Argonne Mobility Research
Impending Electrification

Don Hillebrand
Argonne National Laboratory
2018
Argonne: DOE’s Largest Transportation Research Program

- Located 25 miles from the Chicago Loop, Argonne was the first national laboratory, chartered in 1946
- Operated by the University of Chicago for the U.S. Department of Energy
- Major research missions include basic science, environmental management, and advanced energy technologies
- About 3,500 employees, including 178 joint faculty, 1000 visiting scientists and 6500 facility users
- Annual operating budget of about $750 million (≈80% from DOE)
- Research collaboration and partnerships are highly valued

http://www.anl.gov/
Argonne’s Center for Transportation Research
Unique Facilities and Depth of Expertise

**Basic & Applied Combustion Research**
- Fuels and After treatment

**Modeling and Simulation**
- CFD Engine Combustion
- Vehicle PT Energy & Controls

**Materials Research**
- Tribology
- Thermal Mechanical

**Advanced Powertrain Research Facility**

**EV-Smart Grid Interoperability**

**Smart Mobility**
Argonne Develops Advanced Battery Technologies for Electric-Drive Vehicles

- Advancing electrochemical storage beyond lithium-ion batteries to other systems with new material discoveries
- Developing and demonstrating energy storage prototype, manufacturing, and recycling processes and technologies
- Developing large energy storage and power management systems that improve grid reliability
- Optimizing efficiency, performance, and emissions of electric-drive powertrains
WTW Results: GHG Emissions of a Mid-Size Car (g/mile)

Conventional Internal Combustion Vehicles
- Gasoline (Today's Vehicle): 450 g/mile
- Gasoline: 340 g/mile
- Natural Gas: 270 g/mile
- Gasoline & U.S. Grid Mix: 230 g/mile

Hybrid Electric Vehicles
- Gasoline: 185 g/mile
- Natural Gas: 220 g/mile
- Corn Ethanol (E85): 180 g/mile
- Cellulosic Ethanol (E85): 90 g/mile
- Gasoline & U.S. Grid Mix: 230 g/mile
- Gasoline & Ultra-low Carbon Renewable: 195 g/mile
- Cellulosic Ethanol (E85) & U.S. Grid Mix: 105 g/mile
- Cellulosic Ethanol (E85) & Ultra-low Carbon Renewable: 70 g/mile

Plug-in Hybrid Electric Vehicles (power-split, 10-mile electric range)
- Gasoline: 155 g/mile
- Natural Gas: 180 g/mile
- Gasoline & U.S. Grid Mix: 270 g/mile
- Gasoline & Ultra-low Carbon Renewable: 195 g/mile
- Cellulosic Ethanol (E85) & U.S. Grid Mix: 105 g/mile
- Cellulosic Ethanol (E85) & Ultra-low Carbon Renewable: 70 g/mile
- U.S. Grid Mix: 210 g/mile
- Ultra-low Carbon Renewable: 230 g/mile
- H2 - Distributed Natural Gas: 200 g/mile
- H2 - Coal Gasification w/ Sequestration: 95 g/mile
- H2 - Biomass Gasification: 37 g/mile
- H2 - Nuclear High-T Electrolysis or Ultra-low Carbon Renewable: 42 g/mile

Low/high band: sensitivity to uncertainties associated with projection of fuel economy and fuel pathways

(DOE EERE 2010, Record 10001)
PEV Market

PEV monthly sales volumes are flat and growing slowly
Argonne’s 50-year of Battery R&D Timeline

Prime R&D focus:
1964 → 1998  High/Moderate temperature Li batteries
1998 → 2000  Room-temperature Li-ion batteries
Argonne Works Across the Value Chain

- **Material Discovery**
  Models, Synthesis

- **System-level Analysis**
  Vehicle, Grid, Techno-Economic

- **Material Characterization**
  In Situ, Operando

- **Electrode and Cells**
  Modeling, Characterization

- **Recycling**
  Life Cycle, Processing

- **Cell Diagnostics and Modeling**
  Performance, Degradation

- **Standardized Testing**
  Vehicle, Grid

- **Large Format Devices**
  Pouch, 18650

- **Material Process**
  R&D and Scale Up
  Organic, Inorganic

BATTERY RESEARCH AT ARGONNE
Li-ion, Li-metal, flow batteries, multivalent systems
"Moore’s law" for batteries: 5% per year

Batteries are improving steadily; but at a slow pace.
Costs are Decreasing – Enabling a Range of Possibilities
Lessons from Lithium-ion

Development of Lithium Batteries 1970-2015

Gravimetric Energy Density (W.h/kg)

Cost (US$/kW.h)

Year

LiAl−TiS$_2$

Li−MoS$_2$

Li−MnO$_2$

Li−V$_3$O$_8$

Li-ion
Areas of Research in Container Batteries

Focus on chemistries of the future. And from the past

- Lead
- Graphite
- Silicon
- Li metal
- Mg, Ca, Zn
- Na-ion

- Sulfuric acid
- Liquid electrolyte
- High voltage electrolyte
- Solid conductor
- Liquid electrolytes
- Liquid electrolyte

- Lead oxide
- Metal oxide
- High voltage cathode
- Sulfur, oxygen
- Intercalant cathode
- Intercalant cathode
New Materials for Flow Batteries

- Vanadium, iron
- Zinc
- Hydrogen

High Voltage systems
- Redox Organic Molecules
- Redox active polymers
- Tuned aqueous molecules

- liquid aqueous electrolytes
- Proton exchange membranes

Separation membranes:
- Size selective
- ion exchange

- Vanadium
- Halogens (chlorine, bromine)
- chromium

High Voltage systems
- Redox Organic Molecules
- Redox active polymers
- Tuned aqueous molecules

Next generation redox molecules can help decrease cost
Comparison of Present-day Li-ion Batteries vs. Plug-in vehicle Goals

- Specific Power-Discharge, 10s (317 W/kg)
- Useable Specific Energy-C/1 (96 Wh/kg)
- Power Density (475 W/liter)
- Useable Energy Density-C/1 (145 Wh/liter)
- Cycle Life-70% DOD (5,000 cycles)
- Calendar Life (15 years)
- Production Price @100k/yr ($293/kWh usable)
- Operating Temperature Range (-30 to +50 °C)

Over the next 5 years, PHEVs will become cost effective
The next material on the roadmap: Li metal

All numbers represent theoretical energy densities

- Systems exist that promise very high theoretical energy
- However challenges are significant
Are we seeing a “solar effect” in storage?

Rapidly falling costs of battery packs for electric vehicles

PV Module Price Per Watt
Argonne: longer-range BEVs may be almost as powertrain energy dense as gasoline vehicles by 2045

9 May 2016

An analysis by a team at Argonne National Laboratory (ANL) has found that by 2045, some configurations of battery electric vehicles (BEV) could become almost as energy dense as a conventional vehicle. The team presented their paper at the recent 2016 SAE World Congress.

Hydrocarbon fuels (either fossil- or bio-derived) have high energy densities that are at least 100 times greater than that of a present day lithium-ion battery. Despite projected improvements in battery technology, this form of energy storage is still expected to be significantly less energy dense than gasoline even by 2045. However, the Argonne team argues, the energy density of storage medium (fuel or battery) should not be used as the sole criterion to compare conventional vehicles and BEVs. Rather, powertrain-level energy and power density will be better criteria to compare the propulsion technology used for BEVs and conventional vehicles, they suggest.

This requires assessing the efficiency of the conversion of the stored energy to useful mechanical energy to propel the vehicle.
Comparison of Truck Powertrains

- Argonne performed a study using a performance based sizing process for various powertrain architectures.
- The process was extended to quantify the fuel savings attributable to the powertrain electrification.
- Transit Bus is taken as the example for analysis.

<table>
<thead>
<tr>
<th>Baseline Vehicle</th>
<th>Nova LFS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine</td>
<td>209 kW, 9L, Diesel</td>
</tr>
<tr>
<td>Transmission</td>
<td>6 speed, Automatic</td>
</tr>
<tr>
<td>Auxiliary loads</td>
<td>10 kW</td>
</tr>
<tr>
<td>Test weight</td>
<td>15382 kg</td>
</tr>
<tr>
<td>Cargo/passenger</td>
<td>4000 kg</td>
</tr>
<tr>
<td>Tires</td>
<td>305/70/22.5</td>
</tr>
<tr>
<td>Final drive ratio</td>
<td>5.13</td>
</tr>
<tr>
<td>Starter</td>
<td>8 kW</td>
</tr>
<tr>
<td>Alternator</td>
<td>11 kW</td>
</tr>
</tbody>
</table>
Architectures considered in this study

Conventional

Mild Hybrid (ISG)

Pre-Trans Hybrid (HEV)

Series Plug In Hybrid (PHEV)

Battery Electric (BEV)
Performance Based Sizing Ensures Fair Comparison

Sizing assumptions
- No trade off on payload or performance
  - Fixed payload across all powertrains
  - Match or better the conventional vehicle in performance
- BEVs range will depend on the application. (150 miles assumed in this study)
- PHEVs will have 50% all electric range as the BEV.

As performance parameters are not widely published for heavy vehicles, the baseline values can be estimated through simulations.
Simulated performance estimates were verified against test data from ‘Altoona Bus Research and Testing Center’

- Acceleration and Grade performance matched with test data
- Based on test data and cruising speed observed in similar vehicles, the target performance was set at 60mph.

<table>
<thead>
<tr>
<th>Performance Criteria</th>
<th>Test</th>
<th>Simulation</th>
<th>Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cruising Speed (mph)</td>
<td>50*</td>
<td>72</td>
<td>60</td>
</tr>
<tr>
<td>6% Grade Speed (mph)</td>
<td>30</td>
<td>29</td>
<td>29</td>
</tr>
<tr>
<td>0–30 mph Acceleration Time (s)</td>
<td>14.5</td>
<td>14.3</td>
<td>14.3</td>
</tr>
<tr>
<td>0–60 mph Acceleration Time (s)</td>
<td>NA*</td>
<td>66</td>
<td>66</td>
</tr>
</tbody>
</table>

- A new vehicle, with an electrified powertrain architecture, that matches this performance can be expected to perform the same functions as the baseline vehicle.
**Performance Based Sizing Logic**

- Component power requirements vary with powertrain architecture
- **Goal of sizing**
  - To find minimum component sizes needed to meet performance targets
  - To reduce fuel consumption (not optimization).
  - Fully utilize the components available in architecture

<table>
<thead>
<tr>
<th>Powertrain</th>
<th>Engine</th>
<th>Motor</th>
<th>Battery</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional</td>
<td>Acceleration Grade &amp; Cruise</td>
<td>Size based on Starter &amp; Alternator</td>
<td>Energy: Sustain electric loads for at least 1 minute*</td>
</tr>
<tr>
<td>ISG</td>
<td>Acceleration Grade &amp; Cruise</td>
<td>Maximize regen in ARB Transient</td>
<td>Power: to sustain peak motor output</td>
</tr>
<tr>
<td>HEV</td>
<td>Grade &amp; Cruise</td>
<td>Acceleration Grade &amp; Cruise</td>
<td>Energy: Electric Range Driving Range in EPA 65. Power: Sufficient power to support motor &amp; aux loads</td>
</tr>
<tr>
<td>PHEV</td>
<td>Grade &amp; Cruise</td>
<td>Acceleration Grade &amp; Cruise</td>
<td>Energy: Electric Range Driving Range in EPA 65. Power: Sufficient power to support motor &amp; aux loads</td>
</tr>
<tr>
<td>BEV</td>
<td></td>
<td>Acceleration Grade &amp; Cruise</td>
<td></td>
</tr>
</tbody>
</table>

* Based on EPA off-cycle credit system in LDV. Transit buses could use longer stop time for sizing.
Performance Based Sizing Results

- **ISG**
  - Engine: same as the baseline, 209kW
  - Motor sized for 11kW continuous load
    - Based on Delco Remy alternators (10.8kW) and starter motors (8kW) used in transit bus applications
  - Battery needs 200Wh usable energy to meet 11kW load for a minute
- **HEV**
  - Engine is sized at 176kW (much smaller than a 9L engine)
  - 120kW Motor and Battery pack. Based on commercially available cells, such a HEV pack would also have ~5kWh total energy. (Eg. BAE Hybridrive buses)
- **PHEV**
  - Engine is sized at 160kW
  - 330kW Motor. 230kWh battery pack. It can meet motor power requirements
- **BEV**
  - 374kW Motor. 440kWh battery pack. It can meet motor power requirements

* Based on EPA off-cycle credit system in LDV. Transit buses could use longer stop time for sizing
Approaches: Retrofit vs. New Design

- **New Design**: new body, lighter chassis, efficient auxiliary systems.
- **Retrofit**: Vehicles share the same chassis, body, wheels etc.
  - Adding the mass of the new and replaced components will give the net difference in test weight.

Note: Autonomie class 8 truck weights correlate well with results from electric drive implementation on class 8 trucks by TransPower.
In many aspects the performance of the electrified powertrains are better than that of the conventional baseline.

The increases in weight of the powertrain is offset by the additional power available from the motor.

Results: No Tradeoff in Performance

- Difference in grade speed is within the 2% tolerance allowed in the sizing process.
Fuel savings depends on type of driving

- Vehicles are evaluated over 150 mile drive in 2 drive cycles.
- ISG benefits attributable to
  - High efficiency electric machine replacing the alternator & Idle reduction
- HEVs offer 28% fuel savings in transient driving conditions.
  - Smaller engine & Higher average engine efficiency
- PHEVs and BEVs are necessary to achieve petroleum displacement in highway driving

<table>
<thead>
<tr>
<th>Powertrain</th>
<th>ARB Transient</th>
<th>EPA 55</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Diesel (gal)</td>
<td>Electricity (kWh)</td>
</tr>
<tr>
<td>Conv</td>
<td>31.2</td>
<td>0</td>
</tr>
<tr>
<td>ISG</td>
<td>28.7</td>
<td>0.02</td>
</tr>
<tr>
<td>HEV</td>
<td>22.3</td>
<td>0.02</td>
</tr>
<tr>
<td>PHEV</td>
<td>14.6</td>
<td>167</td>
</tr>
<tr>
<td>BEV</td>
<td>0</td>
<td>357</td>
</tr>
</tbody>
</table>
At 87% cost increase, full petroleum displacement is achieved for transit bus.

PHEV bus achieves 53% fuel displacement at 52% increase in cost

Hybrid bus achieves 30% fuel displacement at 10% increase in cost.

In this study cost implies estimated manufacturing cost based on component cost targets set by DOE. It is typically much lower than the selling price.
A sizing logic is proposed for medium & heavy duty vehicles, without any tradeoff on cargo or performance.

Fuel saving potential of various hybrid powertrains in evaluated in case of transit bus application. When sized for similar performance, 8% - 100% fuel savings can be achieved based on extent of electrification.

Next Steps
- Consider real world driving, fuel costs and optimization of ownership costs for component sizing.
- Consider minimizing cost impact with other design choices
  - Current Estimate: Manufacturing cost increase w.r.t conventional transit bus BEVs (+87%), PHEV(+52%), HEV(+10%)
  - Evaluate a short range BEV option which can charge multiple times during the day. It could cost ~15% higher than conventional bus and still achieve 100% of petroleum displacement.
Concerns

• Infrastructure
  • Grid
  • Wireless Charging
  • Fast Charging
THE FUTURE OF MOBILITY

Don Hillebrand
Energy Systems Division

Future R&D Opportunities in Mobility. Travelling 3 Trillion miles per year and moving 11 Billion Tons of Goods.