybrids ($\sim 2.5\eta$)
  - Ford “Model U” concept car...but tanks $>4\times$ bigger (niche market)
- Better still: ultralight autobodies, low $C_D A$ & $r_0$ ($\geq 3\eta$)
- Power those platforms with IC-engine hybrids ($3.5-4\eta$)
  - Hypercar 5-seat carbon Revolution has the same $m_c$ & $C_D$ as 2-seat aluminum Honda Insight...Insight-engine hybrid version 3.6L/100km
- Best: put fuel cells in such superefficient bodies ($5-6\eta$)
- The aim isn’t just saving fuel and pollution
  - Also strategic goals in automaking, plug-in power-plants-on-wheels, off-oil, primary fuel flexibility, accelerated transition to renewables,...
- H$_2$ needs $5\eta$ vehicles far more than vice versa
- $5\eta$ vehicles make robust the business case for providing the H$_2$ that their fuel cells would need
An example of emerging powertrain breakthroughs

- Fast, small, light, cheap, proven, mature electronic valves permit extremely precise fuel and air injection under real-time closed-loop control.
- This in turn permits unusual event sequences and combustion cycles in camless engines.
- Those are expected to yield ~55–60% efficiency from any fuel (on the fly), with >50% higher torque, >30% smaller size, >10% lower cost, and extremely low emissions needing no cleanup.
- The first such prototype “digital engine” ran 30 January 2007 in a test cell at Sturman Industries near Colorado Springs, Colorado; rapid progress (www.sturmanindustries.com)
And what about plug-in hybrids?

- Better platform physics are the key to making PHEVs efficient and affordable.
- PHEVs can further improve powertrain efficiency and, depending on fuel and power sources, emit comparable or less CO$_2$ per km driven.
- PHEVs can charge with cheap offpeak electricity and sell valuable storage at peak hours back to the grid, paying for the batteries (which the utility may finance or own).
- PHEVs add offpeak storage to the grid, expanding markets for variable renewables (windpower).
- This needs a “smart garage”
Smart vehicle-to-grid (V2G) interface could be important

- Cars are parked ~96% of the time
- PHEV batteries or FCEV fuel cells in a superefficient U.S. light-vehicle fleet have ~6–12× total U.S. electric generating capacity, so even modest V2G displaces all coal/nuclear plants
- First ~2 million US drivers selling that capacity back to utility where/when most valuable could earn back entire car cost
- V2G Hypercar®-class vehicles could ultimately solve up to ~2/3 of the world’s CO₂ problem
- Utilities love G2V: offpeak el. sales, ratebasing grid expansion, el.→transp. GHG shift, battery finance, hi-tech customer bundle

The grid could recharge PHEVs with previously spilled night windpower, then lop daytime peak
Today’s cars: the highest expression of the Iron Age

◊ Extraordinary technical and commercial achievement, $1T/y industry
◊ The most complex mass-produced artifact in human history
◊ Produced every 2 seconds in the U.S. alone
◊ Costs less per kg than a McDonald’s quarter-pound hamburger
◊ Meets demanding and often conflicting requirements with great skill
◊ But many reasons for rapid and fundamental change now emerging
  o convergent products and shrinking niches
  o in saturated core markets
  o at cutthroat commodity prices
  o with stagnant basic innovation
  o and growing global overcapacity
  o forcing increasing consolidation
  o yet thin profits limit investment & recruitment...
  o thus a great industry but a bad business
◊ Time for something completely different!
**Does the frog leap?**

| Incremental, component-level design, from engine toward wheels, emphasizing driveline gains | Whole-car, clean-sheet design, wheels-back, emphasizing platform physics *first*
| Assume steel, gain mass | Ultralight, maximize mass decompounding
| Dis-integrated, specialist | Integrative, holistic
| Huge design group (10³) | Tiny design group (10¹)
| Relay race | Team play
| Lose most synergies | Capture all synergies
| Institutionalized timidity | Skunk Works® boldness
| Baroque complexity | Radical simplicity*
| Complex, hence difficult | Simple, hence difficult

*Einstein: “Everything should be made as simple as possible—but not simpler.”*
Is Detroit ready for transformation by such disruptive technologies?

- Tremendous engineering talent...if unleashed
- Weak balance sheets, slow innovation, many cultural and structural rigidities
- Tend to treat sunk costs as unamortized assets
  - Must base strategic choices on economics, not accounting
  - Must also consider cost per car, not per part or per kg
- Incoherence persists: lobbying and litigation strategy tends to stomp on internal innovation
  - GM’s EV-1, 2001 anti-CAFE, now Pavley (California CO₂ law)
- But cultural obstacles are starting to weaken under the assault of Schumpeterian “creative destruction”
  - Better to embrace disruptive technology early than be forced into it late and grudgingly
Can Detroit use efficiency as a transformative strategy?

◊ Boeing’s crisis in 1997 was like Detroit’s today
  ○ Wrenching changes instituted at BCA, including TPS (e.g., moving assembly); manufacturing and costs brought back under control
  ○ But what about growth? What was in the pipeline after 777?

◊ In 2003, Airbus for the first time outproduced Boeing
  ○ “This is really a pivotal moment...could be the beginning of the end for Boeing's storied airplane business,” said Richard L. Aboulafia, a Teal Group aerospace analyst, in 2003

◊ Boeing’s bold, efficiency-led 2004 response: 787 Dreamliner
  ○ ≥20% more efficient than comparable modern aircraft, same price
  ○ 80% advanced composite by volume, 50% by mass
    ◦ Bigger windows, higher-pressure cabin
  ○ 3-day final assembly (737 takes 11 days)
  ○ 513 orders (490 firm + 23 pending), 314 additional options
  ○ Sold out until 2013—fastest order takeoff of any airliner in history
  ○ Now rolling out 787’s radical advances to all models (Yellowstone)

◊ Airbus: Ultra-jumbo A380, 2 years late, ~€5b over budget
  ○ Response? Efficient, composite A350—probably too late
Key straws in the shifting winds of Detroit

- 2004: RMI suggests OEMs imitate Boeing
- 2006: Alan Mulally, leader of Boeing Commercial Airplanes, becomes CEO of Ford
  - "[He] said the automaker would require a full transformation...of the product line and...of the business"—not the typical Detroit turnaround. —*New York Times*, 24 Oct 2006, p. 1

- OEMs’ increasing openness to basic mfg. change
- UAW and dealers now pushing innovation as the best hope of saving the OEMs
- Emerging prospects of leapfrogs by China, India, and even new market entrants
- Competition, at a fundamental level and at a pace last seen in the 1920s, will change OEMs’ managers or their minds, whichever comes first
Heavy trucks: save 25% free, 65% @ 25¢/gallon

Better aero & tires, better engines etc., less weight

Two recent concept trucks

PACCAR high-eff. concept truck

Colani/Spitzer tanker (Europe), reportedly 11.25 mpg

6.2 to 11.8 mpg with 60% IRR by improving aero drag, tires, engines, mass, driveline, acces. loads & APU; then ~16 mpg via operational improvements; being built 2005

Big haulers’ margins double from 3% to 6–7%...so create demand pull —currently underway, led by major customers
Heavy trucks use 12% of all U.S. oil in 2025; 2004 technologies could save 65% of that use at 25¢/gal diesel

Start: 6.2 mpg


End: 11.8 mpg, then ~16-equivalent w/further improvements (we’ve since found ≥1.5 mpg more, excluding potential in basic logistics, de-materialization, relocalization, longevity, etc.)
Losses and savings multiply
Savings *downstream* make upstream equipment smaller and cheaper

56% engine + 12% idling & aux
2% trans
1% driveline
19% aero
11% tires
4.5% moves truck
6.5% moves cargo

**Result: 50% less fuel**

Reduce idle time by 80% with APU

First, reduce aero and tire drag by 50%

Each unit of avoided energy flow or friction in the pipe saves *ten units* of fuel at the power plant

This and following slide courtesy of M. Ogburn, RMI
New design mentality: “tunnel through the cost barrier”

1. Multiple benefits from single expenditures
2. Piggyback on retrofits
Airplanes: industry agrees fleet can get 2–3× more efficient

- Keys: advanced composites, new engines, aerodynamics
- Could save 45% of EIA 2025 fuel @ av. 46¢/gal Jet-A without Blended-Wing-Body (BWB); ~65% with BWB at comparable or lower cost
- Then another ~2× profitable potential from LH₂-fuel-cell-electric-prop cryoplanes
Conservatisms include no...

- Adaptive engines (ADVENT,...)
- Highly integrated adaptive structures, e.g., morphing aircraft forms and flight surfaces
- Powered wheels, inductive runway integration
- Advanced electric end-use efficiency
- Efficient high-speed propeller propulsion
- Pneumatic blowing, plasma boundary-layer,...
- Full accounting for system benefits of integrating BWB, adaptive engines, and other advanced tech
- Leaner force structures (~5–10x fewer aircraft?) possible with new capabilities, especially BWB
- LH$_2$ cryoplanes
Ultramodern aeronautical technology embodied in a gliding bird

A California Condor (*Gymnogyps californianus*)

**Important Aeronautical Technology Incorporated in Birds**

- Mission Adaptive Wing
- Active Controls/Control Configured Vehicles
- Composite Structures
- Damage Tolerant Structures
- Fully Integrated System Design
- Advanced Manufacturing Techniques

Composite Structure
- Variable Geometry Wing
  - Variable Area
  - Variable Span
  - Variable Sweep

Composite Structure
- Drag Reducing/Lift Enhancing Wing Tip Devices

Alula Vortex Generating Leading Edge High-Lift Device

Active Control/Sensing System

Camber Changing Flap

Leading Edge Load for Side Patch Control

Courtesy of Dr. Paul MacCready, founder and Chairman, AeroVironment, Inc.
After kerosene (>2025), cryoplanes (liquid H$_2$ fuel) with zero carbon? (not assumed in RMI’s efficiency analysis)

- LH$_2$ is 4× bulkier but 2.8× lighter than Jet A—and clearly safer*
- Designed & tested: Airbus, Boeing, Tupolev (TU-154 ’88), USAF
- Typical (767-class) Boeing study w/mass decompounding
  - Bad: empty weight (OEW) +8%, drag +11% (because bulkier)
  - Good: takeoff weight (MTOW) −24%, Initial Cruise Altitude Capability +13%, better climb characteristics, less engine maintenance burden
  - Net: ~4–5% better energy efficiency tank-to-flight based on airframe performance alone, or ~10–15% with H$_2$-optimized engines
  - Liquefaction 300→20K @ modern 4–5 kWh/kg (12–15% of LHV) roughly cancels airplane’s efficiency gain; well-to-tank eff. is comparable to oil’s

- −NO$_x$, 0 smoke/particulates/CO/HC/onboard CO$_2$; H$_2$O vapor?†
- Fuel cells are emerging for APUs—but maybe for propulsion too
  - P.M. Peeters (following NASA’s Chris Snyder) thinks lightweight fuel cells & superconducting-motor unducted fans could double efficiency vs. LH$_2$ turbofan planes: his 415-seat conceptual design (7000 km, 0.75 LF) uses 55% less fuel than 747-400; his 145-seater (1000 km, 0.70 LF) uses 68% less fuel than 737-400 (and at Mach 0.65, block time increases only 10%; might be faster if hubless, point-to-point, GPS-free-flight, ultralight, lower aero drag)
  - Thus ~20% long-haul and ~50% short-haul savings beyond RMI’s analysis

*NASA-Glenn CR-165525 & CR-165526 †Gauss et al. 2003, J Geophys Res 108(D10):4304, say climate impact is ~15x smaller than avoided CO$_2$ (kerosene vs climate-safe hydrogen in a huge subsonic fleet), but do discourage stratospheric and polar flight
Hypothetically assuming full deployment in 2025 (actually we realize half the savings by then); these curves assume no further invention in 2005–25

It pays to be bold: saving half the oil for $12/bbl is better than saving a fourth at $6/bbl — else alt. supplies cost too much
>12 TCF/y (340 billion m³/y) of US natural gas could be saved by efficiency, at an average cost ~$0.9/GJ (~1/8th current price)

Each 1% of kWh savings (including peak hours) saves 2% of total US gas use and cuts the price of natural gas by 3–4%

2004 gas demand: 19.5 TCF
2025 gas demand: 23.9 TCF
Electricity efficiency savings: 0.5 TCF
Fuel cell CHP savings: 4.8 TCF
Gas efficiency savings: 8.1 TCF
Remaining demand: 2.7 TCF
Remaining demand & petrochemical savings: 2.5 TCF

10 TCF/y can be used either to substitute for oil or to power the H₂ transition

2025 N. American production: 31.4 TCF
2025 domestic production: 2.5 TCF
New biofuel technologies could provide 3.7 Mmbbl/d cheaper than oil—without subsidies or crop/land/water problems

- Brazil has replaced 26% of gasoline with sugar-cane ethanol, competitive without subsidy (the startup subsidy has been recovered ~50× over)
- Sweden is going off oil by 2020 via cellulosic ethanol; also anticipates H\textsubscript{2}
- Europe in 2003 made 17× as much biodiesel as US: oil companies distribute >50%; shifts farmers from subsidy to revenue
Great flexibility of ways and timing to eliminate oil in next few decades

- Buy more efficiency (it’s costing only half as much as the oil it replaces)
- Efficiency is only half captured by 2025—7 Mbb/d still in process
- “Balance” can import crude oil/product (can be all N. Amer.) or biofuels
- Or saved U.S. natural gas @ $0.9/million BTU can fill the “balance”...or
- H₂ from saved U.S. natural gas can displace “balance” plus domestic oil
- Not counting other options, e.g. Dakotas windpower—50 MT/y H₂ source
Mobilization: Accelerating Change

4.5 Mbbl/d saved, $391 billion in retail fuel savings

90–100% State of the Art vehicles by 2040
Big, fast changes have happened

- U.S. automakers switched in 6 years from 85% open wood bodies to 70% closed steel bodies—and in 6 months from making four million light vehicles per year to making the tanks and planes that won World War II
- Boeing transformed its planes in 4 years, 2004–08
- GM’s small team took EV1 from launch to street in 3 years
- Major technological diffusions take 12–15 years for 10%→90% stock adoption, but policy can speed takeoff by 3 years
- In 1977–85, U.S. cut oil intensity 5.2%/y—equivalent, at a given GDP, to a Gulf every 2.5 years
  - Biggest contribution: U.S.-made new cars gained 7.4 mpg in 6 y (47%, 4.9%/y)—96% from smarter design, only 4% from smaller size
- If every light vehicle on the road in 2025 were as efficient as the best 2004 cars & SUVs, they’d save twice as much oil as the U.S. now imports from the Persian Gulf
Military energy efficiency: “endurance” as the emerging fifth strategic vector

- After speed, stealth, precision, networking...
- DoD is increasingly handicapped by half-century-old pattern of using & getting energy, designed for massive steel forces “floating to victory on a sea of oil”
  - 6/7ths of fuel that defeated Axis came from Texas; today, war-fighting is 16× more oil-intensive, and Texas is a net importer of oil
- Today’s warfighting needs just the opposite—unprecedented agility, mobility, maneuver, range, persistence, reliability, autonomy, low cost—via inherently far greater “endurance”
- Fat fuel-logistics tail now a magnet for insurgents, a serious military liability, and a huge financial burden
- DoD needs less/little/no reliance on long, brittle supply chains... and ≥3–4× lower platform fuel consumption, which is feasible
- Yet DoD has assumed fuel logistics to be free and invulnerable
- Major strategic shift to efficiency now emerging
Dramatic gains in combat effectiveness and energy efficiency are available in almost all military uses, e.g.:

- **BWB quiet aircraft:** range & payload $\times \sim 2$, sorties $\div 5–10$, fuel $\div 5–9$ ($\Sigma 2–4$)
- **SensorCraft (CISR):** 50-h loiter, sorties $\div 18$, fuel $\div >30$, cost $+ 2$
- **VAATE engines:** loiter $\times 2$, fuel $– 25–40\%$, far less maintenance, often lower capital cost
- **Optimum Speed Tilt Rotor (OSTR):** range $\times 5–6$, speed $\times 3$, quiet, fuel $\div 5–6$
- **Re-engine M1 with modern diesel:** range $\times \geq 2$, fuel $\div 3–4$
- **Hotel-load retrofits:** could save $\sim 40–50\%$ of onboard electricity (thus saving $\sim 1/6$ of the Navy’s non-aviation fuel)
- **Actuators:** performance $\times 10$, fault tolerance $\times 4$, size & mass $\div 3–10$
- **FOB uses 95% of genset fuel to cool desert:** could be $\sim 0$ with same or better comfort
- **25% lighter, 30% cheaper advanced composite structures:** aircraft can have $\sim 95\%$ fewer parts, weigh $\geq 1/3$ less, cost less
- **Advanced propulsors can save much noise and fuel**
- **Rugged, 2.5-W PC, $\sim 150$, solar + back-up crank**
- **A zero-net-energy building:** it’s been done in $–44^\circ$ to $46^\circ C$ at lower cost
- **160-Gflops supercomputer, ultrareliable with no cooling at $31^\circ C,$ lifecycle cost $\div 3–4$
What if DoD investment in advanced light materials could transform the U.S. economy as profoundly as Internet, GPS, and chips?

◊ Advanced materials & propulsion systems can find a Saudi Arabia (>9 Mbb/d) of saved oil under Detroit & Seattle...

◊ ...and help DoD transform its forces, strengthen warfighting capability, and cut fuel cost by billions of $/y and logistics cost by tens of billions of $/y

◊ The U.S. could cut oil use by 50% by 2025, imports by 75%

◊ The key DoD action needed is S&T investment in advanced materials, especially high-volume/low-cost manufacturing

The prize

◊ A nega-Gulf every 7 y

◊ Vastly less world dependence on oil and conflict over oil

◊ A competitive Big 3

◊ Cheaper oil; more balanced U.S. trade, global development, and diplomacy

◊ More capable and confident warfighting

◊ Less need for it

◊ A safer world
Even 100% (not ~55%) implementation by 2025 would occur at reasonable speed.

**U.S. oil intensity, 1975–2025**

- Actual
- Projected

1975 av. new light vehicle = 13.1 EPA adjusted mpg
1987 best: 22.1 mpg
State of the Art: 73.1 mpg

- Actual and EIA barrels oil/$ real GDP
- Actual and EIA new light vehicles' gal/mi
- RMI 2004 State of the Art technical potential
- RMI State of the Art new light vehicles' gal/mi
Implementation is underway via “institutional acupuncture”

◊ RMI’s 3-year, $4-million effort is leading & consolidating shifts

◊ Need to shift strategy & investment in six sectors
  ○ Aviation: Boeing did it (787 Dreamliner)...and beat Airbus
  ○ Heavy trucks: Wal-Mart led it (with other buyers being added)
  ○ Military: emerging as the federal leader in getting U.S. off oil
  ○ Fuels: strong investor interest and industrial activity
  ○ Finance: rapidly growing interest/realignment will drive others

◊ Cars and light trucks: slowest, hardest, but now changing
  ○ Alan Mulally’s move from Boeing to Ford with transformational intent
  ○ UAW and dealers not blocking but eager for fundamental innovation
  ○ Schumpeterian “creative destruction” is causing top executives to be far more open to previously unthinkable change
  ○ Emerging prospects of leapfrogs by China, India, ?new market entrants
  ○ Competition, at a fundamental level and at a pace last seen in the 1920s, will change automakers’ managers or their minds, whichever comes first—watch this space!
There have been some skeptics....

Getting off oil, you say?
Now they’re more interested
Innovative public vehicles too (though our analysis assumes none)

◊ Novel ultralight rail (www.cybertran.com) w/system cost ~$2.5M/km or $15k/seat; in testing at Alameda Naval Air Station

CyberTran test vehicle, ~$100k, 12m L, 2m H & W, 6–20 seats w/122-cm pitch, 4 doors on each side, 149 kW, 3.4 T empty, 4.54 T loaded, 30–240+ km/h, styled to taste; guideway for two lanes can be retrofitted over a typical road median, yielding 1.3–2.1× more seats/system mile than a saturated 4-lane road; cf. ULTra, www.atsitd.co.uk, and Austrans, www.austrans.com/index.php

◊ Curitiba (Brazil) “surface subway” bus system
  ○ 3/4 of commuting in Houston-sized city, beats cars

◊ T.U. Delft highway “Superbus” for 2008 Olympics
  ○ “Triple stretch limo,” 0.1 MJ/p-km (<TGV, <maglev) @ 250 km/h, 2.5m W × 50m L, 2 m high at cruise, $C_D$ 0.18, 6 T GWV ($n=25$)
The solution is not just technical: transportation is a means, not an end

- The aim is to get access to where we want to be
  - Be there already (sensible land-use)
  - Virtual mobility (move only electrons)
  - Physical mobility (move protoplasm...but how?)
    - Walking
    - Personal vehicle (bicycle, scooter, motorcycle, car,...)
    - Shared personal vehicle or public vehicle

- How far does public policy let trips and negatrips compete fairly—not just transport modes?
- What if we stopped mandating/subsidizing sprawl?
- What if drivers got what they paid for and paid for what they got? if all modes, & negatrips, competed?
- All key Qs...but focus here is on vehicle technology
  - Whole-system efficiency potential is far larger (~10x)
  - Even better styling flexibility; if it’s not efficient, it’s not beautiful
Peeling layer upon endless layer of the tears-free efficiency onion...

◇ Beyond Hypercars® (4–6×): transport demand mgt; mode-switching (Curitiba/Bogatá/Lima bus, Cybertran™, hybrid bikes...); vehicle-sharing (Stattauto, ZIPcar,...); mobility-/access-based business models (mobility.ch...); don’t mandate/subsidize sprawl...: 10×

◇ Beyond efficient aircraft (2–5×): big operational gains at airport & system levels; point-to-point in smaller aircraft (hubless w/gate & slot competition); air taxis; mobility-/access-based models; virtual mobility...: 10×

◇ Beyond efficient trucks (2–3×): trains, logistics,...: 10×

◇ This is what we can now clearly see as practical and profitable—but innovation will probably continue
Time to reinvent the wheels...

“Sometimes one must do what is necessary.”

— Churchill

www.oilendgame.com,
www.fiberforge.com,
www.rmi.org (Library),
www.natcap.org,
www.10xE.org