Advanced Technology Vehicles: Overview and Constraints

John German, ICCT
EIA Energy Conference
April 26, 2011
Where Does the Energy Go?

http://www.fueleconomy.gov/FEG/atv.shtml
Friction reduction
Cylinder deactivation
DI turbo
Aero, tires
Variable valves
Transmissions
Cylinder deactivation
Friction reduction
Efficiency/CO2 Reduction Strategies

No single solution – multi-pronged approach

Research for mass production
Fleet tests
EV/FCV development for future
HEV expansion
Clean diesel
High efficient gasoline engine
Base engine and vehicle improvements

Efficiency/CO2 reduction
Joint-Agency TAR: Technology Packages

- Major CO₂-reduction potential from emerging technologies by 2025
  - US EPA’s OMEGA used many technology packages, 19 vehicle classes to evaluate scenarios
  - Increasing costs from incremental efficiency, to hybrid, and to electric technology

Price in figure refers to the incremental cost to the consumer due to the new technology packages; technology packages include many different technologies; technology labels are approximate for illustration; grid electricity applies US EPA assumptions and accounting method for US electric grid (538 gCO₂e/kWh) for electric and plug-in hybrids.
Technology costs: Near- vs. Long-term

- Technology availability increases - and its costs decrease - over time
  - Incremental vehicle costs and percent improvements are in reference to MY2008 baseline
  - Data from US EPA/NHTSA 2012-2016 rulemaking and EPA/NHTSA/CARB TAR for 2020
Next-generation Gasoline Engines

Fiat MultiAir Digital Valve Actuation

Honda Prototype Engine Base (Electro-magnetic valve)

Improvement in fuel economy: 30%

Heat release rate vs. Crank angle [ATDC deg]

Requires increasing the self-ignition region

Dual-loop high/low pressure cooled exhaust gas recirculation

Requires increasing the self-ignition region
Turbo-Boosted EGR Engines

- Highly dilute combustion – considerable efficiency improvement
- Advanced ignition systems required

Terry Alger, Southwest Research Institute, “Clean and Cool”, Technology Today, Summer 2010
Lightweight materials offer great potential

Material composition of lightweight vehicle body

- **Reference**
- **Lotus (Low Development)**: 16% improvement
- **Volkswagen / SuperlightCar**: 39% improvement
- **Lotus (High Development)**: 42% improvement
- **RMI Revolution**: 57% improvement

Approximate fuel economy improvement:
- 10%
- 25%
- 27%
- 37%

Also incremental improvements in aerodynamics and tire rolling resistance
In 2020-2025 timeframe, mass-reduction will be a core technology
- Looked at many studies (e.g., US DOE, Sierra Research, MIT, Lotus)
- Mass reduction typically deployed before hybrid; with increasing cost
- Various technical studies suggest feasible levels of mass reduction of 20-35%
  - Every TAR scenario for 2025 found average vehicle mass reduction of 14-26%
Post-TAR: Ongoing Work

- Lotus/FEV mass-reduction crash simulation work
  - CARB/EPA/NHTSA collaboration
  - Computer-Aided Engineering (CAE)
  - Simulate vehicle in front, side, offset crashes
  - Lotus: Validate crashworthiness of 30%+ mass-reduced vehicle (high development case)
  - FEV: Validate crashworthiness of HSS vehicle (low development case)
  - Completion in winter/spring 2011

- FEV also updating cost assessments
Hybrid Technology Advances

- Synergies with other technologies and optimized control strategies
  - Engine (Atkinson, Miller, lean-cruise, digital valve); optimization of engine and transmission operation; mass-reduction; dual-clutch transmission

- New P2 hybrid – single motor with two clutches
  - Pre-transmission clutch: engine decoupling and larger motor
  - Nissan, VW, Hyundai, BMW, and Mercedes
  - Approximately 1/3 lower cost than input powersplit with 90-95% of benefits

- High-power Li-ion batteries – smaller, lighter, and lower cost
Synergies Between Parallel Hybrid and DCT

DCT: Dual-clutch automated manual

<table>
<thead>
<tr>
<th>Problem</th>
<th>Solution</th>
</tr>
</thead>
<tbody>
<tr>
<td>DCT has problems launching the vehicle</td>
<td>Launch vehicle using high torque from electric motor</td>
</tr>
<tr>
<td>Limited space for electric motor between engine and transmission</td>
<td>Mount motor on the rear of the DCT</td>
</tr>
</tbody>
</table>

The electric motor is mounted parallel to the transmission shafts and is connected via an electro-magnetic clutch that allows it to connect to either of the two gear sets.
### EPA/NHTSA 2025 Technology Assessments

<table>
<thead>
<tr>
<th>Scenario: 2025 Levels</th>
<th>Technology Path Focus</th>
<th>Mass Reduction</th>
<th>HEV Penetration</th>
<th>PHEV Penetration</th>
<th>EV Penetration</th>
<th>Preliminary Per-Vehicle Cost Estimates ($)</th>
<th>Monetary estimate of lifetime fuel saving ($)</th>
<th>Payback Period (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>3%/year</strong></td>
<td>HEV</td>
<td>15%</td>
<td>11%</td>
<td>0%</td>
<td>0%</td>
<td>$930</td>
<td>$5,930</td>
<td>1.6</td>
</tr>
<tr>
<td>47 mpg 190 gCO₂/mi</td>
<td>All</td>
<td>18%</td>
<td>3%</td>
<td>0%</td>
<td>0%</td>
<td>$850</td>
<td>$5,950</td>
<td>1.5</td>
</tr>
<tr>
<td>ICE &amp; lightweight</td>
<td>18%</td>
<td>3%</td>
<td>0%</td>
<td>0%</td>
<td>$770</td>
<td>$5,970</td>
<td>1.4</td>
<td></td>
</tr>
<tr>
<td>PHEV/EV/HEV</td>
<td>15%</td>
<td>25%</td>
<td>0%</td>
<td>0%</td>
<td>$1,050</td>
<td>$5,950</td>
<td>1.9</td>
<td></td>
</tr>
<tr>
<td><strong>4%/year</strong></td>
<td>HEV</td>
<td>15%</td>
<td>34%</td>
<td>0%</td>
<td>0%</td>
<td>$1,700</td>
<td>$7,600</td>
<td>2.5</td>
</tr>
<tr>
<td>51 mpg 173 gCO₂/mi</td>
<td>All</td>
<td>20%</td>
<td>18%</td>
<td>0%</td>
<td>0%</td>
<td>$1,500</td>
<td>$7,500</td>
<td>2.2</td>
</tr>
<tr>
<td>ICE &amp; lightweight</td>
<td>25%</td>
<td>3%</td>
<td>0%</td>
<td>0%</td>
<td>$1,400</td>
<td>$7,600</td>
<td>1.9</td>
<td></td>
</tr>
<tr>
<td>PHEV/EV/HEV</td>
<td>15%</td>
<td>41%</td>
<td>0%</td>
<td>4%</td>
<td>$1,900</td>
<td>$7,200</td>
<td>2.9</td>
<td></td>
</tr>
<tr>
<td><strong>5%/year</strong></td>
<td>HEV</td>
<td>15%</td>
<td>65%</td>
<td>0%</td>
<td>1%</td>
<td>$2,500</td>
<td>$9,000</td>
<td>3.1</td>
</tr>
<tr>
<td>56 mpg 158 gCO₂/mi</td>
<td>All</td>
<td>20%</td>
<td>43%</td>
<td>0%</td>
<td>1%</td>
<td>$2,300</td>
<td>$9,000</td>
<td>2.8</td>
</tr>
<tr>
<td>ICE &amp; lightweight</td>
<td>25%</td>
<td>25%</td>
<td>0%</td>
<td>0%</td>
<td>$2,100</td>
<td>$9,100</td>
<td>2.5</td>
<td></td>
</tr>
<tr>
<td>PHEV/EV/HEV</td>
<td>15%</td>
<td>49%</td>
<td>0%</td>
<td>10%</td>
<td>$2,600</td>
<td>$8,100</td>
<td>3.6</td>
<td></td>
</tr>
<tr>
<td><strong>6%/year</strong></td>
<td>HEV</td>
<td>14%</td>
<td>68%</td>
<td>2%</td>
<td>7%</td>
<td>$3,500</td>
<td>$9,700</td>
<td>4.1</td>
</tr>
<tr>
<td>62 mpg 143 gCO₂/mi</td>
<td>All</td>
<td>19%</td>
<td>43%</td>
<td>2%</td>
<td>7%</td>
<td>$3,200</td>
<td>$9,800</td>
<td>3.7</td>
</tr>
<tr>
<td>ICE &amp; lightweight</td>
<td>26%</td>
<td>44%</td>
<td>0%</td>
<td>4%</td>
<td>$2,800</td>
<td>$10,200</td>
<td>3.1</td>
<td></td>
</tr>
<tr>
<td>PHEV/EV/HEV</td>
<td>14%</td>
<td>55%</td>
<td>2%</td>
<td>14%</td>
<td>$3,400</td>
<td>$9,100</td>
<td>4.2</td>
<td></td>
</tr>
</tbody>
</table>
Are We Looking the Wrong Way?

Combustion work focuses on raising output efficiency over typical driving cycles
– From roughly 20% to 35%

Heat losses are the 800-pound gorilla in the closet
HD: National Academy of Sciences study

- NAS study (March 2010) was commissioned as a result of the 2007 EISA
- Fuel consumption reduction potential close to 50% for most vehicle types

Potential fuel savings for new vehicles in 2015-2020

Significance of Fuel Cell and Electric Vehicles

Fuel cell and electric vehicle technology have the potential to concurrently help solve the problems of air pollution, global warming, and limited energy resources.

- Developing alternative fuel technology (vehicles and infrastructure) to address energy sustainability
- Further advancing fuel efficiency through conventional engine hybrid and other technologies
- Reducing air pollution with conventional engine technology

hybrid and internal combustion engine technology

Fuel cell and electric technology

Energy Sustainability

Climate Change

Air Quality

past

today

present

future
# The Liquid Fuel Advantage

**ENERGY FUTURE: Think Efficiency**

American Physical Society, Sept. 2008, Chapter 2, Table 1

<table>
<thead>
<tr>
<th></th>
<th>Energy density per volume</th>
<th></th>
<th>Energy density per weight</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>kWh/liter</td>
<td>vs gasoline</td>
<td>kWh/kg</td>
<td>vs gasoline</td>
</tr>
<tr>
<td>Gasoline</td>
<td>9.7</td>
<td></td>
<td>13.2</td>
<td></td>
</tr>
<tr>
<td>Diesel fuel</td>
<td>10.7</td>
<td>110%</td>
<td>12.7</td>
<td>96%</td>
</tr>
<tr>
<td>Ethanol</td>
<td>6.4</td>
<td>66%</td>
<td>7.9</td>
<td>60%</td>
</tr>
<tr>
<td>Hydrogen at 10,000 psi</td>
<td>1.3</td>
<td>13%</td>
<td>39</td>
<td>295%</td>
</tr>
<tr>
<td>Liquid hydrogen</td>
<td>2.6</td>
<td>27%</td>
<td>39</td>
<td>295%</td>
</tr>
<tr>
<td>NiMH battery</td>
<td>0.1-0.3</td>
<td>2.1%</td>
<td>0.1</td>
<td>0.8%</td>
</tr>
<tr>
<td>Lithium-ion battery (present time)</td>
<td>0.2</td>
<td>2.1%</td>
<td>0.14</td>
<td>1.1%</td>
</tr>
<tr>
<td>Lithium-ion battery (future)</td>
<td></td>
<td></td>
<td>0.28 ?</td>
<td>2.1%</td>
</tr>
</tbody>
</table>
Electricity versus Hydrogen

- Both are energy carriers – can be dirty or clean, depending on how created
- Neither will replace gasoline internal combustion for a long time

<table>
<thead>
<tr>
<th></th>
<th>Advantages</th>
<th>Needed improvements</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Electricity</strong></td>
<td>• Existing infrastructure  ???</td>
<td>• Driving range – energy storage breakthrough</td>
</tr>
<tr>
<td></td>
<td>• Battery charge/discharge losses lower than fuel cell losses</td>
<td>• Lower carbon grid</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Safe place to plug in</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Charge time</td>
</tr>
<tr>
<td></td>
<td></td>
<td>15 min = 440v x 1,000 amp</td>
</tr>
<tr>
<td><strong>Hydrogen</strong></td>
<td>• 90% of energy from air</td>
<td>• Breakthrough in hydrogen storage and delivery</td>
</tr>
<tr>
<td></td>
<td>• Remote generation (wind, geothermal, waves, solar)</td>
<td>• Better ways to create hydrogen</td>
</tr>
<tr>
<td></td>
<td>• Cogeneration – heat and electricity for home, fuel for car</td>
<td>• New infrastructure</td>
</tr>
</tbody>
</table>
Natural Market Barriers

- Need for technological advances
- Learning by doing
- Scale economies
- Resistance to novel technologies
- Lack of diversity of choice
- Chicken or egg?
  - Lack of fuel availability
  - Lack of vehicles to use new fuel

DOE’s hydrogen study estimated transition costs of $25-40 billion
In gauging the potential for advanced vehicles, remember that the competition is changing. What looks good against today’s (conventional) car may not look so good against tomorrow’s.
Fuels
<table>
<thead>
<tr>
<th>Performance Specification</th>
<th>Fuel Type</th>
<th>Megajoules/litre</th>
<th>BTU/U.S. gallon</th>
<th>RON</th>
<th>MON</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diesel</td>
<td></td>
<td>40.9</td>
<td>147,000</td>
<td>91-98</td>
<td>81-89</td>
</tr>
<tr>
<td>Gasoline</td>
<td></td>
<td>32.0</td>
<td>125,000</td>
<td>93</td>
<td>85</td>
</tr>
<tr>
<td>E10</td>
<td></td>
<td>28.06</td>
<td>120,900</td>
<td>129</td>
<td>96</td>
</tr>
<tr>
<td>E85</td>
<td></td>
<td>19.59</td>
<td>84,400</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Butanol</td>
<td></td>
<td>29.2</td>
<td>104,800</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

A Critical Barrier to E85......Reduced Energy Density

300 mile range on gasoline drops to 215 miles on E85
Next-Generation Biofuel Pathways

- Multiple pathways possible from non-food biomass.
- Many pathways result in fuels that are fungible with today’s fuels.
- Some examples for liquid transportation fuels are shown here.

**Ligno-Cellulosic Biomass**
- Crops
- Residue / Waste

**Micro-Algae**

**Waste Oils & Fats**

---

**Sacharification**

**Gasification**

**Pyrolysis**

**Hydrotreating**

**Dehydration / Hydrogenation**

**Fermentation**

**Fischer-Tropsch**

---

**Ethanol & Butanol**

**Gasoline-like Fuels**

**Diesel-like Fuels**
New Customer Discounting of Fuel Economy Benefits
Out of 60 households (125 vehicle transactions) 9 stated that they compared the fuel economy of vehicles in making their choice.

4 households knew their annual fuel costs.

None had made any kind of quantitative assessment of the value of fuel savings.
Consumers are, in general, LOSS AVERSE

2002 Nobel Prize for Economics
(Tversky & Kahnemann, J. Risk & Uncertainty 1992)

- Uncertainty about future fuel savings makes paying for more technology a risky bet
- What MPG will I get (your mileage may vary)?
- How long will my car last?
- How much driving will I do?
- What will gasoline cost?
- What will I give up or pay to get better MPG?

“A bird in the hand is worth two in the bush.”

Causes the market to produce less fuel economy than is economically efficient
"Energy Paradox"

2002 NAS/NRC CAFE Report Technology Cost Curves

Price and Value of Increased Fuel Economy to Passenger Car Buyer, Using NRC Average Price Curves

\[ PV = \int_{t=0}^{L} P(1 + \frac{1}{E_o} - \frac{1}{E_t}) e^{-r} dt \]

Assumes cars driven 15,600 miles/year when new, decreasing at 4.5%/year, 12% discount rate, 14 year vehicle life, $2.00/gallon gasoline, 15% shortfall between EPA test and on-road fuel economy.
The implications of a 3-year payback requirement and uncertainty-loss aversion are the same.
New Customer Profile

- Innovator
- Early Adopter
- Early Majority
- Majority
- Hanger-On

Increasingly risk averse
New Consumer Discounting is Fixable

- Increase fuel taxes
- Feebates: Pay manufacturers and consumers up front for value of the fuel savings
Uncertainties Larger Barrier for PHEVs

- How much am I going to save on fuel?
- How much will I pay for electricity?
- How often do I need to plug in?
- How much hassle will it be to plug in?
- Can I be electrocuted in the rain or if I work on my vehicle?
- What will it cost to install recharging equipment?
- How long will the battery last?
  - And how much will it cost to replace it?
- How reliable will the vehicle be?
- What will the resale value be?
  - Especially since the next owner also has to install recharging equipment
- What kind of PHEV is best for me?
  - Would a blended strategy be better than electric-only operation?
  - What amount of AER would be best for my driving?
  - What if I move or change jobs?

It’s bad enough to spend $300 on a Betamax - but $30,000+ ?
Capitol Investments and Leadtime
Capitol Intensity

Manufacturers need adequate leadtime

* The additional upfront capital investment compared to the baseline case divided by the total amount of emissions avoided during the lifetime of the investment. For measures where upfront investments decrease over time with a learning rate, the weighted average investment over time has been used.

Source: McKinsey Global GHG Abatement Cost Curve v2.0
The Real Barrier - Leadtime

- Too many technology options, each with uncertain costs and benefits

- Must allow time to ensure quality and reliability
  - Rigorous product development process
  - Prove in production on a limited number of vehicles
  - Spread across fleet – 5-year minimum product cycles
  - Enormous capitol costs

- Longer leadtime is needed for new technologies
Real Cost of Driving
Real Gasoline Price

Motor Gasoline Retail Prices, U.S. City Average, adjusted using CPI-U

Real Gasoline Prices
(2007 $ per gallon)

$3.82/gal

AEO2009 April 2009 update

New Vehicle Fuel Economy

New Vehicle MPG (CAFE values)
Combined car and light truck

34.8 in 2016
plus 4% per year

2008 EPA FE Trends Report

New Vehicle Gasoline Cost per Mile

Real Gasoline Cost for New Vehicles - Cents per Mile
(2007 $ per gallon)

$3.82/gal
Real Fuel Cost - % of Disposable Income

Real Fuel Cost of Driving a New Vehicle 10,000 Miles
% of Per Capita Disposable Income

Forecasted Per Capita Disposable Income from AEO2009 April 2009 update
Future Directions

• Hybrid costs are dropping and synergies are developing
  • Mass market acceptance likely within 15 years

• Gasoline engines and gasoline-electric hybrids are improving rapidly – raising bar for other technologies
  – Especially a problem for diesels & PHEVs

• No silver bullet
  • Energy and GHG so immense we must do everything
    – avoid trap of single solutions

• Consumer risk/loss aversion challenges:
  • Most customers will continue to value performance, features, and utility higher than fuel savings
  • More difficult to implement advanced technology
Technology du jour

- 25 years ago – Methanol
- 15 years ago – Electric vehicles
- 10 years ago – Hybrid/electric vehicles
- 6 years ago – Fuel cell vehicles
- 4 years ago – Ethanol
- Today – BEVs and PHEVs

What’s next?

Extremely disruptive and wasteful
Thank You