U.S. Transportation Research Trends
Alternate Fuels, Vehicle Electrification and
Searching for the Silver Bullet

The Greening of Transportation 2:
Sustainability via Alternative Fuels
The Transportation Center
Northwestern University

Don Hillebrand, Ph.D.
Director – Center for Transportation Research
Argonne National Laboratory
05 October, 2010
We have Probably Picked all the Low Hanging Fruit (and it doesn’t grow back)
World energy demand expands by 45% between now and 2030 – an average rate of increase of 1.6% per year – with coal accounting for more than a third of the overall rise.
February 8, 2010 - Transportation Petroleum Gap
Oil Prices are Rising Again
Drops in price are “research killers”

And Natural Gas appears to be heading down
## A Quick History of “Oil Killers”

<table>
<thead>
<tr>
<th>Fuel of Choice</th>
<th>Year of Birth</th>
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</thead>
<tbody>
<tr>
<td>Synthetic Fuels – from Shale</td>
<td>– 1980</td>
</tr>
<tr>
<td>Methanol</td>
<td>– 1990</td>
</tr>
<tr>
<td>Electricity (BEV)</td>
<td>– 1995</td>
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<tr>
<td>Hydrogen</td>
<td>– 2000</td>
</tr>
<tr>
<td>Ethanol</td>
<td>– 2008</td>
</tr>
<tr>
<td>Electricity again (PHEV)</td>
<td>– 2010</td>
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</tbody>
</table>
Argonne Is One of U.S. Department of Energy’s Largest National Laboratories

- Basic science, applied technology and engineering research and development
- System Assessment Section, Energy System Division
- Assessment of transportation fuels and advanced vehicle technologies
Among the National Labs, Argonne Has the Lead
R&D Role in Several Automotive Fields

- Hybrid vehicle systems, incl PHEVs
  - Modeling
  - Benchmarking and evaluation
  - Component integration
- Engine emissions control
  - In-cylinder combustion
  - Bio-fuels
  - Laser-ignition for natural gas engines
- Batteries
- Fuel cells
- Vehicle recycling
- Applied materials research
  - Tribology
  - Nanofluids
- High-performance computing
- Analysis and System Assessments

4-wheel drive dynamometer for hybrid vehicle evaluation

Hydrogen Engine Test Stand

MATT HIL
Mobile Automotive Technology Testbed Hardware-In-the-Loop
Argonne’s Systems Assessment Group

- Life-cycle analysis with the GREET model
- Economics of fuel production and distribution infrastructure
- Evaluation of alternative-fuel vehicle demonstration for DOE’s Clean Cities Program
- Marketability and commercialization of advanced vehicle technologies
- Present key projects
  - Non-petroleum fuels
  - Biofuels
  - Hydrogen
  - Hybrid electric vehicles and plug-in hybrid electric vehicles
  - Battery-powered electric vehicles
  - Fuel-cell vehicles
Examples of Argonne Vehicle Testing in FY10

- 2010 Toyota Prius (Gen III)*
- 2010 Ford Fusion Hybrid
- Mercedes Benz S400h
- 2010 Honda Insight
- Mini-E (BEV)
- Tesla Roadster (BEV)
- NDA Protected Testing

* Also In-depth component research
Prime Areas of Research

- Electric Systems
- Advanced Combustion
- Alternate Fuels
Electric Systems

Petroleum Displacement through Fuel Substitution and Improved Efficiency

Administration Goal: 1 Million PHEVs by 2015

Types of Vehicles and Benefits

- **HEV**
  - Example: Toyota Prius
  - 50 MPG
  - 1 kWh battery
  - Power Rating: 80kW
  - System Cost: $3000

- **PHEV**
  - Example: Chevy Volt
  - 100 MPGe
  - 16 kWh battery
  - Power Rating: 170kW
  - System Cost: est. $16,000

- **EV**
  - Example: Nissan Leaf
  - All Electric
  - ≥ 40 kWh battery
  - Power Rating: ≥ 110kW
  - System Cost: est. $36,000

2009 Status

- **Status**: $8000-$12,000 for a PHEV 40-mile range battery
- **Status**: Current cost of the electric traction system is $40/kW

Targets

- **2014 PHEV**: Battery that has a 40-mile all-electric range and cost $3,400
- **2015 PEEM**: Cost for electric traction system no greater than $12/kW peak by 2015

Status and Targets
Projections for 2020 Market Shares indicate that Electric Vehicle share will Grow
Roland Berger: Powertrain 2020

<table>
<thead>
<tr>
<th></th>
<th>U.S.</th>
<th>Europe</th>
<th>Japan</th>
<th>China</th>
</tr>
</thead>
<tbody>
<tr>
<td>HEV</td>
<td>13%</td>
<td>7%</td>
<td>9%</td>
<td>6%</td>
</tr>
<tr>
<td>PHEV</td>
<td>9%</td>
<td>15%</td>
<td>11%</td>
<td>9%</td>
</tr>
<tr>
<td>EV</td>
<td>4%</td>
<td>5%</td>
<td>4%</td>
<td>6%</td>
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http://www.rolandberger.com/media/pdf/Roland_Berger_Li-Ion_batteries_20100222.pdf
Electric Vehicles have limited Range

Range Anxiety is addressed via Several Approaches

- Battery Swaps
- Fast Charging
- Really Big Batteries
- Research on better Batteries

In Perspective:
- A major electric vehicle company produced 700 vehicles last year.
- In 1985 - Sterling Height Assembly Plant made 700 vehicles in half a day.
Battery Swaps - Back of the Envelope

- Need standardized or interchangeable batteries
- Need sufficient vehicles to justify the infrastructure
- Need a cost model that can work

Current EV Battery Pack is listed as costing $12,000 for replacement
(Which we all believe to be wildly optimistic)
$12000 x 5% annual return on investment = $600
3 year battery life means amortizing cost is $4000
Annual Return for each pack must surpass $4600 per year

For battery swapping profit, must drive 1300 miles per day per battery pack!

Conclusion: The EV Battery is twenty times too expensive for the swap model.
Fast Charging - Back of the Envelope
To make the economics work will require Subsidies

- Need to handle Thermal Loads and power distribution
- Massive investment in infrastructure required – similar to hydrogen
- Fast Charging will not be the first resort, because there will be other options, so the gasoline forecourt model will not hold.

Cost of level three charger is $15K – $60K
Value of electricity is about $5 per car

- EDF estimate: $15,000 charger is estimated to return a profit of $60 per year
- Scottish power estimates that a break even cost for electricity is 60 cents/ kW-h (making fast charge electric vehicles more expensive per mile than gasoline.)
Increasing engine efficiency is one of the most cost-effective approaches to increasing fuel economy

Benefits All Vehicle Classes

Cars
- Power Rating: 100-300hp

Trucks
- Power Rating: 200-400hp
  25-40% Improvement

Class 2b-8
- Power Rating: 250-600hp
  Up to 50% Improvement

Targets

2015 Passenger Vehicle: Improve gasoline vehicle fuel economy by 25% and diesel vehicle fuel economy by 40%; compared to 2009 baseline

2015 Commercial Engine: Improve commercial engine efficiency by more than 20%; compared to 2009 baseline

2015 HEV & PHEV Improvements:
Could provide >70 MPG HEV

“Support improved mileage performance of internal combustion engines…” – Secretary of Energy

Steven Chu
### Direct Displacement of Petroleum and Enabling Advanced Engine Technology

Ethanol “Blend Wall” is approximately 11-15 billion gallons per year with E10

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<th>Technologies and Benefits</th>
<th>R&amp;D Focus</th>
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<tr>
<td><strong>LD Fuels</strong></td>
<td>i-blends: (\text{overcome blend wall, displace oil &amp; meet RFS mandates})</td>
</tr>
<tr>
<td>- 7B gallons displaced in 2008</td>
<td>• Emissions results looks similar to E0. Catalyst temperature increase seen.</td>
</tr>
<tr>
<td>- Renewable and synthetic fuels, such as E85 and F-T</td>
<td>• $38M project includes emissions, durability, driveability, and materials compatibility for vehicles, small engines, and infrastructure</td>
</tr>
<tr>
<td>- Little consumer sacrifice and currently available</td>
<td></td>
</tr>
<tr>
<td>- Opportunity for greater optimization with some blends</td>
<td></td>
</tr>
<tr>
<td><strong>HD Fuels</strong></td>
<td></td>
</tr>
<tr>
<td>- 250M gallons displaced in 2008</td>
<td></td>
</tr>
<tr>
<td>- Biodiesel &amp; 3rd Generation Renewable Fuels</td>
<td></td>
</tr>
<tr>
<td>- Easier deployment with larger fleets'</td>
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### Targets and Status

**2009 Status**

**2009:** Intermediate blends testing in support of E15 waiver on-track to finish 2010.

**2009:** Approximately 10.5 billion gallons of renewables used

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<th>2011 Target:</th>
<th>2022 Target:</th>
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<td>Have definitive answer on viability of E15 and B20</td>
<td>Attainment of RFS II mandate – 36 B gallons/year including expanded E85 use</td>
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**Biodiesel - Increase acceptance for legacy equipment.**

**2009:** Approximately 10.5 billion gallons of renewables used

**2011 Target:** Have definitive answer on viability of E15 and B20

**2022 Target:** Attainment of RFS II mandate – 36 B gallons/year including expanded E85 use
Background & Motivation

U.S. Renewable Fuel Standard requires an increase of ethanol and advanced biofuels to 36 billion gallons by 2022.

Impact of ethanol and butanol as oxygenates on SI/ID engine efficiency and emissions using steady-state and transient test procedures.

Adapted from: *Renewable Fuels Standard (Federal Register, 75(58))*. 

*Iso-Butanol*
More Than 100 Fuel Production Pathways from Various Energy Feedstocks

The yellow boxes contain the names of the feedstocks and the red boxes contain the names of the fuels that can be produced from each of those feedstocks.
Coal-Based Fuels Pose a Trade-Off Between Energy Security and GHG Emissions

Many Potential Biofuel Production Pathways

- **Sugar Crops for EtOH**
  - Sugar cane
  - Sugar beet
  - Sweet sorghum

- **Starch Crops for EtOH**
  - Corn
  - Wheat
  - Cassava
  - Sweet potato

- **Oils for Biodiesel/Renewable Diesel/Renewable Jet Fuel**
  - Soybeans
  - Rapeseed
  - Palm oil
  - Jatropha
  - Waste cooking oil
  - Animal fat

- **Landfill Gas**
  - CNG/LNG
  - Fischer-Tropsch diesel
  - Hydrogen
  - Methanol
  - DME
  - Fischer-Tropsch jet fuel

- **Cellulosic Biomass via Gasification**
  - Fischer-Tropsch diesel
  - Hydrogen
  - Methanol
  - DME
  - Fischer-Tropsch jet fuel

- **Cellulosic Biomass for EtOH**
  - Corn stover, rice straw, wheat straw
  - Forest residues
  - Municipal solid waste
  - Dedicated energy crops
  - Black liquor

- **Butanol**
  - Corn
  - Sugar beet

- **Algae**
  - Biodiesel
  - Renewable diesel
GHG Emissions of Corn Ethanol Vary Considerably Among Process Fuels in Plants; Cellulosic Ethanol Consistently Achieve Large Reductions

GHG Emission Reductions By Ethanol Relative to Gasoline

GHG effects of potential land use changes are not fully included in these results.
Resource Management Must Be Addressed at Regional Level

- Significant regional variations in irrigation water consumption for corn
- Water consumption factor for non-irrigated cellulosic biofuel is comparable to that of petroleum gasoline.
- Published in *Journal of Environmental Management*
- Results provided key references for GAO’s biofuel report to Congress (Sept. 2009) and Congressional testimony by GAO on Energy and Water (July 2009)

Water quality impact associated with biofuel production
- Regional environmental loading to waterways
- Nutrient accumulation in surface and ground water

Competing water use from multiple sectors and projects
- Power
- Biofuel
- Agricultural
- Urban development
- Others

Compounding effect on water body could be devastating
- Hypoxic zone expansion
- Aquatic ecosystem degradation
# How Much Water Is Consumed To Drive A Passenger Car For A Mile?

<table>
<thead>
<tr>
<th></th>
<th>Corn Ethanol</th>
<th>Cellulosic Ethanol</th>
<th>Petroleum Gasoline</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Regions</strong></td>
<td>USDA 5</td>
<td>USDA 6</td>
<td>USDA 7</td>
</tr>
<tr>
<td><strong>Production process</strong></td>
<td>Dry milling</td>
<td>Thermochemical</td>
<td>Biochemical</td>
</tr>
<tr>
<td><strong>Share of fuel production</strong></td>
<td>52%</td>
<td>14%</td>
<td>30%</td>
</tr>
<tr>
<td><strong>Share of feedstock production</strong></td>
<td>52%</td>
<td>16%</td>
<td>20%</td>
</tr>
<tr>
<td><strong>gal water/gal gas. eq.</strong></td>
<td>15</td>
<td>26</td>
<td>492</td>
</tr>
<tr>
<td><strong>gal water/mile travelled</strong></td>
<td>0.6</td>
<td>1.1</td>
<td>21.0</td>
</tr>
</tbody>
</table>

* Advanced biochemical process
Natural Gas?

- Natural gas reserves are growing at unprecedented levels
- Projections are for natural gas prices to stay low
- On the flip side, natural gas is valuable for just about everything
- And studies indicate that natural gas is more efficiently spent making electricity for plug-in hybrids.
- How long will Fracking be legal?
Conclusion: There are no silver bullets, but many bronze bullets

- Economics rule! – It better make cost sense
- No single fuel/system will replace oil
  - Ethanol
  - Iso Butanol
  - PHEVs
  - Diesel-cycle Engines
- Long Term
  - Lithium air batteries
  - Algae-based fuel

STUDY FINDS SILVER BULLETS LARGELY INEFFECTIVE AGAINST WEREWOLVES

July 28 2009

Berlin, Germany – A new study though has indicated that the silver bullet theory may be nothing more than a myth and that Werewolves may in fact be much harder to dispose of than previously thought.

Mankind has long held onto a connection with the animal. From the Anubis of Egypt to the dragons of China to the American Bald Eagle, the animal world has long held a great fascination for human beings. Because of that connection animals quite often integrate themselves into popular culture and become personified.

There is perhaps no better of example of that than the Werewolf, a fusion of the human and one of the most vicious of animals is tale that has been told throughout human culture across the world.
Integrated Development of Transportation Fuels and Engines

Approach: a system-level, iterative feedback loop - new feedstocks, processing, combustion science, modeling, real-world testing, optimization, and life-cycle analysis.

Bio-Processes

Feedstock Optimization

Bio-based Feedstock Selection

Processing and Separations

Production

Solar/Bio Feedstocks

Catalyst Design and Synthesis

in situ Testing and Characterization

Chemical Processes

Production

Feedstock to Wheels Lifecycle Analysis

Modeling, Testing, Design, and Optimization

Modeling and Fundamental Testing

in situ Engine Studies

Vehicle Integration