Medium and Heavy-Duty Battery Electric Vehicles Technology Assessment

September 2, 2014
Sacramento, California
Outline

- Technology Overview
- Vehicle Charging
- Optimal Duty Cycles and Applications
- Technology Advancement and Commercialization
- Next Steps and Conclusions
- Contacts
Technology Overview

Chargers, Inverters, Rectifiers, Converters, Batteries, Motors, Auxiliaries
Benefits of battery electric trucks
- Reduced exposure to criteria pollutants
- Less fatiguing operations for driver
- Reduced O+M costs for vehicles
- Reduction in emission of GHGs

Great advancements in last decade
- Electric buses in deployment phase
- Electric delivery vehicles are finding their niche
- HD electric vehicles are now being demonstrated
Battery Electric Vehicle Components

- All the vehicle power requirements met with on-board energy storage system

- Components:
  - Vehicle chargers
  - Inverters, rectifiers and converters
  - Energy storage systems (including batteries)
  - Electric motors
  - Vehicle auxiliaries
Chargers

- Charging systems
  - AC chargers
    - Level 1: Household 120V; 15A
    - Level 2: 240V; 30A
    - Higher level AC chargers are theoretically capable
      - J1772 plug has is designed maximum of 80A
  - DC fast chargers
    - 500 V; 125A
    - Tesla technology patent open sourced

- On-board chargers
  - Allow for more ubiquities access to fast charging
  - No current HDV standard

* None in service
Inverters Rectifiers and Converters

- Role of inverters and rectifiers
  - AC to DC and DC to AC conversions
- Role of converter
  - DC to DC voltage conversion
    - DC energy from traction motors to correct voltage for vehicle axillaries
  - Typical Vehicle 12 volt DC system
    - Vehicles may maintain 12 volt lead acid battery system
Energy Storage System

- Battery Management Systems (BMS)
  - Manage battery charging
  - Voltage Control
  - Cell Balancing
  - Track battery performance and health

- Battery considerations for vehicle applications
  - Energy to weight ratio
  - Energy to volume ratio
  - Power to weight ratio
  - Battery lifetime
  - Charging time
  - Temperature management
Battery Considerations

- Battery characteristics to consider
  - Safety of battery in specific applications
  - Considerations for battery chemistries
    - High power density
    - High energy density

- Battery degradation/Useful Life
  - % capacity reduction due to usage
    - Based on number of discharge/charge cycles
    - Factors affecting battery life
  - Reusability and recyclability
Battery Chemistries

Currently available and in use
- Nickel–Metal Hydride (NiMH)
- Molten Sodium (ZEBRA)
- Li–ion

Future prospects
- Lithium Sulfur
- Lithium–Air
- Flow Batteries
Nickel Metal Hydride

- **NiMH**
  - Features
    - Specific Energy: 70 Wh/kg
    - Low cell voltage: 1.2V
      - Low specific energy
    - Long cycle and storage life
    - Low toxicity, safe
  - Not favorable for medium- and heavy-duty applications
    - Large amount of cells required due to low energy density
      - Dramatically increases weight of vehicle
ZEBRA Batteries

- Molten Salt Batteries
  - Features
    - Specific energy: 90–120 Wh/kg
    - Cycles: 3000 at 80% DOD
    - Requires heat for usage: requires insulated case
    - Limited power density
  - Suitable for HDV application because:
    - Appropriate energy density
    - Demonstrated in use for MDV and HDV applications
  - Being considered for rail operations
Li–ion Batteries

- Currently the battery of choice for BEVs
- Based on Li–ions shuttling between electrodes
  - Variations in chemistries
- Three basic components
  - Anode (–)
  - Cathode (+)
  - Electrolyte

<table>
<thead>
<tr>
<th>Material Examples</th>
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<tbody>
<tr>
<td>Anode (–)</td>
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<tr>
<td>Graphite</td>
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<tr>
<td>Lithium Titanate</td>
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<tr>
<td>Hard Carbon</td>
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<td>Tin/Cobalt Alloy</td>
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</table>
# Common Lithium-Ion Batteries for MDV and HDV

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<tr>
<th>Chemistry</th>
<th>Wh/Kg</th>
<th>Positives</th>
<th>Negatives</th>
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<td>NCA (Nickel/Cobalt/Alum)</td>
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<td>Life Expectancy</td>
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<td>Range of Charge</td>
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<td>LMO (Li Manganese Oxide)</td>
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<td>LFP (Li Fe PO₄)</td>
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<td>Low Temp Performance</td>
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<td></td>
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<td>Deutsche Bank 2009</td>
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</table>
Electric Motors

- Electric Motors
  - Important Properties
    - Motor Cost
    - Power Output: (kw or hp)
    - Efficiency
  - Majority of plug-in electric vehicles (PEV) utilize rare-earth permanent magnet motors
    - High power density, specific power, efficiency, and constant power-to-speed ratio
  - AC motors vs DC motors

<table>
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<tr>
<th>AC Motor</th>
<th>DC Motor</th>
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<tbody>
<tr>
<td>Single-Speed Transmission Capable</td>
<td>Multispeed Transmission Required</td>
</tr>
<tr>
<td>Light Weight</td>
<td>Heavier for Equivalent Power</td>
</tr>
<tr>
<td>Less Costly</td>
<td>Higher Cost</td>
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<tr>
<td>95% Efficiency at Full Load</td>
<td>85–95% Efficiency at Full Load</td>
</tr>
<tr>
<td>Expensive Controllers</td>
<td>Simple and Less Expensive Controllers</td>
</tr>
</tbody>
</table>
Auxiliaries

- Electrification of auxiliaries in BEVs
  - Represent up to 9% of the energy used in a conventional truck.
    - Typical belt driven auxiliaries need to be electrified
      - HVAC
      - Power steering
  - Electrification of hydraulic pump system
    - Need for increased efficiency compared to conventional vehicles
      - Fifth wheel lift
      - Kneeling bus
      - Wheel chair lift
Vehicle Charging

Locations, Types, Challenges
Vehicle Charging

- **Charger Location:**
  - Home or Yard Charging
    - Facilitate charging overnight at lower rates
    - Allow fast charging
    - Facilitate V2G
  - Roadway Charging
    - Dynamic and semi–dynamic
  - Opportunity Charging
    - Can reduce size of battery therefore reduce incremental cost of vehicle
    - Require defined routes due to limited availability of infrastructure
Vehicle Charging

- Conductive Chargers
  - Physical contact between vehicle and grid
    - Connector plugs
    - Contact plates
    - Dynamic technologies
      - Allow for on the go charging
  - Light–Duty Standard for Connector
    - SAE J1772
      - Level 1 and 2 charging only
Vehicle Charging

- Dynamic Electric Vehicle Charging
  - Embedded roadway conduit to supply power for vehicle locomotion
  - Catenary system for delivering power to vehicle
    - Siemens eHighway system
Vehicle Charging

- Inductive Charging
  - A primary coil in the base station installed in roadway or yard to allow for wireless charging
  - Air between road and vehicle coils
  - Ease of use
Vehicle Charging

- Semi–Dynamic Conductive Chargers
  - Roadway imbedded vehicle charging
    - Shaped Magnetic Field Resonance
    - Charging while vehicle is underway
    - South Korea: City of Gumi
Vehicle Charging

- Vehicle-to-Grid (V2G)
  - Vehicle used as a power source when stationary and connected to grid
  - Supply power back to grid
    - Generate revenue for vehicle owner
    - Grid stability
    - Power back to grid
  - Supply power to building
    - Reduce demand charges
  - Ability to reduce payback period of BEVs
  - Vehicles can provide emergency power when needed
Vehicle Charging

- Considerations on BEV Charging
  - Uniform standard for plugs and technology
    - No HDV standard
    - Timing of charging events is important

- Peak Demand Charges
  - Light rail example of dealing with peak demand charge

- High Infrastructure Costs
  - Consideration of electrical grid capability
    - May encourage off-peak charging for grid load balancing

- Renewable Charging Capability
  - Solar BEV Type-D school bus: Gilroy Unified
Optimal Duty Cycles and Applications

Near and Long-term
Dependent on energy storage system

- Energy per mile (Estimates)
  - Medium-Duty: 1.8 kWhr/mile
  - Heavy-Duty: 2.8 kWhr/mile

- Battery requirements for 100 mile range
  - Medium-Duty: 180 kWhr
  - Heavy-Duty: 280 kWhr

Battery costs expected to come down

- Current cost: ~$500–$700/kWhr
Preferred Duty Cycles

- Defined vehicle route
- High start and stop duty cycle
- High idle time
- Duty cycles with lower average speeds
- Optimal vocation duty cycle (near-term): Delivery, Urban Bus and Refuse

Advanced Tech MD/HD Applications Potential Pilot Deployments

Class 7/8 Tractors
- Over the Road
- Short Haul/Regional

Class 3-8 Vocational Work
- Urban
- Rural/Intracity
- Work site support

Class 2B/3
- Pickups/Vans

2020
2030
2040
Technology Advancement and Commercialization

Commercialization Pathway, Market Overview
Commercialization Pathway

- Research and Development
- Demonstration Phase
- Pilot Phase
- Deployment Phase
- Commercialized/Widespread Adoption

<table>
<thead>
<tr>
<th>Commercialization Stages</th>
<th>Production Volume</th>
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<tbody>
<tr>
<td>R&amp;D</td>
<td>NA</td>
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<tr>
<td>Demonstration Phase</td>
<td>1–5</td>
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<tr>
<td>Pilot Phase</td>
<td>5–100+</td>
</tr>
<tr>
<td>Deployment Phase</td>
<td>100+</td>
</tr>
<tr>
<td>Commercialized/Widespread Adoption</td>
<td>10,000+ (annually)</td>
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</table>
Market Overview

- **Light-Duty Vehicles**
  - Early Commercialization: Limited technology transfer to HDV but significant effect on future battery costs

- **Transit Buses**
  - Pilot Phase: Illustrating O+M savings

- **School Buses**
  - Demonstration phase: New CEC project with V2G

- **Medium-Duty Vehicles**
  - Early Deployment/Pilot Phase: 400 HVIP vouchers so far

- **Heavy-Duty Vehicles**
  - Demonstration Phase: Hybrid truck market helping lower costs of components and motors
## HVIP Funded BEVs

- ARB’s HVIP program incentivizes the purchase commercial BEVs

### HVIP Vouchers for BEVs (as of 7/14)

<table>
<thead>
<tr>
<th>Vocation</th>
<th>Class 3</th>
<th>Class 4&amp;5</th>
<th>Class 6</th>
<th>Class 7</th>
<th>Class 8</th>
<th>Total</th>
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<tbody>
<tr>
<td>Parcel Delivery</td>
<td>30</td>
<td>50</td>
<td>101</td>
<td>--</td>
<td>--</td>
<td>181</td>
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<tr>
<td>Beverage Delivery</td>
<td>3</td>
<td>--</td>
<td>27</td>
<td>--</td>
<td>--</td>
<td>30</td>
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<tr>
<td>Other Truck</td>
<td>1</td>
<td>1</td>
<td>69</td>
<td>--</td>
<td>10</td>
<td>81</td>
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<tr>
<td>Food Dist.</td>
<td>1</td>
<td>1</td>
<td>106</td>
<td>--</td>
<td>--</td>
<td>108</td>
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<tr>
<td>Buses</td>
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<td>--</td>
<td>--</td>
<td>10</td>
<td>14</td>
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<tr>
<td><strong>Total</strong></td>
<td><strong>35</strong></td>
<td><strong>56</strong></td>
<td><strong>303</strong></td>
<td><strong>--</strong></td>
<td><strong>20</strong></td>
<td><strong>414</strong></td>
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</table>
Light-Duty

- Over 50,000 light-duty passenger BEVs on CA roads
- ~100,000 Passenger BEVs sold in the nation

<table>
<thead>
<tr>
<th>Make</th>
<th>Weight</th>
<th>Range Miles</th>
<th>Battery Size kW·hr</th>
<th>Motor Size kW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nissan Leaf</td>
<td>Light Duty</td>
<td>75–100</td>
<td>24</td>
<td>80</td>
</tr>
<tr>
<td>Ford Focus e</td>
<td>Light Duty</td>
<td>75</td>
<td>23</td>
<td>107</td>
</tr>
<tr>
<td>Tesla Model S</td>
<td>Light Duty</td>
<td>200–300</td>
<td>60 or 85</td>
<td>225–310</td>
</tr>
</tbody>
</table>

- Reduction in battery costs will be driven by light-duty vehicles

ANL, 2010. Argonne National Laboratory.
“Modeling of Manufacturing Costs of Lithium Ion Batteries for HEVs, PHEVs, and EVs.
Transit Buses

- Optimal Duty Cycle for BEVs
  - Frequent start and stops
  - Low speed operation
  - Defined routes

- Two main types of battery all-electric transit buses
  - Fast charge
  - Slow charge
Transit Buses–Fast Charge

- Require a charge time of only minutes
- Example: Proterra BEV transit bus
  - Fast charging on route
    - Under 10 minutes
  - Use overhead charging system–500kw
    - Utilizes wireless bus identification
    - Automatic speed limiting and assisted docking
    - Guide scoop seats charge head into place and connects to charge batteries
  - Small Battery Pack
    - 100 kW–hr pack, Lithium titanate
    - Range of 30–40 miles, fast charging allows for essentially infinite range
  - Drive Motor: 220 kW
Transit Buses—Slow Charge

- Require a charge time of a few hours, typically overnight
- Example: BYD Transit Bus
  - Range is 155 miles on a single charge
  - Charging time of:
    - 5 hours with a 60kW charger
    - 1.6 hours with a 200kW charger
  - Large Battery Pack
    - 324 kW–hr pack, Lithium Iron Phosphate
  - Motor: 90 kW or 180 kW
  - Wall mounted AC charger, output power of ≤ 80kW

<table>
<thead>
<tr>
<th>Make</th>
<th>Weight</th>
<th>Range Miles</th>
<th>Battery Size kW–hr</th>
<th>Motor Size kW</th>
</tr>
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<tr>
<td>Proterra</td>
<td>Heavy Duty</td>
<td>30–40</td>
<td>100</td>
<td>220</td>
</tr>
<tr>
<td>BYD</td>
<td>Heavy Duty</td>
<td>155</td>
<td>324</td>
<td>90 or 180</td>
</tr>
</tbody>
</table>
Transit Buses—Economics

- High capital cost coming down as production volumes increase
  - Currently ~$800k for battery electric buses
    - incremental cost of $400k compared to diesel
  - Charging infrastructure
- Low operating costs
  - 70% fuel/energy cost savings
- Low maintenance costs
  - No engine, oil changes
  - Motor has fewer moving parts
  - Less repairs/replacements with regenerative braking
Transit Buses—Economics

- Expect future capital costs to decline as production volumes increase
- Primary battery electric component incremental costs estimated to decrease 70% by 2030:
  - battery pack (324 kWh),
  - motor (180 kW)

Estimated Incremental Battery Electric Component Costs over Time

Source: CALSTART, I710 Project Zero Emission Truck Commercialization Study Draft Report
School Buses

- Set duty cycles
- Limited usage during the day
  - Opportunity charging during day
    - Vehicle to Grid (V2G) being demonstrated
- Reduce children's exposure
- Cost savings for school districts
- Demonstrations
  - ARB funded
    - TransTech/Motiv Type A School Buses
    - TransPower Type D School Buses

<table>
<thead>
<tr>
<th>Make</th>
<th>Class</th>
<th>Range Miles</th>
<th>Battery Size kW·hr</th>
<th>Motor Size kW</th>
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<tr>
<td>Transpower School Bus</td>
<td>Type D (Heavy-duty)</td>
<td>50–75</td>
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<td>100</td>
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<tr>
<td>TransTech/Motiv School Bus</td>
<td>Type A (Medium-Duty)</td>
<td>60–80</td>
<td>84</td>
<td>150</td>
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</table>
Medium-Duty

- Transfers technology from light-duty passenger BEVs to heavy-duty battery electric trucks
- Used in applications typically requiring less power (lower payload) and range
  - Applications suitable for BEVs
    - Parcel delivery
    - Food distribution
- Incremental cost ~$60–80K
- Payback from 3–5 years*

<table>
<thead>
<tr>
<th>Make</th>
<th>Weight</th>
<th>Range Miles</th>
<th>Battery Size kW-hr</th>
<th>Motor Size kW</th>
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<tbody>
<tr>
<td>Boulder FB–1000</td>
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<td>105 or 120</td>
<td>120</td>
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<tr>
<td>EVI Walk–In</td>
<td>Medium Duty</td>
<td>Up to 90</td>
<td>99</td>
<td>120</td>
</tr>
<tr>
<td>EVI Parcel Delivery Van</td>
<td>Medium Duty</td>
<td>Up to 90</td>
<td>99</td>
<td>120</td>
</tr>
</tbody>
</table>

* U.S. EPA WCC
Vocations for heavy-duty BEVs could be expanded via battery developments and lowered vehicle component costs

- Greater battery energy density and shorter charge times would increase vehicle applicability
- Reducing battery pack weight would increase cargo capacity of BEV trucks
- Reducing cost would make BEVs more attractive to fleet purchasers

Potential for significant emission reductions and fuel savings

Demonstration of technology in HD applications has potential to drive advancement
Heavy-Duty Demonstrations

- **Transpower Class-8 electric drayage truck**
  - 75–100 mile range 300 kW AC motor
  - 215 kW–hr LFP battery
    - 7000 pound energy storage system

- **Motiv 60,000 lbs refuse hauler**
  - City of Chicago, one in revenue service–order for 20 over 5 years
  - Up to 60 mile range, 280 kW motor
  - 210 kW–hr Sodium Nickel battery

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<tr>
<td>Motiv–(Refuse)</td>
<td>Heavy Duty</td>
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<td>210</td>
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# Summary of Vehicle Specs

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<td>Motiv School Bus</td>
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Conclusions

Next Steps, and Conclusions
Next Steps

- Move forward with HHD BEV Demonstrations
  - Demonstrate viability of technology in different applications and weight classes
    - ARB zero-emission drayage demonstration
  - Better understand economics for fleet owners
  - Provide confidence to fleet owners on ROI
  - Demonstrate mechanisms to reduce payback period (V2G)

- Continue to incentivize adoption of battery electric trucks
  - HVIP, AQIP HD Pilots, air district plus ups

- Opportunities for innovative financing approaches to reduce barriers to acceptance
Conclusions

- Heavy-duty BEVs best for applications with defined route (range 30–100 miles), lots of starts/stops and idle, and low speeds
  - Currently well-suited to urban and worksite support vehicles, especially delivery and refuse trucks, urban and school buses
- Light-duty BEV developments transfer to heavy-duty
- Applicability of heavy-duty BEVs could be expanded via battery developments, charging infrastructure expansion, and lowered vehicle component costs
- Demonstrations underway
Team Contacts

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  - elandber@arb.ca.gov  916.323.1384
- BEV Team Members
  - Marijke Bekken
  - John Gruszecki P.E.
  - Lynsay Carmichael
  - Patrick Chen

Submit comments by Oct. 1 to:
http://www.arb.ca.gov/msprog/tech/comments.htm