Heavy-Duty Hybrid Vehicles
Technology Assessment

September 2, 2014
Sacramento, California

California Environmental Protection Agency
Air Resources Board
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
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

Transit Bus (Series)
Hino Class 5 delivery/local delivery food distribution hybrid box truck
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
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., CO$_2$)
  - Positive benefits – reduced CO$_2$
  - Fuel economy improvement – cycle dependent
- Criteria Pollutant Emissions (e.g., NO$_x$)
  - Emissions impacts – cycle dependent
  - Potential to reduce NO$_x$ emissions
  - Current hybrid technologies: in some cases NO$_x$ increased
    - Engine operating at non–optimum torque map
    - Lower exhaust temperatures – affect SCR performance
  - Series hybrids – good potential for addressing NO$_x$ issues
- System Integration – Crucial for controlling both GHG and NO$_x$ 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

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

<table>
<thead>
<tr>
<th>Cycle</th>
<th>NO&lt;sub&gt;x&lt;/sub&gt;</th>
<th>CO&lt;sub&gt;2&lt;/sub&gt;</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>

### Average Emissions and Fuel Consumption Over the Cycles (g/mi) – Hybrid

<table>
<thead>
<tr>
<th>Cycle</th>
<th>NO&lt;sub&gt;x&lt;/sub&gt;</th>
<th>CO&lt;sub&gt;2&lt;/sub&gt;</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>
</tr>
<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>
</tbody>
</table>
Hybrid Fuel Economy: Function of Duty Cycles

**EPA GHG**

- Phase 1: 1 - 668 secs.
- Phase 2: 245 - 1144 secs.
- Phase 3: 1309 - 1608 secs.

**Weight Factors for Duty Cycles**

<table>
<thead>
<tr>
<th>Category</th>
<th>Transient (%)</th>
<th>55 mph Cruise (%)</th>
<th>65 mph Cruise (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vocational</td>
<td>12</td>
<td>21</td>
<td>37</td>
</tr>
<tr>
<td>Hybrids</td>
<td>75</td>
<td>9</td>
<td>16</td>
</tr>
<tr>
<td>Day Cabs</td>
<td>19</td>
<td>17</td>
<td>64</td>
</tr>
<tr>
<td>Sleepers</td>
<td>5</td>
<td>9</td>
<td>80</td>
</tr>
</tbody>
</table>

**UDDS**

**HTUF 4**

**NY Comp**
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
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
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>

Hybrid and Zero–Emission Truck and Bus Voucher Incentive Project (HVIP)

- 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></td>
<td>10+</td>
<td>&lt;10</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>Medium-Duty Electric and Hybrid Electric Trucks</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>Volvo Plug-In Hybrid–Electric Drayage Truck</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>
Conclusions

Conclusions and Contacts
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
- 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