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

Background

- 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
  - CO_2 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

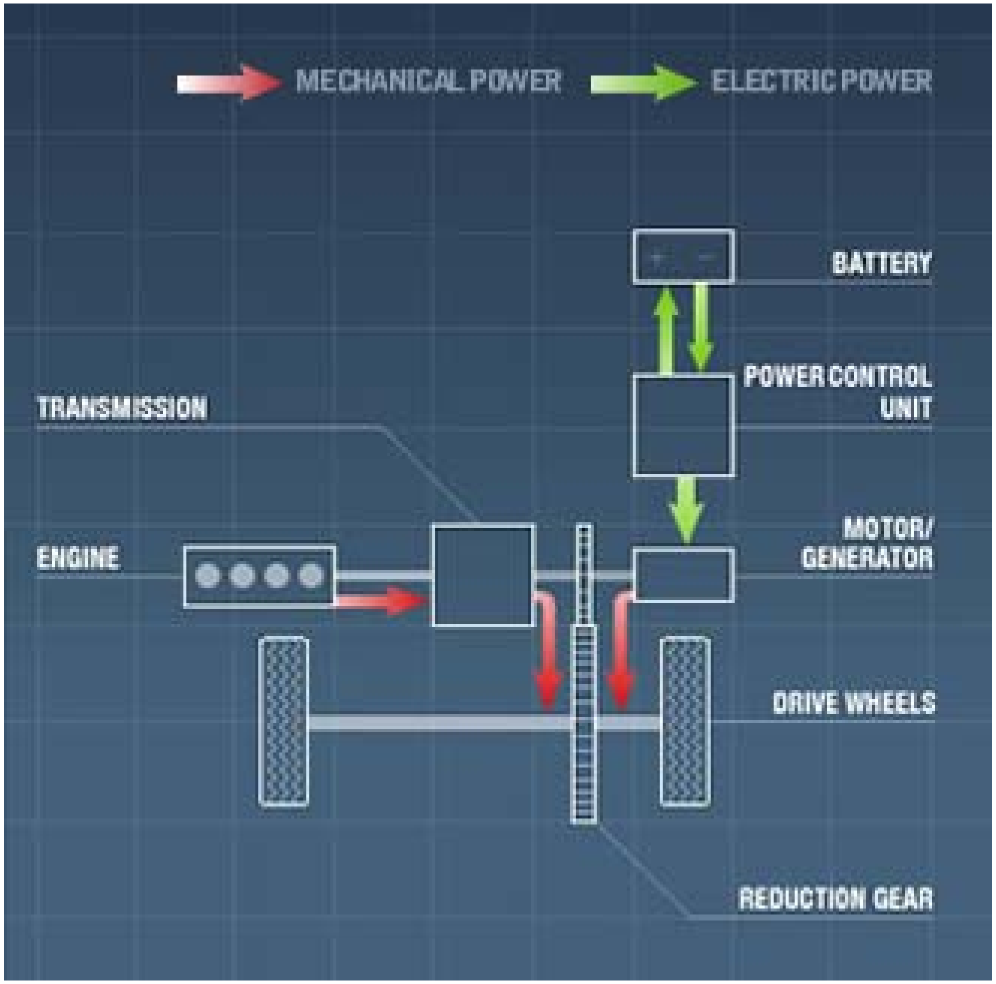
Mild Hybrid vs. Full Hybrid

- 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

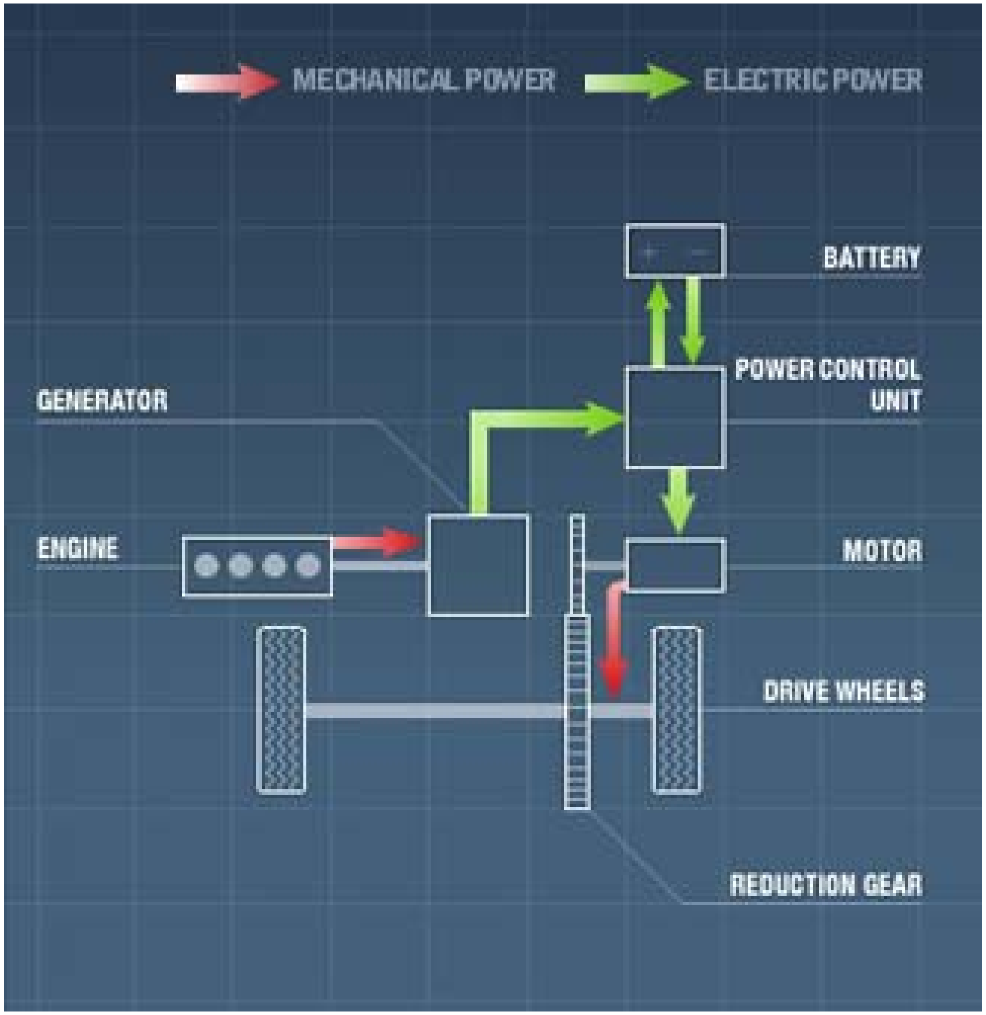
Parallel Hybrid



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

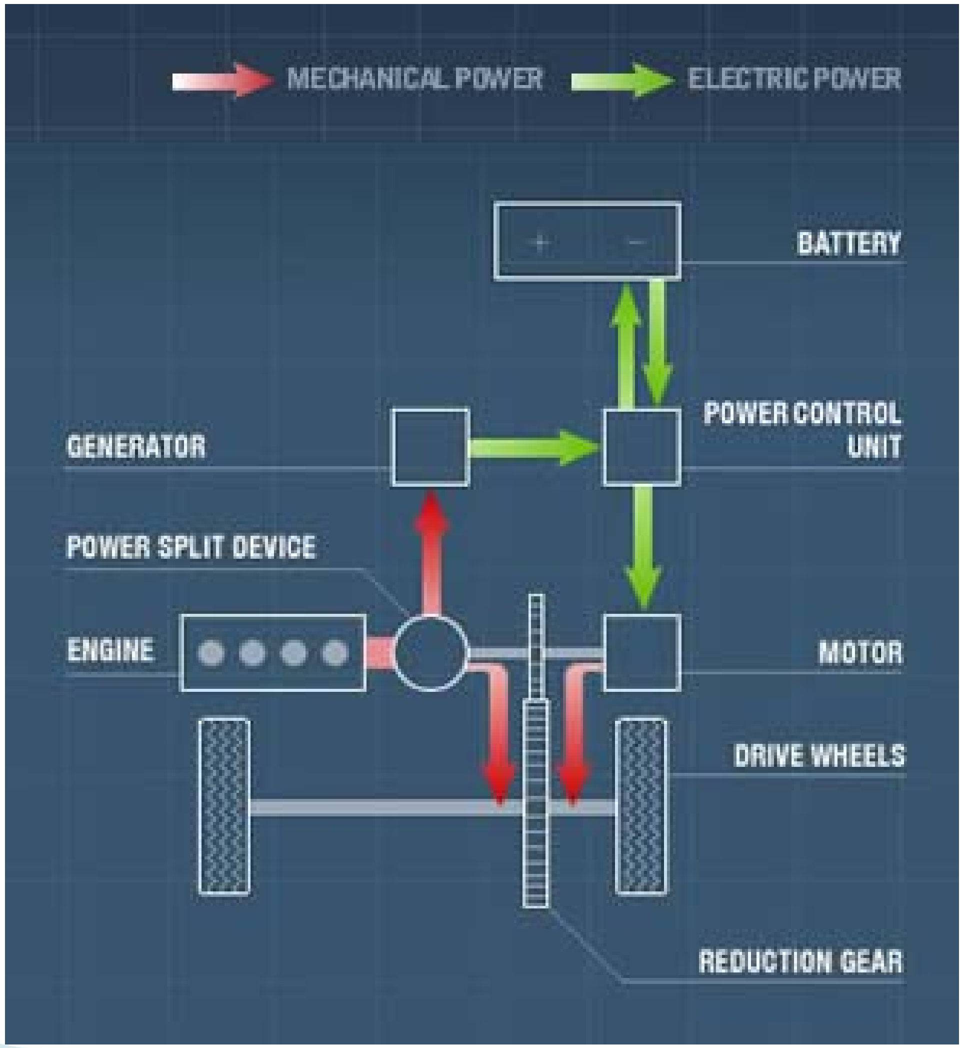
Series Hybrid



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

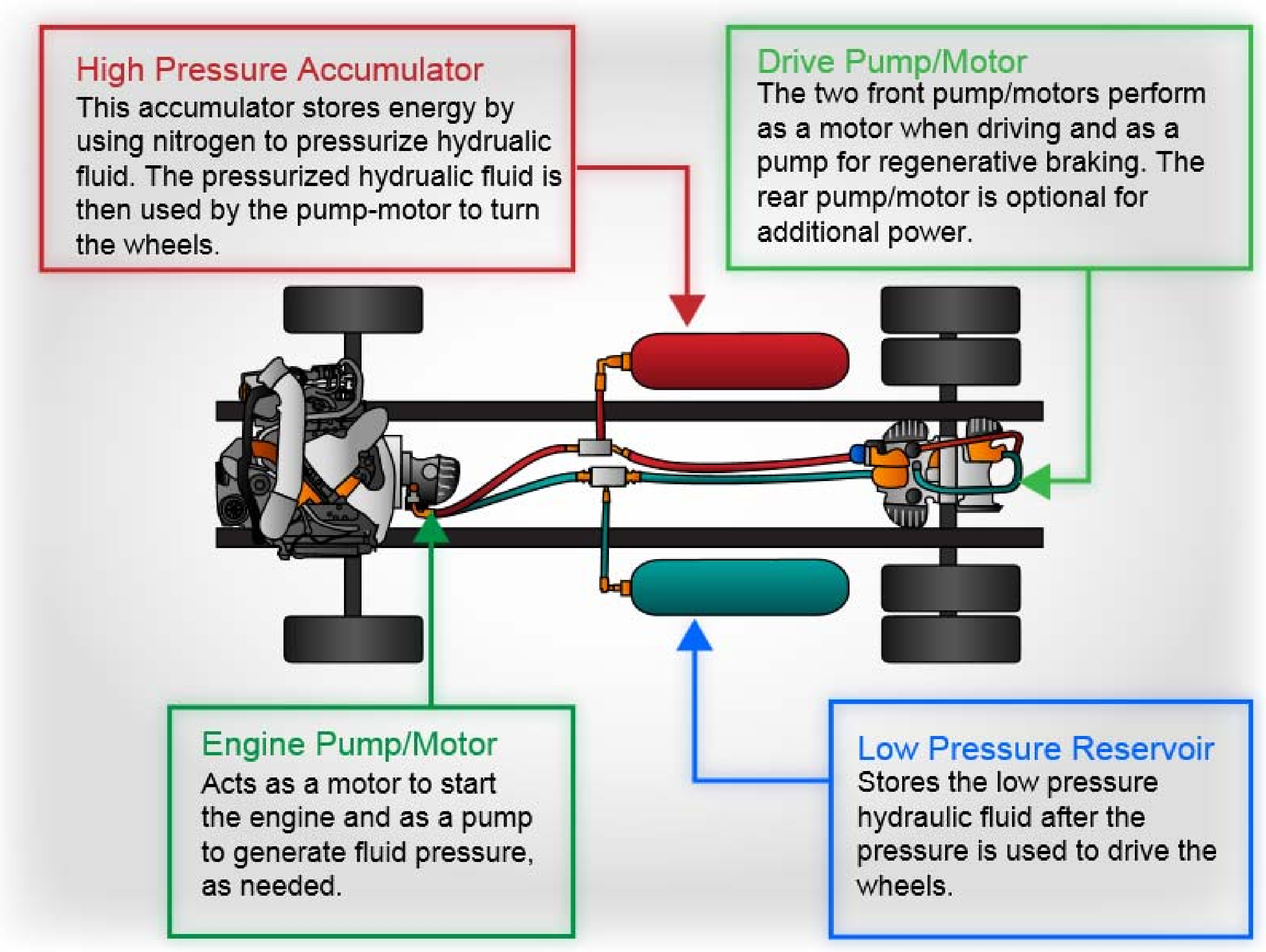
Hino Class 5 delivery/ local delivery food distribution hybrid box truck

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_2
- Energy released: Inert gas expands and pushes hydraulic fluid through the actuator into a low-pressure reservoir

Hydraulic Hybrid Vehicles



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., 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

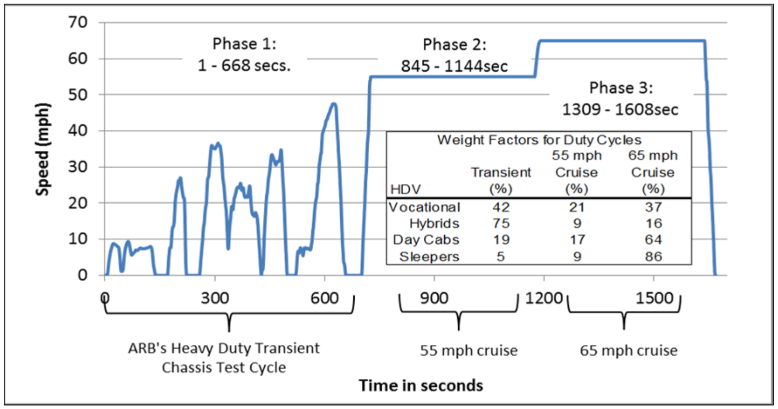
ARB and NREL: Chassis Dynamometer Testing Heavy-Duty Hybrid and Conventional Trucks

Summary of Preliminary Test Results – Parcel Delivery Drive Cycle

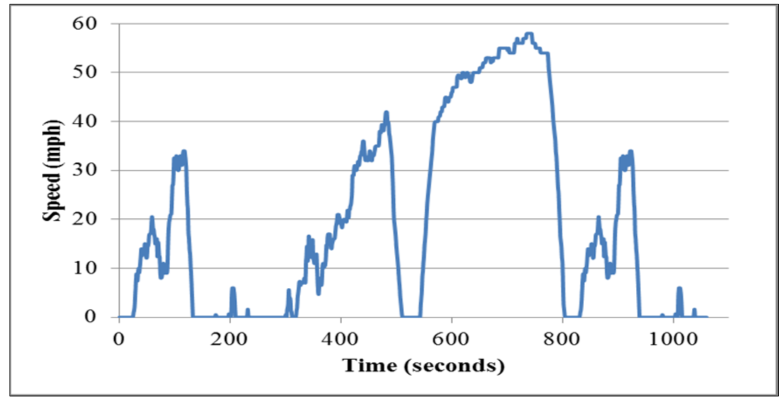
Average Emissions and Fuel Consumption Over the Cycles (g/mi) – Conventional				
Cycle	NO_x	CO_2	mpg	% FE
EPA GHG	0.52	712	13.25	--
UDDS	0.84	819	11.46	--
HTUF 4	1.63	1011	9.27	--
NY Comp	3.40	1308	7.12	--
Average Emissions and Fuel Consumption Over the Cycles (g/mi) – Hybrid				
EPA GHG	1.07	733	13.24	0.0 %
UDDS	2.88	723	13.55	18.2 %
HTUF 4	1.96	800	12.33	33.0 %
NY Comp	5.92	873	11.21	57.4 %

Hybrid Fuel Economy: Function of Duty Cycles

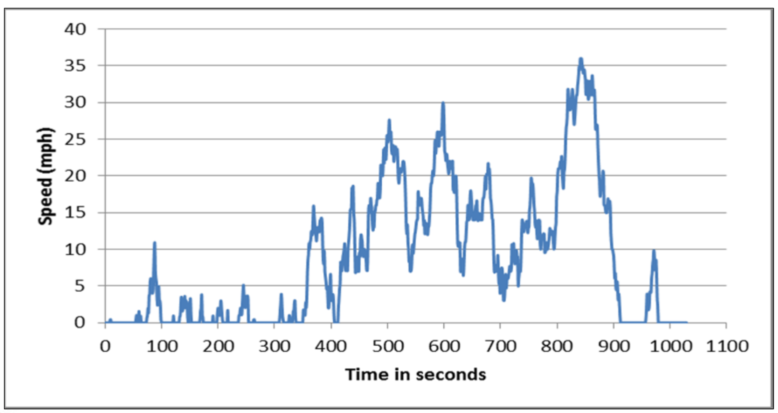
EPA GHG



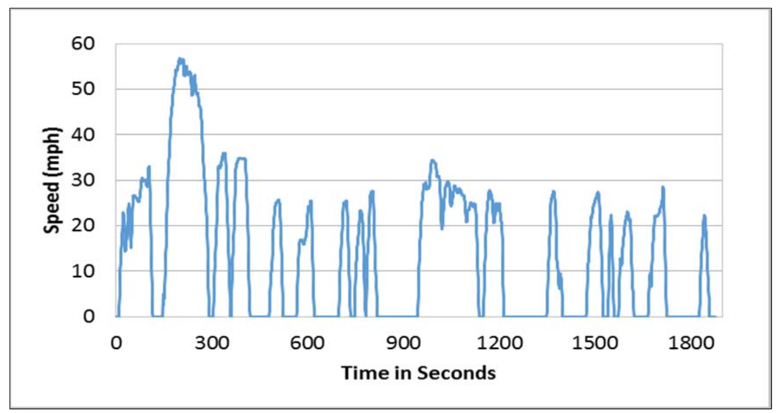
UDDS



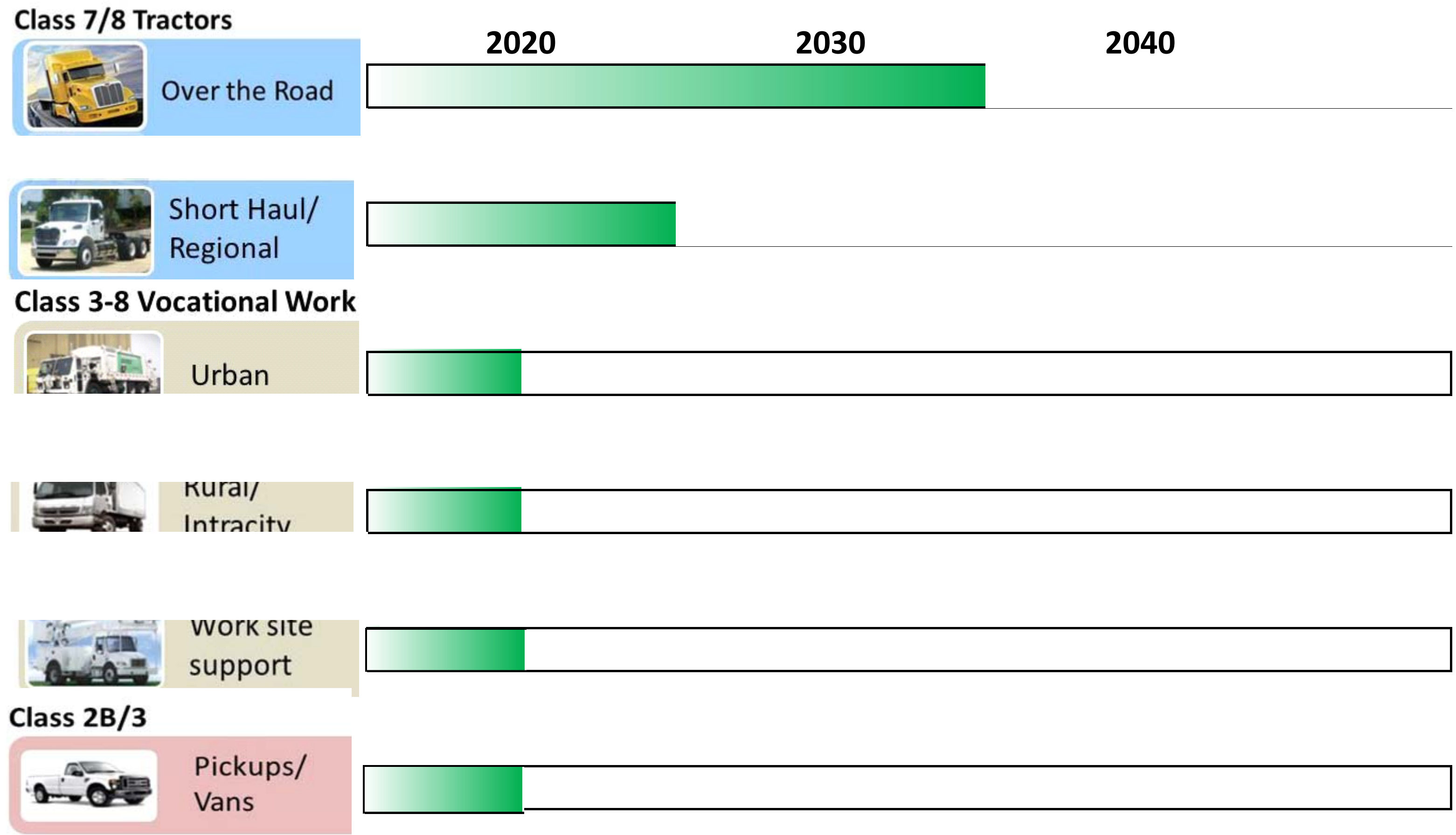
HTUF 4



NY Comp



Advanced Tech MD/HD Applications Potential Pilot Deployments



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)

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

Source: National Academy of Sciences, "Review of the 21st Century Truck Partnership, Second Report, p74, 2012.
"Forecasted cost" assumes 47% cost reduction by 2020 from current costs

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

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

- 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

Vehicle GVWR	Total Number of Deficiencies				
	2013/2014 MY		2015 MY		
	10+	<10	9-14	5-8	≤4
14,001 – 26,000 lbs	$12,000	$16,000	$8,000	$12,000	$16,000
26,001 + lbs	$16,000	$20,000	$12,000	$16,000	$20,000

HVIP Vouchers Issued by Hybrid Vehicle Type

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

Vehicle Type	Vouchers	Vehicle Type	Vouchers
Parcel delivery	503	Tow truck	68
Beverage delivery	408	School bus/other bus	33
Other truck	263	LP pick-up & delivery	27
Food distribution	55	Refuse hauler	23
Uniform & linen delivery	112	TOTAL	1,492*

*75% of total vouchers issued
Data as of July 2014

Hybrids and Freight Applications

PROJECT	DESCRIPTION	PROJECT TIME FRAME
Medium-Duty Electric and Hybrid Electric Trucks	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&E (4 utility), Coca Cola (15 all electric refrigerated delivery trucks)	2014-15
Volvo Plug-In Hybrid-Electric Drayage Truck	Build a Class 8 heavy-duty plug-in hybrid drayage truck	2015-16

Hybrids and Freight Applications

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

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_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 CO_2 but can increase NO_x
  - Need to improve system integration, certification requirements to prevent NO_x increases
  - Series hybrid able to mitigate the NO_x 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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- Submit comments by Oct. 1 to: http://www.arb.ca.gov/msprog/tech/comments.htm