The Transit Bus Niche Market For Alternative Fuels:

Module 7:
Overview of Emerging Diesel Technologies in Transit

Clean Cities Coordinator Toolkit

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Transit Buses with EGR to Control NOx Are Now Being Deployed

- Exhaust Gas Recirculation (EGR) is one of the most effective engine control methods for reducing NOx emissions
- Spent combustion gases recirculated back into the intake system serve as a diluent to lower the oxygen concentration and to also increase the heat capacity of the air/fuel charge
- Cooled EGR (aftercooler) is used to minimize combustion temperatures, thus reducing NOx emissions
- However, particulate matter (PM) emissions may increase and fuel economy may decrease.
- The proper balance of EGR and temperature may provide the proper characteristics for decreasing NOx emissions while not increasing PM
- Meeting 2010 transit bus engine standards will require various combinations of:
  - NOx aftertreatment
  - PM filter
  - Cleaner fuels (ULSD or alternative fuels)
  - Careful **INTEGRATION** of all strategies utilized

Where Does the Heavy-Duty Diesel Engine Go From Here?

- Currently, exhaust aftertreatment for NOx is limited by the “lean” environment
- Selective catalytic reduction (SCR) systems are being developed
  - Injects a reductant (ammonia or urea) into the exhaust upstream of the catalyst
  - Reductant decomposes and reacts across a catalyst to reduce NOx emissions (>70%) at reasonable cost
  - Most of the issues appear to be logistical (packaging, communication of the SCR system with the engine’s computer controls, etc.)
  - SCR may be used for some transit buses beginning with 2007 MY, although most engine manufacturers now say only “heavy” EGR is needed
- Longer term:
  - NOx adsorbers (traps) could be available at reasonable cost
  - Efficiency could be greater than 70 percent
  - Commercial availability time frame is still in question
- Most aftertreatment technologies for diesel will require low-sulfur fuels, because sulfates plug particulate traps and foul catalysts

Progress Towards 2007 Emissions Standards (According to EPA)

1) Engines

- Focus has shifted from R&D programs to product development
- Engine companies have reached (or are approaching) technology down-select
- Most companies have multiple technology paths capable of achieving 2007 std.
- NOx control options focus on "heavy EGR" with engine mods
- Aftertreatement (NOx adsorber or urea-SCR) may not be needed, because provisions of 2007-2009 standards effectively allow OEMs to achieve engine family **average** of 1.2 g/bhp-hr NOx
- Companies preparing for formal gate reviews to choose final 2007 package

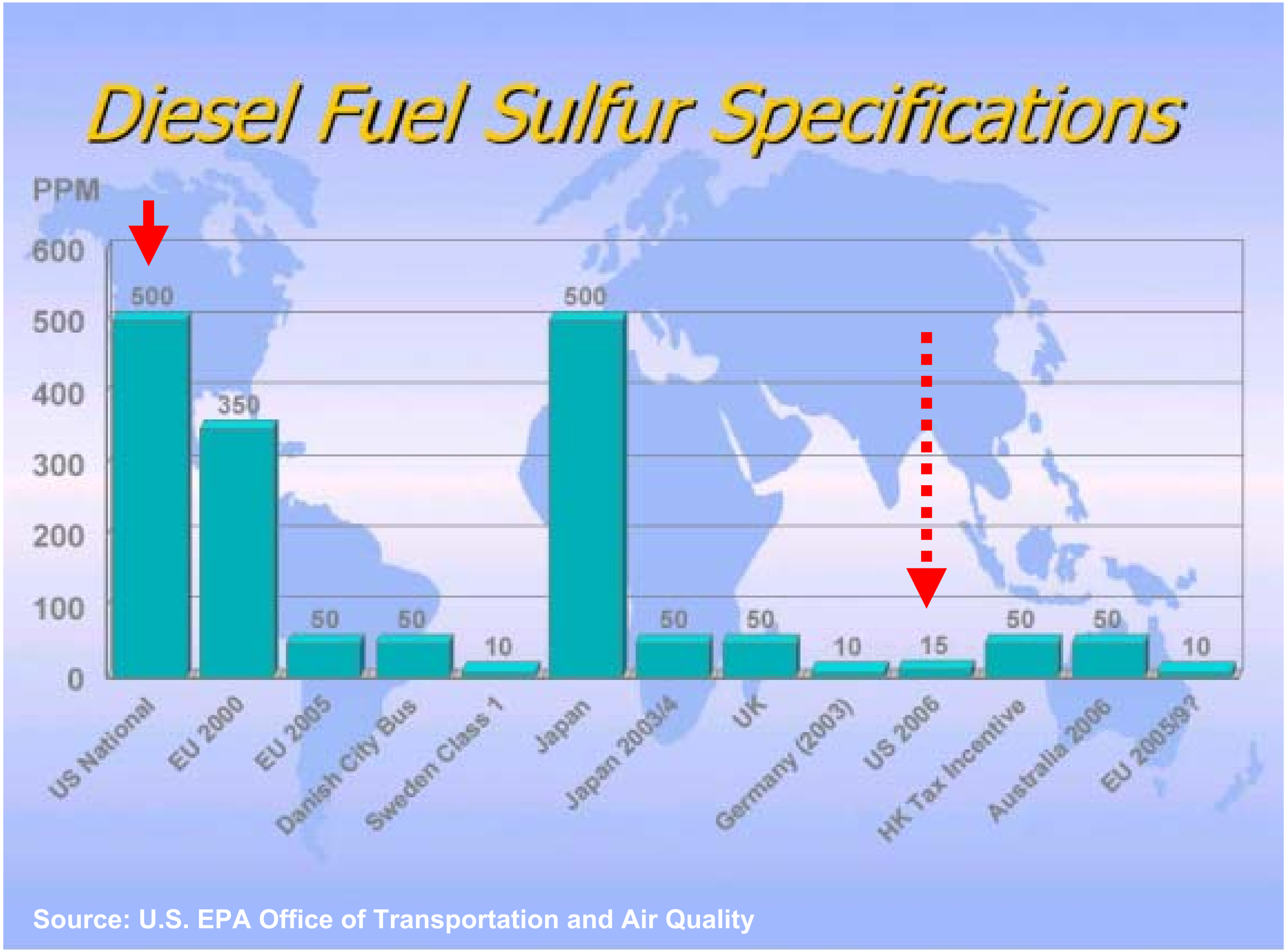
2) Diesel Fuel

- Industry is on target to comply -- 15 ppm fuel will be "widely available"
  - >95% of highway diesel fuel volume produced in 2006 will be ULSD
  - Highway diesel fuel supply will be "sufficient"
- EPA will summarize the results and publish a report soon

Source: Presentation by Bill Charmley, US EPA Office of Transportation and Air Quality, 2003 DEER Conference, August 24, 2003

Ultra-low Sulfur Diesel and Advanced Diesel Technologies

Sulfur Content in Diesel Fuel is Declining Worldwide . . . .



Ultra-Low Sulfur Diesel

- Already mandated for transit fleets in California
- Nationwide, refiners must start producing ULSD by June 2006
- Reduces sulfur content in diesel fuel by 97% (from 500 to 15 ppm)
- Already being used by some transit fleets nationwide (e.g., Chicago TA)
- Requires no major changes to transit operations or infrastructure
- Reduces particulate matter by about 15% in typical transit engines
- Introduced as **"technology enabler"** to pave way for advanced, sulfur-intolerant after-treatment technologies that can meet 2007 standards for NOx and PM
  - Diesel particulate filters
  - NOx catalysts
- ULSD allows "passive" regeneration of advanced PM technologies (e.g., Johnson-Matthey Continuously Generating Trap, or CRT)
- Estimates for the **incremental cost** of ULSD in 2006 range from 5 to 13 cents per gallon

ULSD-Fueled Buses Are Being Rolled Out at Various Transit Agencies

- Transit users include Chicago Transit Authority (CTA), Massachusetts Bay Transportation Authority (MBTA), several properties in the Seattle area, Washington Metro (WMATA)
- February 2002: Chicago Transit (CTA) decided to switch from #1 Diesel to ULSD in 100% of its diesel fleet (buses and non-revenue vehicles)
  - CTA uses 21.2 million gallons of diesel per year
  - British Petroleum (ARCO) is supplying ULSD
  - CTA to use ULSD in conjunction with diesel particulate filters (DPFs) on newest buses (Nova order) -- expecting 90% to 95% reduction in PM
  - Total cost including ULSD, DPFs, added filter maintenance, and new equipment = $16 million over 4 years
  - Expected to be completed by December 2003
- The real value and purpose of ULSD is to “enable” the use of NOx and PM aftertreatment devices, which can’t tolerate sulfur
- California Air Resources Board study of emissions from transit buses fueled by CNG and “green diesel” (ULSD with DPF) can be found at:

http://www.arb.ca.gov/research/cng-diesel/cng-diesel.htm

Installation of Particulate Traps on Transit Buses Creates Challenges

Series 50 DDEC Bus CRT™ installation

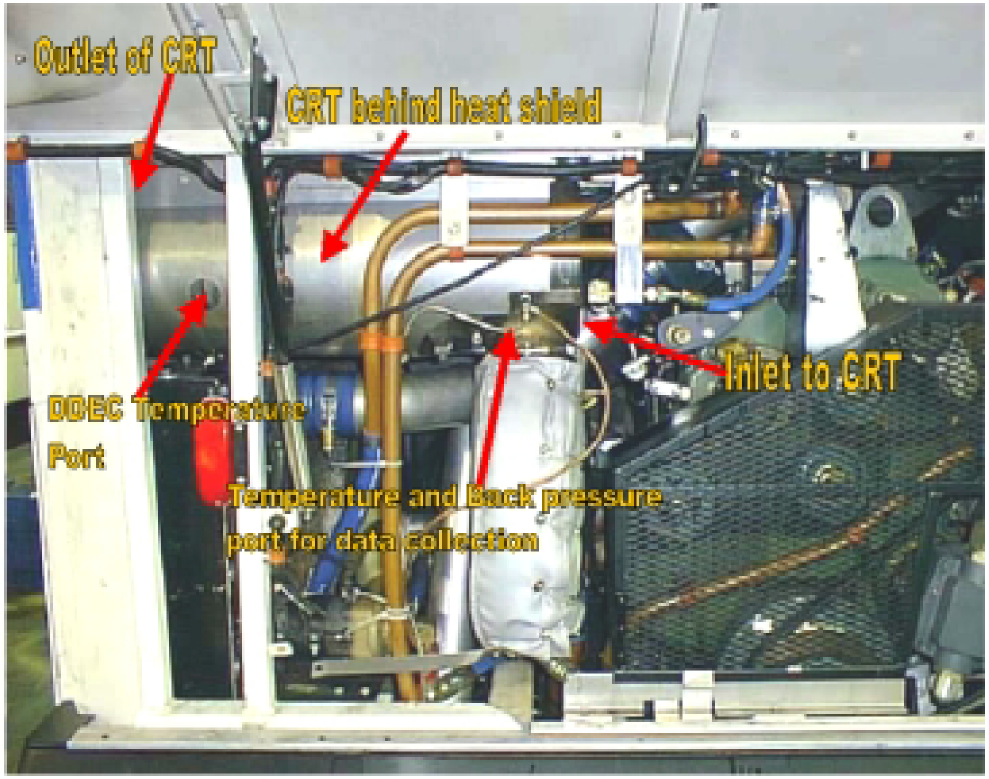


Photo from Johnson Matthey, Emission Control Systems for Retrofit Applications on Heavy-Duty Diesel Engines, http://www.corning.com/environmentaltechnologies/products__services/diesel_whitepapers/Chatterjee/sld001.htm

NYCT’s Challenges with“Clean Diesel” Technology in Transit Applications

Particulate Filters (Available Today)

- “Standard” installations are elusive
- Need duty cycle that’s generates sufficient heat profile
- Filters create backpressure problems and mask underlying engine problems
- New replacement filters are expensive ($2,500 to $5,000)

EGR Engines (Available Today)

- Immature in HDVs: durability and maintenance can be poor (but are improving)
- Space and packaging issues
- Adds more heat load to “already marginal” engine cooling system

EGR + Particulate Filters (Post 2004 Technology)

- Reduced NOx from EGR negatively affects PM filter’s catalysis
- Difficulties with engine programming to control smoke and provide good power
- Initial EGR system failures caused a high incidence of PM filter failures
- New EGR engines and plugged filters show a high correlation

Source: Dana Lowell, “NYCT Experience with Clean Diesel Technologies,” January 17, 2003, online at http://www.worldbank.org/cleanair/global/learningactivities/diesel_days/presentations/dlowell_nymta.pdf

NYCT's Conclusions on "Clean Diesel" in Transit Applications

- "Clean diesel" technologies can significantly reduce in-use diesel emissions
- Some technologies are quite mature and present little challenge (4-stroke engine, catalyst mufflers, reduced sulfur fuel)
- More aggressive technologies provide much higher benefits but are less mature, more costly, and more complex (catalyzed filters, EGR, hybrid)
- **There is no "free lunch" - all emissions reduction technologies increase engine/system complexity, resulting in increased maintenance costs**
- Capital and operational costs for ULSD
  - Purchase price at $0.12 more per gallon (CARB, NYCT)
  - Incremental cost of $0.04 / mile
- Capital and operational costs for catalyzed PM filter
  - $5,000 to $7,000 (including installation and back-pressure monitoring)
  - Annual maintenance: $300 to $600 / year / bus to remove, clean and replace @ 2 to 4 hours each (NYCT)

Source: Dana Lowell, "NYCT Experience with Clean Diesel Technologies," January 17, 2003, online at http://www.worldbank.org/cleanair/global/learningactivities/diesel_days/presentations/dlowell_nymta.pdf

2002 Review of Advanced Technologies for DART by NREL / Battelle

- **NOx Adsorber** – ULSD, NOx adsorber and a diesel particulate filter (possibly with EGR)
- **SCR** – ULSD fuel for a diesel engine using at least a SCR system and a DPF (possibly with EGR)
- **Natural Gas** – 0.5 g/bhp-hr capability with after-treatment technology
- **Hydrogen** – ICEs using 100% hydrogen or or a mixture of CNG/H2
- **All Electric** – electric propulsion system with energy storage onboard
- **Diesel Hybrid --** complete diesel hybrid electric bus system
- **Natural Gas Hybrid** – complete natural gas hybrid electric bus system
- **Turbine Hybrid** – one 60kW Capstone turbine or 2-30kW Capstone turbines in a hybrid electric bus, with diesel or natural gas as the fuel for the demonstration phase
- **Fuel Cell** – PEM fuel cell engine (probably fueled by hydrogen, possibly hybridized with battery or other energy storage device)

2002 Review of Advanced Technologies for DART (cont'd)

- Categories were chosen to measure the various advanced propulsion systems based on DART's objectives for the ZEP program
- The questions presented and answered for each technology boiled down to two issues –

  (1) Will the chosen technology be available at DART in 2007 - 2010 in large enough numbers to replace the entire standard bus fleet?

  (2) Is this technology going to be available for testing in the next 4 years?

- Based on the answers and scoring used in the assessment presented in this report, the technologies were ranked with the total score (out of 25 total) as follows:

Fuel / Technology	Points
Diesel Hybrid	24
NOx Adsorber	23
Selective Catalytic Reduction	22
Turbine Hybrid, Diesel	21
Turbine Hybrid, Natural Gas	20
Natural Gas ICE	19
Natural Gas Hybrid	19
Fuel Cell	18
Hydrogen ICE	12
All Electric (e.g., 100% Battery)	6

Results of DART Review (2002): Top Technologies to Demo and Evaluate

- 1. **Diesel Hybrid** – technologically mature compared to others, easily integrated into DART operations
- 2. **NOx Adsorber or SCR (not both)** – Unknown which technology to choose; allow engine manufacturer to determine
- 3. **Turbine Hybrid (Diesel or natural gas, not both)** – demonstrating microturbine technology should suffice for DART's knowledge, but to meet 2007 emissions standards, natural gas may also be required
- 4. **Natural Gas ICE and Natural Gas Hybrid –** Test advanced natural gas ICE as fourth option, but test natural gas hybrid technology as part of the diesel hybrid testing
- 5. **Fuel Cell** – Most benefits, but entails highest capital investments to accommodate fuel cell buses and hydrogen infrastructure
- 6. **Hydrogen / CNG Blend ICE** – As a alternative to fuel cells that can transition to hydrogen fuel cells

Note: **for DART's needs** (40-ft. buses with a range of 350 to 400 miles), battery electric technology was found to be an unrealistic option

Hybrid Electric Buses

Overview of Diesel Hybrid-Electric Buses

- HEBs (unlike battery electric buses) are **not limited to smaller vehicles**
- Developed in a wide range of vehicle sizes, including shuttle buses, 40-foot transit buses, 60-foot articulated buses, and over-the-road coaches
- **More than 30 organizations** in the United States are currently demonstrating hybrid bus technologies
- Early hybrid bus demonstration projects involved small numbers of vehicles, but **interest has grown recently**
- The promising results from early projects have led several agencies to place **large orders for hybrid buses**
- More than 600 hybrid buses could be placed into service around the country during the next few years
- A system that uses a "clean fuel" (e.g., NG or ULSD) and advanced NOx exhaust aftertreatment, in conjunction with an optimized hybrid electric system, has the **potential** to achieve near-zero emissions
- Hybrid buses can be **stepping stones to fuel cell propulsion** systems, which show promise for zero or near-zero emission transit buses

Hybrid-Electric Buses (HEBs)

- Urban buses: frequent stop and go
- HEBs reduce high polluting episodes
- HEBs use Two motive power sources
  - Battery pack/ultra-capacitors & electric motor
  - APU (internal combustion engine, microturbine)

Basic Types of Hybrid Electric Buses

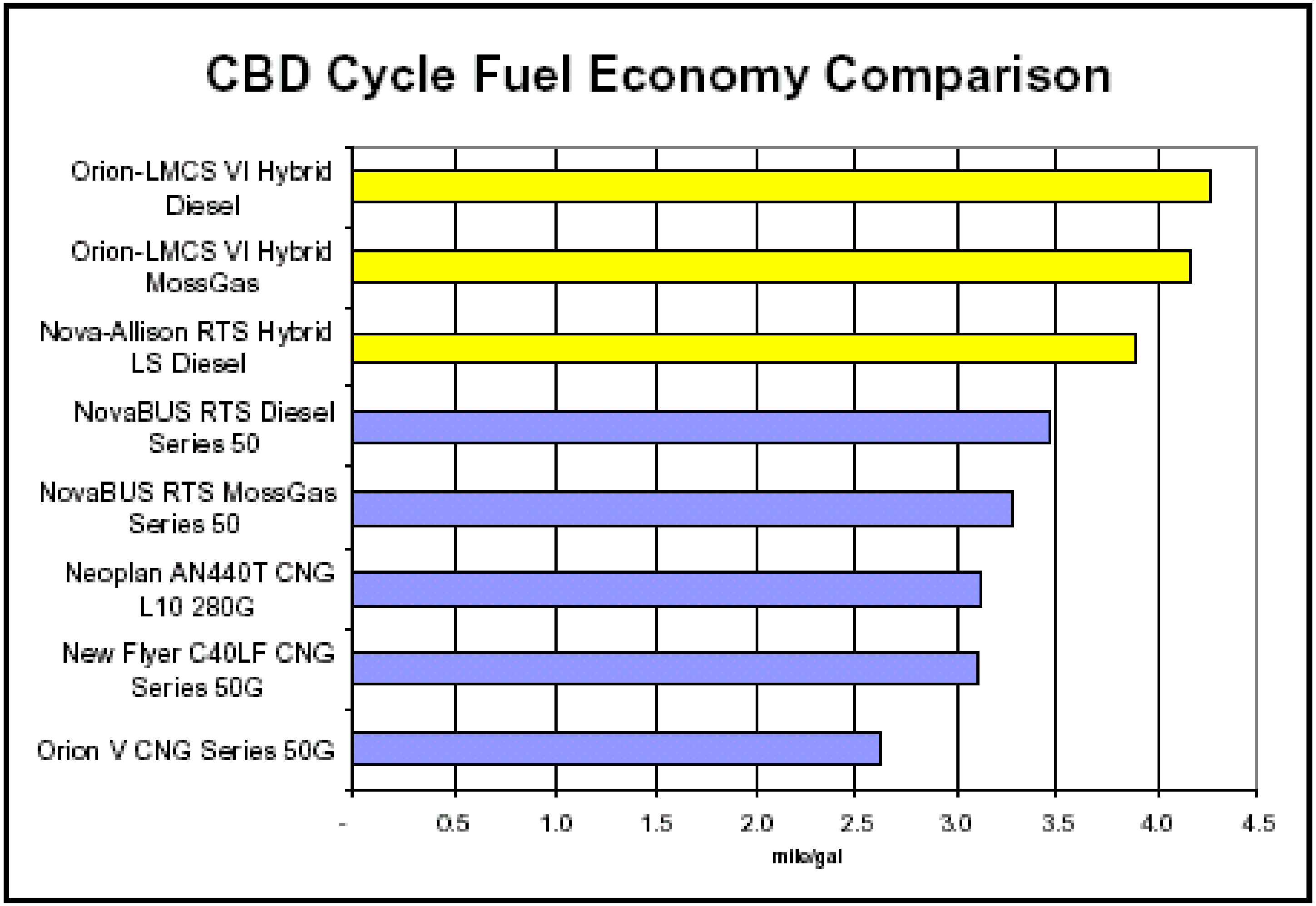
- **Series Hybrid —** power plant provides electrical power to the motor, which drives the wheels. There is no mechanical connection between the power unit and the wheels. An advantage of this configuration is being able to set the engine to operate at its maximum efficiency.
- **Parallel Hybrid**—This configuration has two power paths. It allows the wheels to be driven by the power unit, the electric motor, or both. A vehicle in this configuration has the advantage of higher power because the motor and engine can provide power simultaneously.
- **Fuel Cell**—Fuel cells, which have been used to generate power in space for decades, combine hydrogen and oxygen in a chemical process to produce electrical power with water as the only byproduct. Many fuel cell vehicles are in a hybrid configuration, with the fuel cell as the primary power source. Fuel cells for vehicle applications are in their early stages of development, yet as clean and efficient power sources, they have great potential.
- **Note:** a big advantage of hybrids and electric drive is the ability to convert kinetic energy into electricity to recharge an on-board energy storage device (usually a battery pack) upon deceleration or braking (regenerative braking)

Roof-Mount is Typical for Battery Pack on Hybrid Electric Transit Buses

- Enables use of low-floor buses
- Gull-wing shroud protects battery pack (similar to protection for fuel cylinders on CNG buses)
- Nickel-metal hydride batteries used
- Batteries provide 1) peaking power and acceleration, and 2) capability for regenerative braking

Photo from CTTRANSIT website (http://www.cttransit.com)

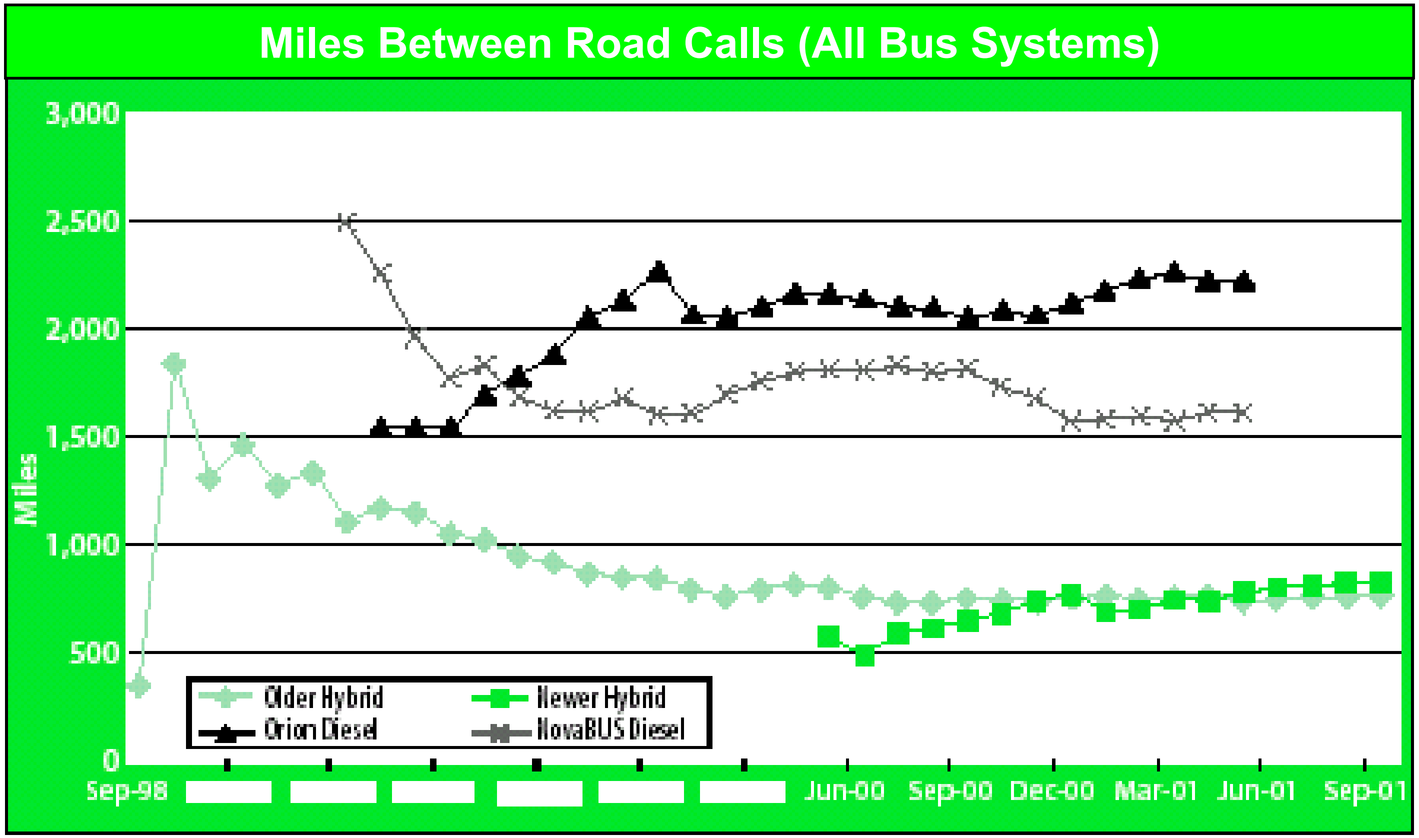
Hybrid electric buses provide the highest fuel economy of commercially available transit bus platforms



Source: Northeast Advanced Vehicle Corsortium, Hybrid Electric Heavy-Duty Vehicle Testing Project: Final Emissions Report, http://www.navc.org/Navc9837.pdf, February 2002. “MossGas” is a diesel fuel.

Early versions of HEBs have been less reliable than conventional diesel buses

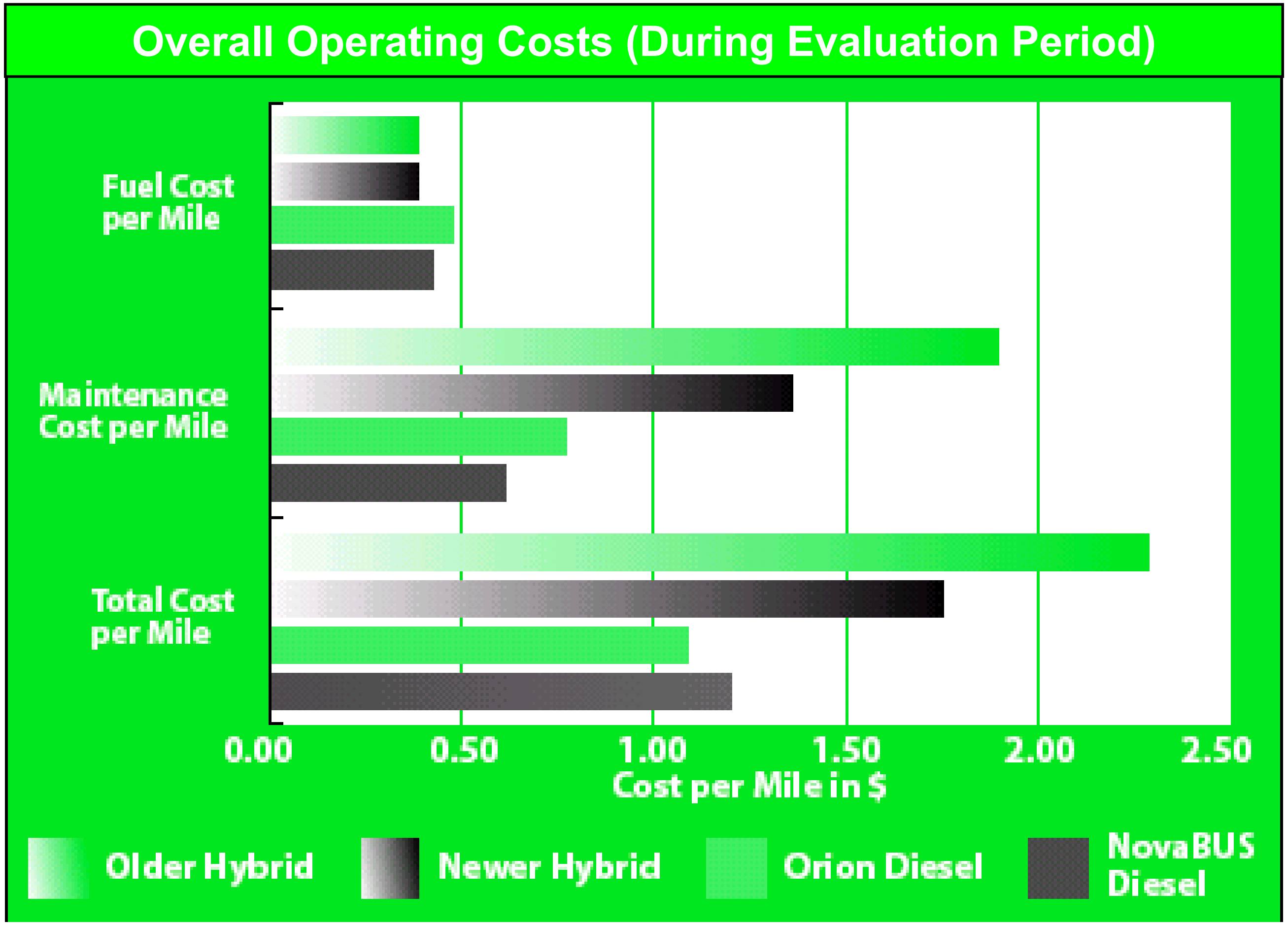
- NYC Transit documented more miles between road calls for its conventional deisel buses than its test hybrid-electric buses
- NYC Transit expects the durability of HEBs to improve as technology matures



Source: U.S. DOE and NYC Transit, “NYCT Diesel Hybrid-Electric Buses Final Results, 2002

The Total Costs per Mile of HEBs Are Improving With Newer Technology

- NYC Transit's HEBs had reduced fuel costs, but increased maintenance costs
- The HEBs' total cost per mile improved with newer technology, but still significantly exceeded those of the conventional diesels



Source: U.S. DOE and NYC Transit, "NYCT Diesel Hybrid-Electric Buses Final Results, 2002

For detailed information about the NYC Transit program:

This report is online at:
http://www.dieselforum.org/background/downloads/cleanppt.pdf

or contact:

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Additional online resources

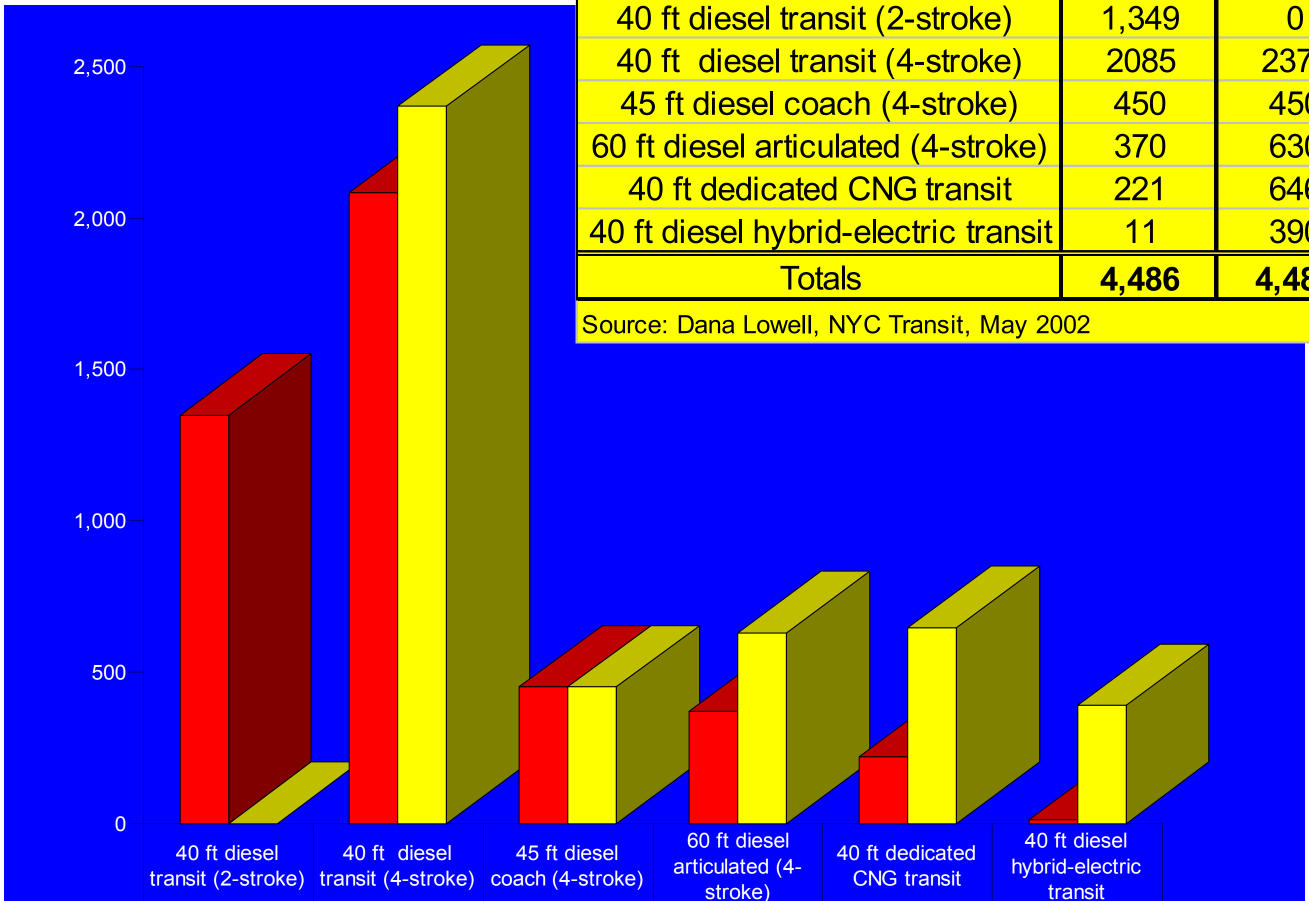
1) http://www.epa.gov/otaq/retrofit/documents/ny_crt_presentation.pdf

2) Technical Assessment of Advanced Transit Buses at DART, http://www.afdc.doe.gov/pdfs/dart_tech_assess.pdf
3) Bus Futures: New Technologies for Clean Cities, Inform, http://www.informinc.org/busfutr.pdf

NYC Transit's Changing Fleet Profile

Bus Size / Type / Technology	2001	2006	Increase / Decrease	% Change
40 ft diesel transit (2-stroke)	1,349	0	-1,349	-100%
40 ft diesel transit (4-stroke)	2085	2370	285	14%
45 ft diesel coach (4-stroke)	450	450	0	0%
60 ft diesel articulated (4-stroke)	370	630	260	70%
40 ft dedicated CNG transit	221	646	425	192%
40 ft diesel hybrid-electric transit	11	390	379	3445%
Totals	**4,486**	**4,486**	**0**	**0**

Source: Dana Lowell, NYC Transit, May 2002



	40 ft diesel transit (2-stroke)	40 ft diesel transit (4-stroke)	45 ft diesel coach (4-stroke)	60 ft diesel articulated (4-stroke)	40 ft dedicated CNG transit	40 ft diesel hybrid-electric transit
2001	1,349	2085	450	370	221	11
2006	0	2370	450	630	646	390

A NOVA Hybrid Electric Bus Undergoes Acceptance Testing by NJ Transit

- ***No. Purchased: 3***
- ***Fuel: Diesel***
- ***Drivetrain: Hybrid Electric from ISE Research***
- ***Model Year 2002***
- ***Bus Manufacturer: NOVA Bus***
- ***Model No.: 82VN***
- ***Cost: $1.034 Million***

Photo by Trevor Logan (from http://www.davemackey.com/njt/gallery/4001.html)

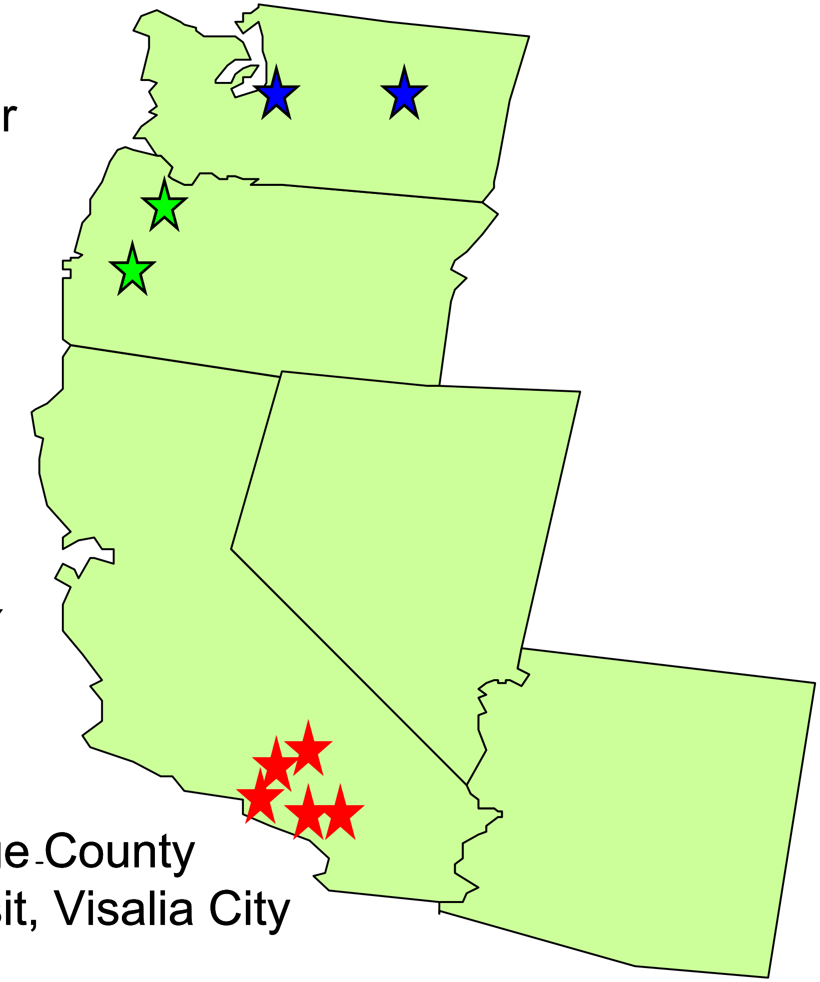
Other Hybrid Electric Buses in the Northeast and Mid Atlantic Include:

- 12 purchased and operated by **Southeastern PA Transit Authority**
- Connecticut Transit: purchased two diesel-battery electric 40 ft. transit buses purchased in mid 2003
- Funding:
  - Federal highway funding
  - East Coast Hybrid Consortium ($100k)
- Model: 2003 New Flyer DE 40LF (low-floor)
- Cost: **$511,878 per bus**
- Entered service in June 2003
- Objective: two-year study of HEBs in revenue service
- Partners: UConn, Connecticut DOT, New Flyer, Allison Transmission, East Coast Hybrid Consortium, Connecticut Academy of Science and Engineering

Photo from Connecticut Transit website (http://www.cttransit.com)

Southeastern Pennsylvania Transit Authority

Numerous Transit Agencies in Pacific States Are Testing Diesel HEBs



Washington:

- King County Metro - 1 existing, 200 on order (60 ft. articulated dual mode buses)
- Spokane Transit - 4 to be purchased (2005 MY transit buses)

Oregon:

- Tri County Metro (Portland) - 2 existing 2002 MY transit buses
- Lane Transit (Eugene) - 6 existing 2001 MY paratransit vehicles

California:

- Users include: Fresno Area Express, Orange County Transit, Torrance Transit, Long Beach Transit, Visalia City Coach, and Santa Barbara MTD
- Users in South Coast are currently subject to Rule 1192 limitations

Note: based on 2003 APTA database for reporting transit agencies

King County Metro’s 60-foot hybrid diesel-electric bus testing program

Specific targeted niche for 60 ft HEBs:

Metro hopes 60 ft articulated HEBs can replace 236 aging “dual-mode” Breda buses, which operate on diesel ICE power above ground, and in electric mode (via catenary wires) when underground in Seattle’s 1.3 mile tunnel system.

If ‘02-’03 testing is successful:

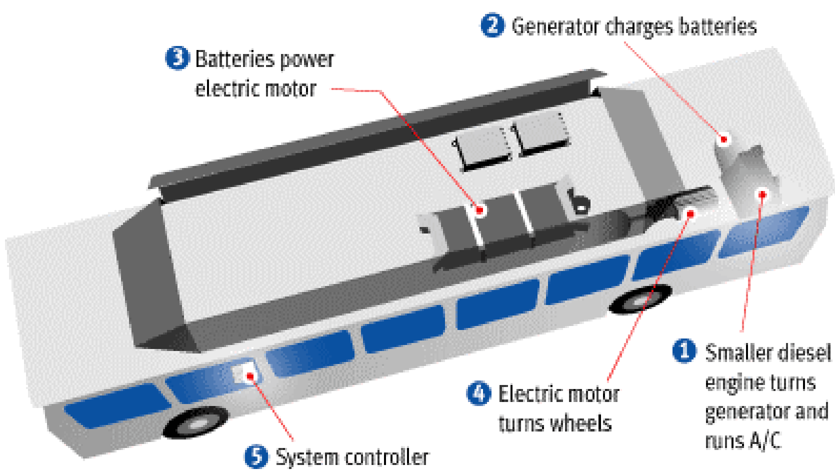
200 similar HEBs will be ordered for ‘04-’05

- Single unit purchased in 2002 as a test-bed for greater HEB use
- **First articulated HEB in America**
- Chassis: New Flyer Industries
- Drive system: Allison EP-50 Hybrid-Electric Drive
- Cost: **$963,328**
- Metro projects operating costs will be reduced by 30% to 50% compared to existing “dual-mode” buses:
  - 20-30 % reduction in fuel consumption
  - Reduced maintenance costs
- Metro estimates NOx and PM reductions of 50% and 90% compared to cleanest diesel buses in its fleet
- “Remarkable” early results
- July ‘03: Cummins engine replaced w/ Caterpillar (lower emissions)

Photo / source: King County Metro website (http://transit.metrokc.gov)

Tri-Met (Portland) began testing a full-sized HEB in 2002

- Chassis: New Flyer of America
- Electric drive system: Allison Drives
- Diesel auxiliary engine: Cummins



Source of photo and diagram: Tri-Met website (http://www.trimet.org/environment/hybridbus.htm)

Some Hybrid Electric Buses Operate on Gasoline Fuel

OMNITRANS' New Flyer -ISE Research Gasoline-Electric Hybrid (photo from OMNITRANS website)

OCTA's Hybrid Electric Buses

- First transit agency on the West Coast to place a full size hybrid-electric transit bus into commercial service
- 2000 MY New Flyer of America with advanced hybrid-electric powertrain developed by Allison Transmission (Allison Electric Drives E S System)
- Part of Allison's hybrid "preview program" to bring HEBs to transit agencies throughout North America
- Cummins ISB engine:
  - Includes catalyzed particulate filter
  - Reportedly reduces PM by 90%
  - NOx, HC and CO also reduced compared to conventional diesel buses

TransTeq's EcoMark I Hybrid-Electric Buses in Denver Use CNG

- 36 buses operating in Denver
- 4 at Los Angeles International
- 45 ft. long, 116 passenger
- Series hybrid configuration
- CNG-fueled 70-hp 4-cylinder industrial ICE acts as generator set
- 2 DC electric motors deliver 440 hp to drive wheels
- Provides "zero-emissions" (battery-only) mode when needed, for limited range
- Cost: ~$585,000

Advice from Agencies Currently Testing Advanced Technologies (Eudy)

- Research New Technologies
- Plan for Higher Costs and Added Resources
- Apply a Teamwork Approach
- Train Maintenance and Other Staff

Summary on Emerging Diesel Technologies in Transit Applications

- Multiple technology paths are being pursued by OEMs to meet 2007/2010, in conjunction with ULSD fuel
- Progressively more aggressive "clean diesel" technologies will be needed, which are likely to result in **more-costly and less-reliable** diesel buses
- Hybrid-electric buses are being deployed across the U.S. in field trials: results are **promising, and commercialization is rapidly moving forward**
- Diesel HEBs provide **increased fuel efficiency** (15% to 18%) over conventional diesel buses, and they also provide **emissions benefits**
- Diesel HEBs have **higher capital costs, higher operational costs, and reduced durability**, but this is expected to improve
- **Alternative-fueled HEBs** are being tested that **further accentuate emissions benefits** associated w/ electric drive and hybridization (Module 8)
- Many transit agencies appear to be delaying near-term bus procurements to see if HEBs will become less expensive and more reliable
- Strong training programs are essential (internal, or from the outside)
- Diesel HEBs are "bridge technology" to advanced technology transit buses, including those powered by hydrogen fuel cells (see Module 8)