FTA-CA-26-7044-2033

Federal Transit Administration

Analysis of Fuels and Propulsion System Options for BRT Vehicles

WestStart-CALSTART
Pasadena, California

2004

REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE **September 2004**	3. REPORT TYPE AND DATES COVERED **BRT Final Report, September 2004**

4. TITLE AND SUBTITLE **Analysis of Fuels and Propulsion System Options for BRT Vehicles**	5. FUNDING NUMBERS **CA – 26 – 7044-2033**
6. AUTHOR(S) **Matt Peak**	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **WestStart-CALSTART** **2181 East Foothill Boulevard** **Pasadena, CA 91107**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) **Federal Transit Administration** **U.S. Department of Transportation** **Washington, DC 20590 Website URL [http://www.fta.dot.gov]**	10. SPONSORING/MONITORING AGENCY REPORT NUMBER

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12a. DISTRIBUTION/AVAILABILITY STATEMENT **Available From:** National Technical Information Service/NTIS, Springfield, Virginia, 22161. Phone 703.605.6000, Fax 703.605.6900, Email [orders@ntis.fedworld.gov]	12b. DISTRIBUTION CODE

12. ABSTRACT (Maximum 200 words)

This document provides information that will assist in making BRT fuel and propulsion system choices that are compatible with community, environmental, regulatory, and vehicle demands. Accordingly, it provides a deeper understanding of the fuels and technologies that the communities demand, while placing these fuels and technologies in the context of current and future emission, environmental, and industrial drivers.

Among other findings, this publication illustrates that there are a multitude of fuels and technologies, from refined diesel technologies to alternative fuels, from which transit agencies can select in order to fulfill customer demands, to comply with future emission standards, and to effectively compliment other BRT system characteristics. It discusses both currently available and emerging BRT fuels and technologies, outlining their respective emission reduction potentials, advantages, disadvantages, examples of implementation, and current manufacturers. This publication also identifies actual and potential compliance methods for meeting 2007 and 2010 EPA and California emission standards, emerging fuels and technologies that can power BRT systems of the future to meet the demands of future emission drivers, and which fuels and propulsion systems work most effectively with desired BRT system characteristics.

14. SUBJECT TERMS **Bus Rapid Transit Bus Propulsion Methods Bus Emission Technologies** **Bus Vehicle Characteristics Bus Feature Preferences Alternative Fuels**	15. NUMBER OF PAGES **131**
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	

NSN 7540-01-280-5500 Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18298-102

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Forward by John Boesel, President, WestStart-CALSTART

Bus rapid transit (BRT) is a higher capacity, faster mass transit system that can dispel the perception that buses are an inferior way to travel. BRT's potentially sleek appearance, timely service, and other options allow those who are implementing BRT systems the opportunity to rethink vehicles, fuels, and propulsion systems. In fact, an extensive survey of BRT vehicle and system demand performed by WestStart-CALSTART for the Federal Transit Administration (FTA) in 2004 titled "BRT Vehicle Demand Analysis Update" indicates that those making procurement decisions are doing just that, as there is particularly high demand for unique designs and system services that are different from ordinary bus operation.

In fact, this analysis revealed that a significant percentage of those planning to implement BRT service seek vehicle and propulsion system features, such as low-emission and hybrid electric systems, that are unlike those commonly used on bus systems of the past. These new features are attracting new riders in addition to those who ordinarily take transit, thereby reducing the number of private vehicles on the road. This reduction, combined with the use of cleaner fuels and technologies on BRT vehicles, helps improve air quality and reduce dependence on foreign oil. BRT is particularly intriguing in this aspect because it can provide the cleaner, quieter, and faster bus service that transit operators seek while also offering a cleaner and more environmentally friendly bus service.

Coincidentally, the desire for these unique BRT features is growing at a time when stringent government and state emission standards are combining with other factors to reduce emissions to levels previously thought impossible. Therefore, the need for a review and analysis of fuels and propulsion system options for BRT vehicles is timely.

This document seeks to provide information that will assist those involved with BRT service, from mechanics to transit authorities to regulators, in making fuel and propulsion system choices that are compatible with community, environmental, regulatory, and vehicle demands.

This publication was made possible by funding provided by the FTA under the direction of Walter Kulyk. The FTA provides substantial funding towards the research, development, and promotion of Bus Rapid Transit. WestStart-CALSTART is thankful for the opportunity to work with the FTA on BRT issues and for the support that the FTA provided to WestStart-CALSTART and to the BRT community.

The author of this document is Matt Peak, Project Manager at WestStart-CALSTART. Matt worked tirelessly to compose a clear analysis of BRT fuels and propulsion systems that addresses the myriad of regulatory and technical issues facing the BRT community. WestStart-CALSTART thanks him for his effort on this valuable work.

I would also like to thank two other members of the WestStart-CALSTART team, Fred Silver and Bill Van Amberg, who helped provide information, edit drafts, and offer opinions. Without their input, support, and dedication, this project would not have been possible. Also, James Cannon and Jeff Georgeson from Energy Futures, Inc. provided editing services for this report.

WestStart-CALSTART continues to be committed to supporting the growth of Bus Rapid Transit through projects such as this one as well as its Bus Rapid Transit Design Competition, the previously mentioned “BRT Vehicle Demand Analysis,” BRT Vehicle Compendium, BRT Vehicle Selection Toolkit, and BRT Newslane, which is the only national publication dedicated to BRT news and issues. The organization will continue to pursue projects such as these and others in order to see the potential of BRT systems realized.

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Glossary of Abbreviations

ACCOLD-EGR	Active clean and cold exhaust gas recirculation
APU	Auxiliary power unit
ARB	Air Resources Board
B100	100 percent biodiesel
B20	A mixture of 20 percent biodiesel and 80 percent diesel fuels
B100	100 percent biodiesel
BHP	Brake horsepower
BMEP	Brake mean effective pressure
BRT	Bus rapid transit
BTU	British thermal unit
CARB	California Air Resources Board
CEGR	Cooled exhaust gas recirculation
CI	Compression ignition
CNG	Compressed natural gas
CO	Carbon monoxide
CO_2	Carbon dioxide
DI	Direct injection
DOC	Diesel oxidation catalyst
DOE	Department of Energy
DOT	Department of Transportation
DPF	Diesel particulate filter
EGR	Exhaust gas recirculation
EPA	Environmental Protection Agency
FCV	Fuel cell vehicle
FTA	Federal Transit Administration
g/bhp-hr	Grams per brake horsepower hour
GHG	Greenhouse gas
GPS	Global positioning system

GTL	Gas-to-liquid
HC	Hydrocarbons
HC-SCR	Hydrocarbon selective catalytic reduction
HD	Heavy-duty
HDV	Heavy-duty vehicle
HE	Hybrid electric
HEB	Hybrid electric bus
HEV	Hybrid electric vehicle
HPDI	High pressure direct injection
ICE	Internal combustion engine
LACMTA	Los Angeles County Metropolitan Transit Authority
LNC	Lean NOx Catalyst
LNG	Liquefied natural gas
LPG	Liquefied petroleum gas, or propane
LS	Low sulfur
MATES	Multiple air toxics exposure study
MBSI	Miles between service interruptions
MBTA	Massachusetts Bay Transportation Authority
MECA	Manufacturers of Emission Controls Association
MIT	Massachusetts Institute of Technology
MTA	Metropolitan Transportation Authority
NABI	North America Bus Industries
NATSO	National Association of Truck Stop Operators
NG	Natural gas
nm	Nanometer
NMHC	Non-methane hydrocarbon
NOx	Nitrogen oxides
NRC	NOx reduction catalysts
NREL	National Renewable Energy Laboratory
NYCT	New York City Transit
OEHHA	Office of Environmental Health Hazard Assessment

OEM	Original equipment manufacturer
PACCOLD-EGR	Passive clean and cold exhaust gas recirculation
PAH	Polycyclic aromatic hydrocarbon
PEM	Proton exchange membrane
PM	Particulate matter
ppm	Parts per million
SAE	Society of Automotive Engineers
SCAQMD	South Coast Air Quality Management District
SCR	Selective catalytic reduction
SI	Spark ignition
SUV	Sport utility vehicle
TRB	Transportation Research Board
TTI	Texas Transportation Institute
ULEV	Ultra Low Emissions Vehicle
ULSD	Ultra low-sulfur diesel
VGT	Variable geometry turbocharger
VOC	Volatile organic compounds

Introduction

Picture transit riders waiting at a bus station for a ride to work. It's an ordinary day, but this is not an ordinary bus station, and riders are not waiting for an ordinary bus. Unlike most conventional bus stops, the terminal where the riders are waiting is protected from the elements by a roof while continuously updated electronic readouts inform riders when the next bus is due to arrive. The bus arrives on-time, gliding up in a fluid motion, effortlessly docking within inches of the elevated platform where passengers wait to board. As multiple sets of automated doors glide open, riders step easily onto the level floor of a sleek, rail-inspired carriage at the same time as others disembark, with plenty of room to spare. As the riders settle down into their seats, they are quickly and smoothly whisked away along a designated corridor by a bus that conspicuously leaves neither noise nor air pollution in its wake. Such a vision is the promise of the ideal bus rapid transit (BRT) system.

In September 2002, WestStart-CALSTART and the Federal Transit Administration (FTA) released their "BRT Vehicle Demand and Supply Analysis" that comprehensively surveyed 28 major transit communities to determine BRT vehicle preferences for planned procurement. The study revealed that of 5,004 total vehicles anticipated for potential delivery between 2002 and 2012, transit communities prefer a significant number to be powered by advanced hybrid electric technologies, alternative fuels such as natural gas, and/or low-sulfur diesel fuel. An updated June 2004 WestStart-CALSTART analysis of 48 transit communities reveals this trend towards these technologies and fuels is increasing. As it stands, transit communities indicate a preference for over 40 percent of an anticipated 5,210 vehicles for potential delivery between 2004 and 2013 to be powered by advanced technologies and almost 40 percent to be powered by alternative fuels such as natural gas, while low-sulfur diesel is planned to power 32 percent of acquired vehicles, including many powered with advanced technologies.

At the same time that demand is growing for clean BRT vehicles, the United States (U.S.) Environmental Protection Agency (EPA) and the California Air Resources Board

(CARB) are set to implement strict emission standards in 2007 and 2010. When fully realized, these standards will reduce nitrogen oxides and particulate matter by 90 percent and require the utilization of advanced fuels and technologies. Other issues such as fuel consumption, national security, and energy independence are becoming increasingly important considerations for transit communities. In the future, vehicle fuel and exhaust characteristics, such as the presence or absence of ultrafine particulate matter (PM) or the emissions levels of global warming gases, can be expected to further the drive towards clean transit technologies.

With such strong demand and drivers for BRT vehicles powered by and equipped with advanced, pollution-reducing fuels and technologies, a deeper understanding of and familiarity with these fuels and technologies is necessary in order to determine their comparable advantages and disadvantages. This publication responds to the preferences that were identified in the market demand analyses by providing this deeper understanding of the fuels and technologies that the communities demand, while placing these fuels and technologies in the context of current and future emission, environmental, and industrial drivers.

Among other findings, this publication illustrates that there are a multitude of fuels and technologies from which transit agencies can select in order to fulfill customer demands, to comply with future emission standards, and to effectively compliment other BRT system characteristics. This publication also finds that the 2007 EPA and CARB emission standards will be achievable by all engine makers using currently known technologies, and that compliance methods have already been determined by many manufacturers. On the other hand, the more stringent 2010 standards will require more complicated systems to reduce emissions that will affect the viability and desirability of the various fuels well into the future. Engine manufacturers have not yet determined compliance methods for these standards.

Overall, this publication is designed to serve as a tool for BRT vehicle planning by discussing both currently available and emerging BRT fuels and technologies, outlining their respective emission reduction potentials, advantages, disadvantages, examples of implementation, and current manufacturers. It is also intended to help decision makers determine which fuels and propulsion systems work most effectively with desired BRT system characteristics.

WestStart-CALSTART thanks the FTA for its support and funding that make this publication possible.

Executive Summary

Transit community and rider demands are combining with strict federal and California regulations, due to be implemented in their entirety by the end of the decade, to drive drastic reductions in vehicle exhaust emissions. New federal emission standards will culminate between 2007 and 2010 when nitrogen oxide (NOx) and PM emissions must be reduced by 90 percent from 2004 levels. California standards are currently even more stringent for transit buses, with accelerated implementation of federal emission standards as well as a pollution-free bus requirement. After these standards are fully implemented, other concerns, such as fuel toxicity, PM size, global warming, fuel efficiency, national security, and energy independence issues, can be expected to shape selection considerations of fuels and propulsion systems used by BRT vehicles.

BRT vehicles must place sometimes competing environmental and user demands in the context of overall desired system characteristics. These characteristics include a larger size than conventional buses, quieter operation, stylistic design, faster travel times, redesigned interior, and the presence of other BRT amenities. The fuels and propulsion systems that are selected for BRT service are themselves an integral characteristic of BRT vehicle and system operation, but they also need to compliment other vehicle and system characteristics.

In this time of transition from bus systems of the past to those of the future and from previous emission standards to increasingly stringent standards, guidance is needed to determine which fuels and propulsion systems are able to fulfill the demands of transit agencies, riders, and operators as well as those imposed by environmental and other factors. Currently, there are several technologies and fuels capable of doing so.

<u>Current Compliance Pathway</u>

The current compliance pathway is comprised of options for meeting environmental demands through the use of fuels and technologies that are available today. The approaches range from complex but efficient hybrid electric systems to more proven systems that minimize harmful emissions from conventional diesel engines.

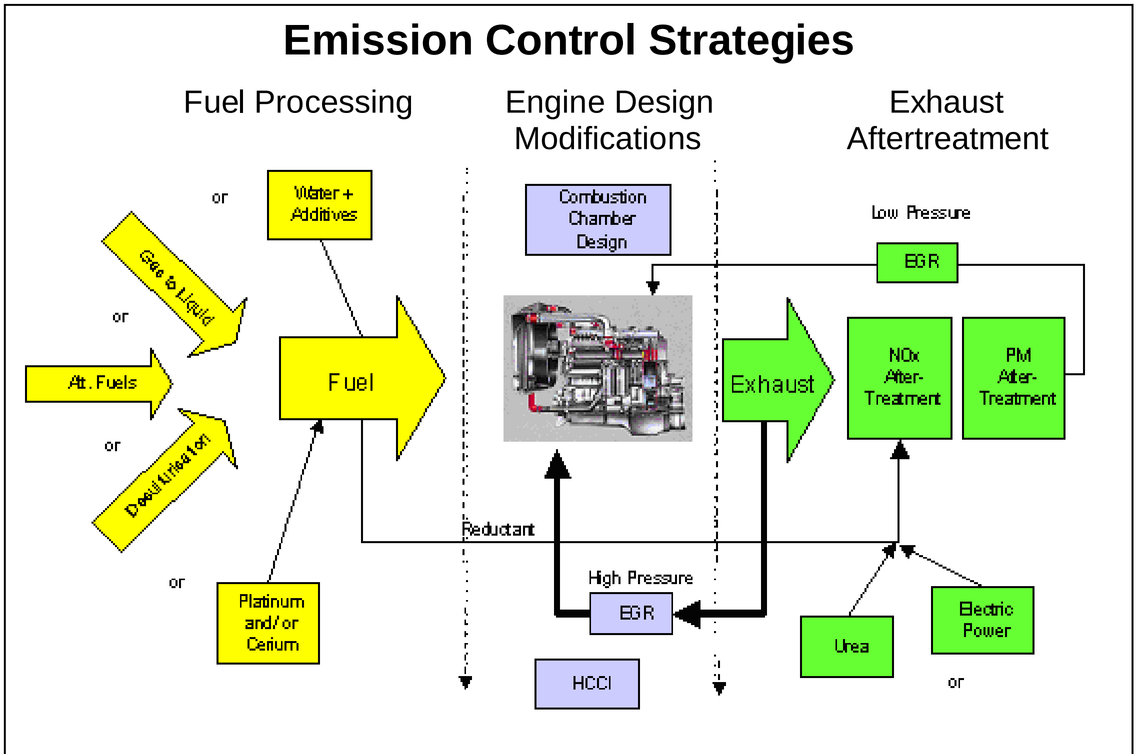
Ultra low-sulfur diesel (ULSD) fuel now entering the market will not only reduce pollution, but will also enable standard diesel internal combustion engines to use pollution-reducing technologies and aftertreatment. Another pollution reduction aid will be the use of blending stocks that are typically mixed with diesel fuel and utilized in vehicles with little or no modification to the vehicle's engine and fuel system. Transit operators also have a selection of currently available alternative fuels and technologies as options for reducing pollution. The following table lists each major aftertreatment technology, fuel blending, and alternative fuel option in the current compliance pathway.

Current Compliance Pathway **Currently Available Pollution Reducing Technologies, Fuels, and Aftertreatment**		
Diesel Technologies and Aftertreatment	**Blending Stocks**	**Alternative Fuels**
• Diesel Particulate Filters • Diesel Oxidation Catalysts • Selective Catalytic Reduction • Lean NOx Catalysts • Exhaust Gas Recirculation • Variable Valve Timing • Variable Geometry Turbochargers	• Biodiesel (B20) • Diesel/water Emulsion • Diesel/ethanol Emulsion	• Compressed and Liquefied Natural Gas • Dual Fuel Engines • Grid Connected–Catenary Overhead Wires • Hybrid Electric

Each technology and fuel in the current compliance pathway reduces pollution differently, by different amounts, and has various tradeoffs associated with its use. These tradeoffs include complexity, maintenance, fuel economy penalties, and incremental costs. The following table compares the demonstrated NOx and PM reduction capabilities and related penalties relative to diesel fuel. It shows a wide array of options available to bus manufacturers as they develop plans to comply with emission standards.

Percent Change Relative to Untreated Diesel Exhaust Emissions		
	PM	**NOx**
Diesel Particulate Filter	-90	+5
Exhaust Gas Recirculation	< +5	-50
Diesel Oxidation Catalyst	-20 to -50	0
Lean NOx Catalyst	0	-25
Lean NOx Catalyst & Diesel Particulate Filter	> -85	-25
Selective Catalytic Reduction	-25	-70
Biodiesel (B20)	-10	+2
Diesel w/Water Emulsion (PuriNOx)	-63	-14
Diesel w/Ethanol Emulsion (Puranol, O2Diesel)	-40	-5
CNG	-90	-30
Dual Fuel (CNG/Diesel)	-70	-50
Grid Connected (Catenary Overhead Wires)	-100	-100
Diesel Hybrid Electric (With Aftertreatment)	-99	-44
Gasoline Hybrid Electric	> -90	> -95

The following diagram illustrates the options available for both transit communities and engine manufacturers to reduce emissions. These options include various fuel choices, engine design modifications, and exhaust aftertreatment. The illustration also shows the interaction between the various technologies and outlines the degree to which fuels and engine control technologies are interrelated.



Source: Jackson, Michael D., TIAX. *Diesel—What the Future Holds,* presented at the California Air Pollution Control Officer's Association (CAPCOA) Conference on Diesel, January 27, 2004.

2007 and 2010: Emission Standards Compliance Methods

Engine manufacturers will utilize various combinations of technologies and aftertreatment in order to meet the EPA's 2007 and 2010 emission standards. While diesel engines will require relatively well-known compliance methods in 2007 that one manufacturer estimates will add a total of about $5,000 to $6,500 to the cost of a diesel engine, the 2010 standards will force the implementation of more complicated, and potentially more costly, technologies. These added costs might make the relative simplicity of alternative fueled engines like natural gas comparatively cheaper at least in the short term through 2010, and therefore more attractive. The playing field between these two fuels post-2010 might be more level as a result of a decrease in the cost of advanced diesel emission technologies combined with the fuel penalty that natural gas buses may suffer if equipped with catalytic converters.

Most diesel bus engine manufacturers have already identified their 2007 compliance methods. The following tables list these compliance methods as well as other general and potential combinations of technologies that are likely to be implemented that are capable of meeting 2007 and 2010 emission standards.

Declared 2007 Compliance Strategies for Diesel Transit Bus Engines	
Engine Manufacturer	**Likely Compliance Strategy**
Cummins, Inc.	Cooled-Exhaust Gas Recirculation + Variable Geometry Turbocharger + Diesel Particulate Filter or Diesel Oxidation Catalyst
Detroit Diesel Corporation	Cooled-Exhaust Gas Recirculation + Variable Geometry Turbocharger + Diesel Particulate Filter

Potential 2007 and 2010 Compliance Methods for Diesel Transit Bus Engines	
2007	**2010**
Diesel Particulate Filter + Exhaust Gas Recirculation	Diesel Oxidation Catalysts + Lean NOx Traps
	Diesel Particulate Filter + Selective Catalytic Reduction
	A combination of: Diesel Particulate Filters, Diesel Oxidation Catalysts, Variable Geometry Turbos, Selective Catalytic Reduction, Variable Valve Timing, Advancing/refining Engine Technologies

<u>Emerging and Future Emission-Reducing Technologies and Fuels</u>

Tailpipe standards beyond 2010 may include fuel toxicity, PM size, and limits on global warming gases. Although not yet feasible for large-scale implementation, a number of emerging technologies may eventually provide transit communities with appealing options for reducing these emissions as well as reducing criteria emissions even further on BRT vehicles in the coming years and decades. These emerging technologies and fuels include:

- **NOx Adsorber Aftertreatment** captures NOx emissions and then reduces them to nitrogen. If challenges are overcome, this technology may eventually be applied to reduce NOx emissions by 95 percent.
- **Renewable Biogas** is methane produced from biomass, energy crops, and/or the anaerobic digestion of animal manure, and may emerge as a greenhouse gas (GHG) neutral fuel for natural gas vehicles and eventually as a feedstock for hydrogen.
- **Gas-to-Liquid (GTL) as a Fuel or Blending Stock** is usually derived from natural gas and is used in compression injection engines. The fuel reduces NOx and PM emissions due to the fuel's characteristics. Hydrocarbon (HC) and carbon monoxide (CO) emission reductions are expected as well.
- **Hydraulic Hybrids** utilize pressurized hydraulic fluid instead of batteries to provide the benefits of a hybrid electric drive system, including improved fuel economy and reduced emissions, at a lower cost.
- **Battery Electric with Extended Opportunity Charging** buses are quiet and emit no mobile-source air pollution. The combined use of battery technology with embedded power collection, which charges the batteries on an "opportunity" basis or provides continuous conduction, may allow buses to operate pollution-free for a significant distance.
- **Hydrogen Powered Buses** can operate with extremely low to zero tailpipe emissions through the use of conventional internal combustion engines (ICEs) or fuel cell technologies. The use of hybrid electric ICE buses may be a way to bring about hydrogen-powered operation on a faster timescale, while fuel cells, which produce electricity electrochemically, provide the benefits of pure electrical operation and emit water vapor as their only byproduct.

Matching Fuels and Propulsion Systems to BRT Vehicle and System Demands

After meeting current and future environmental and user demands, it is essential that BRT fuels and propulsion systems meet the other demands of BRT vehicle and system operation characteristics. These characteristics define BRT system service and are crucial to the operation and efficiency of the system as a whole. As it turns out, various fuels and propulsion systems are able to operate successfully in conjunction with BRT characteristics, although in some cases, particular options are better suited than others.

Larger, higher capacity buses are an initial defining characteristic of BRT systems. As demonstrated in Boston and Los Angeles, where articulated BRT vehicles with CNG propulsion systems have been or are expected to be implemented, and by King County Metro, which is operating articulated hybrid diesel BRT vehicles in Seattle, these heavier vehicles can be powered by various sources as long as horsepower requirements are met.

Another defining BRT characteristic is reduced vehicle noise, a feature that may increase ridership and aid in community acceptance. Reduced noise levels are most likely to be found in advanced technology vehicles, such as hybrid electric vehicles (HEVs), which utilize smaller ICEs that minimize the need for increased radiator cooling fans or that can operate solely on silent electric power part of the time. Full electric buses, such as those powered by catenary overhead wires, batteries, or fuel cells, can also produce significantly lower levels of noise as compared to buses with internal combustion engines.

In addition to styling that conveys the perception of speed, BRT systems are configured to offer faster service times and operation. The fuels and propulsion systems that are matched to these vehicles can play a part in offering this faster service. Providing vehicles with an adequate amount of horsepower can assist in this role, but more specifically vehicles with full or partial electric drive systems can provide faster acceleration after route stops due to their linear torque band.

BRT vehicles also have unique interior layouts, such as continuous low floors and multiple wide doors, that can place constraints on propulsion system choices. Advanced electric propulsion technologies can add to the flexibility of interior layout design by eliminating the proximity and logistical requirements of situating engines and drivetrains.

Altogether, transit communities and engine manufacturers have considerable options for reducing emissions on both current and future BRT vehicles while concurrently satisfying defining BRT vehicle and system characteristics. Through careful analysis of the various fuels and technologies and examination of their tradeoffs regarding emission reductions, complexity, ease of use, and cost, it is possible for BRT communities to procure vehicles that both meet their needs and desires as well as fulfill the demands of various current and future drivers.

Emission Standards and Environmental Drivers

Emission standards and other environmental drivers will play a prominent role in BRT design and procurement for the foreseeable future, due to strict federal and California regulations that will be implemented in this decade. Together, they require significant reductions in PM and NOx emissions in a relatively short time period, while California also requires the limited implementation of buses that are completely emission-free. BRT vehicle producers and purchasers will also be influenced by regulations that, although yet to be designed or enacted, are expected in the near future. This includes measures to address the toxic nature of diesel fuel, regulations that govern the size of particulate matter emissions, and possible limits on greenhouse gases. This section takes a more in-depth look at the key emission standards and other environmental drivers that are and will potentially influence BRT fuels and propulsion systems over the next 10 to 15 years.

Federal Bus Emission Standards

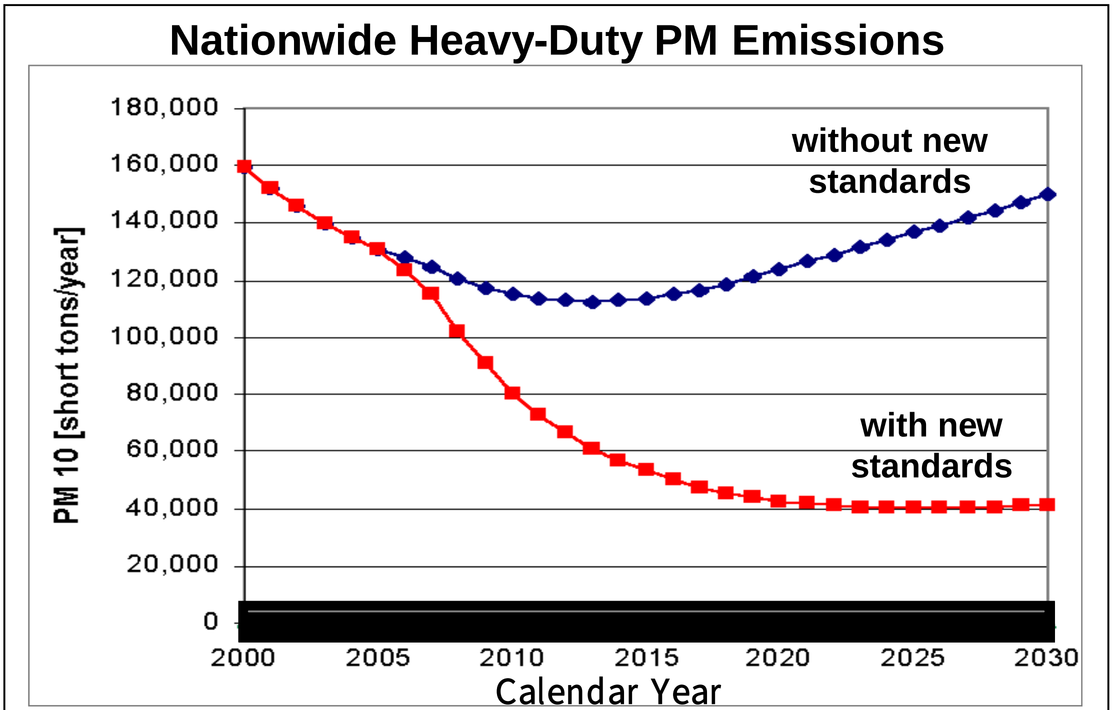
Beginning in 2007, the EPA will implement new caps on PM and NOx emissions from heavy-duty highway engines, including those that are used in transit buses. These caps are based on the use of high efficiency catalytic aftertreatment devices,[1] which will be widely commercialized after the national implementation of ULSD fuel on June 1, 2006. When the first new standard takes effect in 2007, heavy-duty trucks and buses will contribute at least half of all nitrogen oxide and particulate matter emissions from highway vehicles.[2] The new standards will make 2010 model year trucks and buses as much as 95 percent cleaner than model year 2000 trucks and buses. They will also reduce NOx and PM emissions by 2.8 million and 110,000 tons each year, respectively, by the year 2030, and eliminate 33,000 tons each year of toxic air pollutants such as benzene.[3]

Under the new heavy-duty engine standards, PM will be limited to 0.01 grams per brake-horsepower-hour (g/bhp-hr) beginning in 2007. NOx and HC levels must not exceed 0.20 g/bhp-hr and 0.14 g/bhp-hr, respectively. However, unlike the PM standard that takes full effect in 2007, the NOx and HC standards as they apply to diesel engine manufacturers will be phased in between 2007 and 2010. This phase-in will be based on 25 percent of a manufacturer's sales in 2007, 50 percent in 2008, 75 percent in 2009, and 100 percent in 2010. Gasoline engine manufacturers will have to meet all standards in 2007.

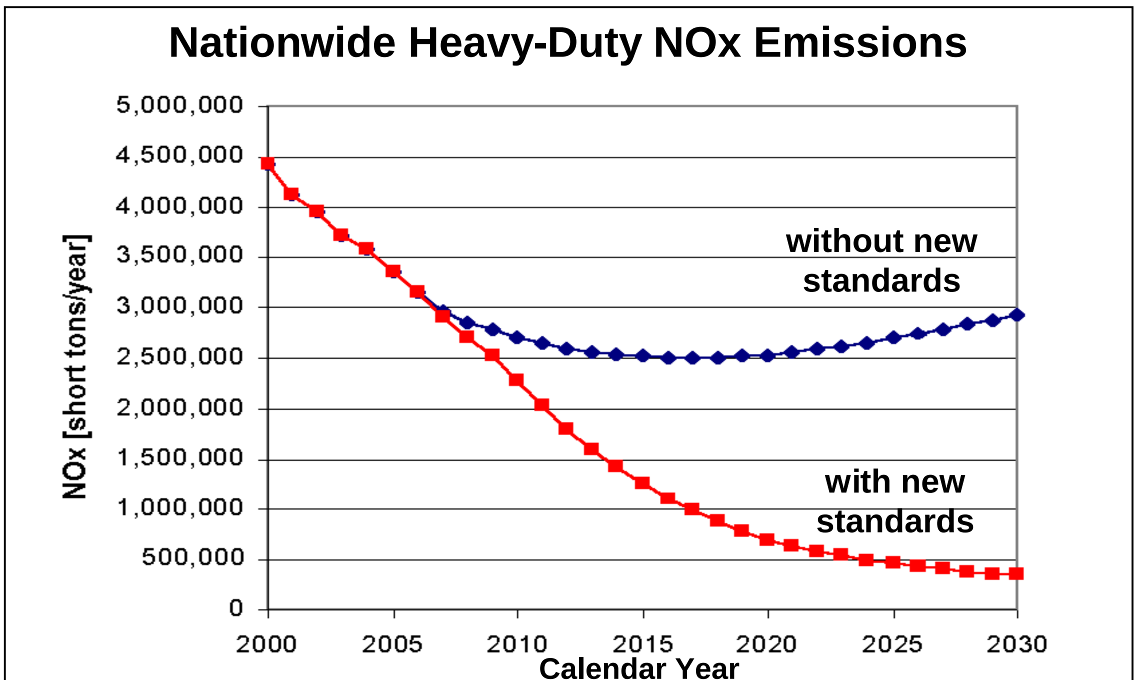
EPA Heavy-Duty Truck and Bus Emission Standards 2004-2010

	2004	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**
PM (g/bhp-hr)	0.10 (0.05 for urban buses)			0.01			
NOx + HC (g/bhp-hr)	2.4 (or 2.5 with 0.5 limit on NMHC)			75% of sales at 1.0	50% of sales at 1.0	25% of sales at 1.0	
NOx (g/bhp-hr)				25% of sales at 0.20	50% of sales at 0.20	75% of sales at 0.20	100% of sales at 0.20
HC (g/bhp-hr)	1.3			25% of sales at 0.14 NMHC	50% of sales at 0.14 NMHC	75% of sales at 0.14 NMHC	100% of sales at 0.14 NMHC
Diesel Sulfur (ppm)	500		80% of sales at 15 ppm maximum (under temporary compliance option) beginning 6/1				100% of sales at 15 ppm

The following two charts reveal the dramatic impact these regulations will have in terms of reducing NOx and PM.



Source: EPA



Source: EPA

EPA expected emission levels show that without new standards (in blue) the levels will continue to decline, but will eventually rise. Implementation of 2007 and 2010 standards (in red) show continuous decreases.

California Urban Bus Rule

In addition to federal emission standards, manufacturers that sell buses in California will be required to meet standards prescribed in the California Urban Bus Rule for those buses as well. California has the ability under the Clean Air Act, unique among states, to set emission standards that are stricter than those of the federal government. This power was granted by the U.S. Congress in 1970 in view of California's severe air pollution problems and the fact that the state was regulating air pollution before the federal government became involved.

The Urban Bus Rule has many of the same elements as the federal heavy-duty emission standards, but on an accelerated timeframe. For instance, while the federal rule requires the sale of low-sulfur diesel fuel to fleets by mid-2006, the California standard required it by July 1, 2002. Yet the California standard differs from the national standard in that it has a zero emission bus (ZEB) requirement and provides manufacturers with two different compliance frameworks: a diesel pathway and an alternative fuel pathway.

Diesel Pathway

The diesel pathway requires the use of ULSD fuel with a sulfur content limited to 15 parts per million (ppm) beginning in 2002, which is four years earlier than the federal rule. It also limits PM emissions from new diesel buses to 0.01 g/bhp-hr beginning in 2004, compared to the old standard of 0.05 g/bhp-hr, three years before the federal rule. NOx emissions are also limited to 0.5 g/bhp-hr in 2004 before decreasing to 0.2 g/bhp-hr in 2007.

Large transit agencies with 200 or more buses that choose the diesel pathway and continue to purchase primarily diesel vehicles were originally required to begin demonstrating the use of at least three zero-emission buses (ZEBs) by 2003. This ZEB requirement increases to 15 percent of new bus purchases/leases between the 2008 and

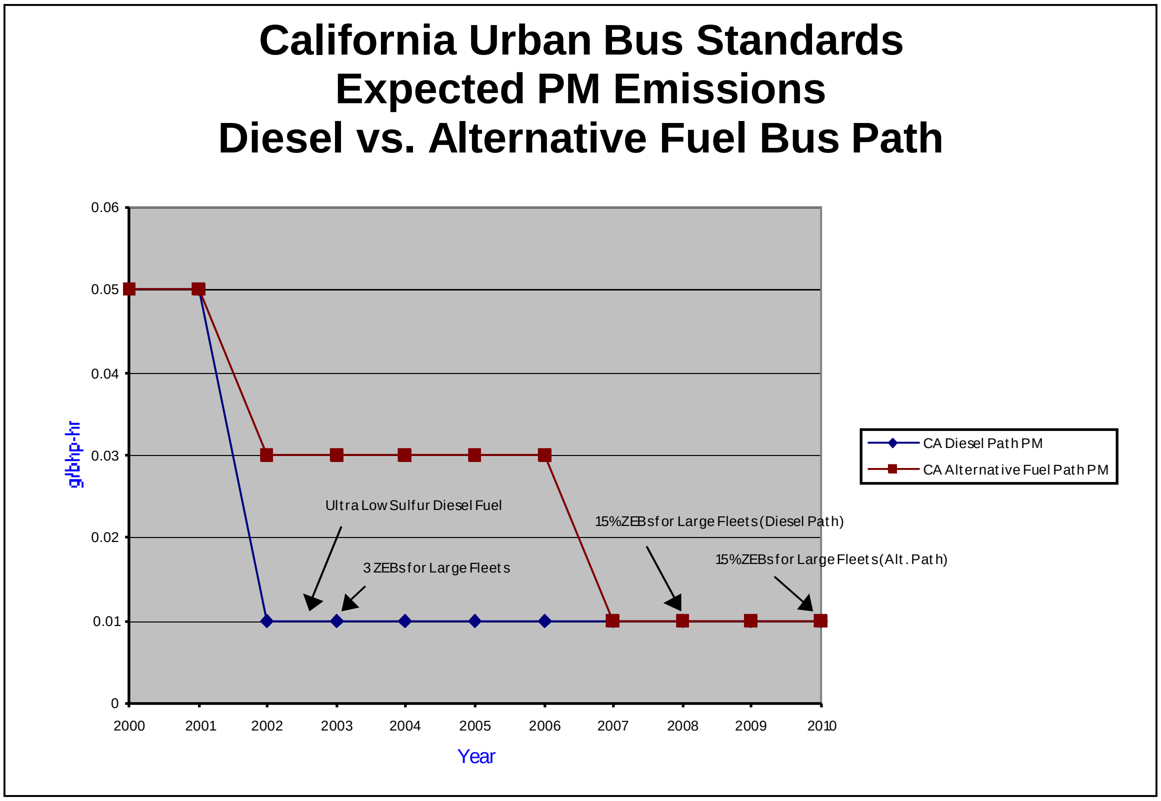
2015 model years. In 2004, the CARB revised the 2003 ZEB requirement to acknowledge a slower than expected availability of fuel cell buses for demonstration purchases.

Alternative Fuel Pathway

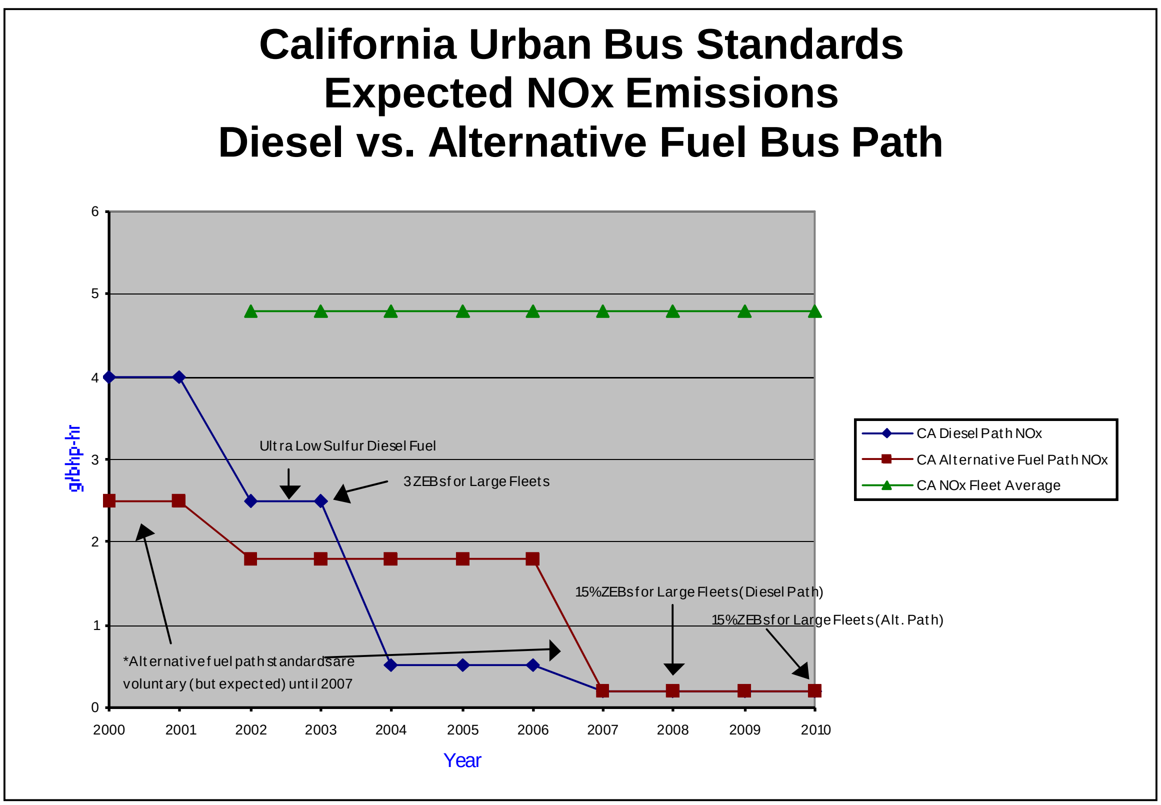
The alternative fuel pathway requires the use of low-emission alternative fuels, such as compressed or liquefied natural gas, propane, methanol, hydrogen, or electricity. It includes a 15 percent ZEB mandate, although it does not take effect until the 2010 and 2015 model year time frame.

Both pathways require new NOx standards of 0.5 g/bhp-hr from 2004 and 0.2 g/bhp-hr from 2007, three years before the federal requirement. These limits are reduced dramatically from the previous standard of 4.0 g/bhp-hr. Also, a NOx fleet average of 4.8 g/bhp-hr became effective in 2002, forcing some transit agencies to retire their oldest and most polluting buses. In 2003, a requirement to retrofit existing buses with devices to reduce PM took effect.

The following two charts illustrate NOx and PM emission standards for both the California diesel and alternative fuel paths.



Source: DieselNet



Source: DieselNet

Alternative fuel users are permitted to emit higher levels of PM and NOx until 2007

Several engine manufacturers say they will be unable to offer diesel transit buses for sale in the state between 2004 and 2006 to comply with the faster implementation of standards in California. The CARB responded in 2004 by modifying its bus rule by adding an option that allows manufacturers to produce and sell hybrid electric diesel transit buses that meet a 1.8 g/bhp-hr NOx standard and offset the difference between 1.8 g/bhp-hr and 0.5 g/bhp-hr NOx by installing retrofit devices or repowering to a lower emitting diesel or alternative-fuel engine.

Possible Future Tailpipe Standards

While the regulations already passed in California and by the federal government drive the industry in the short term, expectations of future tailpipe standards can provide powerful long-term incentives. Based on accumulating evidence and worldwide trends, it can be reasonably assumed that after the California and federal standards dramatically reduce NOx and PM emissions, other emissions factors will drive the industry in the post-2010 era. These other emission factors are the toxicity of diesel fuel, exhaust particulate size, and global warming gas emissions.

Diesel Fuel Toxicity

As advanced diesel technology matures and enables diesel-powered vehicles to meet emission standards, the fundamental nature of diesel exhaust and the air toxics that it contains may serve as a primary driver away from diesel fuel. The EPA, CARB, and the South Coast Air Quality Management District (SCAQMD) as well as a host of public health advocates, including the Union of Concerned Scientists, Natural Resources Defense Council, and the Coalition for Clean Air, all consider diesel exhaust to be a serious threat to public health. As mentioned in a report by the Union of Concerned Scientists, between 1988 and 2002, seven agencies determined diesel exhaust to be a known, probable, or potential carcinogen.[4]

Agencies' Assessments of Diesel Exhaust as a Carcinogen		
Organization	**Year**	**Conclusion**
National Institute for Occupational Safety and Health	1988	Potential occupational carcinogen
International Agency for Research on Cancer	1989	Probably human carcinogen
State of California	1990	Known to cause cancer
California Air Resources Board	1998	Diesel PM is a toxic air contaminant
U.S. Department of Health and Human Services	2001	Reasonably anticipated to be a human carcinogen
American Council of Government Industrial Hygienists (proposal)	2001	Suspected human carcinogen
U.S. Environmental Protection Agency	2002	Likely human carcinogen

Source: Union of Concerned Scientists

Altogether, the CARB lists 41 toxic air contaminants in diesel exhaust, including formaldehyde, benzene, arsenic, aldehyde, and polycyclic aromatic hydrocarbons (PAHs). Studies revealed that these toxins bind to the DNA of humans and animals exposed to diesel exhaust and cause damage on a genetic level. These "genotoxins" are particularly virulent because they are present in both the gas and particle phases of diesel exhaust. The Office of Environmental Health Hazard Assessment's (OEHHA) 1998 meta-analysis on epidemiological cancer assessed the findings of over 30 independent human studies of workers exposed to whole diesel exhaust to confirm a consistent pattern of elevated lung cancer risk.[5]

One contentious contaminant that is not listed as a carcinogen is PM. Diesel PM received significant attention in the 1998 SCAQMD extensive study of air toxics titled the "Multiple Air Toxics Exposure Study II" (MATES II). This study estimated that the carcinogenic risk in the South Coast Air Basin was about 1,400 per million people. It also concluded that diesel PM is highly likely to be carcinogenic, which sparked significant debate. According to information released by the U.S. Department of Energy (DOE), the EPA's Clean Air Scientific Advisory Committee (CASAC) has been critical of MATES II by claiming, among other things, that it did not measure diesel PM, but calculated diesel PM in ambient air based on 20-year-old data. CASAC also states that MATES II did not account for the source of 67 percent of the residual PM with a maximum particle diameter of 2.5 microns (PM2.5) captured at air monitoring stations and, overall, the committee spoke out against classifying diesel exhaust as a carcinogen.

Other organizations, such as the American Trucking Organization, agreed with CASAC's critique and have been critical of classifying diesel exhaust as a carcinogen as well. This is understandable, for when a substance is labeled carcinogenic, under California's Proposition 65, additional pressure can come to bear on makers and operators to remove the threat from the product or remove the product from the market. The industry also speculates that diesel exhaust's association with cancer and other illnesses could result in class action lawsuits not unlike those taken against the tobacco industry.

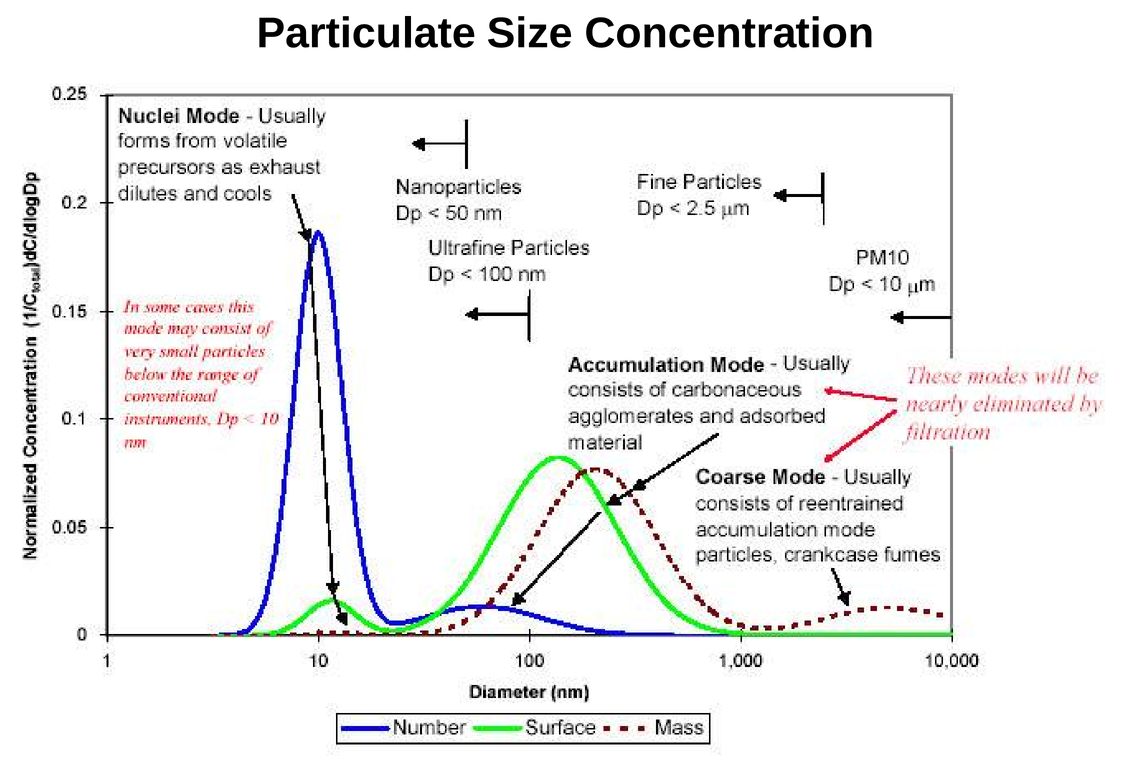
Besides cancer, significant health risks remain from exposure to PM, NOx, and/or other air toxics in diesel emissions. Studies on human exposure to diesel exhaust report chronic respiratory effects, lung inflammation, enhanced allergic response, and bronchitis.[6] In his May 17, 2000, open memo to "All Interested Parties," consultant and former EPA official Michael Walsh stated that the large amount of NOx and PM emissions from diesel engines "contribute to serious public health problems in the United States. These problems include premature mortality, aggravation of respiratory and cardiovascular disease, aggravation of existing asthma, acute respiratory symptoms, chronic bronchitis, and decreased lung function."[7]

It is these concerns about respiratory problems that are of particular relevance to the operation of urban buses. Various studies document greater respiratory problems in children with asthma that are exposed to air pollution, ozone, and particulate matter.[8] Other studies also indicate that people who are exposed to higher than average levels of diesel exhaust have higher risks of lung cancer from diesel.[9] Some groups are raising the environmental justice issue and believe that diesel is having a disproportionately negative impact on urban communities. Diesel exhaust in urban areas, in fact, tends to concentrate around localized hotspots such as transit bus depots, supermarket warehouses, and railroad switching yards that are sometimes located closer to minority or lower-income neighborhoods. As residents and regulators grow concerned with these studies, pressure to remedy these problems will increase.

Particulate Matter Size

As technologies such as diesel particulate filters (DPFs) are increasingly commercialized, nearly all PM emissions after 2007 may become volatile "ultrafine" and "nanoparticles." These extremely small particulates, which aren't targeted by current and forthcoming regulations and aren't already controlled by DPFs, may be a better measure of biological harm than larger particulates. They comprise 90 percent of total particle quantity and contain more surface area than the currently targeted 2.5 and 10 micron particle sizes.[10] They also comprise 70 percent of the particles that are inhaled, lodge deep in lungs, and destroy cellular mitochondria.[11]

The following graph illustrates the spectrum of PM emission sizes and their concentrations. PM10 and PM2.5 are generated in what is known as the "coarse" and "accumulation" modes and appear on the right side of the graph. These particles are largely comprised of soot and smoke. Conversely, ultrafine and nanoparticles, which are smaller than 100 and 50 nanometers (nm), respectively (vs. 30 to 500 nm for larger particles), are generated in the "nuclei" mode, which appears on the left side of the graph, mainly from volatile gaseous precursors, such as hydrocarbons and sulfuric acid, and form *outside* the engine as exhaust gases dilute and cool. The shape of the curves indicates that the concentration of ultrafine and nanoparticles in diesel exhaust is significantly greater than that of the larger soot and smoke particles.



Source: Kittelson, Center for Diesel Research, U. of Minnesota

Soot and smoke are formed on the right side of the graph and are heavier, but are smaller in quantity, than ultrafine and nanoparticles, which are formed on the left side of the graph.

Coarse and accumulation mode particles are sharply or even entirely reduced by better engine technologies and the application of aftertreatment devices. Yet the difficulty with controlling ultrafine and nanoparticles is due to the fact that diesel particulate filters do not trap them. Flow-through catalysts and particle filters may reduce them under some conditions, but these technologies may actually create them under other conditions.[12]

Once current and upcoming PM emissions standards drastically reduce the mass of the emissions, attention may turn to the quantity of particulates emitted. Indeed, the European Union (EU) is already formulating a new PM emission standard, and some believe that the EU will enact ultrafine PM regulations by 2006.[13]

Global Warming

Global warming will act as a significant driver in the coming decades as the environmental and health consequences of the phenomenon are realized. Global warming is caused by excess greenhouse gas emissions, such as carbon dioxide (CO_2), methane, and particulate matter. Scientists predict that the planet will experience an increase in the mean global temperature during this century that will lead to a rise in ocean levels, erosion, droughts, extreme weather patterns, and desertification. Recent studies also indicate that humans will experience direct health effects from global warming, as it will cause an increase in ground-level ozone and, therefore, respiratory problems.

The consumption of fossil fuels, which include coal burned in power plants and oil derived gasoline and diesel used in motor vehicles, is the primary culprit of global warming. The Union of Concerned Scientists states that each gallon of diesel fuel burned results in emissions of 22.8 pounds of greenhouse gases, measured as CO_2 equivalents. The organization also estimates that heavy trucks emit nearly 400 million metric tons of heat-trapping gases annually, accounting for about six percent of U.S. carbon emissions.[14]

Although the federal government has not yet acted to regulate carbon dioxide emissions, which comprise the largest percentage of greenhouse gas emissions, action to address greenhouse gases on the state level is gaining momentum. In July 2002, the California State Assembly passed AB 1493 that instructs the CARB to adopt regulations that achieve the maximum feasible, cost-effective, and technologically achievable reductions of greenhouse gas pollution emitted by new light-duty passenger vehicles. Although this legislation will not affect transit buses, the fact that California is addressing mobile greenhouse gas emissions is a sign that greenhouse gas emissions from all mobile sectors are likely to be regulated sometime in the future.

Other Drivers: Fuel Efficiency, National Security, and Energy Dependence

Global warming is primarily a function of fossil fuel consumption. Therefore, reducing its effects overlap concerns and goals for fuel efficiency, national security, and energy dependence.

The newly adopted EPA heavy-duty vehicle regulations do not set standards for fuel consumption, even though the federal government supports the development of more efficient heavy-duty transportation through research programs, including the 21st Century Truck Initiative. Instead, demand for increased fuel economy will come from the commercial market, where operators are looking to reduce their fuel costs. In an industry where the typical product achieves only a couple miles of driving per gallon of diesel fuel, the promise of advanced technologies, such as hybrids and fuel cells, that can multiply vehicle mileage and thereby significantly reduce operating costs, can be extremely attractive to operators and may serve as a key driver that propels the adoption of these technologies.

Because the United States produces a small percentage of the world's oil and is therefore overwhelmingly an oil importer, reducing consumption also furthers national security and reduces energy dependence. By depending heavily on oil, an energy source potentially obtained from hostile and/or repressive parts of the world, the U.S. economy is vulnerable to supply problems, potentially disadvantageous purchase terms, environmental conflicts, and the resource limitations faced by a finite fuel. Political will in the U.S. is growing to increase fuel economy, reduce oil consumption, and increase the production of fuels from domestic and more compatible regions of the world. In addition to hybrid and fuel cell technologies, alternative fuels such as natural gas, biogas, propane, biodiesel, ethanol, and hydrogen can also play a role in decreasing the nation's dependence on foreign oil.

Currently Available Technologies and Fuels for Meeting BRT Demands

Currently available technologies and fuels can fulfill the demands of transit agencies, riders, and operators as well as those imposed by environmental drivers. Since compliance strategies to meet new emission standards use established, although modified, fuels and commercial propulsion systems, they impose the least amount of disruption and uncertainty on operators and can be optimized for short-term operation and emissions needs. Utilizing these technologies and fuels to meet user and environmental needs provides the current compliance pathway pursued by most vehicle manufacturers and fuel providers.

Current Compliance Pathway

As the EPA's new emission standards are phased in beginning in 2007, conventional #2 diesel fuel will not be able to meet the new requirements. There are, however, fuel and technology options that will allow bus engines to meet emission standards in 2007, 2010, and beyond while maintaining the demands of BRT systems. The first compliance option is to utilize modified diesel fuel that produces less pollution and is able to be used with currently available technologies and/or blended with additives to reduce emissions further. A second compliance option is to power vehicle propulsion systems with proven alternative fuel technologies that emit significantly less pollution and/or can be equipped with currently available pollution-reduction technologies.

Diesel

The use of diesel fuel has a long history in transit applications, with good reason. Diesel engines have good torque and horsepower performance over a wide range of operating conditions, are extremely reliable and durable over one million miles of driving, provide excellent fuel economy, and have excellent overall lifecycle costs.[15] However, these benefits come at a significant environmental cost. Diesel exhaust contains PM, NOx (that combines with hydrocarbons and sunlight to produce ozone and also reacts to form nano-particulates), and toxics contained in hydrocarbon emissions, including arsenic, nickel, benzene, formaldehyde, aldehyde, and polycyclic aromatic hydrocarbons (PAHs).[16] As part of the EPA rulemaking on the 2007 and 2010 heavy-duty emission standards, the EPA estimated the health damage costs caused by diesel emissions as the following:

Pollutant	**EPA Estimates of Economic Costs in 2001** **Based on a U.S. Population of 277 million** **(1999 dollars per ton of pollutant)**
PM	$143,000
NOx	$10,193
SO2	$16,621

Source: EPA

Beginning in July 2006, all diesel fuel sold in the U.S. will have a maximum sulfur content of 15 parts per million (ppm), replacing the 500 ppm sulfur fuel now on the market. Lowering the sulfur content of diesel fuel will act as an "enabler" in the sense that modern technologies, which would be fouled by 500 ppm diesel, can be used on engines running on 15 ppm diesel fuel. The most promising of these technologies include diesel particulate filters (DPFs), exhaust gas recirculation (EGR), lean NOx traps (LNTs), selective catalytic reduction (SCR), and diesel oxidation catalysts (DOCs).

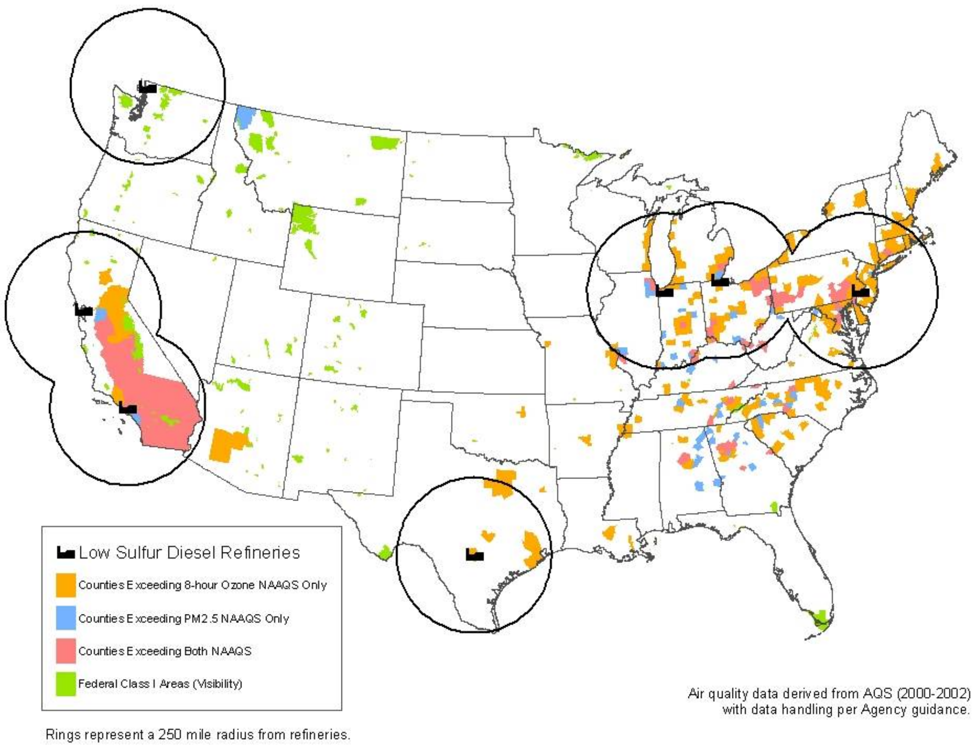
In addition to these technologies, diesel additives, or "blending stocks," can help reduce diesel emissions without the implementation of significant infrastructure changes. These blending stocks include biodiesel, diesel/water emulsion, diesel/ethanol emulsion, and gas-to-liquid (GTL). When combined with ultra low-sulfur diesel (ULSD) fuel, these blending stocks and technologies offer a range of options that enable diesel engines to meet emission standards and secure a role for diesel into the future.

Diesel Transit Bus Engines Domestic Manufacturers and Details				
	Engine Model	**Maximum Power (HP)**	**Torque (lb-ft @ rpm)**	**Misc. Details**
Cummins, Inc.	ISM 330 ISM 280	330 280	1040 @ 1200 900 @ 1200	Robust engine appropriate for 40-ft and 60-ft articulated buses
	ISL 280 ISL 250	280 250	900 @ 1300 730 @ 1300	Light engine with High Pressure Common Rail fuel system
Detroit Diesel Corporation	Series 40E	280	900 @ 1300	6 cylinders, catalytic converter + VGT technologies
	Series 50	250-320	800-1150 @ 1200	4 cylinders, EGR + VGT Technologies

Ultra Low-Sulfur Diesel

The underlying foundation to any emissions benefits from diesel fuel is the reduction of sulfur: The lower the sulfur content in diesel fuel, the higher the PM emission reductions, both for inherent and technology compatibility reasons. The process to lower sulfur content is well understood and already in use in many refineries, including in the Northeast (Philadelphia), the Great Lakes area (Toledo, Ohio and Whiting, Indiana), Texas (San Antonio), California (Los Angeles and Richmond), and the Northwest (Ferndale, Washington).[17] Current incremental costs for ULSD range from 5 to 25 cents per gallon, but the EPA estimates that when fully implemented the sulfur reduction requirement will increase the cost of producing and distributing diesel fuel by about 4.5 to 5 cents per gallon.[18] Depending on the quantity ordered and the transportation cost, these costs can be even less, as demonstrated in the Seattle area where incremental costs as low as 3 cents a gallon have been reported.[19]

Current Low-Sulfur Diesel Availability



Source: EPA

ULSD is currently available in limited geographic areas,
although availability is expanding as 2006 approaches.

Several groups, including the National Association of Truck Stop Operators (NATSO) and American Trucking Association, have raised concerns about the switch to ULSD. These concerns mainly stem from how widespread and common ULSD fuel will be once engines begin to come equipped with low-sulfur dependent aftertreatment technologies, since these technologies are not compatible with 500 ppm diesel fuel. This concern is of more significance for highway heavy-duty vehicles and trucks, but is less applicable to transit buses since they are served by central fueling facilities that will virtually ensure the use of compatible 15 ppm diesel fuel.

The maintenance of ULSD powered buses is predicted to remain unchanged compared to conventional buses burning 500 ppm diesel fuel. ULSD buses use traditional diesel bus parts and standard preventative maintenance procedures, such as tune-ups and fluid changes. Maintenance personnel require no special training to repair ULSD buses, and data to date indicate the miles between service interruptions and the lifecycle engine costs of ULSD buses remain the same as in buses burning 500 ppm sulfur fuel.

In general, the energy content of ULSD is equivalent to standard diesel fuel. However, among different producers, the energy content of ULSD can vary slightly. This is particularly true in cold weather states where the production of ULSD may require more blending with kerosene in order to achieve adequate cold flow properties.

Finally, the low sulfur content of ULSD helps prevent corrosion of engine parts in older diesel engines, maintain cleaner injectors, reduce engine deposits, reduce oil contamination, and reduce engine wear. While the lubricity of ULSD fuel varies due to the use of different crude oil grades and can be lower due to hydrotreating processes, fuel suppliers say that adequate lubricity in ULSD will be maintained through the use of additives.

Key Properties of BP ECD-1
Ultra Low-Sulfur Diesel Fuel

	ULSD Fuel	**#2 (500 ppm Sulfur) Diesel Fuel**
Sulfur	≤ 15 ppm	500 ppm
Aromatics	≤ 25 % volume	35%
Cetane Number	≥ 53	40 - 45
API	30 minimum	30 - 35

Source: British Petroleum

ULSD Compatible Technologies and Aftertreatment

Diesel engine manufacturers state that one component in meeting emissions standards is the refinement of the engine combustion process that will take place through the end of the decade. For example, high-pressure common-rail fuel systems that help improve the efficiency of fuel combustion are currently common only on small bus engines. By the end of the decade, however, the technology will most likely be common on all bus engines. Still, engine refinements such as this one will not be sufficient to meet emission standards on their own. In order to reduce emission levels enough to comply with federal and CARB standards, the use of emission-reducing technologies and aftertreatment will be required.

Once the sulfur level of diesel is reduced to 15 ppm, engines will be able to incorporate technologies and aftertreatment devices that significantly reduce emissions. Diesel particulate filters can be used on ULSD powered buses in order to reduce particulate matter while technologies and devices such as exhaust gas recirculation, lean NOx traps, and selective catalytic reduction can be used to reduce NOx emissions. Diesel oxidation catalysts can also be used to reduce CO and HC.

Ultra Low-Sulfur Diesel Compatible Technologies and Aftertreatment		
Pollutant		
PM	**NOx**	**CO and HC**
• Particulate filters • Diesel oxidation catalysts (DOC)	• Exhaust gas recirculation (EGR) • Lean NOx traps (LNT) • Selective catalytic reduction (SCR)	• Diesel oxidation catalysts (DOC)

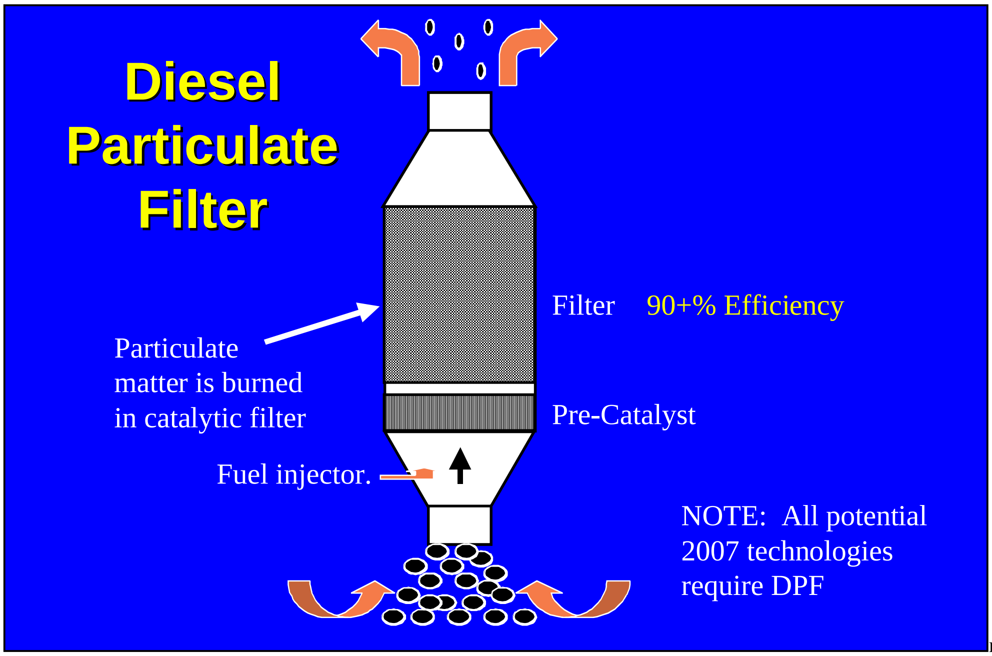
Diesel Particulate Filters

The DPF system consists of a filter positioned in the exhaust stream designed to collect a significant fraction of the particulate emissions, while allowing the exhaust gases to pass through the system. Particulate collection efficiencies of these filters can exceed 90 percent, according to the Manufacturers of Emission Controls Association (MECA).

Since the volume of particulate matter generated by a diesel engine is sufficient to fill and plug a reasonably sized filter over time, some means of disposing of this trapped particulate must be provided. The most promising means of disposal is to burn or oxidize the particulate in the filter, thus regenerating a clean filter. This is accomplished through the use of a catalyst. The catalyst can be placed in front of the filter, applied directly onto the filter, or added as a blend into the fuel. "Active" DPFs have self-regenerative integrated catalysts that utilize burners, electricity, or fuel-borne catalysts to oxidize or combust the collected particulate. Some active filters require external accumulated oil-ash removal after approximately 300,000 miles of use. This includes a filter exchange costing about $150 per service.[20] Accumulated oil-ash will also require engines that are equipped with DPFs to use lube oils with new, low ash specifications beginning in 2007.

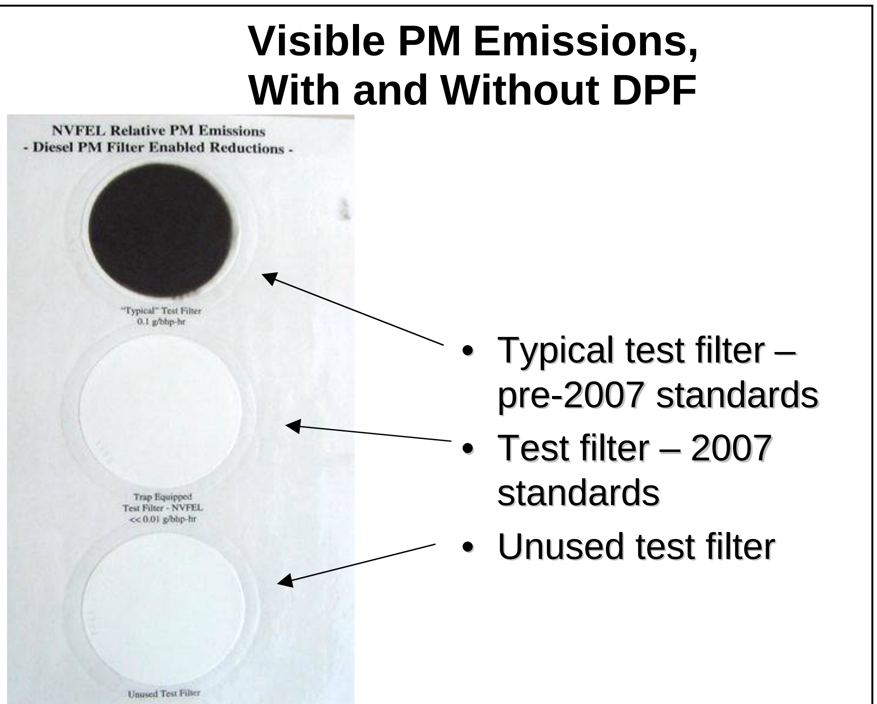
"Passive" DPFs, on the other hand, use a catalyst to either raise the exhaust gas temperature or lower the PM ignition temperature to induce regeneration. Passive filters do not require an additional source of energy for regeneration, but are dependent instead on exhaust temperature. In Sweden, more than 6,500 buses have been equipped with passive DPF systems. They have also been retrofitted on heavy-duty vehicles in Great Britain, Germany, Finland, Denmark, and France. In the U.S., diesel filter retrofit programs are under way in California and in New York City, which plans to retrofit 3,500 city buses with diesel particulate filters. In 2001, ARCO completed a one-year demonstration to evaluate the use of ULSD fuel and passive DPFs in which five truck and bus fleets accumulated over 3,525,000 miles without any major incidents attributed to the DPFs or the ULSD fuel.[21]

Diesel Particulate Filter



Source: Volvo Powertrain Corporation

Some active diesel particulate filters utilize burners to oxidize or combust the collected particulate.



Source: EPA

DPFs that meet the EPA's 2007 0.01 g/bhp-hr PM standards drastically reduce visible PM as compared to pre-2007 0.1 g/bhp-hr standards and achieve visible results similar to an unused filter.

Exhaust Gas Recirculation

Exhaust gas recirculation (EGR) is employed to lower NOx by reducing the temperature at which fuel burns in the combustion chamber. EGR directs part of an engine's exhaust back into the air intake, where it is mixed with the fresh air entering the combustion chamber. EGR produces a lower temperature burn and reduces NOx emissions up to 50 percent because the oxygen level in the combustion chamber is lowered. If the exhaust gas is further cooled before it is directed back into the air intake, this cooled exhaust gas recirculation (CEGR) can reduce NOx emissions even further.

Using EGR can have a minor negative impact on engine durability and reduce fuel economy up to 5 percent. Mack and Volvo report positive customer experiences, however, based on responses from the drivers of 30,000 trucks in service with CEGR in 2002.[22] EGR also increases PM, especially in high engine load modes. This increase in PM that results as NOx levels are decreased is called the "NOx/PM tradeoff," a condition that confronts many emissions engineers. EGR can also be combined with other technologies to minimize the NOx/PM tradeoff and meet emission standards, as discussed later in this chapter.

Diesel Oxidation Catalysts

A diesel oxidation catalyst (DOC) is made of a porous, active catalyst layer applied to a high geometric surface area, honeycomb-like structure called a substrate or catalyst support. The catalyst layer contains a thin coating of precious metals such as platinum or palladium. The catalyst oxidizes CO, gaseous HCs, and liquid HC particles, while reducing smoke and the characteristic diesel odor.

DOC-equipped diesel engines have achieved reductions of 20 to 50 percent for PM and 60 to 90 percent for CO and HCs, including those HC species considered toxic. Retrofitting engines with DOCs has been taking place for well over 20 years in the offroad vehicle sector, particularly in the underground mining industry, with more than 250,000 offroad engines retrofitted. Since 1995, more than 20,000 systems have been retrofitted on buses and highway trucks in the U.S. and Europe, more than 3,000 trucks and buses have been retrofitted in Mexico, and Hong Kong has begun to retrofit thousands of urban buses with DOCs.

Selective Catalytic Reduction

Selective catalytic reduction (SCR) systems have been applied extensively in stationary power applications in the U.S. and in European automotive applications. The systems are similar to DOCs, except that a reductant is added to the exhaust stream in order to help convert NOx to nitrogen and oxygen as the reductant is oxidized. The reductant in mobile source applications can be ammonia, but is normally a urea solution since urea decomposes to ammonia in the exhaust stream, but is safer to handle and non-toxic. The reductant is metered into the exhaust stream in precise amounts that match the amount of NOx being produced at a given time by the engine. It passes through the SCR catalyst, where NOx is reduced and HC emissions as well as a portion of the PM emissions are oxidized. SCR also reduces the characteristic odor and smoke produced by a diesel engine.

Field test results of SCR indicated NOx reduction up to 70 percent over a normal driving cycle, a reduction of steady-state NOx emissions up to 85 percent, and PM reduction up to 25 percent, all without reducing fuel economy. Reductant costs are expected to be about equal to diesel on a per-volume basis, but their consumption is about 1.5 percent of diesel fuel consumption for each g/bhp-hr reduction in NOx.[23] This should add less than one percent to overall vehicle operating costs.[24] SCR systems can also allow for a simplified base engine, extend oil drain intervals, and improve DPF regeneration. So far, heavy duty SCR experience indicates exceptional catalyst durability, with Volvo Powertrain reporting near-zero deterioration after 1.4 million miles of driving by a fleet of 11 trucks.[25]

One of the drawbacks to SCR is that it requires separate reductant tanks on the vehicle and the creation of a reductant-refilling infrastructure. Unlike the case in Europe, where high fuel prices justify the use of more costly SCR and its infrastructure, low U.S. fuel prices lead to a poor domestic business case. For these reasons, some manufacturers have already indicated that they are not going to use SCR as a compliance method in 2007. Several also note that SCR can be easily defeated because failing to refill the reductant fuel tank will disable it. But others respond that manufacturers can simply program engines not to run without sufficient reductant or install interactive sensors to monitor reductant level and operation, as some manufacturers are already doing. Furthermore, the lack of a reductant-refilling infrastructure and the system's ability to be defeated are less of a concern for transit bus use since they are centrally fueled and maintained, thereby ensuring proper reductant level and minimizing infrastructure establishment requirements.

Lean NOx Catalyst

Lean NOx catalysts (LNCs), also known as a NOx reduction catalysts (NRCs) or hydrocarbon selective catalytic reduction (HC-SCR), use diesel fuel as a reductant to catalytically lower exhaust stream NOx emissions by about 25 percent. This is accomplished without causing power loss, the use of EGR technology, or requiring a separate chemical reagent, such as urea or ammonia. Instead, LNCs remove NOx by taking a precise amount of pressurized, filtered, and cooled diesel fuel from the vehicle fuel supply and injecting it into the exhaust stream to react with the exhaust gases on the catalyst.

Because onboard diesel is continuously injected as the reducing agent, there is a slight penalty on fuel economy from LNC systems. However, the use of diesel as the reducing agent eliminates the need for a separate onboard reducing agent. Also, advanced technologies may help to reduce this fuel economy penalty. Onboard diesel reforming to create a hydrogen-rich gas stream, for example, might effectively provide reductants at lower temperatures than diesel fuel. So far, onboard reforming has only been applied to a

2004 Ford F-250 diesel pickup truck; future applicability to heavy-duty engines could provide an effective method to improve LNC catalyst life, improve emissions control during cold startup, reduce the fuel penalty, and lower overall costs.

A secondary benefit to LNC technology is that, when used in conjunction with a DPF, the heat released by the LNC's catalyst increases the PM oxidation rate in the DPF, thereby facilitating DPF regeneration, creating needed backpressure, and eliminating unreacted diesel fuel. Cleaire, based in San Leandro, California, created a product called Longview® that takes advantage of these secondary benefits by integrating an LNC with a DPF to obtain NOx reductions of 25 percent, PM and CO reductions of over 85 percent, and HC reductions of over 65 percent.

Cleaire Longview® Product Features	
Mounting	Vertical or horizontal
NOx reduction	25%
PM reduction	> 85%
CO reduction	> 90%
HC reduction	> 65% (including some toxic air contaminants)
Odor reduction	Yes
Smoke reduction	Yes
Fuel requirement	Low-sulfur (15 ppm) diesel fuel
Duty cycle requirement	> 260 degrees Celsius for > 25% of driving cycle
Maintenance	Annual de-ash of DPF and system inspection
Total weight	approximately 106 lbs

Source: Cleaire

While the heat generated by LNCs can benefit DPF operation, however, prolonged exposure to temperatures above 550º Centigrade (C) can result in LNC performance loss. The normal operating temperature of an LNC should be between 300º and 500ºC.

Variable Valve Timing

While most camshafts allow an engine's valves to remain open for the same fixed amount of time regardless of the engine's speed, variable valve timing (VVT) allows an engine's valves to vary the amount of time they are open and, in some cases, the degree to which they are open based on the engine's speed. VVT adjusts the overlap time between the exhaust and intake valves to optimize torque over all engine speeds. The result is more complete combustion that produces fewer emissions, better torque range, increased smoothness, and improved fuel economy.

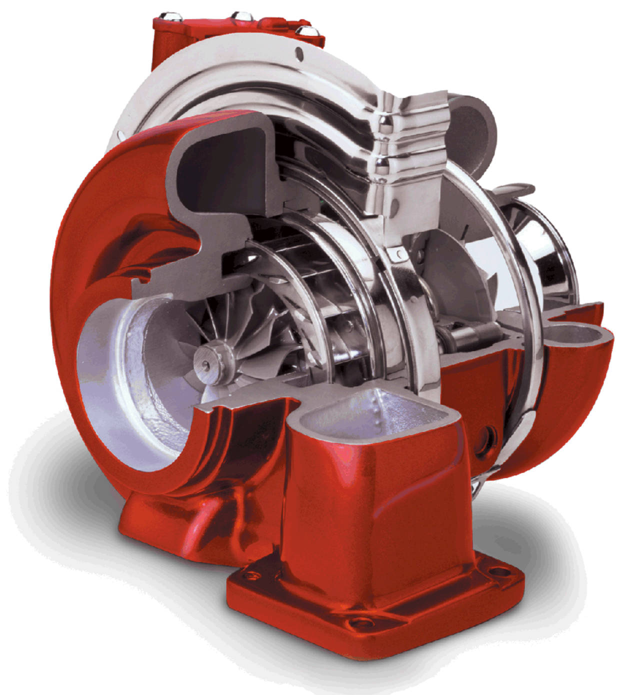
Presently, Caterpillar is the only heavy-duty domestic engine manufacturer to offer VVT commercially. As the 2007 and 2010 compliance dates for new emission standards approach and the demand for increasing the refinement and control of the combustion process increases, more manufacturers may decide to implement this technology. This will prove especially true if Caterpillar achieves superior results due to VVT use. However, other manufacturers may be able to achieve combustion control through the use of other technologies. For example, Cummins Westport stated that it believes it will not need to employ VVT in order to meet the upcoming standards.

Variable Geometry Turbochargers

Turbochargers have been traditionally used to extract the power of a larger engine from a smaller engine, maintain power levels at high altitudes, and increase fuel economy. In the past, the disadvantage of turbocharger use has been "turbo-lag," which is the time difference between the driver depressing the accelerator and the turbocharger providing the appropriate pressure boost to the engine's air intake. However, variable geometry turbochargers (VGTs) can reduce or eliminate turbo-lag in diesel engines by adjusting the air's angle of entry into movable vanes in accordance with turbine speed. This feature allows the pressure boost of the turbocharger to remain adequate at slow speeds without overpressurizing at higher speeds.

Cummins has simplified the typical VGT by replacing the movable vanes with a sliding nozzle, thereby eliminating dozens of parts and potentially increasing dependability and durability. The company's Holset VG Turbo is utilized on engines in conjunction with EGR in order to accurately meter the EGR into the intake system and to offset fuel economy losses. Detroit Diesel also uses a VGT in conjunction with CEGR on its Series 60 engines for the same reasons. The EPA is utilizing these technologies as the basis for its "clean diesel combustion" (CDC) technology. The goal of the program is to cost-effectively reduce engine-out NOx emissions to 0.2 g/bhp-hr or less without relying on radically different technologies. The boost system increases the engine's power and the efficiency of the combustion process and, by combining it with EGR, CDC controls peak combustion temperature, thereby reducing NOx.

Cummins Holset
Variable Geometry Turbo



2007 and 2010 Compliance Strategies

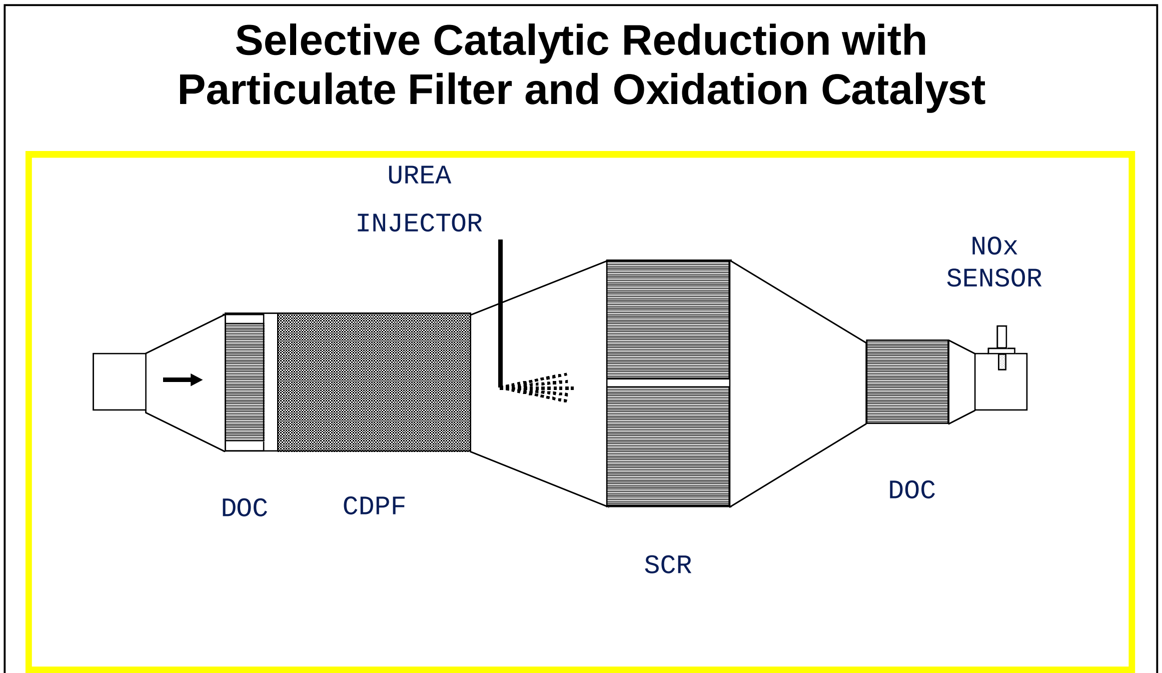
The difficulty that manufacturers face in reducing both NOx and PM emissions comes in the form of what is known as the "NOx/PM tradeoff." What this tradeoff essentially means is that technologies that reduce NOx, such as EGR, tend to increase PM, while technologies that reduce PM, like DPFs, tend to increase NOx. This tradeoff forces the application of multiple technologies in order to obtain both NOx and PM reductions.

Accordingly, engine manufacturers predict that various combinations of technologies and aftertreatment will be used in order to meet 2007 and 2010 standards. Use of ULSD is a primary strategy for manufacturers that plan to apply DPFs to reduce PM. Although SCR can potentially be used to reduce NOx, manufacturers have ruled it out as a compliance option for 2007. LNCs are also not considered because they lack adequate NOx reduction capability for 2007 applications.[26] Instead, the simpler EGR technology will be used to reduce NOx. Cummins is presently using CEGR as well as a VGT in order to meet 2004 standards and will add a diesel oxidation catalyst and possibly a particulate trap in 2007. A paper published by the Society of Automotive Engineers describes work done at the Southwest Research Institute that combines EGR with SCR and DPF technologies, demonstrating the ability to meet 2007 emission standards through the integration of technologies.

Declared 2007 Diesel Compliance Strategies for Transit Bus Engines

Engine Manufacturer	Likely Compliance Strategy
Cummins, Inc.	Cooled Exhaust Gas Recirculation + Variable Geometry Turbocharger + Diesel Particulate Filter or Diesel Oxidation Catalyst
Detroit Diesel Corporation	Cooled Exhaust Gas Recirculation + Variable Geometry Turbocharger + Diesel Particulate Filter

Compliance with the 2010 standards will prove more difficult, as NOx emissions must be reduced to one-sixth the 2007 levels. Meeting these standards will require complex aftertreatment technologies, including the addition of lean NOx traps to reduce NOx emissions and diesel oxidation catalysts to reduce PM. A combination of DPFs, SCR, DOCs, VGTs, VVT, and high-pressure common-rail fuel systems may also be necessary. Cummins, Inc. and Detroit Diesel estimate aftertreatment costs of $5,000 to $6,500 in order to meet 2007 standards. Estimated costs of aftertreatment technologies to meet the 2010 standards vary based on the technologies used.



Source: Volvo Powertrain Corporation

SCR can be effectively combined with DPFs and DOCs to reduce both PM and NOx emissions to levels that meet the 2010 EPA standards.

Manufacturers will also focus on the advancement and refinement of general engine technologies and operation in order to meet the upcoming standards. For instance, engines will utilize advanced air systems and provide optimally timed, high pressure (~1,800 bar), and multiple fuel injections per stroke to reduce emissions and aid in aftertreatment regeneration. The combination of fuel system advances with cylinder design enhancements; base engine strength; and advanced sensors, computing power, and model-based control systems will be used to increase combustion efficiency and reduce emissions. To meet the 2010 standards, engine designs may incorporate the use of homogenous charge compression ignition (HCCI) technology, which uses a combustion process controlled by chemical kinetics to ignite a very lean fuel mixture and provide a highly efficient and fast combustion in order to reduce NOx and PM emissions.

Percentage Change Relative to Unequipped Diesel Engine Likely 2007 and 2010 Diesel Technologies and Aftertreatment				
	PM	**NOx**	**Fuel Economy Penalty**	**Incremental Cost**
Diesel Particulate Filter	-90	5	3	$5,000 - $6,500
Exhaust Gas Recirculation	<5	-50	< 5	
Diesel Oxidation Catalyst	-20 to -50	0	0	?
Lean NOx Catalyst	0	-25	<2	
Lean NOx Catalyst & Diesel Particulate Filter	> -85	-25	5	
Selective Catalytic Reduction	-25	-70	0	

Sources: MECA; Volvo; Mack; Cleaire; Detroit Diesel; Cummins

Blending Stocks

Blending stocks are fuels that are typically mixed with diesel fuel and utilized in diesel vehicles with little or no modification to the vehicle's engine or fuel management system. The use of blending stocks can be an effective way to lower emission levels and/or reduce diesel-based petroleum use. Three available blending stocks for diesel are biodiesel, diesel/water emulsion, and diesel/ethanol emulsion. Each of these additives can reduce pollution and displace petroleum, but with an incremental cost above diesel fuel.

Biodiesel

Biodiesel made from oil and fats such as soy, canola, tallow, and mustard is a fuel that is being produced and used in the U.S. in commercial quantities. It is sometimes used in its pure form, called B100, but more commonly as a blend of 20 percent biodiesel and 80 percent regular diesel, called B20. Biodiesel use can reduce emissions of PM, CO, CO_2, and HC. It has lower toxicity than typical diesel fuel. Using pure biodiesel will "digest" conventional diesel fuel hoses and fuel pump seals in these vehicles, however. The use of B20 does not have these problems. Instead, B20 can be easily used in any diesel vehicle without modifications or adverse effects to fuel systems. It is also compatible with all ULSD fuel technologies.

B20 Emissions Reductions Compared to Petroleum Diesel	
Verified Under Federal Program:	
CO	-11%
HC	-21%
PM	-10%
NOx	+2%
Other Reductions:	
Sulfates	-20%
PAH (Polycyclic Aromatic Hydrocarbons)	-13%
NPAH (nitrated PAHs)	-50%
Mutagenicity	-20%
CO_2	-15.7%*

Source: Noyes, Graham, *The Transparent Solution: Biodiesel's Growing Role,* World Energy Alternatives, LLC, presented at the California Air Pollution Control Officer's Association (CAPCOA) Conference on Diesel, January 27, 2004.
*Source: U.S. Department of Energy

Biodiesel improves diesel performance due to its higher cetane number and high oxygen content. Biodiesel also has excellent lubricity characteristics that reduce wear on engines and components. Tests indicate that even biodiesel levels below one percent can provide up to a 65 percent increase in lubricity in distillate fuels.[27] On the other hand, biodiesel, like other diesel fuels, can cloud in cold weather, and users of biodiesel will experience an increase in cold flow properties. For B20 users, this increase is approximately 3º to 5º Fahrenheit (F). Solutions employed for standard diesel winter operability, such as the use of fuel heaters, cold-flow improvement additives, and storage of the vehicle in or near a building, work for biodiesel as well.[28]

While pure biodiesel can have a solvent effect that may release deposits accumulated on tank walls and pipes from previous diesel fuel use, the issue is less prevalent in B20. Simply monitoring and replacing fuel filters until the petroleum residue is eliminated can prevent clogging. Also, the use of B20 in existing diesel engines does not void parts and materials workmanship warranties of any major U.S. engine manufacturer.

Biodiesel has a slightly lower energy content than diesel. Therefore, B20 suffers a fuel economy penalty of about one or two percent. More than 50 million miles of in-field demonstrations showed similar fuel consumption rates as conventional diesel, however. These tests also showed similar horsepower, torque, and haulage rates when biodiesel was burned.

Because biodiesel is a domestic product that yields 3.2 units of energy for every unit of fossil energy needed for its production, its use can help further national security and reduce energy dependence. Still, there is a cost premium associated with its use. The National Biodiesel Board estimates the incremental cost of biodiesel to be 1 cent per percentage point of biodiesel (i.e., B20 costs $0.20 more than diesel and B100 costs $1 more). The U.S. Department of Energy is working with the biodiesel industry to reduce the cost of B100 to less than $1 per gallon by 2007.

There are seven biodiesel producers in the U.S. B20 can be ordered and delivered easily and stored in conventional diesel storage tanks for about six months, the same length of time as diesel fuel. Biodiesel has a prescribed fuel standard, ASTM D-6751, and the handling procedures for B20 are the same as for petroleum diesel. Some examples of fleets that are running various biodiesel blends are the cities of Breckenridge and Lakewood, Colorado (B20), Cedar Rapid Transit System in Cedar Rapids, Iowa (B5), and Treasure Valley Transit in Nampa, Idaho (B20). The city of Berkeley, California, decided to fuel its entire 200-vehicle diesel fleet with B100, which makes it the largest biodiesel fleet in the world.

National Biodiesel Board Biodiesel Member Suppliers		
Ag Environmental Products Lenexa, KS Phone: (402) 492-3316; (800) 247-1345 Contact: Steve Nogel: snogel@agp.com http://www.soygold.com	**American Biofuels, Inc.** Bonita, CA Phone: (619) 479-6993 Contact: Bill Wason:billwason@earthlink.net	**Archer Daniels Midland** Decatur, IL Phone: (217) 451-6348 Contact: Peter Reimers: peter_reimers@admworld.com http://www.admworld.com
Baker Commodities Los Angeles, CA PH: (323) 268-2801; FAX: (323) 264-9862 Contact: Fred Wellons: fwellons@bakercommodities.com www.bakercommodities.com	**Biodiesel Industries** Santa Barbara, CA Phone: 805-683-8103 Contact: Russ Tealle: Rteall@aol.com http://www.pipeline.to/biodiesel/	**Biotane Fuels** Imperial Western Products, Coachella, CA Contact: Bob Clark: bclark@ imperialwesternproducts.com http://www.biotanefuels.com
Corsicana Technologies, Inc. Corsicana, TX Phone: (903) 874-9565 Contact: Tom Kowalski: tom.kowalski@corsicanatech.com http://www.corsicanatech.com	**Filter Specialty Bioenergy, LLC.,** Fayetteville, NC Phone: (910) 567-5474 Contact: Charles Jackson: Filterspecialty@intrstar.net	**Grain Growers Cooperative** Rocky Mount, NC Phone: (252) 446-7100 Contact Sam Lee Jr.: graingrowers@earthlink.net
Griffin Industries Cold Spring, KY Phone: (800) 743-7413 Contact: Hart Moorejhmoore@griffinind.com http://www.griffinind.com	**Gulf Hydrocarbon** Houston, Texas Phone: (713) 305-3133 FAX: (713) 666-0190 Contact: Jess Hewittemail: jhewitt@buybiodiesel.com http://www.buybiodiesel.com	**Otto Feeds** Bunceton, MO Phone: (660) 427-5444 Contact: Dennis Oser: dooser@midmo.net
Peter Cremer N.A. Cincinnati, OH Phone: (513) 471-7200 Contact: Mack Findley: Hfindley@petercremerna.com http://www.cremer-gruppe.com	**The Procter & Gamble Co.** Cincinnati, OH Phone: (513) 626-5351 Contact: Scott Kadishemail: kadish.sd@pg.com http://www.pg.com	**Renewable Alternatives** Green Bay, WI Phone: (920) 217-3548 Contact: Kelly Maloney: kmaloney@new.rr.com
Southern States Power Riverside, CA Phone: (909) 367-2463 Contact: Harrison McCoy: sspowerco@aol.com http://www.sspowerco.net	**Soy Solutions** Ruthven, IA Phone: (712) 338-2223 Contact: Lon Peterson: soysolutions@iowaone.net http://www.farmerscoopelev.com	**Stepan Company** Northfield, IL Phone: (847) 446-7500 Contact: Jeff Nelson: jnelson@stepan.com http://www.stepan.com
West Central Soy Ralston, IA Phone: (913) 884-8521 Contact: Gary Ha: garyha@westcentral.net http://www.soypower.net	**West Central Soy** Ralston, IA Phone: (712) 667-3200 Contact: Don Irmen: doni@westcentral.net http://www.soypower.net	**World Energy Alternatives** Chelsea, MA Phone: 617.889.7300 Order Line: (888) 785-8373 Contact: Gene Gebolys: Geneg@worldenergy.net http://www.worldenergy.net
	World Energy Alternatives Nevada City, CA Phone: (530) 478-9196 Contact: Graham Noyes http://www.worldenergy.net	

Source: National Biodiesel Board (http://www.biodiesel.org/buyingbiodiesel/producers_marketers/default.shtm)

Biodiesel can be supplied to all domestic locations by any of the suppliers listed above, regardless of proximity.

Diesel/water Emulsion

A mixture of water in diesel fuel promotes a fine, cloud-like atomization of the fuel during injection that increases combustion efficiency significantly, resulting in substantial reductions in PM and NOx. While excessive water added to diesel fuel corrodes a vehicle's engine and fuel components, diesel fuel additives can microscopically suspend water and prevent its corrosive effects. One diesel/water emulsion that is in commercial production is PuriNOx™, a product from Lubrizol Corporation co-developed with Caterpillar, which adds a 20 percent mixture of water along with 3 percent of an additive to 77 percent diesel fuel.

Source: Pure Energy Corp.

PuriNOx™ has a milky-white appearance

Southwest Research Institute used the CARB's alternative diesel verification protocols to test PuriNOx™ emission levels and observed a 5 to 20 percent reduction in NOx emissions and a 20 to 50 percent reduction in PM emissions. CO and CO_2 emission reductions were not determined. The CARB has also certified PuriNOx™ as a verified alternative diesel. Chevron is currently selling the PuriNOx™ diesel/water emulsion blend as its Proformix™ fuel to commercial customers from the Chevron Montebello Terminal in Southern California.

PuriNOx™ Emission Reduction Summary		
	NOx	**PM**
Lubrizol Claim	Up to 30%	Up to 65%
Average Dynamometer	12.6%	46.4%
Average In-Use	26.6%	45.3%
CARB Verification	14%	63%
CARB Confirmation (PuriNOx™ + diesel oxidation catalyst)	20%	≥50%
U.S. EPA Verification	9–20%	16–58%

Source: Serrano, Andres, *Diesel—What the Future Holds*, Lubrizol, presented at the California Air Pollution Control Officer's Association (CAPCOA) Conference on Diesel, January 27, 2004.

Diesel/water emulsion may appeal to the market due to the simplicity of its blend stock (plain water), the ability of the fuel to be utilized in conventional diesel engines without modifications and with minor maintenance (e.g., fuel filter changes), and the substantial potential emissions benefits. However, an incremental fuel cost of $0.20 to $0.35 per gallon over diesel combined with the lower energy content of the fuel, which is about 10 to 15 percent lower due to the zero energy content of the water component, may result in a fuel penalty of 5 to 15 percent and increased operating costs, depending on the engine and operating conditions. Diesel/water emulsion mixtures can break down when held for over 30 days, as experienced by the California Department of Transportation in what was otherwise a generally positive experience.[29]

Diesel/ethanol Emulsion

Although the use of oxygenates in gasoline is a common and proven method of reducing tailpipe emissions, the use of most conventional oxygenates, such as MTBE and TAME, have not been proven suitable for blending with diesel fuel. Ethanol, which is also an oxygenate, is compatible with diesel, but it does not blend effectively with diesel because the fuels phase separate when exposed to small amounts of water or low temperatures. However, new additives now allow ethanol and diesel to successfully blend to create a new, lower-emission fuel.

Pure Energy Corporation produces a diesel/ethanol emulsion product called Puranol. It is a non-toxic additive that, when added to diesel fuel in a concentration of 1 to 3 percent, allows blends of up to 15 percent ethanol. Another product is O_2Diesel™, or E Diesel, which is provided by O_2Diesel, Inc. and is a blend of Octimax 4931 additive with 7.7 percent ethanol and ULSD fuel. No infrastructure or vehicle modifications are necessary in order to use these products, and they can be blended "in-line" at the terminal or splash-blended in the storage tank or tank truck prior to delivery. The mixture stores well even under extreme conditions. Both Puranol and O_2Diesel™ have energy contents similar to diesel. As a result, Pure Energy Corporation estimates less than a 7 percent fuel economy penalty.

Ethanol blended in diesel increases lubricity, stability, conductivity, and cold temperature operability. It is a domestically produced renewable oxygenate, useful in furthering national and energy security goals. Also, the price of Puranol is approximately $7.50 per gallon. To blend 10 percent ethanol into diesel takes about a 0.5 percent Puranol dosage, thereby adding approximately 3.75 cents to the cost of standard diesel. This cost can be higher in colder climates, as a higher percentage of Puranol is required. However, with a $0.51 tax credit per gallon of ethanol, there may be no additional cost to the final emulsion. With this potentially low incremental cost along with emission reductions of about 40 percent PM, 25 percent CO, and 5 percent NOx over diesel fuel, ethanol emulsion can provide an economical method of reducing pollution.

Percent Change Relative to Diesel
Blending Stocks

	GHG	**PM**	**NOx**	**Fuel Economy Penalty**	**Cost Premium (per gallon)**
Biodiesel (B20)	-16	-10	2	2	$0.20
Diesel w/Water Emulsion (PuriNOx)	?	-63	-14	5 to 15	$0.20 to $0.35
Diesel w/Ethanol Emulsion (Puranol, O2Diesel)	-7[g]	-40	-5[g]	< 7	$0.00 to $0.10

Sources: U.S. Department of Energy; World Energy Alternatives; National Biodiesel Board; CARB; Lubrizol; Pure Energy Corporation

Alternative Fuels and Infrastructure

Diesel engines will technically be able to meet the federal and California 2007 and 2010 emission standards, but the increasing complexity and cost of the technologies and aftertreatment required to make these engines compliant can make the use of alternative propulsion systems more appealing. Further driving the attention to alternative fuels are future tailpipe expectations including the toxicity of diesel exhaust and PM size. The most established, viable, and proven alternatives to diesel fuel are compressed and liquefied natural gas as well as grid-connected electricity obtained from catenary overhead wires. Although biodiesel can be completely substituted for diesel fuel, it is more commonly used as a blending stock and thus is not discussed in this section.

Natural Gas Propulsion

Natural gas is a mixture of hydrocarbons comprised primarily of methane (CH_4) and is mainly produced either from gas wells or in conjunction with crude oil production. Currently, natural gas is the primary alternative to diesel fuel for transit vehicles. Approximately 7,000 transit buses in the U.S. are powered by natural gas, and they are responsible for about a quarter of all new transit bus orders. Natural gas buses comprise a total of over 12 percent of the entire transit bus fleet, almost 11 percent as compressed natural gas (CNG) and close to 2 percent as liquefied natural gas (LNG).

The main force driving the adoption of natural gas transit buses is the inherent clean air advantages natural gas has over diesel. It contains nearly no sulfur, and its burning emits less NOx and PM pollution and fewer overall toxic emissions than diesel fuel. Compared to pre-2002 diesel vehicles, natural gas engines emit 60 percent less NOx and 90 percent less PM, and compared to current diesels (without aftertreatment devices), natural gas engines emit 30 percent less NOx and 90 percent less PM.[30] In fact, Southwest Research Institute and Cummins Westport indicate that operating an SI natural gas engine as lean as possible may result in NOx levels of approximately 0.7g/bhp-hr, which would meet the 2007 requirement without the use of aftertreatment technologies.

The inherent cleanliness of natural gas as a fuel combined with the application of aftertreatment devices is likely to allow its combustion to remain cleaner and less toxic than the cleanest diesel engine, even after the implementation of ULSD fuel and diesel aftertreatment technologies. The lower engine-out NOx emissions of natural gas engines also enable them to use simpler aftertreatment systems to meet 2010 standards. For instance, lean-burn natural gas engines can be equipped with oxidation catalysts and NOx exhaust controls. If natural gas engines are run at stoichiometric levels, where a richer mixture of fuel is completely burned in an ideal combustion process, rather than lean-burn levels, they can be equipped with simple three-way catalytic converters to reduce pollution levels. Studies by the Swiss Federal Institute of Technology indicate use of 25 percent CEGR technology in SI natural gas engines reduced knock tendency, which allowed for the use of a higher compression ratio that increased efficiency, lowered exhaust temperature, and greatly reduced NOx levels.[31] Cummins Westport speculates that it may be possible to use CEGR to achieve NOx levels of 0.4 to 0.6 g/bhp-hr. If SCR is applied to natural gas systems, the lower engine-out NOx levels mean that less reductant use is necessary and, therefore, the associated reductant cost is reduced. However, the richer fuel mixture increased fuel consumption by 15 to 20 percent on eight stoichiometric natural gas buses that were demonstrated in Helsinki, Finland.

Another force driving natural gas adoption is that nearly all of the natural gas consumed in the U.S. is produced in North America and most of it is domestically produced, which is advantageous for national security and energy dependence issues. Combustion also releases 10 to 20 percent fewer CO_2 emissions per BTU as compared to diesel, thereby helping to reduce the impact of global warming.

Natural Gas
Turnkey Infrastructure and Fuel Providers

ANGI International
15 Plumb St. P.O. Box 39
Milton, WI 53563
Phone: (608) 868-4626
Fax: (608) 868-2723
http://angiinternational.com/

A.E. Schmidt Environmental
8100 Balboa Place
Van Nuys, CA 91406
Phone: 818 786 2373
Fax: 818 786 5440
http://www.aese.com/index.html

Clean Energy Fuels
3030 Old Ranch Parkway Suite 280
Seal Beach, CA 90740
Phone: (562) 493-2804
Fax: (562) 493-4532
http://www.cleanenergyfuels.com/

Cryogenic Fuels, Inc.
2197 Sowego Rd.
Catlett, VA 20119
Phone: (540) 788-1000
Fax: (540) 788-1088
http://www.cryogenicfuels.com/

FuelMaker Corporation
3109 Normandy Dr. McKinney, TX 75070
Phone: 800-898-3835
Fax: (972) 542-2940
http://www.fuelmaker.com/

GreenField Compression, Inc.
909 North Bowser Rd. Richardson, TX 75062-2208
Phone: (972) 541-6079
Fax: (972) 541-5038
http://www.gfcomp.com/

Hurricane Compressors
1015 N. Hurricane Rd. Franklin, IL 46131
Phone: (317) 736-3800
Fax: (317) 736-3801
http://www.hurricane-compressors.com/

IMW Industries Ltd.
45831 Hocking Ave Chilliwack, BC V2P 1B5
Canada
Phone: (604) 795-9491
Fax: (604) 792-3806
http://www.imw.ba.ca/

Kraus Global Inc.
25 Paquin Road Winnipeg, MB R2J 3V9
Canada
Phone: 204-663-3601
Fax: 204-663-7112
http://www.krausglobal.com/

Pinnacle CNG Systems LLC
P.O. Box 2499 Midland, TX 79702
Phone: (915) 686-5989
Fax: (915) 686-1557
http://www.pinnaclecng.com/

QUANTUM Technologies Inc.
17872 Cartwright Rd. Irvine, CA 92614
Phone: (949) 399-4552
Fax: (949) 399-4600
http://www.qtww.com/

Questar Gas Company
180 East 100 South PO Box 45360
Salt Lake City, UT 84145-0360
Phone: (801) 324-3651
Fax: (801) 324-3484
http://www.questar.com/

The Hanover Company
20602 E. 81st Street
Broken Arrow, OK 74014
Phone: (918) 259-2275
Fax: (918) 259-2386
http://www.hanover-co.com/home/index.htm

Trillium USA
136 East South Temple Ste 1900
Salt Lake City, UT 84111
Phone: (801) 531-1166
Fax: (801) 521-7692
http://www.trilliumusa.com/

Source: The Natural Gas Vehicle Coalition Business Directory (http://www.ngvc.org/ngv/ngvc.nsf/bytitle/businessdirectory.htm)

CNG Infrastructure, Safety, Maintenance, and Cost

CNG is a readily available fuel that can be tapped to refill vehicles straight from an extensive North American pipeline system. CNG vehicles store the fuel in heavy, 3,600 pounds per square inch (psi) cylinders. The energy density of even the highly compressed gas does not provide the same range as a comparable volume of LNG or diesel fuel. Adding more or larger fuel tanks can compensate for CNG vehicles' shorter range, however, allowing CNG vehicles to match the range of diesel vehicles.

There are four general fueling station design approaches for CNG vehicles. The first one, **direct fast fill**, utilizes natural gas that is supplied to the station via underground pipeline, compresses it, and fills vehicles in a timeframe similar to liquid fueling practices. Trillium, a CNG fueling service provider that currently fuels over 1,000 buses per day, reports that their stations have refill times of less than four minutes per bus by using direct fast fill. A second method, **fast fill from storage**, works similarly to direct fast fill except that it fills buses by using multiple storage tanks that are at progressively higher pressures. This requires the use of a smaller compressor, but requires a storage volume three to four times larger than the storage volume onboard the bus in order to achieve fast fill. Fast fill from storage works best with smaller fleets that are able to fill at different times throughout the day, because the amount of storage capacity required for larger fleets can be even more expensive than the larger compressors required for a direct fast fill system.[32] **Slow fill** uses a compressor to fill many vehicles directly and simultaneously over a long period, usually overnight. Slow fill designs have not been applied extensively to transit buses due to the fact that slow fill compressor flow rates become approximately equal to those associated with more convenient fast fill designs for fleets of more than 40 vehicles.[33] The **fast/slow fill** approach primarily fills vehicles using a slow fill system, but additional onsite storage is provided for occasional fast filling and/or topping off. This method is most efficient for smaller fleets or for fleets with smaller vehicles.[34]

For a fleet of 200 buses, CNG equipment, including gas meters, dryers, compression, storage, and auxiliary equipment, requires about 5,000 to 10,000 square feet of space, with new stations at the low end of this spectrum. For safety reasons, it is essential that these fueling stations have ventilation and/or explosion-proof equipment at the ceiling level and in the "pits" underneath the vehicles where mechanics stand to perform underbody maintenance. It is also necessary to have ignition interlocks to protect against some drive-away scenarios and precautions for static electricity discharge.

While CNG refueling technology complies with the National Fire Protection Association set of safety requirements (NFPA 52), it is an expensive infrastructure. Initial capital investments for fueling facilities can vary widely based on gas proximity, construction costs, land issues, labor issues, and geographic location. Still, the California Natural Gas Vehicle Coalition states that, as a general rule, initial capital investments for fueling facilities are about $25,000 per bus for fleets over 100 vehicles. CNG operation also incurs significant compressor operating costs, which are higher when compression is done using electric motors instead of natural gas engines. The price of a CNG bus is generally $30,000 to $40,000 higher than a similar diesel bus, although in some cases this premium can be significantly lower or higher. The natural gas bus industry believes that recent examples of natural gas bus purchase prices that are comparable to diesel bus purchase prices, as the example on the following page shows, are part of a trend. Also, it is important to note that this premium will likely decrease as emissions standards become more stringent and diesel bus engines are equipped with more complicated and costly emission-reducing technologies.

Recent Incremental Capital Cost Example for 40-foot Natural Gas Buses				
	Diesel Bus	**Natural Gas Bus**	**Difference**	**Comparison**
2000 Average Price[i]	$271,700	$317,400	$45,700	17 percent higher for natural gas
2003/2004 Example	$304,752[ii]	$311,626[iii]	$6,874	2.3 percent higher for natural gas

[i] Natural Gas in Transit Fleets: A Review of the Transit Experience, NREL/TP-540-3419 Leslie Eudy, February 2002, Page 12
[ii] 140 Low Floor Emissions Controlled Diesel buses for 2004 delivery (Boston)
[iii] 175 Low Floor CNG Buses with Westport C Gas Plus engines for 2003 delivery (Boston)

CNG buses can command a price premium over diesel buses of $30K to $40K, although in some cases this premium can be significantly lower.

CNG vehicle operation is highly dependent on fuel and maintenance costs. Current CNG vehicle operating costs are 20 percent higher than comparable diesel vehicle operating costs. On average, natural gas is 30 percent cheaper nationwide than diesel. Where there are favorable natural gas prices and where natural gas engines have performed very well, operational expenses for modern CNG buses equal or are less than those for new diesel buses. Pierce Transit in Lakewood, Washington states that their experience with CNG reveals fuel costs of 7 cents per mile, compared with 13.6 cents per mile for diesel buses.

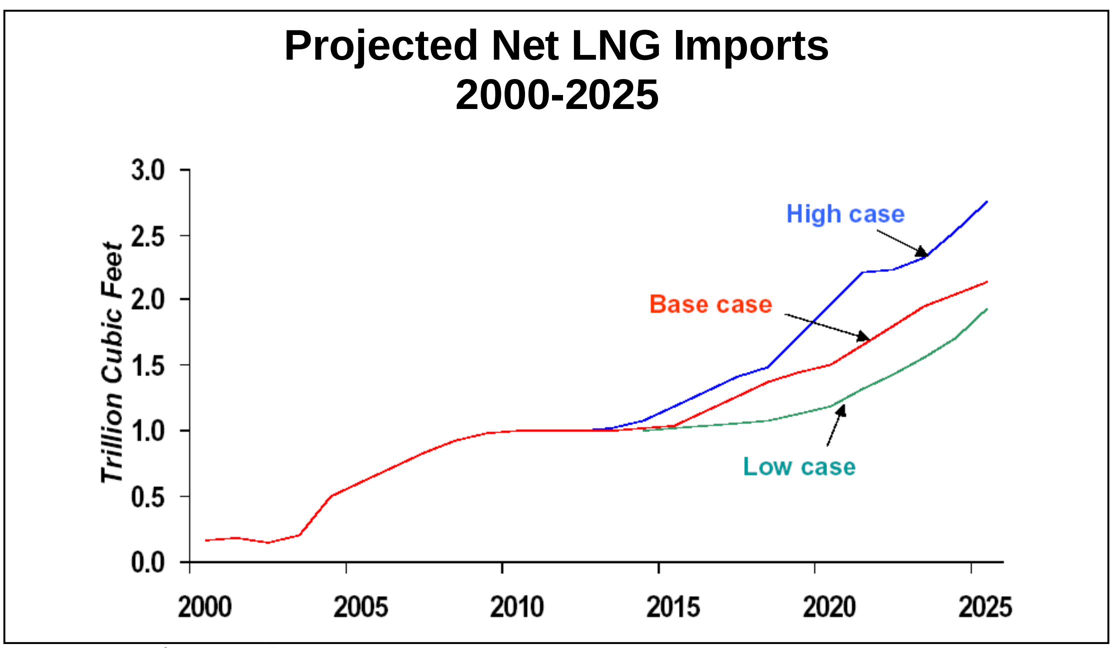
While most of the maintenance requirements for SI natural gas engines are comparable to diesel engines, natural gas engines require their spark plugs to be replaced after approximately 1,000 to 1,500 hours, or after about 20,000 miles of driving, a requirement that diesel engines don’t have. However, natural gas engines are inherently cleaner burning and they experience less engine wear and premature fouling of engine oil.

Transit communities continue to establish and invest in CNG infrastructures due to positive perceptions of CNG-fueled vehicles, air quality improvements, and political commitment to support CNG infrastructures once they are established in order to recoup initial investment.

LNG Infrastructure, Safety, Maintenance, and Cost

Natural gas can be cryogenically cooled to -259º F, liquefied, and used in SI engines. LNG is stored onboard vehicles in double-walled, vacuum-insulated pressure vessels, where it develops pressure by being warmed to -190º F in a process called "conditioning." Once LNG is conditioned, it can be utilized in a similar fashion as CNG.

LNG can be supplied in a variety of ways. On-site liquefaction, where pipeline CNG is passed through a liquefier rather than a compressor, is the most convenient method of obtaining the fuel, but it is generally not the most economical method. Instead, LNG is most often, and most economically, delivered by truck from centrally located liquefiers to on-site storage tanks. LNG is also commonly imported by ship through one of four continental U.S. ports: Everett, Massachusetts; Lake Charles, Louisiana; Cove Point, Maryland; and Elba Island, Georgia. The imported fuel is deposited at an LNG terminal and then trucked to on-site storage tanks. As shown in the next figure, imports of LNG into the U.S. are projected to rise dramatically in the next two decades.



Source: Energy Information Administration

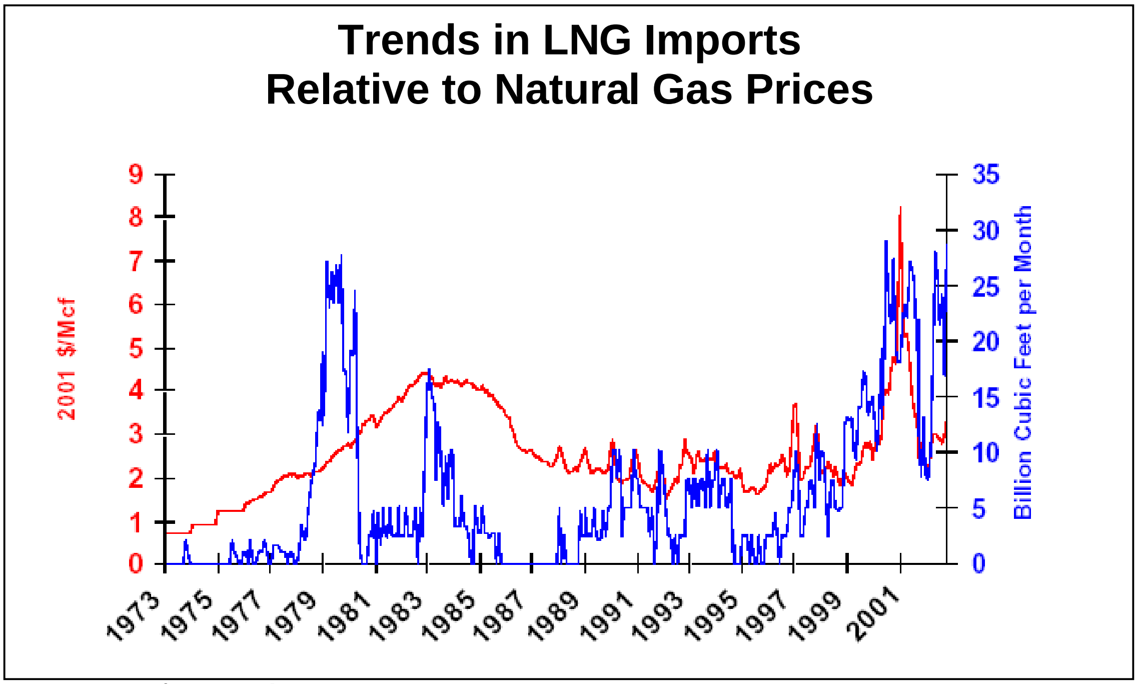
LNG imports are projected to grow in coming decades as domestic energy use and demand for cleaner burning fuels increase.

On-site storage tanks are vacuum-insulated with multiple wraps of highly reflective fabric. As insulated as these tanks are, over time they absorb heat that causes an increase in vapor pressure. LNG storage tanks are equipped with redundant pressure relief valves that vent excessive vapor. This vented vapor represents air pollution and wasted LNG. To prevent venting, LNG should not be stored longer than two weeks at the storage facility or one week onboard vehicles.[35]

All garage modifications recommended for CNG apply to LNG. Moreover, as a cold liquid, LNG can cause frostbite if it comes in contact with skin and, since it is heavier than air, can settle as cold, dense vapor. Precautions for minimizing risk include wearing proper clothing and equipment when handling the fuel's components and explosion-proofing the electrical wiring, and incorporating methods to prevent LNG leaks from flowing into drains.[36]

LNG vehicle emissions are essentially identical to CNG vehicle emissions, and the costs to establish an LNG refueling station are similar as well. One of the advantages of LNG over CNG is that it contains more energy per unit of volume as compared to CNG, since it is 1/600th the volume and can provide vehicles with about 2.5 times the range. LNG stations require less power to refill vehicles, as the submerged centrifugal pump, which is capable of dispensing fuel at rates of 30 to 40 gallons per minute and providing refill times equal to those of diesel buses, requires only 1/40th the power to operate than a CNG compressor station with comparable capacity.[37] The fuel itself is formed almost entirely from pure methane, which minimizes impurities, ensures fuel quality, and eliminates the need to filter the fuel. LNG operation also adds less weight to a vehicle than CNG operation.

LNG can also be stored on-site and evaporated to produce CNG. "L/CNG" refueling consists of vaporizing compressed LNG in a heat exchanger, then storing the resulting CNG in a buffer tank at high pressure. The compressed gas, which is consistently contaminant free, is then delivered to vehicles at its settled pressure, so no overfilling is needed to compensate for compression heating. The initial station cost of L/CNG can be a fraction of CNG initial station cost for equivalent capacities. Its operation can be an attractive option for operations that have a majority of LNG vehicles along with a smaller fleet of CNG vehicles.



Source: Energy Information Administration

Although LNG prices have been higher than CNG prices in the past, they've been similar and often lower in recent years.

Among the disadvantages, LNG fuel tanks must be double the size of diesel tanks and weigh about 800 pounds more in order to provide a similar range.[38] LNG buses experience a fuel efficiency penalty of as much as 30 percent compared with diesel buses. Even though LNG itself can cost less than petroleum fuels on an energy-equivalent basis, these savings are often not enough to compensate for added capital costs. Also, in circumstances where onboard cryogenic storage is imprecise, LNG fuel tanks can display full readings when the tanks are actually empty. Finally, the high energy density of LNG shipments has inherent risks and raises safety concerns.

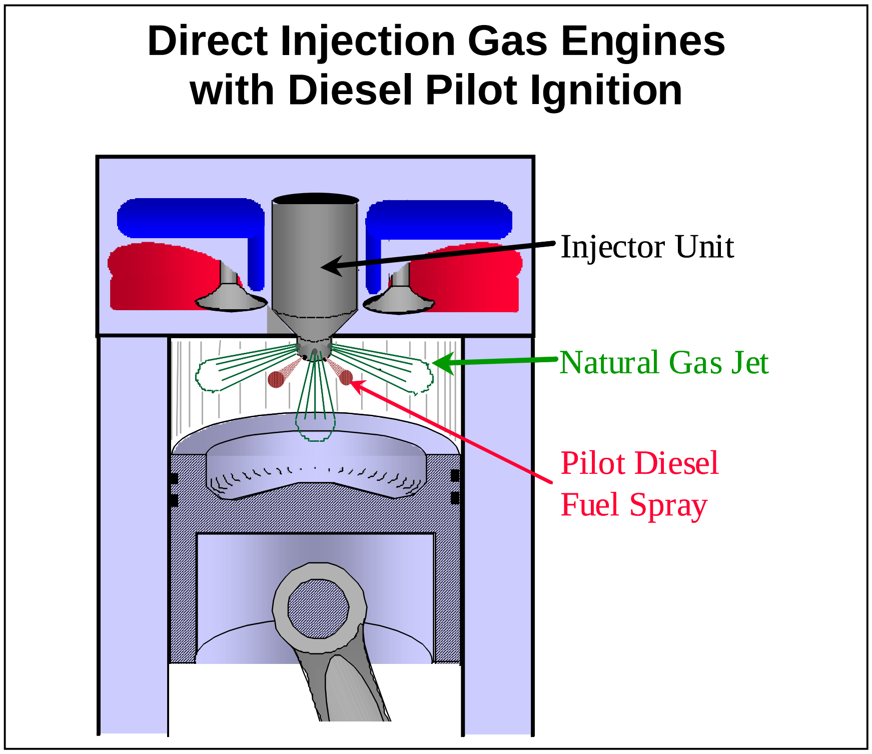
LNG is currently used for transit bus applications in Santa Monica, California, and Phoenix, Arizona. It is also used in Orange County, California, but is being phased out in favor of CNG.

Natural Gas Transit Bus Engine Domestic Manufacturers and Details				
	Engine Model	**Maximum Power (HP)**	**Torque (lb-ft @ rpm)**	**Misc. Details**
Cummins, Inc.	CG-280	280	850 @ 1400	High-powered, designed for variable fuel qualities in urban transit applications
	CG-275	275	750 @ 1400	
	CG-250	250	750 @ 1400	
	CG-250	250	660 @ 1400	
	BG-230	230	500 @ 1600	"B Gas Plus" series; 6 cylinders
	BG-200	200	465 @ 1600	
	BG-195	195	420 @ 1600	
	LG-320	320	1000 @ 1400	"L Gas Plus" series; Articulated bus applications, 6 cylinders w/VGT
Detroit Diesel Corporation	Series 50G	275	800-890 @ 1200	4 cylinders; EGR + VGT technologies

Sources: Cummins, Inc.; Detroit Diesel Corporation

Dual Fuel Engines

Dual fuel engines run on a fuel mixture of approximately 85 percent natural gas and 15 percent diesel fuel in compression injection rather than SI engines. The system uses diesel fuel as a pilot to ignite a high-pressure mixture that provides power characteristics similar to diesel engines, but at greatly reduced engine-out emissions levels. The fuel blend is mixed with air outside the cylinder before cylinder intake, thereby helping to suppress NOx formation. At increased engine loads, the diesel percentage of the fuel mix drops while at low power demand, i.e. less than 60 percent of rated power, and the engine maintains low emissions and high efficiency by changing to a "skip fire" mode where electronic controls deactivate up to three cylinders.



Source: Cummins Westport

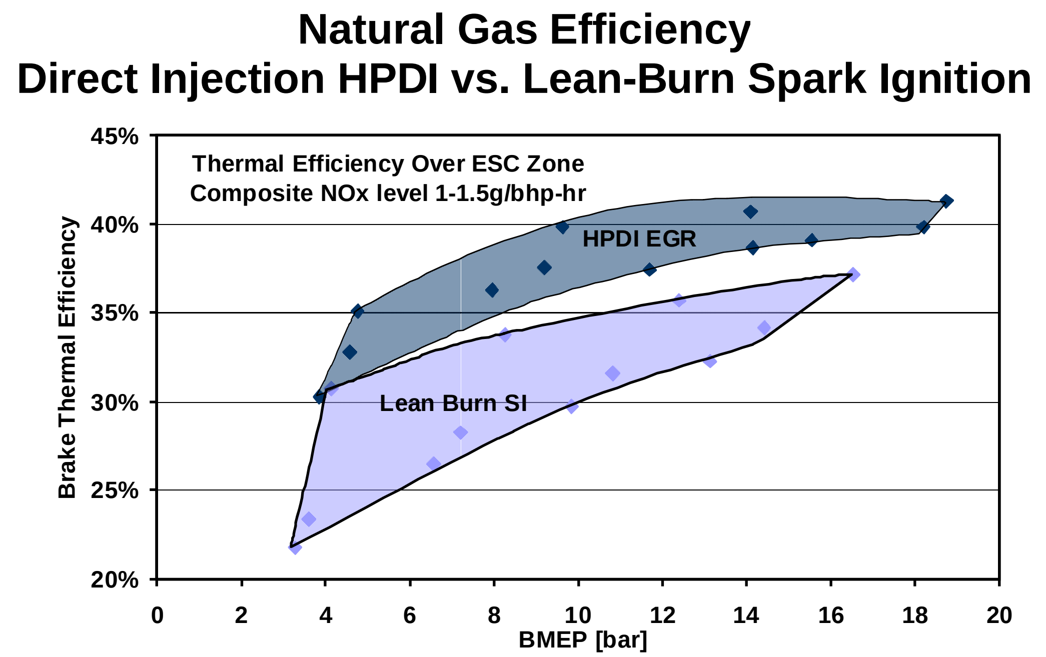
Dual fuel engines use diesel as a pilot to ignite a mixture of 85 percent natural gas and 15 percent diesel fuel in compression cylinders.

Approximate Emissions Reductions Direct Injection Natural Gas vs. Diesel 15 Liter Cummins ISX Engine		
NOx	**PM**	**GHG**
-50%	-70%	-20%

Source: Cummins Westport

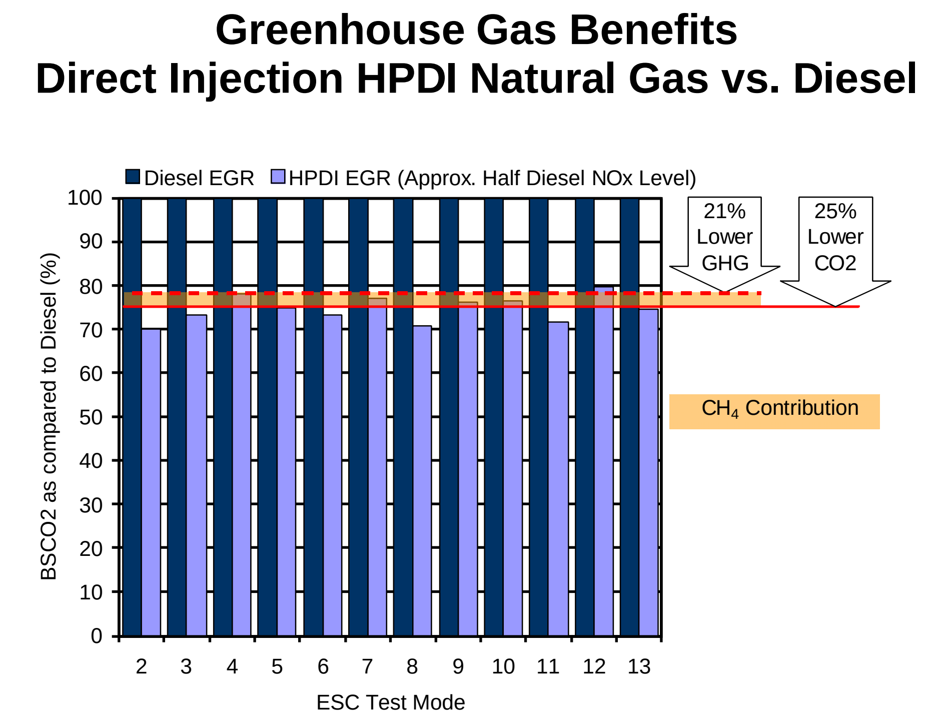
In February 2004, the U.S. DOE Office of Energy Efficiency and Renewable Energy released test results on a heavy-duty dual fuel engine that was built as a result of a partnership between the DOE's National Renewable Energy Laboratory (NREL), Caterpillar Inc., and Clean Air Power, a company that provides dual fuel conversion kits for Caterpillar engines. The project's goal was to demonstrate prototype engine and vehicle technologies capable of reducing exhaust emissions and controlling operating costs for heavy-duty liquefied natural gas vehicles. The project considered two emissions reductions strategies: passive clean and cold exhaust gas recirculation (PACCOLD-EGR) and active clean and cold exhaust gas recirculation (ACCOLD-EGR). PACCOLD-EGR uses a DPF with EGR technology, while ACCOLD-EGR takes the PACCOLD system and augments it with a lean-NOx catalyst. The ACCOLD-EGR was abandoned because it could not meet project objectives, but the PACCOLD-EGR-equipped Caterpillar C-12 dual-fuel engine demonstrated 0.54 g/bhp-h NOx and 0.0004 g/bhp-h PM emissions that easily met the EPA's 2007 emission standards.

Similar to a dual fuel system is the Cummins Westport high-pressure direct injection (HPDI) system. Although not yet commercially available, this system also uses a natural gas/diesel mixture, but uses less diesel fuel, about two to five percent. The HPDI system injects fuel directly into a compression ignition combustion cycle typical of diesel engines. Because of this, Cummins Westport states that the system has a 10 to 20 percent higher torque capability than dual fuel engines based on SI combustion and achieves parity with diesel in torque per unit of displacement, yet with lower emissions. HPDI engines are about 25 percent more efficient than lean burn spark ignition engines.
The HPDI combustion approach is also highly EGR tolerant, thereby achieving ultra-low NOx levels.



Source: Cummins Westport

The efficiency of HPDI engines with EGR is greater than lean burn spark ignition engines over the European ESC test cycle range of potential power output, as measured by cylinder pressure.



Source: Cummins Westport

HPDI engines with EGR technology can reduce CO_2 levels by 25 percent and total GHG emissions by 21 percent as compared to diesel with EGR.

Grid Connected–Catenary Overhead Wires

A transit bus can operate without any tailpipe emissions if it connects extended conductors from its roof to catenary overhead electrical wires. This technology can either be implemented as the sole source of power, forcing vehicle routes to follow the location of overhead wires, or in “dual-mode” applications with two forms of propulsion systems: an engine for most driving requirements and an electric motor for traveling through environmentally sensitive areas, such as city centers and tunnels.

Although the use of catenary technology complies with California’s zero emission bus program, new implementation is limited due to higher operating and infrastructure costs as well as the negative aesthetic impacts that catenary overhead wire systems impose on communities. Catenary bus technology is still in use in some North American communities, including San Francisco; Boston; Philadelphia; Seattle; and Dayton, Ohio, but transit authorities are passing on the option as other versatile and cheaper vehicle technologies grow in numbers and popularity. For instance, King County Metropolitan Transit Authority and Sound Transit in Washington operated dual-mode buses on overhead electric wires while passing through a 1.3-mile underground downtown bus tunnel. In October 2003, however, these transit authorities announced the purchase of 235 diesel electric hybrid buses to replace the dual-mode buses. The hybrids are able to fulfill the role of the dual-mode vehicles more cost effectively while offering a payback over the bus’ 12-year service life from reduced fuel and maintenance costs.

Catenary wire vehicle technology may be a difficult fit for BRT applications, as the costly installation and maintenance of the overhead wire infrastructure may undermine the affordability advantage BRT systems held over rail systems, even on designated busways. Still, the technology allows for limitless range in smooth, quiet, and fast buses. Catenary wire technology was implemented in BRT service in 1996 in Quito, Ecuador. The Trolleybus Busway system, dubbed “El Trole,” operates on ten miles of busway; is comprised of 113 articulated trolleybuses, each with a diesel standby motor; and carries

170,000 passengers per day. The trolleybus service allows for reduced noise and pollution-free operation through the city's historic center.

Neoplan N6020
Articulated Trolley Bus
Basel, Switzerland

Source: Neoplan

Trolleybus BRT Service
Quito, Ecuador

Source: World Bank

Tailpipe Emission Reductions Percent Change, Relative to Diesel				
	GHG	**PM**	**NOx**	**Current Cost Premium**
CNG	-21	-90	-30	Vehicle: $30K to $40K; Fuel: -30%; Oper Costs: 20%
Grid Connected (Catenary Overhead Wires)	-100	-100	-100	1.5 to 1.8X standard diesel bus costs Maintenance costs (due to catenary system) are significantly increased

Sources: Westport Innovations; Environmental and Energy Study Institute; King County Transit

Hybrid Electric

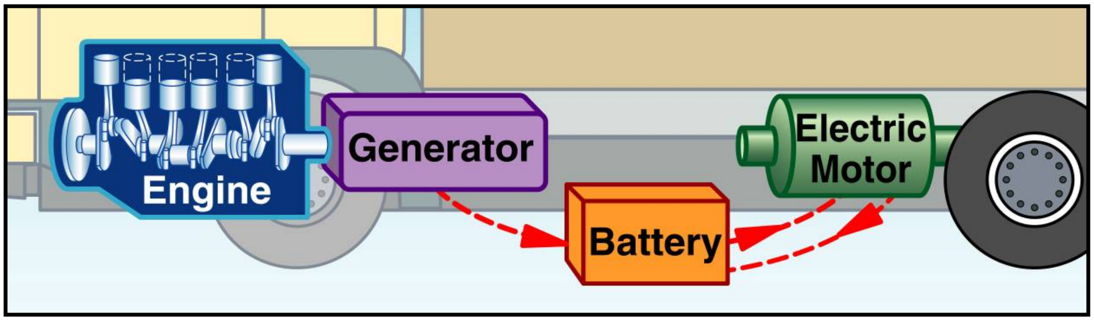
Hybrid electric buses (HEBs) combine power from an auxiliary power unit (APU), which is typically an ICE; an energy storage device; and an electric motor in order to optimize driving efficiency. Like conventional ICE buses, they are capable of running on various fuels, including diesel, gasoline, and natural gas. Power controls and computer algorithms automatically control the flow of power between the APU, generator, and batteries. There are two main types of hybrid-electric drivetrains: series and parallel.

<u>Commercial Benefits of Hybrid Electric Buses</u>

- Reduced Emissions (up to 90 percent)
- 25 to 50 percent Better Fuel Economy
- Improved Driveability, Quieter
- Improved Performance
- Reduced Maintenance (brakes, transmission)
- Uses Standard Fuels
- Similar to Today's Vehicles

Series hybrids are constructed similarly to diesel locomotives. An APU powers a generator that in turn feeds electricity to an electric motor powering a vehicle's wheels. This type of drivetrain works well with vehicles such as urban transit buses that do not operate for extended periods at cruising or high speeds, since electric motors have superior efficiency at low speeds. Examples of series hybrid transit buses are BAE Systems Orion VI and VII transit buses, the Toyota Coaster bus, and Capstone microturbine-powered HEBs built by Ebus and others.

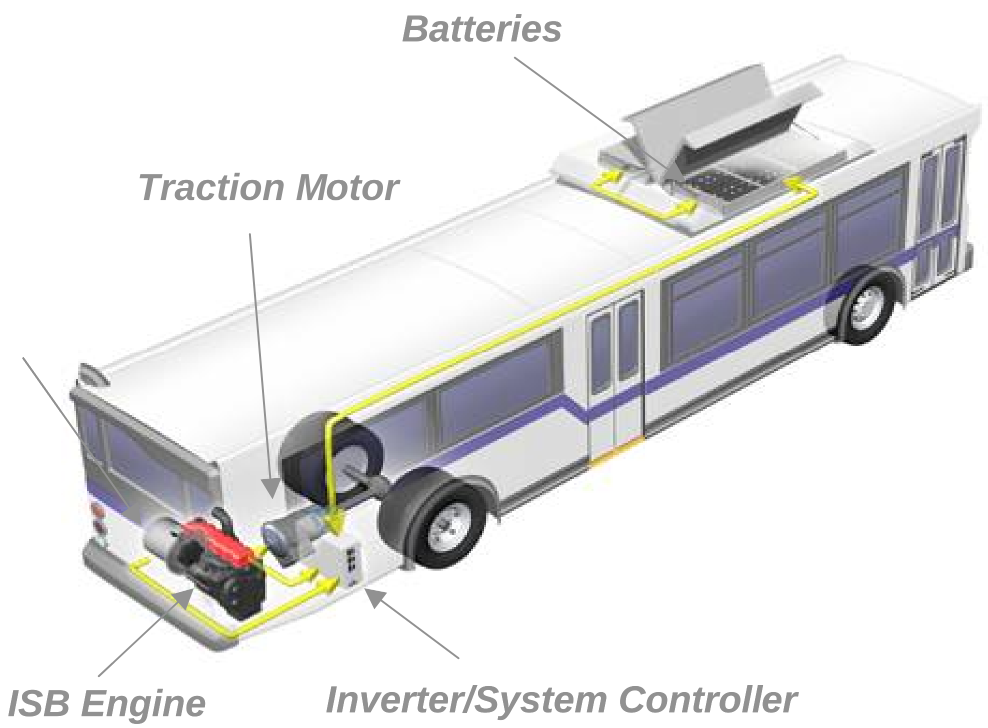
Series Hybrid Configuration



Source: Southwest Research Institute

The engine powers a generator that in turn feeds electricity to an electric motor powering the vehicle's wheels. A battery pack is used to supplement the generator and to store converted braking energy.

BAE SYSTEMS
Orion VII Series Hybrid Electric Transit Bus



Source: BAE Systems

On the Orion VII, the battery pack is mounted on the roof.

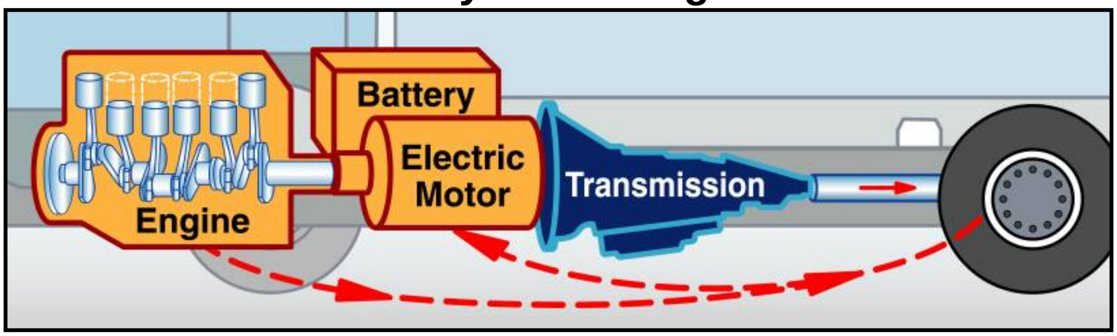
E-traction developed an innovative series hybrid transit bus that integrates electric motors into the rear wheels, thereby eliminating friction-producing parts that waste energy. A small diesel-powered generator that is about the size of a compact car's engine is inserted into the bus' engine bay and run at a constant 1,700 revolutions per minute to maintain battery charge. The small size of the engine allows for ample soundproofing, reducing noise levels by 90 percent compared to conventional buses, leading to the nickname "the whisperer." Also, the constant engine speed allows for the more efficient application of aftertreatment, thereby making it easier to reduce pollution levels. The vehicle began a six-month demonstration and evaluation in Apeldoorn, The Netherlands, in January 2004.

"The Whisperer" Hybrid Bus
with Integrated Wheel Motors

When used in the context of heavy-duty hybrids, the term "parallel" usually refers to what is actually a "dual" parallel system that is able to operate on electric drive only, APU only, or in combination. These "split" hybrids are useful in cases where the HEV will be used in both stop-and-go and higher-speed steady-state operation, such as for BRT applications. At startup, they use the electric motor, which is highly efficient at low speeds, and run solely on electric drive. At cruising speed, they use the higher efficiency of the APU under those conditions and operate solely on APU power. The power controls can also automatically determine the optimal balance of both power sources when transitioning between startup and cruising speeds. This efficiency maximization results in overall higher efficiency through a wider range of work demands than that of series drives. The 235 60-foot articulated diesel powered HEBs purchased by King

County and Puget Sound transit agencies use a dual parallel system from GM Allison Electric Drives.

Parallel Hybrid Configuration



Source: Southwest Research Institute

The engine and motor work individually or in combination to propel the vehicle, while the battery pack captures brake energy.

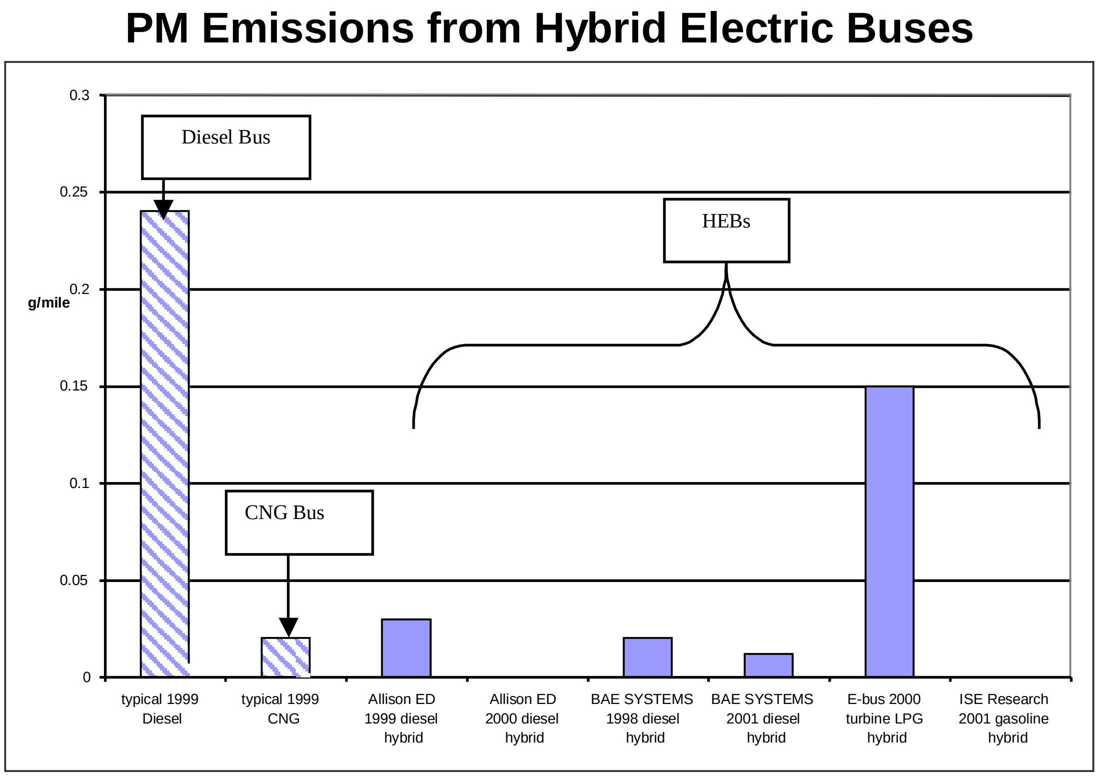
In other mild or “light” parallel hybrids, the APU drives the wheels at all times while the electric motor adds power when needed. These parallel hybrid systems usually integrate the electric motor into the transmission driveline to provide boost power and are less expensive than series or dual hybrid systems, but they don’t offer the level of performance, emissions benefits, regenerative braking, and fuel savings of a full hybrid. In some cases, light parallel hybrid systems consist of little more than an integrated starter/alternator system that provides an idle-stop feature plus minimal boost power and regenerative braking capability. Light parallel hybrids are rare in transit bus applications and are more commonly found in light-duty vehicle applications. The first generation Hino HIMR buses and trucks, on the market in Japan since 1991, use a light parallel hybrid system.

Hybrid Electric Emissions

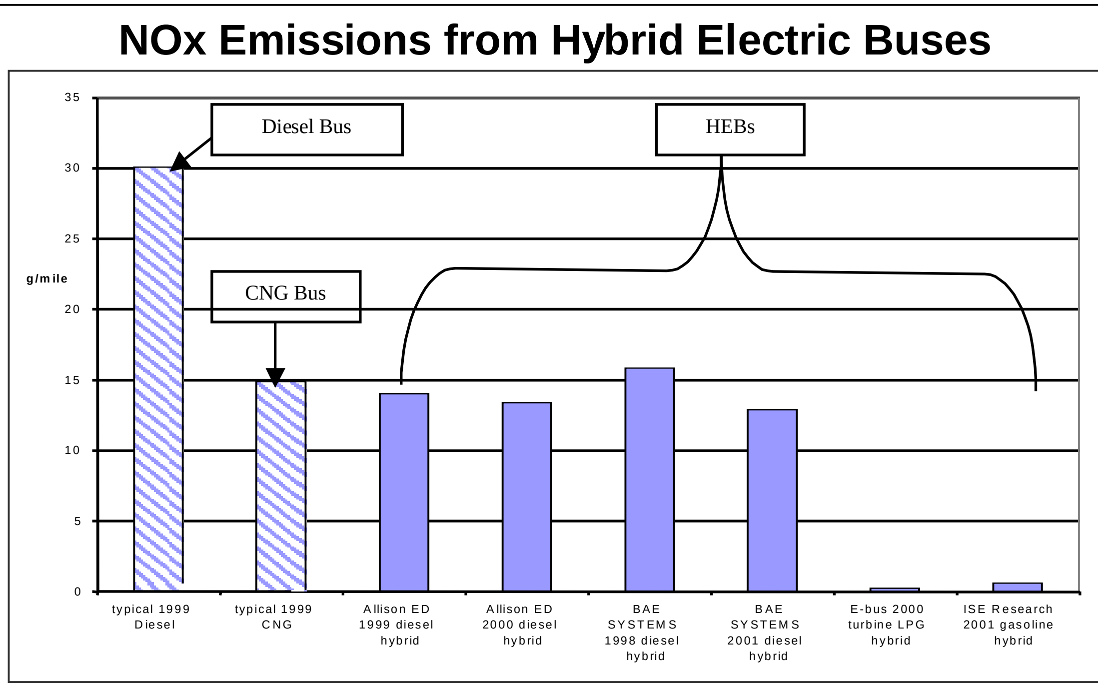
Comparing the emission reduction benefits of HEBs with conventional buses can be difficult because current certification methods were designed for engines used in conventional drivetrain configurations and measure emissions as grams per brake horsepower hour. In order to capture the benefits of hybrids, entire chasses need to be certified and emissions need to be reported in grams per mile so that electric-assist and pure electric modes of operation can be represented.

The Society of Automotive Engineers approved as a recommended practice a chassis test procedure, SAE J2711, specifically for HEBs that reports emissions in grams per mile. A limited number of first generation HEBs and conventional drivetrain buses were subjected to this chassis test procedure and the results were reported in the CARB's September 6, 2002, Staff Report. This report covered the testing of eight different buses, seven fueled by diesel and one fueled by gasoline. All were built on 40-foot platforms except for the E-bus, which was built on a 22-foot platform. Older and newer diesel hybrid electric technologies were provided by two manufacturers, Allison Electric Drives and BAE Systems. The diesel HEBs that the CARB tested used DPFs, while the gasoline HEB was equipped with a catalytic converter.

These results indicate that HEBs offer significant emissions reductions over conventional drivetrain diesel buses and are often cleaner than natural gas buses with conventional drivetrains. The 1999 Allison diesel-electric buses reduced NOx by 55 percent and PM by 96 percent, while the BAE Systems Orion VI bus reduced NOx emissions by over 50 percent, PM by over 90 percent, and greenhouse gases by 35 percent. Fuel economy in the HEBs was increased by 50 percent compared to conventional diesel drivetrains.



Source: CARB Staff Report, September 6, 2002



Source: CARB Staff Report, September 6, 2002

The CARB observed greatly reduced emissions of hybrid systems as compared to conventional diesel and CNG systems.

The gasoline hybrid electric bus, built by ISE Corporation, achieved such significant levels of emission reductions that transit agencies took notice. In spring 2003, Long Beach Transit in Long Beach, California, announced the first multi-vehicle purchase of gasoline fueled HEBs. The complete order for 27 ThunderVolt 40-foot New Flyer buses could ultimately exceed 100 through 2007 if options and "piggyback" orders from other California transit agencies are exercised.

ISE Research
2001 Gasoline Hybrid

Source: ISE Research

Although diesel-electric hybrids tend to be more common, ISE Research's gasoline-electric hybrid bus reduced NOx and PM emissions drastically, as reported by the CARB in its September 6, 2002, Staff Report. A standard Ford V-10 ULEV SUV engine powers the bus.

In February 2002, NREL published "New York City Transit Diesel Hybrid-electric Bus Site Final Data Report." This report is based on real-world data collected on the operation of 10 Orion VI series diesel fueled HEBs with BAE Systems technology. The buses were precommercial pilot products and were accepted by New York City Transit (NYCT) with the understanding that maintenance, performance, and reliability might not be up to the expectations of a commercial product.

BAE SYSTEMS Orion VI
Series Hybrid Electric HybriDrive™
NYCT Transit Bus

Source: NYCT

The prototype buses logged over one million fleet miles of revenue service, showing a 10 to 20 percent improvement in fuel economy over 24 months of usage from the vehicles' lead acid batteries and doubled brake life. The HEBs were widely accepted by drivers and riders. Comparisons between these diesel HEBs and conventional NYCT diesel buses over 17,000 hours of operation per bus showed that the HEBs would eliminate about eight kilograms of PM, 0.331 tons of NOx, and 26.7 tons of CO_2. PM emissions from the HEBs were 99 percent lower than the conventional diesels', 44 percent lower for NOx, and 33 percent lower for CO_2.

NYCT Hybrid and Conventional Diesel Buses Manhattan Cycle					
	HEB (g/mi)	**Diesel (g/mi)**	**Percent Reduction**	**Incremental Emissions (g/mi)**	**Incremental Emissions (tons/year)**
PM	<0.005	0.48	99%	Approx. –.475	.001 ton (17.75 lbs.)
NOx	22.6	40.3	44%	–17.7	.331
CO_2	2841	4268	33%	–1427	26.7

Source: West Virginia University Manhattan-cycle dynamometer testing of NYCT hybrid and conventional diesel buses

NYCT ordered 325 of BAE Systems' next generation Orion VII buses to be delivered beginning in 2004, with options for 50 more in 2006. Unlike the Orion VI demonstration program, these 325 buses will be commercial products that have been more fully optimized for fuel economy and emissions. Results from one pilot bus already in service and operating for 21 hours per day indicate no propulsion system problems and 30 percent better fuel economy.

BAE SYSTEMS Orion VII
Series Hybrid Electric HybriDrive™
NYCT Transit Bus

Source: NYCT

In February 2000, the Northeast Advanced Vehicle Consortium (NAVC) released the final emissions report on its “Hybrid-Electric Drive Heavy-Duty Vehicle Testing Project” that compared the real-world efficiency and emissions of conventional buses fueled by ULSD and CNG with diesel HEBs in the fleets of Boston and New York City transit operators. The buses were evaluated over six different emission test cycles with average speeds ranging from 3 to 17 miles per hour and duty cycles ranging from 4 to 18 stops per mile. The results demonstrated that diesel HEBs offer reduced drive cycle emissions relative to conventional diesel buses and comparable to those achieved by conventional CNG buses.[39] The HEBs reduced PM emissions by 50 to 70 percent, NOx emissions by 30 to 40 percent, and CO emissions by 70 percent over conventional diesel. The hybrids also obtained 30 to 65 percent higher fuel economy than conventional diesel and as much as 100 percent better fuel economy than CNG buses when operated on severe duty cycles. In most cases, HEBs set the in-use emissions benchmark, except for NOx emissions.[40]

Although it wasn’t based on a transit bus application, another important recent testing of heavy-duty hybrid emissions came from a collaboration between Federal Express and Environmental Defense. The goal of this collaboration was to develop a delivery truck for Federal Express that met rigorous environmental, fuel economy, and price standards. The winning prototype, from Eaton, reduced NOx by 54 percent and PM by 93 percent, and improved fuel economy by 45 percent.

Summary of Southwest Research Institute FTP Test Results
Source: Environmental Defense, *FedEx-Alliance Future Vehicle Program Eaton Hybrid Electric Vehicle Description & Measured Performance* March 24, 2003

FedEx Requirements	FedEx FVP Program Targets	Comparison of Eaton Hybrid Truck to the Baseline Truck
Fuel Economy Requirements		
Fuel Economy (MPG)	50% Increase	45% Increase
Environmental Requirements		
NOx (g/mile)	90% Reduction	54% Reduction
PM (g/mile)	90% Reduction	93% Reduction
Functional Requirements		
Payload Capacity - Weight (lbs.)	Same as baseline	within 330 lbs.
Payload Capacity - Volume ($ft.^3$)	Same as baseline	Unchanged - no intrusion to cargo area
Cruise Speed (MPH)	Same as baseline	Unchanged
0-60 MPH Acceleration (seconds)	Same as baseline	16% improvement
Braking System	Same as baseline	Unchanged
Range (miles)	Same as baseline	Unchanged - downsized fuel tank for weight reduction
Turning Radius (feet)	Same as baseline	Unchanged
Maximum Launch Grade (%)	Same as baseline	52% Improvement
Maximum Grade at 55 MPH (%)	Same as baseline	28% Improvement
Cost Requirements		
Lifetime Cost (Cents / Mile)	Cost competitive	Improved over baseline

Hybrid Electric Cost Effectiveness

Cost is a critical factor that can either encourage or dissuade the acquisition of hybrid electric transit buses. With the incremental cost of HEBs between $100,000 and $200,000, an important question is whether the lower cost of fuel and fewer brake replacements needed by HEBs will recoup the incremental cost of the buses. While it would be premature to conclude the true lifetime cost of acquiring and operating production hybrid vehicles due to the immaturity of the industry and lack of definitive data, a few initial analyses give an idea as to the cost and operational criteria where hybrids prove beneficial.

Recent Hybrid Electric Bus Purchase
King County Metropolitan Transit Authority and Sound Transit
King County, WA

Hybrid Bus	60-foot, articulated diesel electric parallel hybrid
Powertrain	General Motors Allison Transmission; Caterpillar C9 ACERT engine
Bus Manufacturer	New Flyer Industries
Purchase Announcement	October 2003
Quantity	235 (213 for King County Metro and 22 for Sound Transit)
Price	**$645,000 each**
Premium Over Similar Conventional Bus	**+$200,000**

Source: New Flyer Industries

2000 Transportation Research Board HD HE bus study

The National Research Council's Transportation Research Board (TRB) 2000 study, titled "Report 59, Hybrid-Electric Transit Buses: Status, Issues, and Benefits," used an analytical framework that spread the capital acquisition cost of Orion VI HE buses over 15 years. It assumed 27,000 miles of driving per bus per year, a fuel cost of $0.72 per gallon, and four lead-acid battery pack replacements at 3-year intervals. The cost estimates for these battery packs were between $5,000 and $12,500 per pack, based on the type used, bringing the lifetime estimate for cost of battery replacement to between $20,000 and $50,000. The study concluded that the 15-year total lifetime cost of a $400,000 HEB, including capital, fuel, batteries, and maintenance, would be about $1,232,000, compared with $1,011,000 for a diesel bus with an initial cost of $280,000, resulting in a cost increment for the hybrid technology of $221,000.

The study noted that the major factor determining whether total lifetime HEB costs fell above or below that of a diesel bus was the cost of a hybrid's batteries. The study added that an HEB would need production volumes of at least 1,000 annually in order to lower maintenance and battery costs to be competitive with conventional diesel buses.

A $221,000 incremental cost for an HEB spread over the course of the 15 years of service translates to $14,733 per year. Even with the lower-priced battery pack, the premium would only be reduced by $2,500 annually, bringing the figure down to $12,333. Certainly, many other factors could come into play to skew these figures, such as the price of fuel, lower cost of maintenance as repair expertise increases, and the rising cost of diesel systems as they begin to comply with 2007 and 2010 EPA standards.

NREL report on one year of NYCT hybrid bus operation

Each of the 10 preproduction Orion VI buses that were part of NYCT's hybrid bus operation, described above, cost $474,900, while the Orion VII HEBs will cost $385,000 each for its order of 325 units, about $100,000 more than a conventional diesel bus.

The NYCT experience with Orion VI hybrid buses revealed reduced fuel and brake costs, but increased maintenance costs that more than offset the savings. Of the 10 HEBs, the first five delivered had higher maintenance costs, so the NYCT defined them as "older" and the later ones as “newer” to separate the higher and lower levels of maintenance costs in analysis.

Per Mile Costs of NYCT HEB Operation Manhattan Duty Cycle	
Fuel	$0.39
Older HEB Maintenance (including brakes)	$1.90
Older HEB Brakes	$0.17
Newer HEB Maintenance (including brakes)	$1.36
Newer HEB Brakes	$0.14

Assumptions: $1.03/gallon fuel costs, 2.65 miles per gallon, 17,000 miles per year
Source: National Renewable Energy Laboratory

NYCT HEB Fuel and Maintenance Incremental Costs
Manhattan Duty Cycle

	Percentage Increase/Decrease	Cost per Mile ($)	Cost per Year ($)
Older HEBs			
Fuel Consumption	– 9	– .03	– 510
Brake Costs	– 12	– .02	– 340
Incremental Cost of Maintenance (excluding brakes)	+ 179	+ 1.14	+ 19,380
Incremental Cost of Fuel and Maintenance (including brakes)	+ 90	+ 1.08	+ 18,360
Newer HEBs			
Fuel Consumption	– 9	– .04	– 680
Brake Costs	– 27	– .05	– 850
Incremental Cost of Maintenance (excluding brakes)	+ 103	+ .64	+ 10,880
Incremental Cost of Fuel and Maintenance (including brakes)	+ 45	+ .55	+ 9,350

Source: National Renewable Energy Laboratory

Beginning in 2010 when the full force of the federal and California emission standards is effective, HEBs will be well positioned to enter the marketplace. Some bus manufacturers are even predicting that hybrid electric powertrains will be the most attractive candidate. This prediction is based in part on the testing results of the Allison hybrid drive system. While the 2004 Allison system sells for roughly $154,000 per unit, reflecting a $130,000 to $140,000 premium over conventional automatic transmission systems, the incremental cost will most likely be less than $100,000 by 2006. Suppliers state that once that figure reaches about $80,000, the cost-effectiveness of hybrid systems will be attractive to bus purchasers.

Hybrid Electric Maintenance

One encouraging aspect of the NYCT experience with the Orion VI HEBs has been that maintenance costs were lower in the newer group of buses than in the older. NYCT reports that this was due in part to their mechanics' becoming more familiar with the hybrid electric systems. Despite the fact that maintenance costs were not well understood at that time, the TRB study made estimates of HEB maintenance costs between $1.44 and $1.76 per mile. This estimate is only 5 to 7 percent lower than the NYCT's real world range of $1.36 per mile for the older HEBs and $1.89 for the newer ones. This is encouraging in that it demonstrates that HEB maintenance costs, while higher at this stage of product development, are likely to follow conventional learning curves and drop over time.

Justifying Higher Hybrid Electric Costs

Although transit authorities may not benefit monetarily from the use of HEBs now, their lower emissions compared to the diesel bus can serve as justification for higher lifetime costs. The added lifetime costs are estimated to be between $12,333 and $14,733 per year to eliminate 50 percent of the PM, 36 percent of the NOx, 19 percent of the CO_2, and 53 percent of the volatile organic compounds (VOCs) from a diesel engine. Transit operators must determine whether this amount of pollution abatement justifies the incremental cost.

In some areas, mobile pollution sources, including bus fleets, can sell air pollution credits resulting from using low-emissions vehicles to stationary businesses. This practice puts a monetary value on lowering emissions and allows fleets to recoup some of the premium for hybrid electric technology. The TRB report used the figures of $1,000/ton for NOx and $3,000/ton for VOCs as the rate for emissions credits. It therefore priced the NOx and VOC emissions mentioned above at $324 and $5 per year per bus, respectively. With application of these pollution credits, the incremental costs are reduced slightly to between $12,004 and $14,404.

Other justifications for higher HEB prices are intrinsic attributes not found in competing vehicles. For instance, HEBs are powered by downsized engines that, when configured with a dual-parallel system, are propelled part of the time totally by the electric motor with the engine turned off. These two features can combine to dramatically reduce the noise that HEBs make compared to conventional diesel and natural gas vehicles, especially in urban areas where stop-and-go driving is prevalent. Furthermore, the reduced noise level along with a potentially smoother ride with less vibration can increase ridership, while an HEB's advanced electronic system can allow amenities, such as laptop computer power access, to be available to riders.

Percent Change Relative to Diesel

	GHG	PM	NOx	CO	Fuel Efficiency Gain	Cost Premium
Diesel Hybrid Electric[1]	-35	-99	-44	-70	30 to 65	$100K to $200K
Gasoline Hybrid Electric[2]	-25	> -90	> -95	-25	> 20	$100K to $200K

Sources: [1]NREL, NAVC, NYCT; [2]ISE Research

Hybrid Electric Domestic Bus/Drive System Manufacturers		
	Manufacturer	**Details**
Drive Systems	BAE Systems	HybriDrive™ series hybrid; 250hp (320hp peak); Cummins ISB 5.9L engine; 2700 @ 0 RPM
	Allison Transmission	EP 40 split-parallel hybrid; 280hp (350hp peak); Cummins ISB engine; 910 @ 2300
		EP 50 split-parallel hybrid; 330hp (400hp peak); Cummins ISB engine/Caterpillar C9; 1050 @ 2300
	ISE Corporation	TB-40HD series hybrid; 214hp (386 peak); Cummins ISB02 direct injection diesel engine
		TB-40HG series hybrid; 214hp (386 peak); Ford Triton V-10 6.8L;
Buses	New Flyer	DE40LF 40-ft bus; Allison EP 40 parallel hybrid
		GE40LF 40-ft bus; ISE Corporation TB-40HG series gasoline hybrid
		DE60LF 60-ft bus; Allison EP 50 split-parallel hybrid system
	Orion	Orion VII Low Floor 40-foot bus; BAE Systems HybriDrive™ series hybrid
	Gillig	40-foot bus; Allison parallel hybrid system

Sources: Various manufacturers

Emerging and Future Technologies and Fuels for Meeting BRT Demands

There are a number of emerging technologies that can play a role in reducing the emissions of BRT vehicles in the coming years and decades. None are commercially viable at this time, although some are likely to be simple and easy to implement. Others will involve radical changes in vehicle propulsion design. The level of uncertainty is higher than that for currently available technologies and fuels for each emerging and future technology. The groundwork and early implementation results of these technologies can provide a sense about the technologies' potential BRT applicability and demand.

NOx Adsorber Aftertreatment

NOx adsorbers work by capturing emissions that are generated through lean engine operation. Once the device becomes saturated, the exhaust system runs rich for several seconds, which reduces stored NOx to nitrogen. NOx adsorbers have demonstrated the ability to reduce NOx emissions by 95 percent with an associated 1.5 percent fuel economy penalty. These systems are currently very complex and expensive, with the amount of precious metals for a single 12-liter engine alone costing about $4,300.[41] It also suffers from reduced durability due to degradation from excessive sulfur levels and catalyst sensitivity. While there is speculation that simplified and cheaper systems will prove effective for light-duty applications, it is questionable whether a simplified and cost-effective system for heavy-duty applications will emerge. Caterpillar suspects that overcoming cost, complexity, and durability issues for heavy-duty applications will require enormous research and significant breakthroughs.[42]

Renewable Biogas

In the future, natural gas may be produced as "biogas," which is methane extracted from sources such as landfills, sewage treatment plants, and slaughterhouse wastes. Most promising from an environmental standpoint, biogas can also be produced as a GHG-neutral, renewable fuel from biomass (forestry and agricultural wastes), energy crops (such as corn and soybeans), and the anaerobic digestion of animal manure. The current difficulty with biogas as a source of propulsion is that it needs to be purified before it can be used in vehicles. After purification, however, the gas is so pure that engines actually perform better on biogas than they do on natural gas.

Sweden, which has no domestic sources of natural gas, has been a pioneer in the production of biogas for vehicle use. The country has already established six biogas plants and 25 biogas stations that support over 2,500 vehicles and demonstrated the fuel's applicability in the transportation market. Sweden aims to provide 5 percent of its transportation sector fuel as biofuel in 2005 and has planned 40 new filling stations through 2006. WestStart-CALSTART, in partnership with Business Region Goteborg, formed the California-Sweden Biogas Initiative in late 2003 to capitalize on the advances made in Sweden and expand the production and use of biogas in California.

The success of this initiative and the eventual domestic establishment of biogas as a fuel for vehicles depend in part on the fuel's economic advantages. Because biogas production creates economic value for agricultural and animal waste that is normally discarded at a financial detriment, the economics behind biogas production and use may actually become one of its strongest attributes, especially as the problems associated with agricultural waste disposal brought about by the consolidating agricultural industry increase. Furthermore, renewable biogas production and use can help achieve other goals that provide associated benefits to domestic industries and society, such as reducing foreign energy dependence and potential sources of groundwater contamination.

Gas-to-Liquid (GTL) Fuel and Blending Stock

GTL, also known as Fischer-Tropsch diesel, is a backwards-compatible liquid fuel that is manufactured primarily from natural gas. Most of the attention on GTL fuels has centered on how its production can be profitable in remote natural gas fields that are too distant from markets to justify transportation of raw natural gas. When a GTL plant is built at the well site, the resulting product is a higher-value, energy-rich, cleaner alternative fuel than diesel.

GTL fuels have virtually no sulfur, are not toxic to animals, are lower in aromatic content and biodegradable, have a higher cetane number and lower aquatic toxicity than diesel fuel, and exceed all World-Wide Fuel Charter specifications, except density.

Fuel Properties
GTL vs. #2 Diesel

Property	GTL	#2 Diesel
Total Aromatic %	0.1-2%	35%
Density at 15 degrees Celsius (g/cm^3)	0.7695-0.7905	0.8464
Cetane Number	>74	44.9
Sulfur Content (ppm)	<1	15 (for low-sulfur diesel)
Hydrogen (wt %)	~15	13-15.5

Source: Oshinuga, Adewale, *Diesel Fuel Advancement, Gas-to-Liquid Fuel*, SCAQMD, presented at the California Air Pollution Control Officer's Association (CAPCOA) Conference on Diesel, January 27, 2004 (originally printed in: *Oil & Gas*, July 2002); Ken Kimura, British Petroleum.

As of June 2002, there were eight operating GTL plants:

Existing GTL Plants
as of June 2002

	Location	Capacity (barrels per day)	Feedstock
Sasol	South Africa	175,000	Coal
Mossgas	South Africa	30,000	Natural Gas
Shell Bintulu	Malaysia	12,500	Natural Gas
BP	Alaska	300	Natural Gas
Synfuels	Texas	12	Natural Gas
Synenergy	Calgary	4	Natural Gas
Syntroleum	Oklahoma	2	Natural Gas
Rentech	Colorado	<1	Simulated Syngas

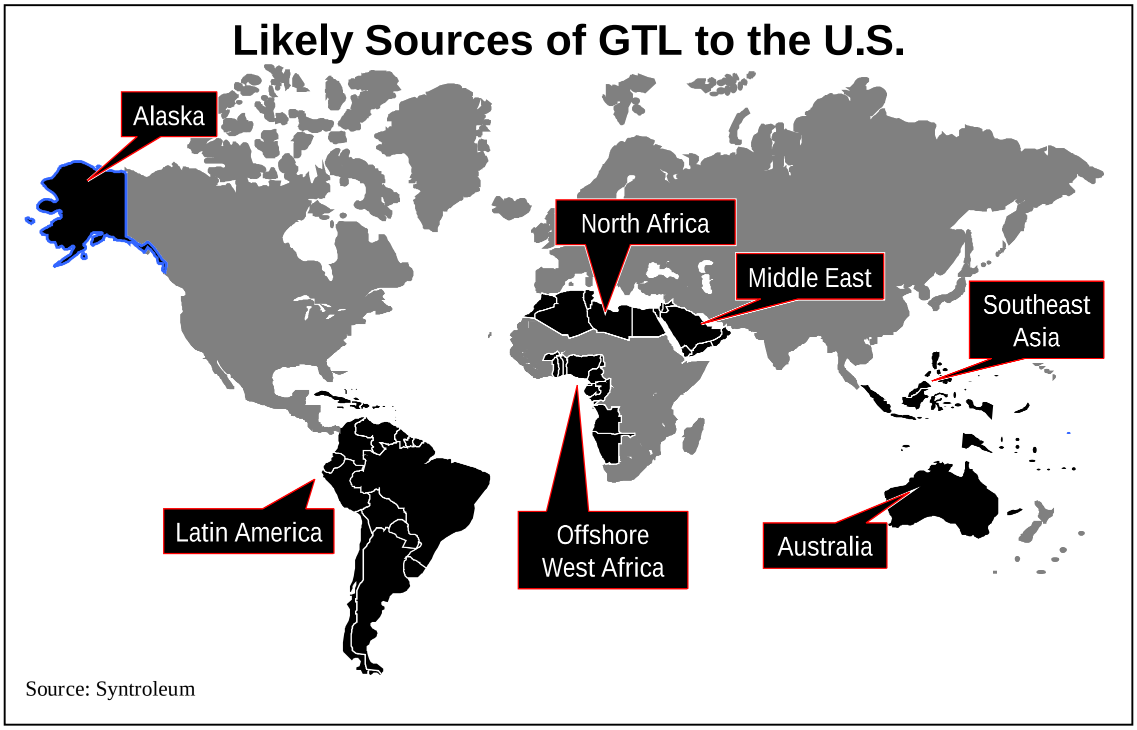
Source: Oshinuga, Adewale, *Diesel Fuel Advancement, Gas-to-Liquid Fuel*, SCAQMD, presented at the California Air Pollution Control Officer's Association (CAPCOA) Conference on Diesel, January 27, 2004 (originally printed in: *Oil & Gas*, July 2002).

In addition to these existing GTL plants, nine more projects were announced as of June 2002:

Announced GTL Projects as of June 2002			
	Location	**Capacity (barrels per day)**	**Feedstock**
Syntroleum	West Australia	11,500	Natural Gas
Chevron/Sasol	Nigeria	34,000	Natural Gas
Sasol/Qatar Petroleum	Qatar	34,000 (with eventual expansion to 120,000)	Natural Gas
Shell	Indonesia	75,000	Natural Gas
Shell	Iran	75,000	Natural Gas
Shell	Trinidad & Tobago	75,000	Natural Gas
Shell	Egypt	75,000	Natural Gas
Ivanhoe Energy	Egypt	45,000	Natural Gas
Shell	Qatar	140,000	Natural Gas
Ivanhoe Energy	Qatar	165,000	Natural Gas

Source: Oshinuga, Adewale, *Diesel Fuel Advancement, Gas-to-Liquid Fuel,* SCAQMD, presented at the California Air Pollution Control Officer's Association (CAPCOA) Conference on Diesel, January 27, 2004 (originally printed in: *Oil & Gas*, July 2002).

Chevron anticipates that its Escravos, Nigeria, site will become a commercial reality in 2007, producing 34,000 barrels per day, while the Sasol/Qatar Petroleum Project will become a commercial reality in 2005. Although the volumes of GTL produced will not replace conventional diesel, they will offer a viable blendstock option to raise general diesel quality.



GTL may profitably develop remote gas fields that are
too distant from centers of use and distribution.

In the past, Shell blended GTL with diesel to lower the sulfur content and sold the blend in California for several years. It is now supplying the mixture to Thailand and other markets. With studies showing no perceived difference from diesel fuel, customer acceptance of the blend is good.

GTL technology can be used to produce customized “designer fuels” that will enable engines to improve efficiency while lowering emissions. Tests on GTL fuel conducted at the Southwest Research Institute have shown lower NOx and PM emissions than diesel fuel, attributed to GTL’s relatively high hydrogen/carbon ratio, high cetane number, and low sulfur and aromatic content. There are currently multiple demonstration projects in progress to assess the emissions reduction potential and durability of GTL fuel along with aftertreatment devices. One program, sponsored by the SCAQMD, DOE/NREL, Shell, Yosemite Waters, and Johnson Matthey, consists of six vehicles, three with PM traps and three without PM traps, and is designed to assess and compare engine performance when burning GTL fuel. Another project is looking at the performance of GTL fuel in engines using EGR, lean NOx catalyst, and catalyzed PM trap technologies. Although both projects will not be completed until November 2004, the second project is already showing the benefits of GTL through dynamometer tests.

Engine Dynamometer Emissions (g/bhp-hr)				
	NOx	**Total HC**	**PM**	**BSFC**
ARB LS Diesel	2.08	0.33	0.125	197
GTL w/o aftertreatment	1.96	0.22	0.102	192
GTL w/ aftertreatment	1.17	0.04	0.005	205

Source: Oshinuga, Adewale, *Diesel Fuel Advancement, Gas-to-Liquid Fuel,* SCAQMD, presented at the California Air Pollution Control Officer's Association (CAPCOA) Conference on Diesel, January 27, 2004 (originally printed in: *Oil & Gas*, July 2002).

Percentage Change Relative to LS Diesel GTL				
	NOx	**Total HC**	**PM**	**Fuel Penalty**
GTL w/o aftertreatment	-6	-33	-18	5 to 10
GTL w/ aftertreatment	-44	-88	-96	5

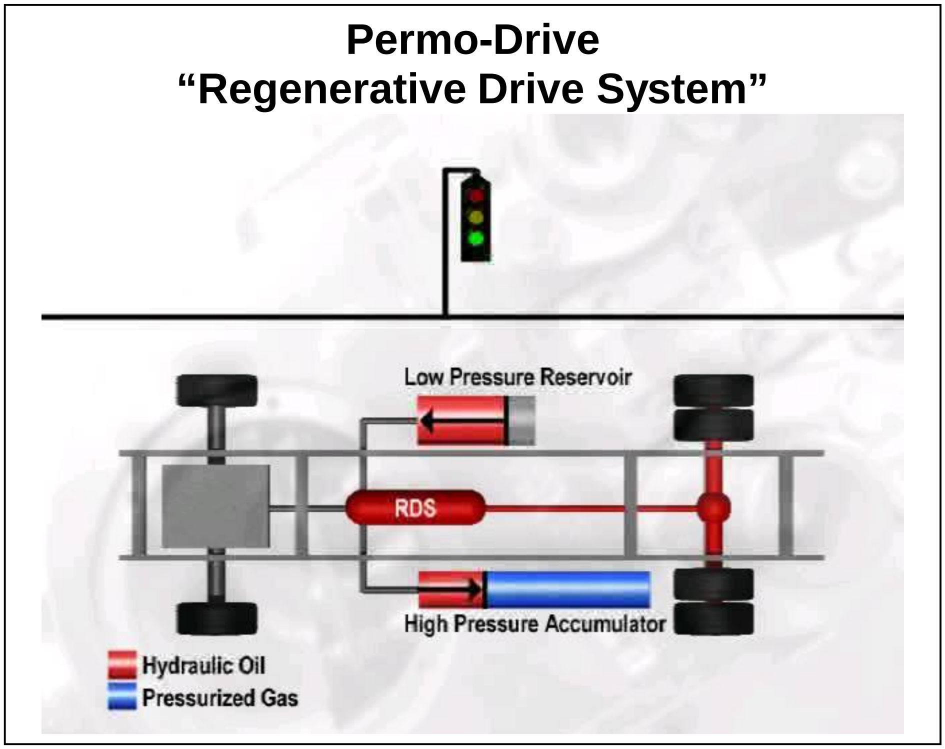
Source: Oshinuga, Adewale, *Diesel Fuel Advancement, Gas-to-Liquid Fuel,* SCAQMD, presented at the California Air Pollution Control Officer's Association (CAPCOA) Conference on Diesel, January 27, 2004 (originally printed in: *Oil & Gas*, July 2002).

The results of previous studies suggest the use of GTL fuels with NOx and PM trap technologies may lead to longer technology life, longer regeneration cycle time, reduced maintenance intervals, and increased engine life.

With the predictable increase in demand for cleaner fuels in the next ten years, GTL fuels may transition from a product waiting for a market to a product the market will seek. With the need for increased production of cleaner, reformulated, and designer fuels, the demand side of the equation may take over and pull greater quantities of GTL fuels into the market.

Hydraulic Hybrids

Hydraulic hybrid technology is emerging as a less expensive method to provide the benefits of a hybrid drive system. While hybrid electric vehicles capture regenerative energy in batteries or ultracapacitors, hydraulic hybrids capture this energy in the form of pressurized hydraulic fluid in an accumulator. When the vehicle requires boost power, pressurized gas in the accumulator forces the hydraulic fluid through a hydraulic motor, providing power to the vehicle's driveshaft, and into a low-pressure reservoir. When the vehicle brakes or if the pressurized hydraulic fluid drops below a certain level, the hydraulic motor turns into a hydraulic pump, utilizing the vehicle's engine to force the fluid from the reservoir back to the accumulator. Hydraulic hybrid technology has not yet been applied commercially to transit buses, but it has been tested in several other vehicle types with encouraging results.



Source: Permo-Drive

The low-pressure reservoir and high-pressure accumulator work in conjunction to store energy in the form of pressurized hydraulic fluid and release energy to provide motive assistance.

A higher percentage of regenerative energy can be captured and released in hydraulic hybrid systems than in hybrid electric systems. This ability to provide greater assistance upon startup and to capture more energy during frequent stops can provide significant advantages for HEVs in urban driving cycles, such as transit buses, that accelerate and decelerate often. What the impacts are for BRT vehicles, which operate at cruising speed for longer distances and experience fewer startup and stops than typical transit buses, is unknown. Depending on the size of the accumulator, reservoir, and amount of stored hydraulic fluid, tests to date suggest hydraulic hybrids can provide the fuel economy, engine life, reduced brake wear, and reduced driveline component wear benefits of hybrid electric systems. In fact, Charles Gray of the EPA stated that fully optimized hydraulic hybrid systems have the capability of improving fuel economy from 70 to 85 percent.[43]

Permo-Drive Technologies Ltd. has an experimental hydraulic hybrid concept vehicle that achieved a 15 percent reduction in time, 17 percent reduction in distance, and 20 percent reduction in fuel consumption to accelerate from 0 to 100 kilometers per hour, compared to a conventional vehicle. The concept vehicle also achieved a 17 percent reduction in time and a 15 percent reduction in distance to decelerate from 100 to 50 kilometers per hour. More recent tests have demonstrated a 37 percent reduction in fuel in a simulated urban drive cycle analysis. However, these results do not include open highway cycles, where retardation and propulsion assistance is minimally required.

Eaton Corporation, in collaboration with the Ford Motor Company and the EPA, also developed a hydraulic hybrid system for heavy-duty vehicles as part of a larger hydraulic hybrid development effort for automotive and commercial powertrains. Its hydraulic launch assist (HLA™) technology initially debuted at the 2002 North American International Auto Show, and a second-generation system was displayed at the 2003 Michelin Challenge Bibendum in a Ford F350 TONKA Super Duty truck. The EPA states that a Ford Excursion equipped with HLA™ achieved an 85 percent improvement in fuel economy over the standard urban driving cycle.[44] HLA™ is a parallel hybrid regenerative braking system that is targeted at Class 2B through Class 8 commercial vehicles. Eaton states that HLA™ can provide a 25 to 35 percent improvement in fuel economy and similar reductions in exhaust emissions in light duty trucks, with even higher percentages in heavier vehicles, when the driving cycle involves frequent starts and stops. Eaton states that the HLA™ product could be ready for commercial introduction by mid-decade and that the total potential of this technology could approach $500 million industry-wide by the end of the decade.

Eaton Corporation
Hydraulic Launch Assist (HLA™)

Battery Electric

Electric vehicles powered by batteries emit no tailpipe air pollution. Even after factoring in power plant emissions that are created to generate electricity used to charge onboard batteries, their total emissions levels are drastically improved over other vehicles. Battery electric vehicles provide riders with a quiet, smooth, and fast riding experience that reduces the vibrations and hesitations experienced with ICE vehicles. Furthermore, with only one moving part in battery electric motors, they require significantly less maintenance than ICE vehicles.

In the early 1990s, battery technology was predicted to progress to the point where it could power electric vehicles for a sufficient range at a competitive cost. Since then, batteries have improved drastically, with new technologies such as nickel-metal hydride and lithium ion providing superior energy density and performance characteristics to traditional lead-acid batteries. However, batteries still cannot provide vehicles with comparable gasoline-powered operational range and cost. Full size 40-foot battery electric buses have been successfully operated for niche routes, yet for typical transit applications, the issue is the number of batteries that are required to provide a bus of this size with an adequate range and the batteries' associated weight and costs. Although San Francisco's MUNI is considering making significant use of battery powered transit buses with 100-mile ranges as part of its "Zero Emissions 2020" clean air plan, the application of battery-only electric vehicle drive systems to bus applications has been primarily confined to smaller 22- and 30-foot vehicles that have limited routes. Promising markets for these buses include shuttles for universities, ski resorts, and amusement parks.

Embedded Power Collection—Opportunity Charging

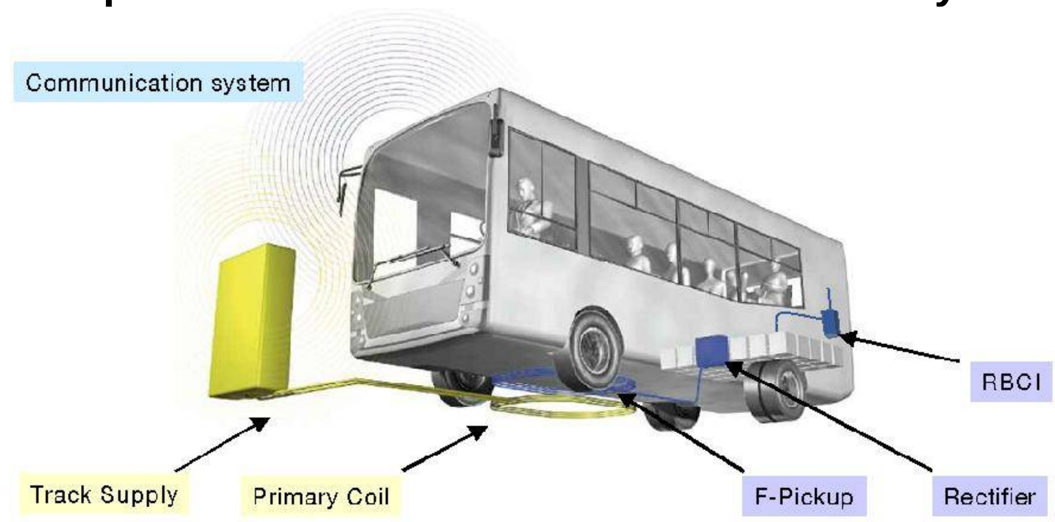
To avoid the drawback of limited range and long recharging times associated with battery electric buses, transit authorities can utilize these vehicles in combination with embedded power collection technology. This technology embeds electrical power in a roadway, track, or designated area to inductively recharge a battery-electric bus on an "opportunity" basis, thereby extending its range. When combined with the use of advanced batteries, opportunity charging may enable battery electric buses to extend their range to a practical level.

Inductive charging transfers electricity over an air gap using electromagnetic principles. Unlike conductive electricity transfer, no contact between transfer points is required, so the system is extremely safe in all weather conditions. Furthermore, the unobtrusive system can offer automated charging, reduced onboard battery capacity (e.g., by 33 to 50 percent), lower costs, increased battery lifetime, and increased vehicle efficiency.

Typically, inductive charge systems consist of primary and secondary parts that are magnetically coupled. The primary side is stationary and consists of a power supply linked to underground coils. The secondary side consists of energy pickups and rectifiers that are located on a vehicle. These pickups and rectifiers work in harmony with the underground coils to receive induced charging, while maintaining the designated air gap.

Wampfler, a global company with U.S. headquarters in Kentucky, has already implemented inductively assisted systems on a trolley in Los Angeles, California, and on E-Bus models in Genoa, Italy, that prove the validity of the system and identify where the application of the technology can be successful. The company's system, called IPT® (inductive power transfer) charge, aligns a vehicle's pickups and rectifiers with underground coils at designated stops. The vehicle automatically lowers its pickups to between 10 and 40 millimeters of the underground coupling and charges the vehicle's batteries during "dwell" times, when passengers are boarding or disembarking. As the vehicle prepares to depart, it automatically stops charging and raises its pickups while the primary side shuts off power.

Wampfler IPT® Embedded Power Collection System



Source: Wampfler

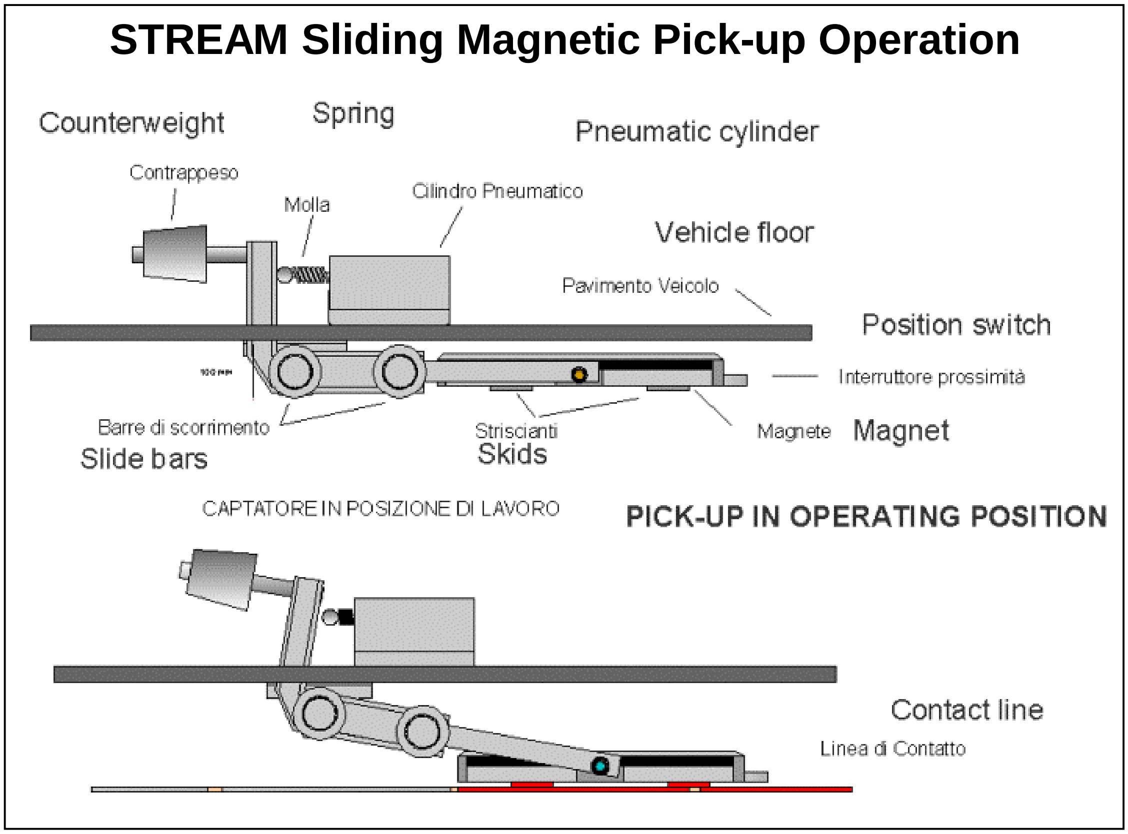
The track supply provides power to the embedded primary coil, which inducts electricity into the F-Pickup and through to the onboard batteries.

The system is described as intrinsically safe and has been certified by competent independent institutions according to existing norms (TUV, VDE 0848-4/A3). These results demonstrate that the magnetic field values do not exceed the current limits recommended by the safety standard committee for safe human exposure.

The number and distribution of primary systems is dependent on a number of variables, including the bus specifications, manufacturer, number sold, and site-specific route information. Assuming charging and battery systems can accommodate 60 kilowatts (kW) of power, the IPT® Charge system requires two 30 kW pickups and between one and two minutes of charge time per mile of travel for 20- to 22-foot buses. Because all of the systems now in use in the U.S. are unique, the company does not yet have general pricing information.

Embedded Power Collection—Continuous Conduction

In addition to opportunity charging systems, another emerging technology allows continuous electrical conduction from safe underground contact points to vehicles' electrical systems and motors. The system, dubbed "STREAM," was developed by Ansaldobreda of Italy and utilizes Neoplan dual-mode low-floor articulated buses for a demonstration project in Trieste, Italy. The system consists of a protected embedded contact line from which properly equipped buses can use sliding magnetic pick-ups to cause a flexible belt to rise and supply current to the bus' electric motors. The contact line is sufficiently submerged to prevent accidental electrocution to pedestrians, and non-STREAM vehicles are able to share the roadway with STREAM vehicles, as the track does not present obstacles. Buses in STREAM operation contain a reduced number of batteries needed to supply the sole source of power along stretches, such as on bridges, where contact line installation isn't feasible or desirable.



Source: Ansaldobreda

A pneumatic cylinder, attached to slide bars and skids, mechanically lowers the magnet into position.

The STREAM system can be a particularly good fit for BRT applications. It eliminates the poor aesthetics of catenary overhead wire operation, while providing all of its benefits, including limitless range, pure electrical drive qualities, higher speed operation, low maintenance, and zero emissions. The limited need for onboard batteries combined with the use of electric wheel motors increases the free interior space in BRT vehicles. Furthermore, designated BRT busways and lanes can be equipped with the 60 by 30 centimeter trench required to set the six meter long pre-cast concrete modules and can easily incorporate automated guidance devices that enable vehicle docking and driverless operation.

STREAM Bus and Contact Line Operation

Source: Ansaldobreda

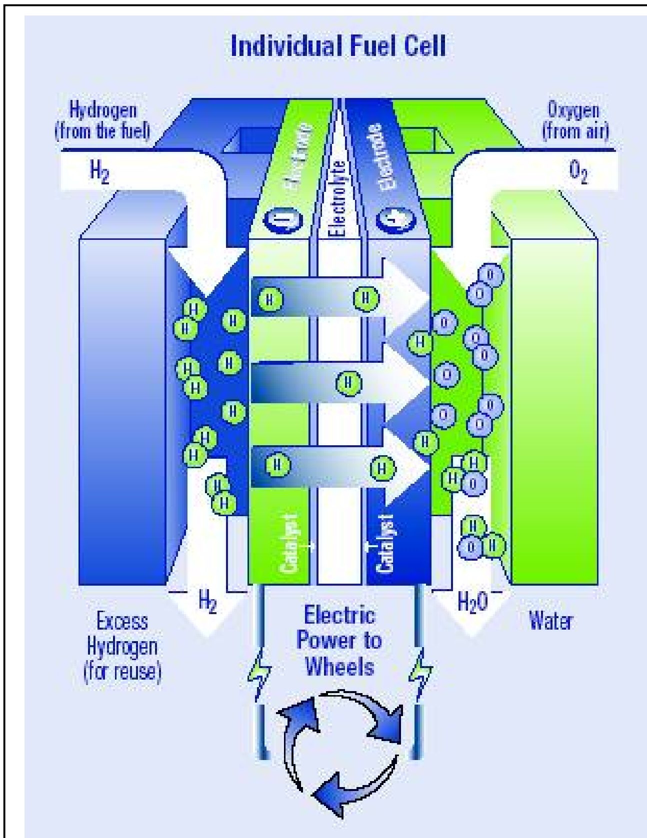
Hydrogen-Powered Buses

In recent years, hydrogen has gained attention as the likely fuel of the future due to its abundance (it is the most common element in the universe) and its potential to be a pollution-free energy carrier. For vehicle applications, hydrogen can either be used in fuel cells to produce electric current to drive an electric motor or it can be burned in a specially designed ICE. Hydrogen can be stored onboard a vehicle in the form of a hydrogen-rich carrier where it can be extracted by a reformer, or as a gas, liquid, or hydride that is obtained through offboard reformation or water electrolysis and used in a centralized hydrogen refueling structure. Centralized refueling along with fixed route operation, fewer packaging and weight constraints, the use of highly skilled mechanics and technicians, and a subsidized purchasing system make transit buses likely to experience an earlier transition to hydrogen than may be possible for light duty vehicles.

Fuel Cells

Electrolysis passes an electric current through water to separate hydrogen and oxygen and releases them as gases. Fuel cells operate using the same concept but in reverse, combining hydrogen and oxygen gas in an electrochemical reaction to produce electricity and water. Fuel cells consist of two electrodes (a cathode and an anode) that are separated by an electrolyte. A proton exchange membrane (PEM) fuel cell is the most common kind used for vehicle applications due to their high power density and ability to operate at low temperatures. In a PEM fuel cell, hydrogen is fed to the anode where a catalyst-coated membrane allows the hydrogen's proton to pass through but forces the hydrogen's electron through an electrical circuit to create electricity. The electron is then reunited with the proton and combined with oxygen, which is fed to the cathode, to produce water and heat, the fuel cell's only byproducts.

Fuel Cell Operation



Source: Department of Energy

Fuel cells create electricity by separating electrons from protons in hydrogen atoms.

In addition to PEM fuel cells, there are several other types of transit-applicable fuel cells that are characterized by the type of electrolyte used. The following table lists characteristics of each type of fuel cell now under development:

Fuel Cell Types and Properties

Fuel Cell	Electrolyte	Catalyst	Operating Temperature (degrees Celsius)	Fuel for Anode/Cathode
PEM	Solid polymer membrane	Platinum	80	Hydrogen/pure or atmospheric oxygen
Phosphoric Acid	Liquid phosphoric acid	Platinum	200	Hydrogen/atmospheric oxygen
Direct Methanol (DMFC)	Solid polymer membrane	Platinum	50–100	Methanol solution in water/atmospheric oxygen
Alkaline (AFC)	Solution of potassium hydroxide in water	Nonprecious metals	100–250	Hydrogen/pure oxygen
Molten Carbonate (MCFC)	Molten carbonate salt	Nonprecious metals	650	Hydrogen, methane/atmospheric oxygen
Solid Oxide (SOFC)	Ceramic oxide	Nonprecious metals	800–1,000	Hydrogen, methane/atmospheric oxygen

Sources: DOE HFC&IT Program (http://www.eere.energy.gov/hydrogenandfuelcells); Rocky Mountain Institute (http://www.rmi.org/sitepages/pid556.php); Fuel Cells 2000 (http://www.fuelcells.org/fctypes.htm)

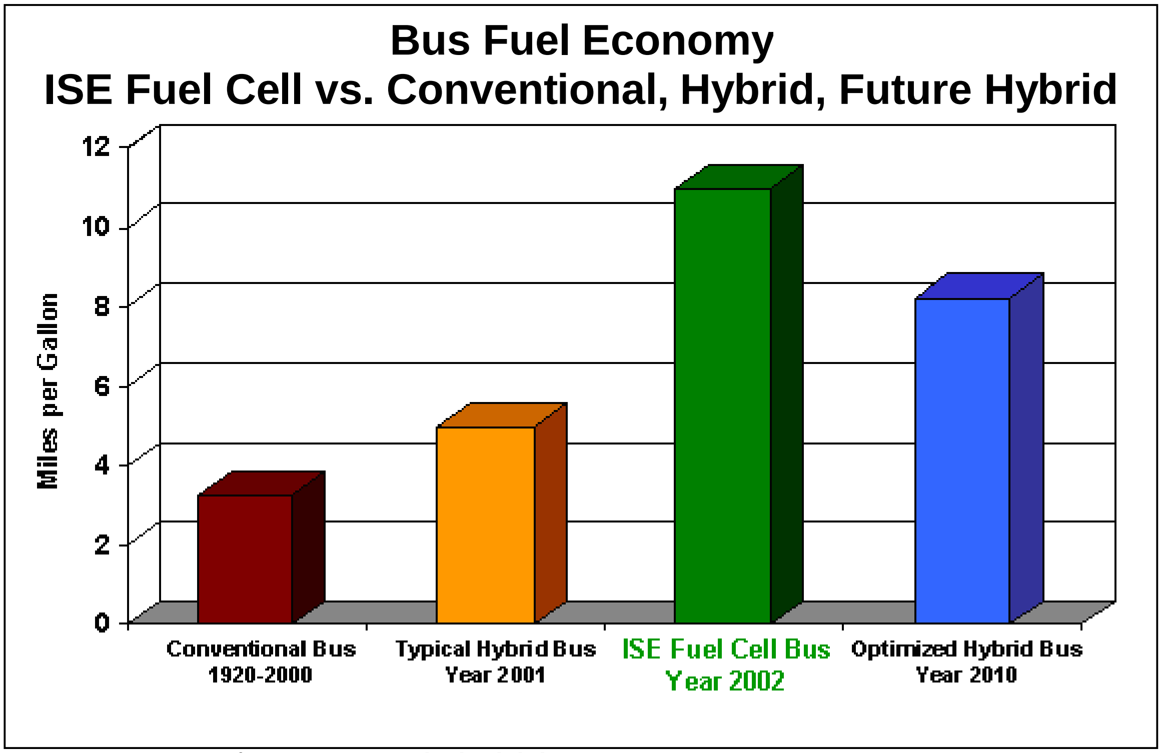
Buses powered by fuel cells provide the advantages of pure electric propulsion, including high torque at low speeds and quieter, smoother operation. Since fuel cell vehicles tend to integrate batteries or ultracapacitors into their vehicle platforms in order to regulate power loads, they also provide many of the advantages of hybrid vehicles as well, such as regenerative braking, that reduce energy consumption and maintenance costs. These features combine to provide a 20 to 30 percent increase in a vehicle's operating efficiency.

Although fuel cell buses have been operating as proof-of-concept vehicles since the early 1990s, routine passenger service is presently not common. SunLine Transit Agency completed a demonstration in February 2003 as part of a collaboration with the DOE's

Hydrogen, Fuel Cells, and Infrastructure Technologies Program. The bus was built by a joint venture between Thor Industries and ISE Research called ThunderPower and was a 30-foot pre-commercial version of the El Dorado National E-Z Rider 2. The vehicle ran for six months in Palm Springs, California, as a demonstration bus. The evaluation was successful, as the bus logged 8,800 miles, 655 fuel cell power plant hours, and obtained an energy-equivalent fuel economy 2.4 times higher than a similar CNG bus operating in the same service at SunLine.[45] The data gathered during the demonstration is being used to help fleets make informed purchasing decisions and help researchers assess whether fuel cell vehicles can meet commercialization requirements.[46]

Thor Industries and ThunderPower Fuel Cell Bus
SunLine Transit Agency

Source: ISE Research–Thunderbolt, Inc.



Source: U.S. Department of Energy; ISE Research–Thunderbolt, Inc.

The ISE (Thunderbolt) fuel cell bus, as demonstrated by SunLine Transit Agency, can achieve significantly improved fuel economy over conventional, typical hybrid, and future optimized hybrid buses.

Various manufacturers have produced dozens of other fuel cell buses, all of which have been limited production, expensive vehicles. Although the price is decreasing, fuel cell buses still cost several million dollars, up to 10 times the cost of a conventional diesel bus, which is a major hurdle to their implementation. The price of fuel cell buses must decrease dramatically before their cost is competitive with other transit bus propulsion systems. This will most likely be accomplished by the advancement of fuel cell technology, including reducing the number of parts used in a stack, automating the assembly, developing the supply chain, and reducing the cost of the catalyst and membranes. Government funded subsidies and purchase requirements that build production demand, such as the CARB's zero-emission bus requirement in its urban bus regulation, could also promote commercialization of fuel cell buses.

In addition to cost issues, transit-applicable fuel cells also need to overcome durability problems. Extreme demands are placed on transit buses, including long hours of continuous operation and significant annual mileage. These demands tend to exhaust a current-generation fuel cell's catalyst after about two years, or after 1,000 to 2,000 hours of operation. The durability of transit-applicable fuel cells needs to be brought to at least the same level as conventional transit powerplants, with their 10,000-hour operational lifetimes. Efforts to reduce the complexity of the fuel cell system will help reduce failure rates.

Fuel Cell Buses and Demonstrations

Fuel Cell Manufacturer	Partnership(s)	Demonstration	Quantity	Date
UTC Fuel Cells	ThunderPower LLC (Thor Industries/ISE Research)	SunLine Transit	1 bus	October 2002
	ThunderPower LLC (Thor Industries/ISE Research) and NABI	SunLine Transit and AC Transit (CaFCP)	4 buses	September 2005
	IrisBus	Turin, Italy	1 bus	2003
	NovaBus (Georgetown Bus Generation II)	Washington, D.C. Metropolitan Transit Authority	1 bus	1998–1999
Ballard Power Systems	Citaro	European Fuel Cell Bus Project	30 buses	May 2003
	Gillig	Santa Clara VTA	3 buses	2004
	MAN	Munich Airport	1 bus	2004
	NovaBUS	Georgetown University	1 bus	December 2001
	Zebus	SunLine Transit (CaFCP)	1 bus	September 2001
	P3 Bus	Chicago and Vancouver	6 buses	1998–2000
	NEBUS	DaimlerChrysler	1 bus	1997
Hydrogenics	New Flyer	Winnipeg, Canada	1 bus	2004–2005
DeNora	Neoplan	Italy	1 bus	October 1999
Proton Motor Fuel Cell GmbH	Neoplan	Munich, Germany	1 display bus	May 2000
Hino Motors	Toyota Motor Corporation	Tokyo Metropolitan Transportation Service	1 bus	August 2003
Electric Fuel Corporation	NovaBus	Regional Transportation Commission of Southern Nevada (Las Vegas) and Upstate New York	1 bus	2001

Source: NAVC (http://www.navc.org/whomakes.html)

Another issue that still needs to be resolved regarding fuel cell operation is functioning in sub-freezing temperatures, when water contained in a fuel cell freezes, incapacitating the system and possibly damaging the fuel cell itself. This issue is more of a problem in passenger vehicle applications than transit applications and is essentially an engineering and packaging issue. Also, the fuel cell's tolerance of contaminants in impure hydrogen needs to be increased. This problem is especially relevant when an onboard reformer is used.

Hydrogen-Powered Internal Combustion Engine Buses

In addition to fuel cell powerplants, conventional ICEs can be slightly modified to run on hydrogen. With the use of different fuel lines, fuel injectors, and combustion control techniques, ICEs burn hydrogen in their cylinders, yielding exhaust that is comprised mostly of water and trace amounts of criteria pollutants resulting from the combustion of lubricant oils. Proponents of hydrogen ICE transit buses believe one of their benefits is the ability to use hydrogen as a fuel in existing, low-cost engines, thereby bypassing the high cost, durability, and other unresolved technical issues of fuel cells.

A major argument against hydrogen ICE operation is that they require the use of additional or larger fuel tanks in order for a vehicle to achieve an equal range, because ICEs are less efficient than fuel cells. ICE hybrid technology can help overcome the range deficit, however, by significantly increasing the efficiency of ICEs and extending the hydrogen-fueled range. In fact, SunLine Transit of Palm Springs, California, is now testing the first hydrogen fueled HEB. The vehicle is powered by an electric motor in combination with a mass produced V-10 Ford engine that is typically used in Ford's sport utility vehicles. A second vehicle will begin service in Tel Aviv, Israel, in late 2005.

SunBus Hydrogen
Hybrid Electric Bus

Source: SunLine Transit

Hydrogen Production

Since hydrogen rarely exists unattached to another molecule, it needs to be isolated from hydrogen "carriers" before it can be used in fuel cells or ICEs. These carriers contain a significant number of hydrogen atoms that can be separated from their carrier molecules by steam reformation or other processes. Examples of effective hydrogen carriers are natural gas, GTL, methanol, and ethanol. Furthermore, passing an electrical current through water can produce hydrogen through electrolysis.

Steam Reformation

Steam reformation can be employed either onboard or offboard a vehicle to separate hydrogen from other atoms in hydrogen carriers. If the reformation process takes place onboard a vehicle, the hydrogen produced from it is fed immediately into the fuel cell. Onboard reformation, therefore, eliminates the problems of storing pure hydrogen, but it also increases the cost, bulk, and complexity of fuel cell systems.[47]

Reformation entails vaporizing the designated fossil hydrogen carrier and water and then passing the vaporized mixture through a chamber, heated by the fuel cell itself, that contains a catalyst where the molecules are separated into hydrogen, CO_2, and a small amount of CO. Because this process emits the global warming gas CO_2, it is not the cleanest or most sustainable form of hydrogen production. Still, the use of hydrogen carriers for vehicles can significantly reduce criteria and other pollutants to near-zero levels. Early onboard reformer technology had problems responding to fuel cell load transients due to the interdependency between the fuel cell's heat and the reformer's production of hydrogen used to create the heat. This issue has been overcome as current generation reformers produce transients comparable or even superior to ICEs.

Many experts believe that, in the short term at least, ***natural gas*** will be the primary feedstock for hydrogen. It has an established infrastructure, is a low cost fuel, has high hydrogen content (pure methane is about 80 percent hydrogen), and already has a history of being used in reformation processes at industrial facilities. Steam reformation converts natural gas to syngas, from which hydrogen separates easily from carbon atoms. Currently, the reformation of natural gas primarily takes place offboard, yet onboard natural gas reforming is possible. Offboard natural gas reformation may be beneficial for larger operations because it eliminates the need to have hydrogen delivered by truck and it also eliminates most of the need for hydrogen storage due to the continuous synthesis of pipeline natural gas.

GTL fuels have some advantages over natural gas since GTL fuel is fluid at ambient temperatures and can be stored onboard through the use of conventional methods. As GTL fuel production increases, it may substitute for natural gas as a popular onboard hydrogen carrier.

Another hydrogen carrier that has demonstrated its effectiveness in mobile applications is ***methanol***. Also known as methyl alcohol, methanol is a liquid produced mainly from natural gas that can be distributed through the existing diesel and gasoline fuel distribution infrastructure, can be stored at facilities and onboard vehicles at ambient temperatures and in a similar manner as diesel fuel, has similar maintenance facility requirements as diesel, and has an energy content that allows it to provide a comparable range to conventional buses. For example, a fuel cell bus built at Georgetown University uses reformed methanol as a fuel to provide a 300 to 350 mile range. Methanol's disadvantage is that it is a toxic substance that prompts consumer comparisons between it and the much maligned methyl tertiary-butyl ether (MTBE), a gasoline oxidation additive produced from methanol that was responsible for water pollution in states where it was used.

Ethanol, another oxygenate, is being promoted as an alternative hydrogen carrier that can provide many of the same benefits as methanol, such as storage, handling, and maintenance garage design requirements, without its drawbacks. Ethanol is an alcohol-based fuel produced either by fermenting and distilling starch crops that have been converted into simple sugars, such as corn, or from cellulosic biomass, such as wood wastes. Ethanol has greater energy content than methanol (26.8 vs. 19.9 kilojoules per gram), yet because of its more complex molecular composition, the reformation of ethanol is more difficult. For this reason, researchers and manufacturers have so far focused more on methanol than ethanol as a hydrogen carrier. However, this may change as the ethanol industry, which has great support from the U.S. Congress, seeks additional aid for the fuel's expansion of roles.

Water Electrolysis

In addition to reformation, hydrogen can be produced by electrolysis, which uses electricity to split water molecules into hydrogen and oxygen gases. Because of the intensity of the electrical input required for the process, electrolysis would only logically occur offboard the vehicle. High electricity prices define the cost of electrolytic hydrogen production. The large quantity of energy necessary to produce hydrogen using electrolysis usually makes it less cost effective as fuel reformation. However, hydrogen can be a truly pollution-free fuel by using renewable energy sources to produce it through electrolysis.

Onboard Hydrogen Storage

When hydrogen is produced offboard a vehicle, either through steam reformation or electrolysis, it can be stored onboard as either a gas, liquid, or as a solid chemical hydride. Gaseous hydrogen storage can be kept at room temperature, but 3,000 to 10,000 psi tanks are required. These tanks must be very large, even at very high pressures, to store enough hydrogen to provide a vehicle with a reasonable driving range.

Conversely, liquefied hydrogen can be produced at a remote plant, trucked to a cryogenic storage tank at a fueling facility, and then, similar to LNG, dispensed into onboard storage tanks as either a liquid or as a vaporized gas.[48] Liquefied hydrogen has a greater energy density than gaseous hydrogen, but it has to be stored at -253º C, which uses the equivalent of 25 to 30 percent of its energy sources.

Hydrogen hydride storage works on the principle that certain metal alloys, such as magnesium and nickel, absorb hydrogen and release it when heated. The system bypasses the complications involved with high-pressure and cryogenic storage, but encounters new ones concerning weight and methods for exchanging spent hydride on vehicles with hydrogen-rich hydride.

Linking BRT Fuels and Propulsion Systems with BRT Characteristics

Implementing BRT is an opportunity to create a new concept, or “brand,” in bus travel through the use of unique service and design characteristics. The clean-fueled, reduced emissions performance of BRT vehicles differentiate them from older, dirtier cousins and establish them as futuristic vehicles capable of meeting current and future emission standards. It is not surprising that transit communities prefer two-thirds of their vehicles to be powered by the clean fuels and propulsion systems discussed in previous chapters.

BRT fuels and propulsion systems must also meet the other demands of BRT vehicle and system operation characteristics. These characteristics begin with the size of the vehicles, which serve popular routes and are therefore higher capacity. Passengers notice the quieter operation of BRT vehicles and their appealing designs, both of which also aid community acceptance. Low-floor interiors eliminate the time consumption and inconvenience associated with climbing multiple steps on other buses. BRT systems have been implemented without the use of some of these features, but using them in combination can further establish an integrated system and can help maximize BRT’s potential to create an independent association with transit. As demonstrated by the examples below, various fuels and propulsion systems can operate successfully in conjunction with these BRT characteristics.

Larger, Higher Capacity Buses

Because of the fast, high-quality service that BRT offers along popular, well-traveled corridors, ridership can be significantly higher than in non-BRT corridors. This increase in demand translates into either a need for more frequent service, higher-capacity carriages, or both. A recent study of 26 major BRT case studies from around the world showed that in almost all of them, demand was heavy enough, ranging up to 20,000 or more passengers per hour, that utilization of high capacity, articulated buses with a total capacity (standing and seated) of at least 65 places was essential for the cost effectiveness of operation and maintenance.[49] Indeed, high-capacity carriages are often preferable because fewer vehicles are required for service, which translates into fewer drivers and lower maintenance and fuel charges.

WestStart-CALSTART's 2004 BRT Vehicle Demand Analysis indicated that transit communities prefer 63 percent of their vehicles to be articulated, larger-engine buses, which is significantly higher than non-BRT transit corridor applications. While several domestic BRT services, such as the Los Angeles Metropolitan Transportation Authority's (MTA's) MetroRapid and the Massachusetts Bay Transportation Authority's Silver Line in Boston, were initiated with standard 40-foot vehicles; this was done simply because of the longer procurement times for 60-foot articulated buses. Because demand often exceeded the vehicles' abilities to handle the ridership level, these and other transit agencies that have existing BRT systems are favoring the purchase of articulated buses over 40-foot buses as the larger buses become available.

Various fuel and propulsion systems can be configured to run these larger buses as long as they meet the increased power requirements necessary for hauling the heavier load. The Silver Line already has some articulated Neoplan vehicles in operation, while the Los Angeles MTA's first batch of North American Bus Industries (NABI) CNG vehicles are due for arrival in June 2005. In Washington, King County Metro is operating diesel hybrid systems in their New Flyer DE60LF BRT articulated buses. There is even talk of utilizing double articulated buses such as those currently in service in South America and Europe due to existing or anticipated ridership levels. These buses are up to 83 feet in length, can have capacities totaling over 120 passengers,[50] and, like other BRT vehicles, can be powered by various sources as long as horsepower requirements are met.

NABI Model 60-BRT

Source: NABI

The NABI Model 60 BRT will operate in Los Angeles and be fueled by CNG

Van Hool AGG300
Double Articulated Bus

Source: Van Hool

The Van Hool AGG300 is produced in Belgium and is powered by a 360HP diesel engine.

Maintenance and Storage Issues of Larger, Higher Capacity Buses

Consideration must be given to appropriate maintenance facility and storage location design in order to support a BRT system. Depending on the current fleet makeup of a transit community implementing a BRT system, modifications to maintenance and storage facilities, sometimes referred to as "barns," may be necessary in order to accommodate the new vehicles. If a transit community's pre-BRT vehicle fleet is comprised mainly of standard 40-foot buses, then the acquisition of larger 60-foot articulated buses will require either the addition of new facilities or modification of existing maintenance buildings and yards in order to store and service the larger vehicles. These modifications include extending inspection pits, installing three-post axle-engaging hoists, changing or relocating bus maintenance equipment, converting to drive-through maintenance bays, and re-striping bus yards. Bus barn modifications range in cost from a couple million dollars to $25 million or more.

Modifications may also be required of fueling facilities. While single-bay fueling can easily accept articulated buses, tandem-bay fueling facilities designed for 40-foot buses can present compatibility problems. For instance, the CNG facilities at Los Angeles County MTA operations were designed for tandem fueling of 40-ft vehicles. Since their plans for adding BRT maintenance capability meant interspersing 400 40-foot buses with 100 new 60-foot articulated BRT vehicles, their solution was to work with the vehicle manufacturer, NABI, to locate the fuel filler on the BRT vehicle in two locations, thereby allowing both length vehicles to fuel in tandem.

The increased use of articulated BRT vehicles may prove beneficial for vehicle parking. If the purchase of 60-foot articulated buses results in a smaller number of buses in the fleet, the total parking footprint will shrink. Articulated buses can also ease parking planning due to their slightly smaller turning radius as compared to non-articulated buses.

An important issue to consider is the location of the maintenance facility for BRT equipment. Vehicles in BRT service operate at an increased frequency with reduced distances between each vehicle, which translates to an increase in the number of "dead head" runs to and from the facility that do not carry passengers and thus do not generate revenue. Therefore, long distances from the facility to the BRT route can adversely affect operational logistics and costs.

Reduced Vehicle Noise

The demand for vehicles that produce lower noise levels is high in many communities.[51] Consequently, concern for the vehicle exterior acoustic profile as well as interior noise level was expressed by 34 percent of the BRT communities in WestStart-CALSTART's analysis.[52]

Busway volumes can often exceed 100 or more per hour in two directions, and communities are not likely to tolerate offensive noise levels from this operation. This case has been illustrated in the San Fernando Valley corridor of the Los Angeles MTA's BRT system, which runs on CNG. As this corridor was planned to pass through older, established neighborhoods, it was clear that the surrounding communities would demand appropriate noise controls. Los Angeles has imposed a maximum sound level of 78 decibels for its BRT buses.

New emission control requirements by the EPA may increase engine-cooling requirements. This may require changes in cooling designs and fans that could tend to increase noise levels, exacerbating the challenge of reducing noise. Often noise control and acoustic treatments are included with present models in order to control interior noise that passengers are exposed to. Drivetrain noise reduction, both exterior and interior, is a more difficult issue, but each bus manufacturer is striving for improvements in this area. Some manufacturers are concerned about this issue, while others, like Cummins Westport, believe the engine can be cooled without increasing radiator size.

Reduced noise levels are most likely to be found in advanced technology vehicles. For instance, HEVs use downsized engines that are quieter than larger engines and may reduce the need for increased radiator sizes. This is especially true for hybrids that can operate solely on electric power part of the time. Fully electric buses, such as those powered by catenary overhead wires, batteries, or fuel cells, can produce drastically reduced noise levels even lower than HEBs.

WestStart-CALSTART Combined Study Results on Low Noise Articulated Buses	
Community Preference	• Quiet, Lower Drive Noise and Interior Control • Requested for 51 percent of Articulated Buses
U.S. Manufacturers Response	• Acoustic treatments help interior noise control • EPA requirements may exacerbate drive-system fan noise • Hybrid production and implementation will help • Aggressive noise control will take engineering, money, and time • Fuel cell drivetrains may be the long-range solution

Sleek, Rail-inspired Design

Styling and aesthetics can help differentiate BRT systems from other bus systems, thereby assisting in the creation of a distinct BRT "brand." Sleek designs can provide riders with the feeling of riding on a modern, upscale form of transit. Furthermore, coordinating the style and colors of the bus with that of BRT stops, stations, terminals, information signs, graphics, and printed matter emphasizes that BRT is an integrated system.[53]

60 percent of BRT community participants in WestStart-CALSTART's 2004 BRT Vehicle Demand Analysis Update used words like "sleek," "modern," "futuristic," and "rail-like" as adjectives to describe the types of vehicles they seek.[54] While these terms are subjective, the analysis revealed that the BRT communities are seeking vehicles that convey an overall impression of "speed." Indeed, BRT vehicles are incorporating

stylistic notions of speed, as demonstrated by the Civis bus used for Las Vegas's "MAX" line.

Irisbus Civis

Source: Irisbus

BRT vehicles are desired to convey the conception of speed.

Faster Travel Times

BRT communities demand that both the vehicles and the systems in which they perform operate at a faster rate than conventional transit bus service. In fact, one of a BRT system's most defining and appealing characteristics is faster travel times compared to conventional transit buses. It accomplishes this by making fewer stops, using signal prioritization, traveling along designated travel corridors, and employing dock guidance systems.

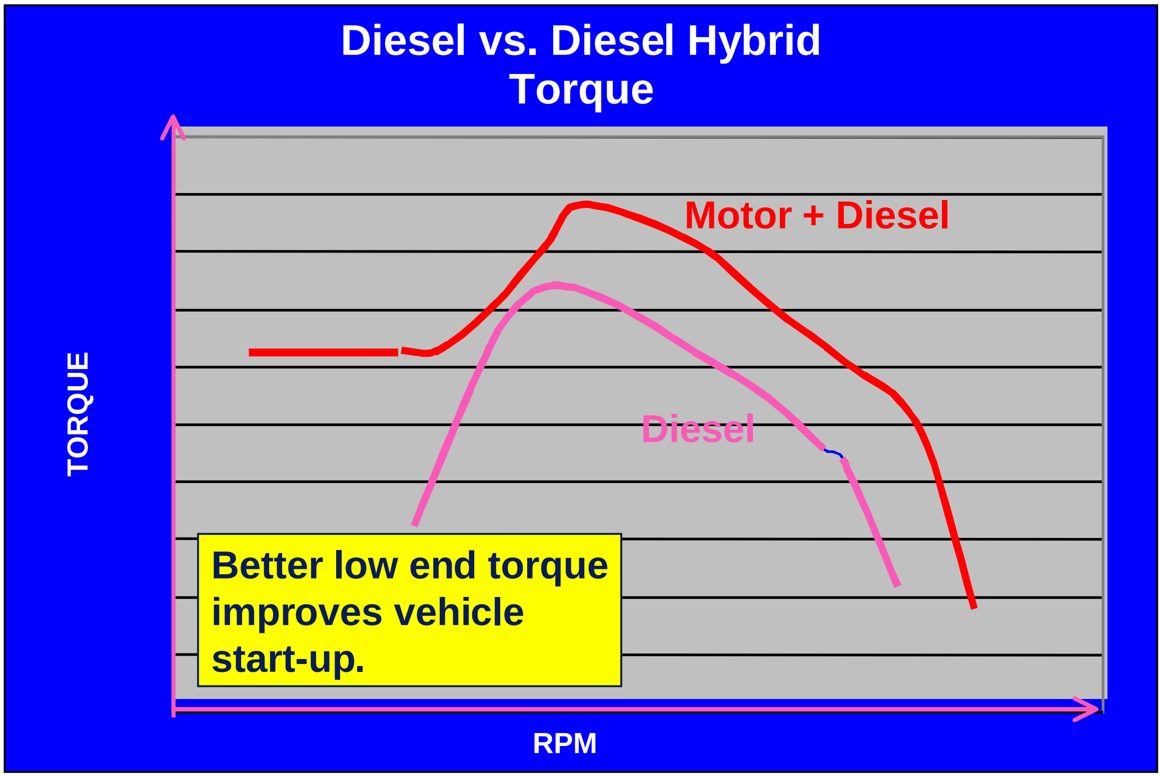
Signal prioritization allows BRT systems to "communicate" with traffic signals, ordering them to either maintain a green light status until the vehicle has passed through the intersection or change the signal from red to green before the BRT vehicle arrives at the intersection. Signal prioritization reduces time spent stopped at red lights and, thus, travel times. In Los Angeles, the MTA's MetroRapid Bus system utilizes signal prioritization to hold green lights for up to 10 seconds, thereby reducing overall travel times by 30 percent.

Signal prioritization is part of intelligent transportation system (ITS) design. In addition to prioritization, ITS components also include automatic vehicle location systems that allow central command centers to separate vehicles, and passenger information systems that convey real-time information via announcements and screens onboard and at stations.

Designated travel corridors, or "busways," are isolated lanes or separate roadways that are accessible only to BRT vehicles. Difficulties with establishing busways include higher initial acquisition and maintenance costs, land procurement difficulties, and community acceptance. If these problems prove manageable, designated corridors are the most effective way to reduce travel times.

Guided vehicles, when used in conjunction with stations having platforms at the same height as vehicle floors, can have vehicle boarding or disembarking times similar to those on heavy rail and some light rail systems, which represents up to a 25 percent improvement over passenger service times for conventional buses or streetcars.[55] There are two basic types of vehicle guidance systems: mechanical and electronic. Mechanical systems utilize special "tracks" and mounted guide wheels that are physically connected to a vehicle's steering system. Electronic systems are either optical, utilizing video cameras to detect the position of the vehicle relative to painted lines on pavement and steering the vehicle via a servo motor accordingly, or magnetic, which utilize magnets buried in the pavement to guide the vehicle. While electronic guidance systems can be as much as five times the cost of mechanical guidance systems ($75,000 to $100,000 vs. $10,000 to $20,000), costs for the electronic systems can be expected to decrease.[56]

BRT travel times are dependent on how quickly the vehicle can regain its cruising speed after a stop has been made. Vehicles with full or partial electric drive systems have an inherent advantage due to their linear torque band. This means that, unlike buses that are powered solely by ICEs with exponential torque bands, buses that are under full or partial electric propulsion have access to larger amounts of torque at low speeds and standstills. This translates to faster acceleration off the line and potentially shorter travel times.



Source: Volvo Powertrain Corporation

Hybrid systems provide additional torque throughout an engine's speed range, especially at the lower end.

Interior Layout

Complimenting an updated exterior is a more functional interior that is itself "rail-inspired." Incorporating interior design features such as a large number of wide doors, an optimized floor height, and wider aisles facilitates easy and rapid passenger boarding and seating that reduces dwell times at passenger service stops.

A greater number of wide doors in BRT coaches give passengers the impression of entering a railroad carriage. They also reduce "friction," which is the interference between boarding and disembarking passengers that causes delays. Wider doors can support simultaneous boarding or disembarkation, and a greater quantity of doors can enable better passenger distribution within a vehicle. Because seats are tied to the outside wall of a vehicle, more frequent doors restrict the number of seats. A commonly used rule for the number of “channels”[i] in the U.S. is to have at least one channel per ten feet of BRT vehicle length for typical radial, suburb-CBD corridors, assuming offboard fare collection.[57]

An optimized floor height improves BRT service and appearance much in the same way that frequent wide doors do. BRT vehicles can have one of three basic floor heights: 100 percent low floor, partial (usually about 70 percent) low floor, and high floor.[58] High floors have an advantage in terms of maximizing carrying and/or seated capacity[59] because little or no interior space is consumed by wheel wells and mechanical equipment, and fuel tanks can be located under the floor. However, unless steps are taken to ease entry into and disembarkation from the high-floor vehicles, such as providing high loading platforms, increased friction dwell times at passenger stops can occur.

[i] Each stream of people comprises one channel. So, regular transit buses tend to have single channel entrances in the front and double channel exits in the back. BRT vehicles with wide doors have double channel entrances and exits.

High Platform Station
Curitiba, Brazil

The floor height of choice for 46 percent of the BRT community respondents in WestStart-CALSTART's analysis was a continuous low floor, a type of partial floor design. New technologies, such as independently suspended wide and extra-strength tires with electric motors and gearboxes, allow more interior flexibility for broader aisles and/or seating arrangements.[60] Also, advanced electric propulsion technologies can help alleviate maintenance and axle-loading concerns that are related to the implementation of a continuous low floor by easing placement constraints for drivetrain components.

Continuous Low Floor
Irisbus Civis

Source: WestStart-CALSTART

Miscellaneous Amenities

BRT systems can further “brand” themselves by creating unique stops that combine rail-inspired features as well as features common in conventional bus systems. The use of styles, colors, and print types that are similar to those of the vehicles can be integrated into the system design, for example. BRT stops can always be covered, thereby protecting passengers from the elements, and hardwired, cellular, and GPS technologies can be installed to provide waiting passengers with updated information on vehicle arrival times. Both of these characteristics add rail-inspired elements to the BRT system and help distinguish it as an improved transit bus service.

Conclusion

This analysis of fuels and propulsion systems for BRT vehicles leads to several conclusions:

First, **the emergence of BRT and the demand for low-pollution buses along with the upcoming implementation of strict emission standards are creating a period of transition in the bus industry.** While buses used to be synonymous with a slow, stodgy, and smoke-emitting method of travel, BRT is modernizing the concept by offering fast, stylish, and clean options. Bus and BRT manufacturers are also transitioning into an era of strict environmental standards that begins when upcoming EPA and California emission standards require NOx and PM levels that are lower than were thought possible just a few years ago.

While soon-to-be-implemented California and federal emission standards are strict, **a multitude of technologies and fuels make it possible for transit authorities to obtain the clean vehicle features they prefer while concurrently satisfying long-term emissions and energy considerations.** Replacing standard diesel fuel with ULSD fuel in 2006 will enable the use of diesel aftertreatment devices, such as DPFs, EGR, DOCs, LNTs, and SCR, that will allow these vehicles to meet 2007 and 2010 standards. Another option for reducing emissions is through the use of blending stocks that require little to no modification in order to be used in diesel engines. Alternative fuels provide a final option for reducing PM and NOx, as well as other undesirable pollutants.

Diesel fueled engines will likely be able to meet strict 2010 emissions standards, but the **increasing complexity of diesel systems may make the relative simplicity of alternative fueled engines like natural gas comparatively cheaper and therefore more appealing. Still, two factors may enable diesel engines to regain their competitiveness with natural gas engines post-2010.** First, because diesel bus engines comprise the majority of bus propulsion systems and sales, volume production of these engines facilitates the large-scale implementation of aftertreatment devices necessary to reduce costs. It may also provide incentives and opportunities for manufacturers to reduce the complexity of emission control systems. Second, if natural gas engines are modified to run at stoichiometric rather than lean-burn levels, they can be equipped with simple three-way catalytic converters to meet 2010 standards. This modification increases fuel consumption of natural gas vehicles by about 15 to 20 percent, thereby increasing operating costs and helping to level the playing field with diesel engines.

An array of **emerging and future technologies may provide transit communities with even more lower-pollution BRT propulsion options in the future.** NOx adsorber aftertreatment has the potential to reduce NOx emissions by 95 percent, while renewable biogas can not only be a GHG neutral fuel, but also can reduce energy independence, groundwater contamination, and provide a revenue stream from an otherwise valueless waste material. GTL has the potential to be an attractive diesel blending stock or eventual replacement fuel because it reduces emissions and has other beneficial attributes, while hydraulic hybrids may ultimately provide the benefits of a hybrid electric drive system for BRT vehicles more cost effectively. Finally, embedded power collection may allow battery electric buses to operate pollution-free on extended ranges, while hydrogen may emerge as a low- to zero-emission form of propulsion.

Finally, **advanced fuels and propulsion systems may enable BRT vehicles to more easily fulfill characteristic BRT vehicle and system requirements.** While horsepower requirements of larger articulated buses can be fulfilled with either advanced or conventional drive systems as long as horsepower requirements are met, HEBs and fully electric buses can reduce vehicle noise levels by minimizing or even eliminating internal combustion engine use. Buses with full or partial electric drive systems can provide faster acceleration after route stops due to their high torque capability. Partially or fully electric propulsion systems can reduce or eliminate the proximity and logistical requirements of situating engines and drivetrains.

Works Cited

[1] *Proposed Heavy-Duty Engine and Vehicle Standards and Highway Diesel Fuel Sulfur Control Requirements,* United States Environmental Protection Agency, EPA420-F-00-022; May 2000: p.1.
[2] *Proposal for Cleaner Heavy-Duty Trucks and Buses and Cleaner Diesel Fuel Fact Sheet,* United States Environmental Protection Agency; May 2000: p.1.
[3] Ibid., p.2.
[4] Monahan, Patricia, and David Friedman, *The Diesel Dilemma: Diesel's Role in the Race for Clean Cars,* Union of Concerned Scientists, January 2004.
[5] Marty, Melanie and Andy Salmon, *Diesel Exhaust Particulate as a Toxic Air Contaminant,* Office of Environmental Health Hazard Assessment. Presented at the California Air Pollution Control Officer's Association (CAPCOA) Conference on Diesel, January 27, 2004.
[6] Ibid.
[7] Walsh, Michael P., *EPA Proposal Regarding Heavy Duty Engines and Diesel Fuel,* United States Environmental Protection Agency, Memo to Interested Parties, May 17, 2000: p.1.
[8] Campbell, Todd R. and Lesley Bobalian, *Failing the Grade: How Diesel School Buses Threaten Our Children's Health,* Coalition for Clean Air, 1999: p.16.
[9] Solomon, Gina, Todd Campbell, Tim Carmichael, Gail Ruderman Feuer, and Janet S. Hathaway, *Exhausted by Diesel,* Natural Resources Defense Council, 1998: p.7.
[10] Kittelson, David B., *Ultrafine and Nanoparticle Emissions: An Ongoing Challenge,* Center for Diesel Research, University of Minnesota. Presented at the California Air Pollution Control Officer's Association (CAPCOA) Conference on Diesel, January 27, 2004.
[11] Ibid.
[12] Ibid.
[13] Walsh, Michael P., *Diesel—What the Future Holds: An International Perspective.* Presented at the California Air Pollution Control Officer's Association (CAPCOA) Conference on Diesel, January 27, 2004.
[14] Mark, Jason and Candace Morey, *Rolling Smokestacks, Cleaning Up America's Trucks and Buses,* Union of Concerned Scientists, October 2000: p.6.
[15] Jackson, Michael D., *Diesel—What the Future Holds,* TIAX LLC. Presented at the California Air Pollution Control Officer's Association (CAPCOA) Conference on Diesel, January 27, 2004.
[16] Ibid.
[17] Zaw-Mon, Merrylin, *EPA's Heavy-Duty Engine Emission Program,* Environmental Protection Agency. Presented at WestStart-CALSTART's 2004 Clean Heavy Duty Vehicle Conference, February 26, 2004.
[18] Environmental Protection Agency, *Regulatory Announcement: Heavy-Duty Engine and Vehicle Standards and Highway Diesel Fuel Sulfur Control Requirements,* EPA420-F-00-057, December 2000.
[19] Zaw-Mon, Merrylin, *EPA's Heavy-Duty Engine Emission Program,* Environmental Protection Agency. Presented at WestStart-CALSTART's 2004 Clean Heavy Duty Vehicle Conference, February 26, 2004.
[20] Greszler, Anthony, *Clean Diesel Development for Heavy Duty Vehicles,* Volvo Powertrain. Presented at the California Air Pollution Control Officer's Association (CAPCOA) Conference on Diesel, January 28, 2004.
[21] LeTavec, C., J. Uihleim, K. Vertin, S. Chatterjee, S. Wayne, N. Clark, M. Gautam, G. Thompson, D. Lyons, K. Hallstrom, K. Chandler, and T. Coburn, *Year-Long Evaluation of Trucks and Buses Equipped with Passive Diesel Particulate Filters,* SAE 2002-01-0433, 2002. As printed in California Air Resources Board, *Staff Report: Technical Support Document,* June 6, 2003: p.4.
[22] Greszler, Anthony, *Clean Diesel Development for Heavy Duty Vehicles,* Volvo Powertrain. Presented at the California Air Pollution Control Officer's Association (CAPCOA) Conference on Diesel, January 28, 2004.
[23] *2007 Emissions: Choosing the Right Technology,* Cummins Inc., 2004: p.10-11.
[24] Greszler, Anthony, *Clean Diesel Development for Heavy Duty Vehicles,* Volvo Powertrain. Presented at the California Air Pollution Control Officer's Association (CAPCOA) Conference on Diesel, January 28, 2004.
[25] Ibid.

[26] *2007 Emissions: Choosing the Right Technology*, Cummins Inc., 2004: p.13.
[27] National Biodiesel Board, *Biodiesel Performance,* http://www.biodiesel.org/pdf_files/Performance.PDF.
[28] Ibid.
[29] California Air Resources Board, *Staff Report: Technical Support Document,* June 6, 2003.
[30] Ouellette, Patric, *Responding to Government Regulations in Changing Times: Opportunities and Challenges for Natural Gas Engine Makers,* Westport Innovations. Presented at WestStart-CALSTART's 2004 Clean Heavy Duty Vehicle Conference, February 25, 2004.
[31] Nellen, C. and Konstantinos Boulouchos, SAE Technical Paper 2000-01-2825, Swiss Federal Institute of Technology, ETH, Zurich as discussed by: Ouellette, Patric. *Responding to Government Regulations in Changing Times: Opportunities and Challenges for Natural Gas Engine Makers,* Westport Innovations. Presented at WestStart-CALSTART's 2004 Clean Heavy Duty Vehicle Conference, February 25, 2004.
[32] Transportation Research Board, *Guidebook for Evaluating, Selecting, and Implementing Fuel Choices for Transit Bus Operations,* Transit Cooperative Research Program, 1998: p.17.
[33] Ibid., p.18.
[34] Ibid.
[35] Ibid., p. 26-27.
[36] Ibid., p. 29.
[37] Ibid., p. 27.
[38] Ibid., p. 26.
[39] Defense Advanced Research Projects Agency, *Hybrid-Electric Drive Heavy-Duty Vehicle Testing Project: Final Emissions Report,* Northeast Advanced Vehicle Consortium. February 2000.
[40] Ibid.
[41] Faulker, Steve, *NOx Adsorber Development,* Caterpillar Engine Research, Diesel and Emissions Technology. Caterpillar, 2002.
[42] Ibid.
[43] Gray, Charles, Director of Emission Control Technology, Environmental Protection Agency. Presented at WestStart-CALSTART's 2004 Clean Heavy Duty Vehicle Conference, February 26, 2004.
[44] Ibid.
[45] U.S. Department of Energy, *SunLine Test Drives Hydrogen Bus,* Hydrogen Fuel Cell & Infrastructure Technologies Program. DOE/GO-102003-1768, August 2003.
[46] Ibid.
[47] Transportation Research Board, *Guidebook for Evaluating, Selecting, and Implementing Fuel Choices for Transit Bus Operations,* Transit Cooperative Research Program, 1998: p. 59.
[48] Ibid., p. 63.
[49] Zimmerman, Samuel L. and Herbert Levinson, "Vehicle Selection for BRT: Issues and Options," *Journal of Public Transportation,* Volume 7, Number 1, 2004.
[50] Ibid.
[51] Ibid., p.11.
[52] Wnuk, Lawrence, *Bus Rapid Transit, Vehicle Demand Analysis Update,* prepared for the U.S Department of Transportation Federal Transit Administration by WestStart-CALSTART, June 2004.
[53] Zimmerman, Samuel L. and Herbert Levinson, "Vehicle Selection for BRT: Issues and Options," *Journal of Public Transportation*, Volume 7, Number 1, 2004: p.17.
[54] Wnuk, Lawrence, *Bus Rapid Transit, Vehicle Demand Analysis Update,* prepared for the U.S Department of Transportation Federal Transit Administration by WestStart-CALSTART, June 2004.
[55] Zimmerman, Samuel L. and Herbert Levinson, "Vehicle Selection for BRT: Issues and Options," *Journal of Public Transportation*, Volume 7, Number 1, 2004: p.14.
[56] Ibid., p.16.
[57] Ibid., p.8.
[58] Ibid., p.9.
[59] Ibid.
[60] Ibid., p.6.