Advanced Vehicle Testing Activity at Idaho National Laboratory:

Evaluation of Vehicles and the Grid together as a System

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INL Programs of National Importance

Nuclear Science & Technology

National & Homeland Security Science & Technology
- Nuclear Nonproliferation
- Critical Infrastructure Protection
- Industrial Control Systems
- Cybersecurity
- Electric Grid Resiliency
- Wireless National User Facility
- Armor & Defense Systems

Energy & Environment Science & Technology
- Hybrid Energy Systems
- Non-traditional Hydrocarbons
- Battery & Energy Storage Technologies
- Clean Energy & Water
- Bio-fuels & Synfuels
- Energy Critical Materials

Fuel Cycle R&D
- LWR Sustainability Program
- Advanced Reactor R&D
- ATR National Scientific User Facility
- Space Nuclear
- NGNP R&D

Research – Development – Demonstration – Deployment
The Idaho National Laboratory Site

We Maintain –

• 890 square miles
• 111 miles of electrical transmission and distribution lines
• 579 buildings
• 177 miles of paved roads
• 14 miles of railroad lines
• 3 reactors
• 2 spent fuel pools
• Mass transit system
• Security
• Museum
• “Landfills”
• 300 metric tons of used fuel
• Educational and research partnerships – CAES

...the National Nuclear Laboratory
Technical Challenges & Objectives

Advance Vehicle Testing and Analysis’ objective is to support DOE’s mission to reduce foreign imports by 50% by 2020, reduce greenhouse gas emissions by 15% by 2020 & achieve 54.5 MPG CAFE mandate by 2025

- Identify real-world potential of technologies to displace petroleum
- Verify / maximize return on investment of DOE-funded technology development, primarily on:
  - Advanced energy storage (i.e., batteries) technologies and chemistries
  - Plug-in electric whole-vehicle technologies
  - Fueling system technologies
    - conductive and wireless grid-connected electric drive vehicle fueling infrastructure
  - Advanced climate control, power electronic, and other ancillary and accessory systems technologies
  - Advanced internal combustion engines (CNG/Turbocharged Direct Injection Diesel)

Feedback to DOE, OEMs, SAE, fleet managers, policy makers and other key stakeholders
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Vehicles and Electric Grid: Together as a System

- Areas of research at INL to improve Vehicle and Grid as a system
  - Renewable energy and non-fossil fuel energy sources
    - Wind, solar, hydro-electric
    - Waste heat (nuclear, other processes)
  - Vehicle Charging Infrastructure Evaluation
    - Utilization of home, workplace, and public charging
    - Wireless and Conductive Charging Evaluation
      - Efficiency
      - Power Quality impact to Grid
  - Test Procedure development
    - Advanced technology vehicles (BEV, PHEV, EREV, Adv. ICE)
      - On-road testing and data collection
        - Captured test fleet (195,000 miles per vehicle (313,800 km) )
        - Data collection from privately owned vehicle
    - Energy Storage R&D, testing, and evaluation
      - Performance Assessment
      - Procedures and Protocols
Vehicles and Electric Grid: Together as a System

image from: Montgomery County, MD And General Motors
Vehicles and Electric Grid: Together as a System

- Vehicle Optimization

image from: Montgomery County, MD And General Motors
Vehicles and Electric Grid: Together as a System

- Vehicle and Grid interaction and Optimization

image from: Montgomery County, MD And General Motors
INL – Battery Test Center and Advanced Vehicles Evaluation

**Development of Next-Generation Low Cost / Reliable Batteries:**
- INL capabilities to lead Performance Science
- Battery Testing Center & Advanced Vehicle Testing
- Strong partnerships with:
  - DOE-EERE (USABC)
  - OEMs
  - Battery Developers
- Enabling / accelerating next gen-batteries

Expansion of Performance Science Life-Time Modeling
INL – Advanced Vehicles & Infrastructure

Enhance Consumer Experience with Advanced Technology Vehicles:

- Big Data Analysis
- Advanced Vehicle Testing & EV Infrastructure Laboratory
- Steward to DOE-EERE, OEMs, SAE & CARB
- Impact: Increasing ROI (Return of Investment) on alt-fuel infrastructure development / deployment

The EV Project

- 3,000 Nissan Leafs and Chevrolet Volts
- 1,000 level 2 residential EVSE
- 6,000 level 2 commercial EVSE
- Up to 220 DC fast chargers
- 19 US states

Big-Data Analysis

Heat Maps of EV Chargers

Global Standardization of wireless charging with SAE & automotive manufacturers

Alf-Fuel Corridor Analysis
Vehicle Charging Levels

- On-board charger (AC power delivered to vehicle)
  - Level 1 (120 VAC)
    - SAE J1772 (~1.4 kW)
  - Level 2 (208 – 240 VAC)
    - SAE J1772 (up to 19.2 kW but typically 3.3 or 6.6 kW)

- Off-board charger (DC power delivered to vehicle)
  - DC Fast Charge (~50 kW)
    - CHAdeMO
    - SAE J1772 CCS (Combo Connector)
Vehicle Charge Connection International Standards

Level 1 & Level 2

DC Fast Charge

<table>
<thead>
<tr>
<th>Type 1/USA</th>
<th>Type 2/Europa</th>
<th>GB/China</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Alternating current (AC)</strong></td>
<td><strong>Direct current (DC)</strong></td>
<td></td>
</tr>
<tr>
<td>SAE J1772/IEC 62196-2</td>
<td>IEC 62196-3</td>
<td>GB Part 2</td>
</tr>
<tr>
<td>IEC 62196-3</td>
<td>IEC 62196-3</td>
<td>GB Part 3/IEC 62196-3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>System A CHAdeMO (Japan)</th>
<th>System B CATARC (PRC)</th>
<th>COMBO1 (US)</th>
<th>System C</th>
<th>COMBO2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Connector</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vehicle Inlet</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Communication Protocol</td>
<td>CAN</td>
<td>PLC</td>
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</tbody>
</table>
Vehicle Charge Connection - Tesla

Tesla Roadster

Tesla Model S
Advanced Vehicle Testing Activity at Idaho National Lab

On-Road Vehicle Driving and Charging Analysis
Advance Vehicle Testing Experience

- Since 1994, INL staff have benchmarked PEVs in field operations (via data loggers), closed test tracks and dynamometers
  - INL has accumulated 232 million miles (373 million km) and 44,300 AC MWh from 27,400 electric drive vehicles and 17,000 charging units

Example: EV Project

- **8,228 Leafs, Volts and Smarts**,  
  - 124 million test miles.  
  - At one point, 1 million test miles every 5 days
- **12,363 EVSE and DCFC**  
  - 4.2 million charge events
Driving and Charging patterns

- Analysis of Driving Patterns
  - Energy consumption
  - Usage patterns
  - Common parking location
    - (i.e. should EVSE / chargers be located here)

- Analysis of Charging Patterns
  - Time of Day utilization
    - Home
    - Away from Home
  - DC Fast Charge
  - Power draw
  - Impact of variable time of day electricity pricing
**Workplace Charging Impact**

- Most charging occurs at Home and Work
- But “Other” charging may be critical to a few drivers

**Workplace Charging:**
- Enabled 14% of commutes to work in a Leaf
- 12% more EV miles on average than not charging at work
- 15 mile range increase on average due to charging at work

_Nissan Leafs_
**EV Miles Traveled (eVMT) Analysis Results**

- **EREV (red)** shows comparable eVMT as pure EV (green)

<table>
<thead>
<tr>
<th></th>
<th>Nissan LEAF *</th>
<th>Chevrolet Volt *</th>
<th>Ford Focus Electric</th>
<th>Ford C-Max EnergI</th>
<th>Ford Fusion EnergI</th>
<th>Honda Fit EV</th>
<th>Honda Accord PHEV</th>
<th>Toyota Prius PHEV</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Number of Vehicles</strong></td>
<td>4,039</td>
<td>1,867</td>
<td>2,193</td>
<td>5,368</td>
<td>5,803</td>
<td>645</td>
<td>189</td>
<td>1,523</td>
</tr>
<tr>
<td><strong>Number of Vehicle Months</strong></td>
<td>35,294</td>
<td>20,545</td>
<td>12,622</td>
<td>39,096</td>
<td>32,022</td>
<td>6,090</td>
<td>1,437</td>
<td>15,676</td>
</tr>
<tr>
<td><strong>Total Vehicle Miles Traveled VMT (miles)</strong></td>
<td>28,520,792</td>
<td>20,950,967</td>
<td>10,043,000</td>
<td>39,376,000</td>
<td>33,098,000</td>
<td>4,912,920</td>
<td>1,794,494</td>
<td>19,772,530</td>
</tr>
<tr>
<td><strong>Total Calculated Electric Vehicle Miles Traveled eVMT (miles)</strong></td>
<td>28,520,792</td>
<td>15,599,508</td>
<td>10,043,000</td>
<td>12,918,000</td>
<td>11,572,000</td>
<td>4,912,920</td>
<td>399,412</td>
<td>3,224,981</td>
</tr>
</tbody>
</table>

**Table:**

- **Avg. Monthly VMT**: 808.1, 1,019.8, 795.7, 1,033.6, 1,033.6, 806.7, 1,248.8, 1,281.3
- **Avg. Monthly eVMT**: 808.1, 759.3, 795.7, 339.1, 361.4, 606.7, 278, 207.0
- **Estimated Annual VMT**: 9,697, 12,238, 9,548, 12,403, 12,403, 9,680, 14,986, 15,136
- **Estimated Annual eVMT**: 9,697, 9,112, 9,548, 4,069, 4,337, 9,680, 3,336, 2,484
- **Annual eVMT (km)**: 15,606, 14,664, 15,366, 6,548, 6980, 15,578, 5,369, 3998

**Data Format Description**

- **Key-On / Key-Off**
- **Enhanced Key-On / Key-Off**

**Geographic Characterization**

- **CA, OR, WA, AZ, TX, TN, GA, DC, PA, IL**
- **Nationwide**
- **CA, OR, NJ, MD, CT, MA, RI, NY**
- **CA, NY**
- **ZEV States and other states**

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*Minimally Charged Vehicles are Not Excluded from analysis. These data include 14% of Accord PHEVs that achieve between 0-50 monthly eVMT*
Distance Bins: =0, >0 to 100, >100 to 200, >300 to 400, >400 to 500, etc.
Advanced Vehicle Testing Activity at Idaho National Lab

On-Road and Laboratory Testing and Evaluation
Advanced Vehicle Testing Process

New Advanced Vehicle

End-of-Test
195k Mi – HEV, PHEV, ICE
60,000 Mi - BEV

In-Lab Battery Characterization

On-Road Operation, Logging, Interim Component Testing

INL Data & WWW Servers

Standardized Dynamometer Testing

Test Track Performance

Intertek
On-Road Vehicle Fleet Test Results

- Information and Results Published to AVTA website
  - Baseline Performance Testing
    - Specifications
    - Acceleration / Braking
    - Test Track energy consumption
  - Battery Test Results
    - Capacity
    - Power Capability
  - Fleet Fuel Economy results
  - Operation over vehicle life
  - Operating Costs Fact Sheet
  - Maintenance History

http://avt.inel.gov/phev.shtml
DC Fast Charging Impact Study on 2012 Leafs

After 50,000 miles (80,000 km):
- NO appreciable difference in capacity loss (~2%) between Level II and DC Fast Charging
- All Leafs were the same color – avoid unequal solar loading
- Leafs’ climate control is set at 23°C year round

http://avt.inel.gov/pdf/energystorage/DCFC_Sudy_FactSheet_50k.pdf
Electric Vehicle Infrastructure (EVI) Laboratory

- Evaluate Conductive and Wireless Charging Systems
  - Efficiency and energy consumption
  - EM field emissions (wireless charging only)
  - Power Quality (static and dynamic)
    - Total Harmonic Distortion
    - Power Factor
  - Cyber Security Assessment

- Wide range of power
  - Level 1, 120 VAC
  - Level 2, 208 / 240 VAC
  - DCFC, 480 VAC 3φ
  - Variable voltage source
    - Grid Emulator
Electric Vehicle Infrastructure (EVI) Laboratory Support of SAE J2954

• Support SAE J2954 Wireless Charging standards
  – providing test results
  – test procedure development
  – document refinement

• INL conducted independent testing using draft J2954 test procedures for:
  – System Efficiency and EM-field across a range of misalignment, coil gap, and output power
    • Off-board vehicle (bench test)
    • On-board vehicle
  – Debris tolerance and response
  – Mock floor-pan characterization

• INL is the only DOE lab to publish wireless charging benchmarking results
Fact Sheet: Wireless Charger Vehicle Test Results

PLUGLESS™ Level 2 EV Charging System (3.3 kW) by Evatran Group Inc.

Results from Laboratory Testing as installed on a 2012 Chevy Volt

Descriptive Specifications:
- System input voltage: 208 to 249 VAC
- Circuit breaker rating: 30 A
- Nominal gap between coils: 100 mm
- Rated maximum power output: 3300 watts
- Parking Pad (Primary coil system) shape: Approximately Circular
  - Size: 355 dia. x 470 long mm
- Vehicle Adapter (Secondary coil system) shape: Rectangular
  - Size: 762 long x 697 width mm

Measured System Parameters during normal, steady state conditions:
- Input Power: 208 VAC
- Input Current RMS: 18.13 A RMS
- Power Factor: 0.60
- Voltage Total Harmonic Distortion (THD): 3.3%
- Current Total Harmonic Distortion (THD): 114.3%
- Wireless Power Transfer Operation:
  - Operating Frequency (MHz): 18 - 20 kHz (variable)
- DC Output Power into On-Board Charge Module:
  - Output Voltage: 215 VDC
  - Output Current: 18.1 A
  - Output Voltage Ripple Factor: 0.70 %

Operating Temperature after 4.0 hours at 3.0 kW output:
- Parking Pad: max observed surface temperature 51 °C
- Vehicle Adapter: max observed surface temperature 48 °C

2. Test conducted at nominal conditions (3.0 kW output, 100mm coil gap, coils aligned) unless otherwise specified

http://avt.inel.gov/evse.shtml
Fact Sheet: Wireless Charger Bench Test Results

Plugless™ Level 2 EV Charging System (3.3 kW) by Evatran Group Inc.

Results from laboratory testing off-board the vehicle:

- **System input Voltage operating Voltage**: 208 to 240 VAC
- **Circuit Breaker Rating**: 30 A
- **nominal gap between coils**: 70 mm
- **Rated maximum power output**: 3300 watts

**System Specifications**:

- **Shape**: Approximately Circular
- **Size**: 559 dia. x 470 long mm
- **Vehicle Adapter (Secondary Coil system)**: Rectangular
- **Size**: 762 long x 487 wide mm

**Measured System Parameters during nominal, steady state conditions**:

- **Input Power**: 200 VAC
- **Input Current RMS**: 28 Amps RMS
- **Power Factor**: 0.60
- **Voltage Total Harmonic Distortion (THD)**: 5 %
- **Current Total Harmonic Distortion (THD)**: 13 %

**Wireless Power Transfer System**:

- **Operating Frequency (kHz)**: 15 - 20 kHz (variable)
- **DC Output Power (into programmable DC electronic load)**
  - **Output Voltage**: 215 VDC
  - **Output Current**: 35 A Amps
  - **Output Voltage Ripple Factor**: 0.76 %

**Operating Temperature**:

- **Parking Pad: Max observed surface temperature**: 51 °C
- **Vehicle Adapter: Max observed surface temperature**: 48 °C

**Magnetic Field Test**:

- **Primary Coil: position relative to Secondary Coil**
  - **Primary Coil position (%)**: 87.3 %
  - **Secondary Coil: position (%)**: 88.9 %

**Electric Field Test**:

- **Electric Field Measurement: 0.1m from center of the Secondary Coil**
  - **Electric Field: 3.1 kW Output Power**
    - **Field (V/m)**: 6.03 V/m
  - **Electric Field: 3.8 kW Output Power**
    - **Field (V/m)**: 7.18 V/m

**System Efficiency**:

- **System Efficiency at Various Output Power**

**Additional Information**:


http://avt.inel.gov/evse.shtml
Charger Power Quality

- Power Quality evaluated across range of charge current for Level 1 and Level 2
  - Efficiency
  - Power Factor
  - Total Harmonic Distortion

- This negatively impacts the grid during a demand response curtailment
  - Efficiency decreases
  - Power Factor decreases
  - Distortion on Current increases

- Figures on right are results from
  - 2012 Chevy Volt

Battery Test Center at Idaho National Lab
Battery Assessment at INL

• Independent, science-based performance assessment of energy storage devices
  - Environmental control
  - Software analysis tools for data analysis and reporting.
  - Standards developed for data acquisition, analysis, quality, and management.

• Protocols & Procedures
  - Internationally accepted manuals for performance assessment of energy storage systems.

• Quality Results
  - Flexible state-of-the-art energy storage test facility capable of supporting current and future development activities.
  - Rigorous NIST traceable calibration procedures for in depth uncertainty analysis
  - Temperature controlled testing for reliable and repeatable results.
Battery Test Manuals

• Recently Published Manuals:
  – Battery Test Manual for Plug-In Hybrid Electric Vehicles (Sept. 2014)
  – Battery Test Manual for 12V Start/Stop Vehicles (Nov. 2013)

• Manual Revisions ongoing:
  – EV Manual, Revision 3

INL Battery Test Center Facilities and Equipment

- Over 500 items tested per year
- ~20,000ft² lab space
- 671 cell test channels
- 27 module test channels
- 7 pack test channels
- ~100 controllable thermal chambers
- Vibration test system

http://www.caesonline.org/ESL/Battery%20Lab.html
Summary

- **INL Advanced Vehicle Testing & Analysis is a DOE Core Capability for advanced automotive technologies**
  - INL has accumulated 232 million miles (373 million km) and 44,300 AC MWh from 27,400 electric drive vehicles and 17,000 charging units

- **Advanced energy storage**
  - Performance Science analysis of Li-ion Batteries from half-cell to vehicle and back

- **Plug-in electric vehicles**
  - Continued testing and analysis of plug-in vehicles
  - Big-Data analysis of vehicle usage
  - Connected Automated Vehicles

- **Infrastructure**
  - Wireless Charging & Level I, II, III – standardization, energy & efficiency
  - Big-Data analysis of infrastructure usage
  - Cyber security

- **Additional Vehicle Testing**
  - Advanced climate control, power electronic, and other ancillary and accessory systems technologies
  - Advanced internal combustion engines (CNG/Turbocharged Direct Injection Diesel)
Tech to Market Workshop at INL

Evening Industry Reception
May 18, 2015

T2M Workshop
May 19 - 20, 2015
Idaho Falls, ID

Directing dialogue on the high quality, detail oriented validation needed to improve the efficient transfer of energy storage technology to the market.