Heavy-Duty Hybrid Vehicles
Technology Assessment

September 2, 2014
Sacramento, California
Overview

- Background
- Technologies Evaluated
- Key Performance Parameters/Performance Goals
- Costs/Economics
- Conclusions
- Contacts
Background

Heavy-duty Hybrids In California Today
Over 1,800 heavy duty hybrid vehicles in CA*

Fuel Economy: Driver for hybrids

Primarily Hybrid Electric Vehicles (HEV); More Recently Hydraulic Hybrid Vehicles (HHV) and Plug-in Hybrid Electric Vehicles (PHEV)

Industry Manufacturers

- Vehicle OEMs: Daimler, Freightliner, Hino, Kenworth, Mack, Volvo, Navistar, PACCAR, Peterbilt
- Powertrain: Allison, Azure Dynamics, BAE, Eaton, Enova, Hino, Odyne, Parker Hannifin, Volvo

Hybrid Technologies

- Catalyst technology towards zero-emission HDVs
- Improve technology/reduce costs
- Market size/vehicle penetration
- CO₂ and NOx emissions/Certification

*Data from HVIP and Transit Fleet Rule reporting database
Technologies Evaluated

Types of Hybrids, Common Elements
Hybrid Technologies Evaluated

- Mild Hybrid and Full Hybrid
- Series, Parallel & Series-Parallel Hybrids
- HEV
- HHV
- PHEV
- Micro-turbine Hybrids
- Catenary Hybrids
Mild Hybrid vs. Full Hybrid

- **Mild Hybrid**
  - Limited hybrid utilization
  - Engine start/stop
  - Regenerative braking

- **Full Hybrid**
  - More extensive integration
  - Electric motor used as tractive power source (full or partial)
  - Power vehicle electrical accessories
  - Larger battery packs
  - Engine start/stop
  - Regenerative braking
Parallel Hybrid

- Both the internal combustion engine (ICE) and the electric motor have direct, independent connections to the transmission
- Either power source –or both together– can be used to turn the vehicle’s wheels
- Smaller battery pack compares to series hybrid
- Often designed so that ICE provides power at high, constant speeds; the electric motor provides power during stops and at low speeds; and both power sources work together during accelerations
- Well-suited to improve the fuel economy of higher speed vocational vehicles
Parallel Hybrid
Series Hybrid

- Engine not directly linked to the transmission or wheels
- Energy produced from the engine converted to electric power by the generator which re-charges the energy storage device in order to provide power to one or more electric motors
- Electric motor system provides torque to turn the wheels of the vehicle and recharge batteries
- Engine can operate at a more optimum rate and can be switched off for temporary all-electric operation
- Well-suited for transit buses, refuse haulers
- Most promising technology to zero emission
Series Hybrid
Series–Parallel Hybrid

- Combines best aspects of series and parallel hybrids
- Either power source – or both together – can be used to turn the vehicle’s wheels
- Utilize series advantage at low speed and parallel advantage at higher speed through power split and/or electronic controller
- From standing start or at low speed operation: ICE is turned off and electric motor propels the vehicle
- Normal operation: ICE power is split, providing tractive power and generate electricity – electric motor also assist with tractive power
- Full-throttle operation: battery provides extra energy
- Well suited for both city, stop–and–go driving and highway high constant speeds
- Efficient Drivetrains, Inc. (MDV application, demonstration bus project in China)
Series–Parallel Hybrid
Hybrid Electric Vehicles

Beverage Delivery (Parallel)
Class 7/8 day cab bulk transport, and day cab and straight-truck side-loader local delivery

Food Distribution (Parallel)
Class 7/8 day cab bulk transport, straight-truck and class 5 step van local delivery

Parcel Delivery (Parallel)
Class 5 step van local delivery

Hino Class 5 delivery/local delivery food distribution hybrid box truck

Transit Bus (Series)
Hydraulic Hybrid Vehicles

- Could be designed as either series or parallel hybrid
- Energy storage via hydro–pneumatic accumulators
- Energy stored: hydraulic fluid is pumped into a high–pressure accumulator and compress an inert gas, typically N\textsubscript{2}
- Energy released: Inert gas expands and pushes hydraulic fluid through the actuator into a low–pressure reservoir
Hydraulic Hybrid Vehicles

**High Pressure Accumulator**
This accumulator stores energy by using nitrogen to pressurize hydraulic fluid. The pressurized hydraulic fluid is then used by the pump-motor to turn the wheels.

**Drive Pump/Motor**
The two front pump/motors perform as a motor when driving and as a pump for regenerative braking. The rear pump/motor is optional for additional power.

**Engine Pump/Motor**
Acts as a motor to start the engine and as a pump to generate fluid pressure, as needed.

**Low Pressure Reservoir**
Stores the low pressure hydraulic fluid after the pressure is used to drive the wheels.
Hydraulic Hybrid Vehicles

Series Hybrids

Parallel Hybrid
Plug-in Hybrid Electric Vehicles

- Shares characteristics of conventional hybrids—draws motive power from a battery and ICE
- Differs from conventional hybrid in that the vehicle can be recharged from an external source of electricity for motive power
- Can operate in all electric mode
Plug-in Hybrid Electric Vehicles

- **Operation modes**
  - Charge depleting mode—operates exclusively on electric power
  - Charge sustaining mode—combines the operation of the vehicle's two power sources

- **Examples of applications:**
  - Bucket/Utility trucks
  - Dump trucks
  - Refrigeration trucks

- **Some features of PHEV applications:**
  - Partial all-electric operations
  - Accessories electrification, ePTO
  - Depot and/or sensitive (e.g., noise, exposure,) operating areas
Plug-in Hybrid Electric Vehicles
Microturbine Hybrids

- Utilizes microturbine generators to charge batteries for vehicle power
- Can operate on battery power alone or a combination of microturbine and battery power
- Turbines are fuel neutral, more fuel efficient compared to ICEs and are lighter in weight (extends the electric range)
Microturbine Hybrids

- Current heavy-duty examples:
  - Wrightspeed Route truck (MHD, refuse and recycling application)
  - WAVE truck (HHD application—*concept only*)
Catenary Hybrids

- Heavy-duty hybrid electric trucks with the ability to access overhead catenary power sources
- Operational flexibility—provides zero emission operations in targeted areas while still providing the range needed for long haul trucking
- Utilizes existing and proven technologies
  - Catenary systems: light rail, city buses, mining equipment
- Unlimited zero emission range when connected to a catenary system
- Space constraints for catenary infrastructure
Catenary Hybrids
Common Elements of Hybrids

- A drivetrain that can recover and reuse energy in addition to the main engine
- An energy storage system (e.g., batteries, hydraulic accumulators)
- Control electronics
- Regenerative braking (over 70% energy recovery)
- Best applications: heavy urban start–stop, highly transient duty cycles (e.g., refuse haulers, transit buses, package delivery)
Key Performance Parameters / Performance Goals

Fuel Economy, Emissions, Performance Goals
Hybrid Performance—Fuel Economy

- **Fuel Economy**
  - Duty-cycle dependent
  - High kinetic intensity duty cycles most beneficial
    - Transient, stop-and-go
  - Improvement range from 10% – 70%
    - Mild Hybrids: 10% – 20%
    - Full Hybrids:
      - Parallel Hybrids: 20% – 50%
      - Series Hybrids: 30% – 70%

- **Motive Power Source Efficiency**
  - On-road heavy-duty diesel engines: 40% – 50%
  - Electric motors: >90%
Hybrid Performance–Emissions

- Emissions need to be carefully scrutinized
- GHG Emissions (e.g., CO₂)
  - Positive benefits – reduced CO₂
  - Fuel economy improvement – cycle dependent
- Criteria Pollutant Emissions (e.g., NOₓ)
  - Emissions impacts – cycle dependent
  - Potential to reduce NOₓ emissions
  - Current hybrid technologies: in some cases NOₓ increased
    - Engine operating at non-optimum torque map
    - Lower exhaust temperatures – affect SCR performance
    - Series hybrids – good potential for addressing NOₓ issues
- System Integration – Crucial for controlling both GHG and NOₓ emissions
Hybrid Performance–Emissions

- ARB and NREL: Chassis Dynamometer Testing Heavy-Duty Hybrid and Conventional Trucks
  - Performed at CE-CERT on 3–4 Cycles Each Vehicle (3–4 repetitions)
- Test Vehicles
  - MY 2010 or newer engines
  - Beverage delivery vehicles, parcel delivery vehicles – hybrid & conventional
### ARB and NREL: Chassis Dynamometer Testing

#### Heavy–Duty Hybrid and Conventional Trucks

**Summary of Preliminary Test Results – Parcel Delivery Drive Cycle**

<table>
<thead>
<tr>
<th>Cycle</th>
<th>NO(_x)</th>
<th>CO(_2)</th>
<th>mpg</th>
<th>% FE</th>
</tr>
</thead>
<tbody>
<tr>
<td>EPA GHG</td>
<td>0.52</td>
<td>712</td>
<td>13.25</td>
<td>--</td>
</tr>
<tr>
<td>UDDS</td>
<td>0.84</td>
<td>819</td>
<td>11.46</td>
<td>--</td>
</tr>
<tr>
<td>HTUF 4</td>
<td>1.63</td>
<td>1011</td>
<td>9.27</td>
<td>--</td>
</tr>
<tr>
<td>NY Comp</td>
<td>3.40</td>
<td>1308</td>
<td>7.12</td>
<td>--</td>
</tr>
</tbody>
</table>

<table>
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<tr>
<th>Cycle</th>
<th>NO(_x)</th>
<th>CO(_2)</th>
<th>mpg</th>
<th>% FE</th>
</tr>
</thead>
<tbody>
<tr>
<td>EPA GHG</td>
<td>1.07</td>
<td>733</td>
<td>13.24</td>
<td>0.0%</td>
</tr>
<tr>
<td>UDDS</td>
<td>2.88</td>
<td>723</td>
<td>13.55</td>
<td>18.2%</td>
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<tr>
<td>HTUF 4</td>
<td>1.96</td>
<td>800</td>
<td>12.33</td>
<td>33.0%</td>
</tr>
<tr>
<td>NY Comp</td>
<td>5.92</td>
<td>873</td>
<td>11.21</td>
<td>57.4%</td>
</tr>
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</table>

*Average Emissions and Fuel Consumption Over the Cycles (g/mi) – Conventional*

*Average Emissions and Fuel Consumption Over the Cycles (g/mi) – Hybrid*
Hybrid Fuel Economy: Function of Duty Cycles

EPA GHG

<table>
<thead>
<tr>
<th>Phase 1: 1 - 668 secs.</th>
<th>Phase 2: 845 - 1144 sec</th>
<th>Phase 3: 1309 - 1608 sec</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 - 30 - 60 - 90 - 120 - 130</td>
<td>55 mph cruise</td>
<td>65 mph cruise</td>
</tr>
</tbody>
</table>

Weight Factors for Duty Cycles

<table>
<thead>
<tr>
<th>Category</th>
<th>Transient (%)</th>
<th>Cruise (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vocational</td>
<td>42</td>
<td>21</td>
</tr>
<tr>
<td>Hybrids</td>
<td>75</td>
<td>9</td>
</tr>
<tr>
<td>Day Cabs</td>
<td>19</td>
<td>17</td>
</tr>
<tr>
<td>Sleepers</td>
<td>5</td>
<td>9</td>
</tr>
</tbody>
</table>

UDDS

<table>
<thead>
<tr>
<th>Time (seconds)</th>
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<tbody>
<tr>
<td>0</td>
</tr>
<tr>
<td>200</td>
</tr>
<tr>
<td>400</td>
</tr>
<tr>
<td>600</td>
</tr>
<tr>
<td>800</td>
</tr>
<tr>
<td>1000</td>
</tr>
</tbody>
</table>

HTUF 4

<table>
<thead>
<tr>
<th>Time in seconds</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
</tr>
<tr>
<td>100</td>
</tr>
<tr>
<td>200</td>
</tr>
<tr>
<td>300</td>
</tr>
<tr>
<td>400</td>
</tr>
<tr>
<td>500</td>
</tr>
</tbody>
</table>

NY Comp

<table>
<thead>
<tr>
<th>Time in Seconds</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
</tr>
<tr>
<td>300</td>
</tr>
<tr>
<td>600</td>
</tr>
<tr>
<td>900</td>
</tr>
<tr>
<td>1200</td>
</tr>
<tr>
<td>1500</td>
</tr>
<tr>
<td>1800</td>
</tr>
</tbody>
</table>
Advanced Tech MD/HD Applications
Potential Pilot Deployments

Class 7/8 Tractors
- Over the Road

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

Class 2B/3
- Pickups/Vans
Performance Goals for Advanced Heavy-Duty Hybrid Propulsion Systems

- **Hybrid Electric Vehicles**
  - Drive unit optimization, cost and integration
    - Engine downsizing
    - Engine and transmission integration
    - Emission control and SCR dosing optimization
    - Engine controls optimization
  - Energy storage system reliability, weight and cost
  - Electrified Power Accessories

- **Hydraulic Hybrid Vehicles**
  - High-pressure energy conversion/storage devices
  - Hydraulic controls
Cost/Economics

Cost, Economics, Incentive Funding
Costs: Hybrids vs. Conventional

- **Incremental costs:**
  - Hybrids: $20,000 – $80,000
  - Hino: $18,000 ($60,000 conventional, $78,000 hybrid)
  - Electric: $40,000 – >$120,000

- **Actual costs:**
  - Conventional: $40,000 – >$160,000
  - Hybrids: $60,000 – ???
Economics

- **Costs**
  - Higher capital costs
- **Savings**
  - Improved fuel efficiency – 10 to 20% FE
  - Maintenance
- **Role of incentives**
  - Reduce capital costs
  - Accelerate technology adoption
- **Return on Investment**
  - Payback period – >5 years
Hybrid Trucks – Break–Even Cost Analysis (Future 2015–2020 Technology)

- 2012 NAS study estimated break-even periods
- 47% cost reduction assumed by 2020
- ~5 year or less payback for
  - Refuse haulers,
  - Mild hybrid in Class 8 tractor trailer
  - Class 3–6 straight box truck
- Other applications had longer payback
  - Incentives and/or requirements would be needed
## Hybrid Trucks – Break-Even Cost Analysis (Future 2015–2020 Technology)

<table>
<thead>
<tr>
<th>Category</th>
<th>Description</th>
<th>Fuel Consumption Benefit (%)</th>
<th>Forecasted Capital Cost ($)</th>
<th>Annual Mileage</th>
<th>Typical MPG</th>
<th>Payback Period (yrs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class 2b Pickups and Vans</td>
<td>Parallel electric hybrid</td>
<td>18</td>
<td>$9,000</td>
<td>27,500</td>
<td>12.5</td>
<td>7.6</td>
</tr>
<tr>
<td>Class 3 to 6 Straight Box Truck</td>
<td>Parallel electric hybrid</td>
<td>30</td>
<td>$20,000</td>
<td>41,250</td>
<td>9.4</td>
<td>5.1</td>
</tr>
<tr>
<td>Class 3 to 8 Bucket Truck</td>
<td>Parallel electric hybrid w/ electric power take off</td>
<td>40</td>
<td>$30,000</td>
<td>13,300</td>
<td>9.4</td>
<td>17.7</td>
</tr>
<tr>
<td>Class 8 Tractor Trailer Truck</td>
<td>Mild parallel hybrid with idle reduction</td>
<td>10</td>
<td>$25,000</td>
<td>137,500</td>
<td>5.75</td>
<td>3.5</td>
</tr>
<tr>
<td>Urban Transit Bus w/ fed subsidy of incremental cost</td>
<td>Series electric hybrid</td>
<td>35</td>
<td>$220,000 ($22,000)</td>
<td>--</td>
<td>6.0</td>
<td>9.1</td>
</tr>
<tr>
<td>Class 8 Refuse Hauler</td>
<td>Parallel electric hybrid</td>
<td>30</td>
<td>$39,000</td>
<td>50,000</td>
<td>4.25</td>
<td>3.7</td>
</tr>
<tr>
<td>Class 8 Refuse Hauler</td>
<td>Parallel hydraulic hybrid</td>
<td>25</td>
<td>$30,000</td>
<td>50,000</td>
<td>4.25</td>
<td>3.4</td>
</tr>
<tr>
<td>Class 8 Refuse Hauler</td>
<td>Series hydraulic hybrid</td>
<td>50</td>
<td>N/A</td>
<td>50,000</td>
<td>4.25</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Vouchers to help California fleets purchase or lease qualified hybrid or zero-emission trucks and buses
- Provides about ½ incremental cost

Base Vehicle Incentive
- The first three HVIP vouchers received by a fleet, inclusive of previous funding years, are eligible for up to $10,000/vehicle
Vehicle Voucher Enhancements
- A hybrid vehicle above 14,000 lbs. which has been ARB-certified is eligible for an additional $15,000 to $20,000 voucher amount
- An additional $5,000 to $10,000 is provided for hybrid school buses purchased by public school districts
- Plug-in electric hybrid vehicles and hydraulic hybrid vehicles that demonstrate at least a 40 percent fuel economy benefit relative to their baseline vehicle (non-hybrid) counterparts may receive an additional $5,000 to $10,000 voucher
Hybrid and Zero–Emission Truck and Bus Voucher Incentive Project (HVIP)

- Voucher Enhancements for Hybrid Vehicles with ARB–Certified OBD

<table>
<thead>
<tr>
<th>Vehicle GVWR</th>
<th>Total Number of Deficiencies</th>
<th>2013/2014 MY</th>
<th>2015 MY</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>10+</td>
<td>&lt;10</td>
<td>9–14</td>
</tr>
<tr>
<td>14,001 – 26,000 lbs</td>
<td>$12,000</td>
<td>$16,000</td>
<td>$8,000</td>
</tr>
<tr>
<td>26,001 + lbs</td>
<td>$16,000</td>
<td>$20,000</td>
<td>$12,000</td>
</tr>
</tbody>
</table>
# HVIP Vouchers Issued by Hybrid Vehicle Type

Fiscal years covered Year 1 (2009-10) to Year 4 (2013-14)

<table>
<thead>
<tr>
<th>Vehicle Type</th>
<th>Vouchers</th>
<th>Vehicle Type</th>
<th>Vouchers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parcel delivery</td>
<td>503</td>
<td>Tow truck</td>
<td>68</td>
</tr>
<tr>
<td>Beverage delivery</td>
<td>408</td>
<td>School bus/other bus</td>
<td>33</td>
</tr>
<tr>
<td>Other truck</td>
<td>263</td>
<td>LP pick-up &amp; delivery</td>
<td>27</td>
</tr>
<tr>
<td>Food distribution</td>
<td>55</td>
<td>Refuse hauler</td>
<td>23</td>
</tr>
<tr>
<td>Uniform &amp; linen delivery</td>
<td>112</td>
<td>TOTAL</td>
<td>1,492*</td>
</tr>
</tbody>
</table>

*75% of total vouchers issued

Data as of July 2014
# Hybrids and Freight Applications

<table>
<thead>
<tr>
<th>PROJECT</th>
<th>DESCRIPTION</th>
<th>PROJECT TIME FRAME</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Medium-Duty Electric and Hybrid Electric Trucks</strong></td>
<td>Currently operating MD delivery trucks. UPS (100 hybrid electric trucks Sac/San Bern.), Staples (53 all electric, 30 in LA), Pepsico Frito-Lay (275 all electric, 105 in CA ), PG&amp;E (4 utility), Coca Cola (15 all electric refrigerated delivery trucks)</td>
<td>2014–15</td>
</tr>
<tr>
<td><strong>Volvo Plug-In Hybrid–Electric Drayage Truck</strong></td>
<td>Build a Class 8 heavy–duty plug-in hybrid drayage truck</td>
<td>2015–16</td>
</tr>
</tbody>
</table>
## Hybrids and Freight Applications

<table>
<thead>
<tr>
<th>PROJECT</th>
<th>DESCRIPTION</th>
<th>PROJECT TIME FRAME</th>
</tr>
</thead>
<tbody>
<tr>
<td>International Rectifier Plug-In Hybrid Electric Vehicle (PHEV) Conversion</td>
<td>Convert 2007 Class 8 Semi-Trailer Tractor for Drayage Duty into PHEV</td>
<td>Q2 2016</td>
</tr>
<tr>
<td>Siemens Catenary Truck Project</td>
<td>Integrate pantograph into various trucks: Volvo Class 8, TransPower natural gas-electric hybrid and battery-electric truck; 1-mile demo catenary</td>
<td>Q4 2016</td>
</tr>
</tbody>
</table>
Role of HD Hybrid Technology

- HD hybrid systems are integral to technology roadmap
- Advancements in both HEV and battery technologies have cobenefits for zero and near-zero heavy-duty trucks
  - Fuel cell and battery EVs
- Series HEV technology highest potential
  - All-electric operation
  - Address NO\textsubscript{x} issues
Conclusions

- Many types of hybrids
  - Mild to full
  - Parallel more widely used now, especially for higher speed delivery routes
  - Series promising longer-term applications for stop-and-go delivery routes
- Ideal vocations for hybrids are highly transient, high-power demand, high idling time
  - Package delivery, refuse haulers, urban transit bus
- Hybrids improve fuel economy
  - 10–20% for mild, up to 70% for full
  - Payback currently > 5 years for most vocations
- Hybrids reduce CO₂ but can increase NOₓ
  - Need to improve system integration, certification requirements to prevent NOₓ increases
  - Series hybrid able to mitigate the NOₓ impact
Conclusions (continued)

- Goals to improve
  - Electric motors/generators, inverter/power electronics, energy storage systems, hybrid systems optimization, electrified power accessories
  - Hydraulic energy conversion devices, hydraulic energy storage, hydraulic controls

- Hydraulic hybrid technology has great potential
  - Lower cost compared to some other hybrids
  - Fuel savings + reduced maintenance = shorter payback

- Hybrid technologies have cobenefits for zero-emission technologies
  - Series hybrid technology
  - PHEV
  - Batteries
Contacts

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- **Team Members:**
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  - Lynsay Carmichael lcarmich@arb.ca.gov

- Submit comments by Oct. 1 to: [http://www.arb.ca.gov/msprog/tech/comments.htm](http://www.arb.ca.gov/msprog/tech/comments.htm)