New York City Transit Riders Council

Analysis of Alternative Fuel Technologies for New York City Transit Buses

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The New York City Transit Riders Council was created by the New York State Legislature in 1981 to represent the interests of bus and subway riders. The fifteen volunteer members are users of the transit system and are appointed by the Governor, upon the recommendation of the Mayor (five members), the Public Advocate (five members), and the Borough Presidents (one member each). For more information on the Council, please visit our website: www.pcac.org.

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Executive Summary

The release of New York City Transit's (NYCT) 2000-2004 Capital Program in September 1999 renewed the debate on the appropriateness of relying on diesel buses to serve the City's bus riders. The agency proposes to purchase 1,056 new buses, of which 756 will be articulated and express buses that use diesel fuel. The remainder will be some mix of compressed natural gas (CNG) and hybrid diesel-electric buses. Some environmental advocates, including community groups and elected officials, strongly disagree with this approach. They feel that buying CNG buses is critical to efforts aimed at cleaning New York City's air.

The air in downstate New York contains dangerously high levels of particulate matter and ozone, two air pollutants that have been associated with a range of illnesses. Exhaust from diesel trucks and buses contributes to these unhealthy conditions. Diesel engines emit high levels of particulate matter, ozone-producing chemicals, and toxic compounds. Some of these exhaust components are known carcinogens, and several health organizations have proposed that diesel exhaust be classified as a cancer-causing agent.

Proponents of natural gas engines feel that this technology is the best way to address these concerns. Natural gas burns more cleanly than diesel fuel and emits lower levels of particulate matter, toxins, and nitrogen oxide, which contributes to ozone formation. The technology has been proven in operation and is being used by several large U.S. transit properties such as the Los Angeles County MTA and the New York City Department of Transportation.

Despite the many positive characteristics of natural gas, the issue is not that straightforward. Natural gas engines are not as clean as their proponents assert. A recent study by the Harvard Center for Risk Analysis notes that natural gas vehicles may emit a greater number of ultrafine particles than diesel vehicles. The New York State Department of Environmental Conservation reached a similar conclusion in tests it ran in the Spring of 1999. Research shows that these smaller particles may be the most significant threat to human health. Natural gas engines also appear to emit high levels of formaldehyde, which is a carcinogen, and are worse than diesel engines for the production of greenhouse gases. The primary component of natural gas is methane, which has about twenty times the global warming potential of carbon dioxide.

Other alternative technologies have demonstrated the ability to equal or better the emissions-reduction performance of natural gas. In several tests, for example, hybrid diesel-electric buses have done as well as natural gas buses for key pollutants. Emissions of particulate matter in one test were 0.027 grams per mile for a hybrid bus, compared to 0.025 grams per mile for a bus using CNG. When diesel fuel containing low levels of sulfur was used, the results were even better. Almost no particulate matter was released. Hybrid buses using standard diesel fuel have performed comparably to the natural gas buses on nitrogen oxide emissions and better on carbon monoxide emissions. Exhaust-treatment systems are emerging that could also lower diesel pollutants to the same levels as natural gas pollutants. The U.S. Environmental Protection Agency (EPA) anticipates that these advances will produce the same dramatic results as catalytic technologies did for gasoline engines.

Further emissions tests would be helpful. Questions need to be answered on how each of the various technologies compares regarding particle size and distribution and emissions of toxins. Environmental advocates have acknowledged that tests should be done both for hybrid and natural gas buses. Later this year, NYCT plans a series of tests that should provide the answers.

Until more is known, NYCT should not be required to commit fully to CNG buses. Converting to this technology poses several obstacles. Bus depots require extensive modifications to make them safe for natural gas fueling. Unlike diesel fuel, natural gas is lighter than air and will rise if there is a leak. The vapors will ignite explosively if they come into contact with an open flame or spark. In the most realistic scenario, NYCT would need until at least 2006 to convert the depots necessary to accommodate an all-CNG approach in the 2000-2004 capital plan. The agency would have to defer a substantial amount of its bus purchases while it is readying the depots. Considering the explosive growth in bus ridership since 1996, NYCT needs buses now and cannot wait several years to expand its fleet.

Cost is a consideration. NYCT would need to spend hundreds of millions of dollars to convert its depots and to replace the bus capacity that would be lost under an all-CNG plan. Annual operating and maintenance expenses appear to be higher for CNG buses than they are for diesel buses. Other agencies have encountered similar issues and have cancelled their CNG programs as a result.

Critically, natural gas is only an interim measure. Fuel cell buses, which generate power through the reaction of hydrogen with oxygen, have been successfully demonstrated in transit applications. This technology could provide emissions-free vehicles and may be commercially viable within only a few years.

NYCT would be imprudent to invest substantial resources in a short-term technology that may be no better than other alternatives. It is using both CNG buses and hybrid buses, is experimenting with low-sulfur diesel fuel and particulate filters, and has approached a manufacturer about conducting a fuel cell demonstration project. This multi-faceted strategy is a more effective use of capital and operating funds and should yield greater emissions improvement than a complete commitment to natural gas buses.

Based on these considerations, the Transit Riders Council recommends that NYCT not adopt an all-CNG policy. The agency, though, can improve its bus program in some respects. The Council shares the concerns of environmental advocates about the large diesel bus component of the upcoming capital plan. Diesel buses pollute more than the other technologies that are currently available or are being tested. Buying some amount of diesel buses is unavoidable given the pressing need for more buses and the unavailability of alternatively fueled articulated and express buses. However, NYCT should limit its diesel bus purchases to only as many as it needs while it evaluates hybrid diesel-electric buses and begins to develop articulated- and express-bus versions of these vehicles. Of the technologies presently available, hybrid buses offer the greatest potential for emissions reduction.

Other TRC recommendations include the following:

- Leading regulatory and health organizations should continue to assess the health effects of fine and ultrafine particulate matter. Natural gas engines are suspected to generate more small particles than diesel engines, and even though natural gas particles are purer, their carbon core may pose a significant threat to health. The EPA and the Health Effects Institute in Cambridge, Massachusetts, are conducting or sponsoring research to examine this issue.

- NYCT should commit fully to hybrid buses if this technology appreciably outperforms the other alternatives in the upcoming emissions tests. The agency should move aggressively to develop hybrid versions of the articulated and express buses.

- NYCT should conduct emissions tests on articulated and express buses. The agency has not included these vehicles in its upcoming test program, noting that their emissions on a per-passenger basis should be comparable to emissions from standard-size diesel buses. NYCT should evaluate the larger buses to confirm whether it is correct, to assess how they perform with low-sulfur diesel fuel and exhaust-treatment systems, and to determine how they compare to hybrid technology.

- NYCT should switch entirely to low-sulfur diesel fuel. Hybrid buses using reduced-sulfur fuel release negligible amounts of particulate matter, and standard diesel buses have outperformed CNG buses on particle emissions when operated with low-sulfur fuel and a catalytic particulate trap. NYCT would incur modest increases in fuel costs of about ten cents per gallon.

- New York State should adopt a standard limiting the sulfur content in diesel fuel to less than 50 parts per million (ppm). The EPA has proposed tightening the federal regulations governing sulfur content, and the European Union has enacted a 30-ppm requirement that will be phased in by 2005.

- NYCT should equip its entire diesel fleet, including articulated and express buses, with catalytic particulate traps if tests of this system are successful. When systems to clean nitrogen oxide emissions become available, NYCT should equip its diesel buses with them.

- NYCT should evaluate other promising technologies such as fuel cell buses. These vehicles offer the potential for the greatest environmental gains. In tests, they have reduced emissions to negligible levels.

Introduction

In recent months, New York City Transit (NYCT) has come under increasing pressure to stop buying diesel buses. Elected officials, environmental groups, and community groups strongly oppose the agency's plan to purchase 756 diesel buses over the next five years. They want NYCT to embrace another strategy: replacing diesel buses with buses that use compressed natural gas. Proponents of this technology cite New York City's serious air pollution problems. They say that diesel buses emit too many harmful pollutants and exacerbate the City's poor air quality. Natural gas, by contrast, is a cleaner fuel that produces relatively low levels of noxious compounds.

The air in downstate New York is among the worst in the U.S. Manhattan exceeds Federal standards for particulate matter, and the metropolitan region is not in compliance with the regulations governing ozone. Particulate matter and ozone are two of the most serious air pollutants. They are respiratory irritants, cause respiratory illnesses such as asthma and bronchitis, and cause headaches, nausea, and eye irritation. Particulate matter is suspected to be a carcinogen.

Diesel exhaust contributes to the area's air pollution problems. Emissions from diesel engines contain a substantial amount of particulate matter, high levels of ozone-producing gases, and many chemicals with toxic and possibly carcinogenic properties. Several health agencies have proposed classifying diesel exhaust as a human carcinogen.

Environmental advocates want NYCT to abandon diesel technology because of the role it plays in air pollution. They instead urge a policy of all natural gas buses, which they claim are cleaner than diesel buses. Natural gas engines emit less particulate matter, a smaller amount of toxic compounds, and less nitrogen oxide, which combines with hydrocarbon to form ozone. Several large transit agencies in the U.S., including the Los Angeles County MTA, have committed to an all-natural-gas policy.

NYCT has pursued a different strategy that it believes will deliver similar environmental improvements. It is buying a large number of hybrid diesel-electric buses that emit less air toxins than standard diesel buses. The agency is experimenting with other technologies, including diesel fuel that contains substantially less sulfur than typical diesel fuel and particulate filters. Both have demonstrated emissions-reducing potential. Within the next decade, fuel cell buses are expected to be widely available. This technology has the potential for zero emissions.

Questions have emerged about the true benefits of natural gas buses. Research by the Harvard Center for Risk Analysis and the New York State Department of Environmental Conservation has found that natural gas engines may generate more ultrafine particles than diesel engines. These smaller particles are now thought to pose the greatest threat to human health. Natural gas engines also generate much higher levels of carbon dioxide and methane, which are powerful greenhouse gases.

Maintaining a fleet of natural gas buses entails costs that are not incurred with diesel buses. Depots must be converted to accommodate natural gas fueling, and operating and maintenance costs appear to be higher. Many agencies have reversed their decision to convert to natural gas because of the complexities involved.

The Transit Riders Council has never taken a formal position on natural gas buses because of the many unanswered questions. With the debate increasing, the Council felt it important to take an in-depth look into the matter and to assess the various sides of the argument. This paper discusses the Council's findings.

Analysis of Issues

Types of Emissions

Motor vehicles emit compounds in the solid and gaseous phase. Not all of the emissions are a problem—water, for example— but most are. They either are hazardous to human health or degrade the environment. The EPA currently regulates four emissions from motor vehicle exhaust: particulate matter, nitrogen oxides, hydrocarbon, and carbon monoxide. All have health effects, and methane hydrocarbon is a greenhouse gas. A discussion of these emissions and their consequences follows.

Particulate Matter

Of the different engine emissions, these solid-phase particles are considered to pose the greatest threat to human health. Particulate matter (PM) is often referred to as soot or smoke and consists of several components. The largest component of PM is a carbon core that contains both elemental (inorganic) carbon and organic carbon. In urban areas, motor vehicles account for most of the elemental and organic carbon particulate mass. Diesel exhaust contributes 50 to 70% of the elemental carbon mass concentration, and motor vehicles account for up to 80% of the organic carbon mass concentration.[1] The other components of PM depend on the type of fuel used and on engine characteristics. Diesel PM contains sulfate, nitrate, ash, and volatile organic compounds. Natural gas particles tend to be purer, but they may contain some levels of ash and volatile organic compounds.

Particulate matter affects human health in several ways. It causes inflammation of the lung, can cause or aggravate respiratory disease, including asthma and bronchitis, is an eye irritant, and can cause headaches and nausea. PM has mutagenic and carcinogenic properties. Although medical research has not definitively determined how the different characteristics of particles affect health, several links are being studied. The carbon fraction of PM has toxicological properties itself, and many of the other components are considered to be toxic. Sulfate has been associated with reduced survival among people living in heavily polluted areas.[2] Ash contains metals that are thought to produce radicals that are toxic to cells.[3] The particles are carriers of toxic compounds, many of which are known carcinogens. Diesel exhaust, for example, contains hundreds of different toxic substances that adhere to the particulate matter.

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[1] U.S. EPA, ***Getting Started: PM-2.5 Emission Inventory***, Emissions Inventory Improvement Program, September 1999, p. 2-3.
[2] Health Effects Institute, ***HEI Communications 8 (The Health Effects of Fine Particles: Key Questions and the 2003 Review)***, January 1999, p. 5.
[3] ***Ibid***., p. 6.

Particle size may be a factor as well. Smaller particles are better able to evade the lung's defense mechanisms and can become deeply embedded in lung tissue. The particles are an irritant to the lung, and they are thought to have a toxic or carcinogenic effect.

The EPA currently has one ambient PM standard that covers particles with a diameter of no more than 10 microns (PM_{10}). Although adverse health effects are associated with coarse particulate matter at the high end of the scale, the smallest particles are thought to pose the greatest threat to health. In 1997, the EPA promulgated new clean-air rules that would have established a separate standard for "fine" particulate matter—$PM_{2.5}$, which is particulate matter with a diameter of 2.5 microns or less—but the U.S. Court of Appeals for the District of Columbia Circuit invalidated these regulations in May 1999. (In June the Federal Government filed a petition for a rehearing of the case.)[4] As noted above, smaller particles can penetrate lung tissue more easily and become deeply embedded in the lung. The human body is better able to filter out larger particles. Medical research has shown an association between fine PM and disease and mortality. A separate standard for $PM_{2.5}$ would be more effective at addressing concerns regarding motor vehicle PM, which contains mainly fine and ultrafine particles. Over 90% of diesel particles, for example, are less than 2.5 microns in diameter, and gasoline and CNG engines emit a large number of small particles.

Nitrogen Oxide

Emitted in the gaseous phase of exhaust, nitrogen oxide (NOx) is a molecule consisting of one nitrogen atom and some number of oxygen atoms. NOx combines with hydrocarbon in the presence of sunlight to form ground-level ozone or smog in the atmosphere. Ozone is an air and water pollutant that causes several adverse health effects. It is harmful to lung tissue, aggravates respiratory illnesses, and increases susceptibility to respiratory diseases such as asthma.

Hydrocarbon

Emitted in the gaseous phase, hydrocarbons are the other component from engine exhaust that contributes to smog formation. Engine exhaust includes many different types of hydrocarbons, some of which are volatile organic compounds that are toxic. Diesel exhaust contains many of these substances, including some complex hydrocarbon chains that are especially potent or carcinogenic. Methane, a greenhouse gas that contributes to global warming, can be present in hydrocarbon emissions from a vehicle, depending on the type of engine and fuel.

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[4] U.S. EPA, ***Fact Sheet: EPA's Revised Particulate Matter Standards***, July 1997.

Carbon Oxides

Engine exhaust contains both carbon monoxide, which is toxic and is regulated by the EPA, and carbon dioxide. Carbon dioxide is non-toxic, but like methane, it is a greenhouse gas. The EPA is expected to issue a standard for carbon dioxide in the near future.

Table 1: EPA Emissions Standards for Diesel Transit Bus Engines (Grams per Brake Horsepower-hour)

Year	Particulate Matter	Nitrogen Oxide	Hydrocarbon	Carbon Monoxide
Current Standards	.005	4.0	1.3	15.5
2002 Standards	.005	2.5 non-methane hydrocarbon and nitrogen oxide		15.5

Emission Characteristics of Natural Gas and Diesel Fuel

Diesel fuel and natural gas engines have different emission properties. Diesel engines emit low levels of hydrocarbons and carbon monoxide, but they produce large amounts of particulate matter and NOx. Diesel exhaust also contains hundreds of toxic compounds that either adhere to the particulate matter or are released in the gaseous exhaust. Particle mass from natural gas engines is low, though recent research indicates that they may generate a large number of ultrafine particles. Natural gas engines generally produce lower emissions of NOx than diesel engines, but if the engine is not tuned optimally, the level of NOx rises. Greenhouse gas emissions are higher with natural gas vehicles. The emissions characteristics of both fuel types are outlined below.

Natural Gas

Unlike diesel fuel, which is comprised of a large number of complex hydrocarbon compounds, natural gas is composed primarily of the relatively simple hydrocarbon methane. Natural gas does not contain as many contaminants as diesel fuel, and as a result, it burns more completely and produces fewer complicated hydrocarbons during the combustion process. Particle emissions, in weight, are substantially lower for a natural gas engine, as are NOx emissions. In tests done by West Virginia University (WVU) in the Spring of 1999, PM emissions for diesel buses ranged from 0.15 to 0.32 grams per mile. PM emissions from compressed natural gas (CNG) buses were 0.007 to 0.041 grams per mile. Diesel bus NOx emissions were between 36.9 to 41.5

grams per mile, compared to approximately 10 grams per mile for New York City CNG buses.[5] Despite these differences, natural gas does have some drawbacks.

Greenhouse gas emissions from natural gas engines are higher than they are from diesel engines. In the WVU tests, hydrocarbon emissions ranged from 20.6 to 31.6 grams per mile for a CNG bus, compared to 0.021 to 0.064 for a diesel bus.[6] Methane, a powerful greenhouse gas with approximately 20 times the global warming potential of carbon dioxide[7], accounts for the majority of the additional hydrocarbon present in CNG exhaust. Carbon dioxide levels in the WVU tests were comparable (2,837 to 3,213 grams per mile for diesel, and 2,656 to 2,867 grams per mile for CNG).[8]

Preliminary research shows that natural gas engines may emit more ultrafine particulate matter than diesel engines. Tests showing lower particle emissions from natural gas engines measure the mass of the particles emitted, not the number or the size. Researchers are now beginning to focus on the latter issue, with results favoring diesel engines. The New York State Department of Environmental Conservation (DEC) performed a series of tests in April aimed at answering this question. There were more ultrafine particles present in natural gas exhaust than there were in diesel exhaust.[9] In a January 2000 report, the Harvard Center for Risk Analysis raised the same concern, noting that several studies suggest that natural gas exhaust may contain more of these smaller particles.[10]

The difference is crucial because smaller particles are thought to pose a much greater health hazard than larger particles. The body can more effectively filter out coarse PM than it can fine and ultrafine PM. Once in the lung, particles are an irritant and may induce a toxic or carcinogenic response. Although diesel particles do contain many more contaminants than natural gas particles, the carbon core of the pure particle is itself considered a hazard. Natural gas PM may also contain some contaminants, including ash and volatile organic compounds. DEC tests show high levels of formaldehyde emissions from a CNG engine.[11] Formaldehyde is toxic and carcinogenic.[12]

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[5] Northeast Alternative Vehicle Consortium, ***Internal Brief: Comparison of Emissions Performance for Alternative Fueled (CNG) and Conventional Fueled Heavy-Duty Transit Buses***, June 1999, p. 3. (NOx emissions varied for the CNG buses. Emissions were between 8.8 and 11.2 grams per mile for the New York City buses tested. These vehicles were from Orion and used a Detroit Diesel engine. NOx levels were as high as 32.2 grams per mile for Neoplan buses using a Cummins engine.)
[6] ***Ibid.***
[7] Toy, Edmond, et al., "Fueling Heavy Duty Trucks: Diesel or Natural Gas?" Risk in Perspective (Harvard Center for Risk Analysis) 8:1, January 2000, p. 3.
[8] ***Comparison of Emissions Performance***, p. 3
[9] Personal communication, Ken Newkirk, DEC, December 1999.
[10] ***Fueling Heavy Duty Trucks***, p. 2.
[11] Personal communication Dana Lowell, NYCT Department of Buses, January 2000.
[12] Health Effects Institute, ***Diesel Exhaust: A Critical Analysis of Emissions, Exposure, and Health Effects***, April 1995, p. 24.

Diesel Fuel

Diesel fuel exhaust has been the subject of much research that has clearly established it as a toxin. There is also considerable evidence that many of the components of diesel emissions are carcinogenic. The chief problem with diesel exhaust is the volatile organic compounds that are present as solid and gaseous matter. Other hazards associated with diesel emissions include high levels of NOx and the carbon core of the particulate matter.

PM is the primary concern regarding diesel exhaust. Over 90% of diesel particles are less than 2.5 microns in diameter, and by weight, diesel engines emit more particulate than CNG engines. However, as noted above, recent tests show that CNG emissions contain more fine and ultrafine particles than diesel exhaust. Diesel PM contains many more compounds than natural gas particulate matter. Similar to natural gas PM, a diesel particle is comprised mainly of a carbon core, most of which is elemental carbon. Contaminants present in diesel fuel and compounds created in the combustion process account for the remainder of diesel PM. Included in this matter are sulfate, nitrate, ash, and volatile organic compounds. This material either adheres to the particle or is released as separate particles. Some matter may adhere to sulfate particles and enter the atmosphere that way.

All of these components are hazardous to health. They have been associated in research with increased disease or mortality. The greatest threat to human well-being comes from the volatile organic compounds. A diesel particle may contain hundreds of these substances, which are present as the soluble organic fraction of PM. Many of them have toxic properties or are known carcinogens. Advances have been made in reducing the soluble organic fraction. On a percent basis this fraction has been shown to account for no more than 20% of the diesel PM in more recent engine models. It is as high as 60% in older engines.[13]

The contaminants present in diesel PM are the result of incomplete combustion. Engines running at higher temperatures consume this material more completely. However, if engine temperature were increased, the amount of NOx emissions would rise, since more NOx is generated in hotter engine conditions. Diesel engines already emit a high level of NOx, as shown by the WVU tests. Hydrocarbon emissions for a diesel engine are low, and carbon monoxide emissions in the WVU tests were comparable to those from a CNG bus. The gaseous exhaust from a diesel engine contains the same volatile organic compounds that are present in the particle stream, though at lower levels.

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[13] Graboski, Mark, et al., ***Heavy-Duty Diesel Testing for the Northern Front Range Air Quality Study***, Colorado Institute for Fuels and High Altitude Engine Research, Colorado School of Mines, 1998.

Table 2: Comparison of Emissions from CNG and Standard Diesel Engines (Grams per Mile)

Bus (Engine)	PM	NOx	HC	CO	CO_2
Orion CNG (Detroit Diesel - Series 50G)	0.007	11.2	26.2	9.38	2656
Orion CNG (Detroit Diesel - Series 50G)	0.022	9.19	31.6	13.5	2832
Orion CNG (Detroit Diesel - Series 50G)	0.041	8.79	20.6	9.59	2867
Nova Diesel (Detroit Diesel - Series 50)	0.32	38.0	0.021	2.95	3213
Nova Diesel (Detroit Diesel - Series 50)	0.21	41.5	0.064	2.95	3122
Nova Diesel (Detroit Diesel - Series 50)	0.15	36.9	0.038	2.27	2837

Source: ***Comparison of Emissions Performance***. (Note: Three separate Orion CNG and three separate Nova diesel buses were tested, accounting for the different results.)

Vehicle and Fuel Technologies

Several options exist for reducing the amount of solid and gaseous matter from motor vehicle exhaust. The development of the natural gas engine is one approach. Advanced vehicle technologies, such as New York City Transit's (NYCT) hybrid diesel-electric bus, are another. Reduced-sulfur diesel fuel and exhaust after-treatment are being tried as well. Fuel cell technology, which creates electricity from hydrogen, offers the greatest potential for emissions reduction. Depending on how a fuel cell vehicle is configured, it can have zero on-vehicle emissions. The other technologies have succeeded as well, though to varying degrees. This section discusses these approaches and the different issues associated with each.

Natural Gas Buses

Natural gas buses have been in wide use for approximately a decade and are the favored alternative to diesel buses for environmentalists and several U.S. transit properties. Most agencies use compressed natural gas (CNG), though some use liquefied natural gas (LNG). Derived from methane, natural gas is popular for many reasons. It is a proven technology, has a good track record of success, and is cheaper than other clean fuels like methanol. Natural gas engines offer many emission benefits over diesel engines, including lower levels of toxic compounds and NOx. Any of the new technologies being tested, including modern exhaust treatment and advanced vehicle designs, must provide comparable performance, vehicle and operating costs, and emissions benefits as natural gas in order to gain acceptance.

A number of transit agencies comparable to NYCT have extensive natural gas bus programs. In response to a local law that requires all city motor vehicle fleets to use alternative fuel technology, the New York City Department of Transportation (NYCDOT) is converting the entire private bus fleet to CNG operations. Currently, there are 340 CNG buses in the fleet, and within four years, more than half of the 1,265 buses will be CNG.[14] NYCDOT chose CNG because at the time of its decision methanol was prohibitively expensive, and a commercially viable hybrid diesel-electric bus was not available.[15] The Los Angeles County MTA (LACMTA) decided in 1999 to convert its fleet of 2,200 buses to CNG technology. The agency currently has 602 CNG buses and will have 2,066 CNG buses by the end of 2001. The Greater Cleveland Regional Transit Authority has 166 CNG buses in its 879-bus fleet, and New Jersey Transit has 50 CNG express bus coaches, with an order of 27 more planned.[16]

Long Island Bus (LIB), NYCT's suburban counterpart, is one of many smaller agencies that are converting to CNG operation. LIB is converting its entire fleet of 320 buses and already has 240 CNG buses.[17] Other small operators using CNG buses include Pierce Transit in Tacoma, Washington; Sacramento Regional Transit District; and SunLine Transit in Thousand Palms, California, which has fully converted its fleet.[18] Sun Metro in El Paso, Texas, has converted over half of its 240-vehicle fleet to natural gas operation and uses both CNG and LNG vehicles.[19]

Using natural gas buses is more complicated than diesel buses. Operators incur higher capital costs with natural gas buses and possibly higher operating and maintenance costs. Agencies report differing experiences with running costs, but recent data indicate that these costs exceed those for diesel buses.

Natural gas buses cost between $40,000 and $50,000 more than diesel buses, and depots must be converted to accommodate CNG fueling. Agencies need to install a fueling station, and safeguards must be taken to protect against

[14] Data on NYCDOT, LACMTA, and Cleveland fleets taken from a spreadsheet provided by NYCT Department of Buses.
[15] Personal communications with Jai Theratil, NYCDOT.
[16] Jeanne M. Fox, "Diesel Buses Choking City," ***New York Daily News Online***, December 27, 1999.
[17] Personal communication with Larry Penner, Federal Transit Administration; "City Could Breath Easier with Natural-Gas Buses," Editorial, ***Newsday***, January 2000, p. A34.
[18] Linda Metler, "Alternative Fuels: A Muddled Picture Remains Muddled," ***Bus Ride Magazine***, December 1999, pp. 80-81.
[19] U.S. Department of Energy, ***Case Study: Sun Metro - 6.2 Million Miles on Natural Gas***, May 1997.

an explosion. Unlike diesel fuel, which is liquid, CNG is a gas and is lighter than air. If there is a fuel leak, CNG vapor will collect at the ceiling level. It will ignite explosively if it comes into contact with a spark or open flame. For this reason, many precautions must be taken at CNG depots. A methane detection system is necessary to alert depot workers of leaks. The ideal site for the fueling station is outdoors, which provides a natural escape route for the vapor. However, in dense urban areas such as New York City, it may not be feasible to place the station outside. Extensive depot modifications become necessary in that case. Blast-proof walls around the fueling station must be constructed, open space must be created to provide an escape path for the vapors, and additional ventilation must be installed. Open-flame heaters must be replaced with an enclosed heating system, and wires at ceiling level must either be relocated or replaced with explosion-proof wiring.

The total costs to equip a depot for CNG operation vary depending on the agency. LACMTA reports lower costs than are experienced in New York City, $6.3 million for the fueling station and $0.8 million for depot modifications.[20] Its costs are relatively low because its depots are single-story structures with outdoor parking. Less interior modifications are necessary at such facilities. NYCDOT's cost per depot is approximately $10 million, divided evenly between the fueling facility and the depot modifications.[21] NYCT reports costs of $20 million to convert the Jackie Gleason Depot to CNG operation and estimates that retrofitting the Manhattanville Depot could cost as much as $40 million. However, the incremental costs at the Coliseum Depot will be closer to NYCDOT's costs, since it is a new facility.[22]

Obtaining a reliable measure of operating and maintenance costs for natural gas buses is difficult. Several agencies report lower expenses, and other properties say that their costs are higher. The cost differential between natural gas and diesel buses is a factor of fuel price, engine efficiency, and the type of maintenance required for the two technologies. Vehicle age and operating conditions are other determinants.

Many of the operators report lower fuel costs for natural gas, on a diesel gallon equivalent (DGE) basis. Sun Metro's LNG costs are $0.54 per DGE, compared to a cost of $1.30 per gallon for diesel fuel.[23] Pierce Transit says that its costs are lower, and NYCT is paying less per DGE for CNG at the Jackie Gleason Depot ($0.74 for CNG and $0.80 for diesel fuel). NYCT, though, says its CNG costs will vary depending on the supplier; Brooklyn Union Gas, for example, agreed to provide CNG at a price comparable to what NYCT pays for diesel fuel.

[20] LACMTA, ***Fuel Strategies for Future Bus Procurements***, August 1999, p. iii.
[21] Personal communication with Jai Theratil, NYCDOT, December 1999.
[22] Personal communication with Dana Lowell and Bill Parsley, NYCT Department of Buses, January 2000.
[23] ***Sun Metro***, p. 5.

Fuel price is only one factor in the total fuel costs for a natural gas bus. Operating efficiency is a determinant. Diesel buses have greater fuel economy than natural gas buses. In a demonstration program sponsored by the New York State Energy Research and Development Authority (NYSERDA), average miles-per-gallon for three of the participating agencies were 2.98 for CNG and 3.65 for diesel.[24] NYCT reports fuel economy of 1.65 miles-per-gallon for its Brooklyn CNG fleet and 2.82 miles-per-gallon for its Brooklyn diesel buses. With the average bus operating 30,000 miles per year, this difference equates to a $5,100 per year savings with diesel fuel ($13,500 in CNG bus fuel costs and $8,400 in diesel bus fuel costs).[25] Smaller operators report costs savings with natural gas. Sun Metro estimates that it saves $1.6 million per year with natural gas,[26] and in a joint study, Sacramento Regional Transit District (SRTD) and SunLine Transit reported that diesel fuel costs over a three-year period were almost twice that of CNG fuel costs.[27] However, transit properties in small cities do not operate under the same stressful conditions as NYCT and may experience better operational efficiency with natural gas buses. In addition, SRTD and SunLine compared new CNG buses to older diesel buses,[28] a critical factor that may account for both the fuel and maintenance cost savings they experienced.

Natural gas buses require maintenance activities that are not necessary with diesel buses. Natural gas buses require an ignition system, which diesel buses do not. The fuel system on natural gas buses is more complex and contains more parts than the fuel system on diesel buses. However, because natural gas engines are cleaner than diesel engines, some operators say that they do not need to replace the lubricating oil as often on a natural gas bus, tune the engines as frequently, or rebuild them as soon as they would have to overhaul diesel engines.[29]

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[24] ***Alternative Fuels for Vehicles Demonstration Program***, NYSERDA, October 1997, Volume 3, p. 3-31. (Five agencies participated in the program: Central Regional Transportation Authority (CENTRO) in Syracuse; the Rochester-Genesee Regional Transportation Authority (RGR) in Rochester; LIB; the Niagara Frontier Transportation Authority (NFTA) in Buffalo; and Broome County Transit. Fuel economy was collected for all five operators, but it was included only for CENTRO, LIB, and Broome County Transit. CNG fuel economy could not be accurately determined for RGR and NFTA because of deficiencies in the data.)

[25] Personal communication with Dana Lowell and Bill Parsley, NYCT Department of Buses, January 2000; NYCT Department of Buses spreadsheet.

[26] ***Sun Metro***, p. 5. (Calculation in the paper is based on multiplying DGE of natural gas consumed per year—2.1 million DGE—by the $0.76 per-gallon savings for natural gas over diesel fuel. However, the actual difference appears to be approximately $700,000 per year, based on comparing the annual cost of natural gas—2.1 million DGE * $0.54 per DGE, or $1.1 million—to the annual cost of diesel fuel—1.4 million DGE * $1.30, or $1.8 million.)

[27] "Muddled Picture," p. 82.

[28] ***Ibid.***

[29] "Muddled Picture," pp. 82 and 84; ***Sun Metro***, p. 5. (The assertion on engine tune-ups is open to doubt. The actual level of emissions benefits from a natural gas engine depends on how well the engine is tuned. Greater benefits are achieved with a more finely tuned engine. Frequent engine tune-ups are therefore important, and NYCT estimates that it needs to tune its CNG engines every 18,000 miles. Similar tune-ups are not required with NYCT's diesel engines.)

Experience with natural gas maintenance costs has been mixed, with some operators reporting savings over diesel buses. SRTD and SunLine found that expenses for labor and parts were substantially higher for diesel buses than they were for CNG buses.[30] Findings were similar in the NYSERDA study, where parts and labor costs for CNG buses were 83% of parts and labor costs for diesel buses.[31] CNG maintenance costs for private bus operators in New York City appear to be comparable to diesel maintenance costs, according to NYCDOT.[32]

Closer examination of the data raises doubts about the reported cost savings. The private bus operators in New York City do not report CNG and diesel maintenance costs separately; NYCDOT bases its estimates on data that shows that maintenance costs have not risen in proportion to the number of CNG buses in the fleet.[33] In addition, the NYSERDA program had mixed results. The costs actually favored diesel buses on a per-mile-driven basis because all but one of the operators got more miles from the diesel buses tested. Total CNG maintenance costs were $1.10 for every diesel mile traveled. The report also notes that the per-bus costs were probably biased by the relative age of the CNG and diesel buses. The CNG buses were newer, and the engine repairs were done under warranty.[34] SRTD and SunLine compared new CNG buses to older diesel buses[35], and repairs for SRTD were performed under warranty.[36] LACMTA reports that SCRTD's maintenance costs increased over 50% once the warranty expired on the CNG buses.[37]

After analysis of data from several operators, LACMTA estimated that the total operating and maintenance costs for CNG buses are higher than they are for diesel buses. NYCT, for example, performed an in-service test that compared same-age and same-model diesel and CNG buses. Operating costs for the CNG buses were 49% higher.[38] LYNX in Orlando, Florida, conducted a similar test and found its CNG operating costs to be 65% higher.[39] However, there are also some questions about these results. Both NYCT and Lynx tested Orion V buses that experienced component failures attributable to the newness of the technology.[40] NYCT has developed design improvements for its CNG buses that should reduce maintenance costs for future procurements.[41] Although the true operating and

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[30] "Muddled Picture," p. 82.
[31] ***Alternative Fuels for Vehicles***, p. 3-40.
[32] Personal communication with Jai Theratil, NYCDOT.
[33] ***Ibid.***
[34] ***Alternative Fuels for Vehicles***, pp. 3-39 to 3-40.
[35] "Muddled Picture," pp. 82 and 83.
[36] ***Fuel Strategies***, p. ii.
[37] ***Ibid***.
[38] ***Ibid.***
[39] "Muddled Picture," p. 84.
[40] Personal communications with Dana Lowell and Bill Parsley, NYCT Department of Buses, January 2000; "Muddled Picture," p. 84.
[41] Personal communications with Dana Lowell and Bill Parsley, NYCT Department of Buses, January 2000.

maintenance costs for natural gas buses remain uncertain, large urban operators will probably experience some increased costs with natural gas vehicles.

The overall picture for natural gas buses remains equally unclear. Many operators are satisfied with their fleets, including NYCDOT, SRTD, SunLine, and Sun Metro. Others find the increased operating, maintenance, and capital costs too burdensome and have reevaluated their policies. Bi-State Regional Transit Authority cancelled plans to purchase an additional 300 CNG buses for its fleet. Capital Metropolitan Transportation Authority in Austin, Texas, and the City of Mississauga abandoned plans to convert to CNG operation.[42] Even the LACMTA report questions the wisdom of converting to CNG, citing not only the additional costs, but the actual contribution a full CNG fleet would make to improving air quality in Southern California. Its study estimates NOx and particulate emissions would be only 0.07% and 0.09% lower, respectively, with a full CNG fleet than with a half-diesel, half-CNG fleet.[43]

The lack of consensus on natural gas is one of the factors driving development of new vehicle and fuel technologies. Agencies such as NYCT are exploring other approaches to reducing diesel emissions. Whether these approaches are a viable alternative to natural gas will depend on their emission savings as well as on their capital and operating cost efficiency. Despite the uncertainties about natural gas, it remains the standard by which alternatives to diesel fuel will be measured.

Hybrid Electric Buses

A step in the direction of zero-emission, fuel cell buses is a hybrid bus that uses a dual-energy system. The propulsion system on the bus is driven by an electric battery that draws its energy from a combustion engine. The combustion engine can use diesel fuel or an alternative fuel source such as natural gas. NYCT's production models are diesel-electric buses. A hybrid electric bus offers many benefits over a standard diesel-powered bus, chiefly lower exhaust emissions and better fuel economy. This technology should also serve as a bridge to fuel cell buses, which use an electric drive as well, but a different means of powering this system.

Hybrid electric buses provide emission savings over diesel buses for two primary reasons. They use a smaller diesel engine than standard buses do; the diesel engine on NYCT's hybrid electric bus is 25% smaller than a typical diesel engine. The engine size, though, is not the critical factor. The electric drive provides the greatest gains. In a hybrid electric bus, the diesel engine does not directly power the vehicle; the electric drive does. The diesel motor is used instead as a generator for the batteries, and as a result, it operates closer to a steady-state mode throughout the driving cycle. Eliminating the transient engine

[42] ***Fuel Strategies***, pp. iii and iv.
[43] ***Ibid.***, pp. iv and v.

conditions normally encountered while the bus accelerates and decelerates substantially lowers the level of emissions, since most diesel exhaust is produced when the engine is working hardest. NYCT's hybrid buses also use an exhaust-treatment system to reduce the amount of emissions even further.

Preliminary results from a hybrid diesel-electric bus are encouraging. In test results reported in 1995, the Orion V hybrid diesel prototype had NOx emissions of 13.82 grams per mile.[44] This number compares favorably to the CNG results in the 1999 WVU tests, which were approximately 10 grams per mile for New York City buses.[45] The Orion V prototype did not perform particularly well for PM emissions, with the level reported at 0.372 grams mile per mile.[46] CNG results in the WVU tests were no higher than 0.041 grams per mile. However, the engine in the Orion V bus was an older technology diesel engine, and hybrids using more modern engines have demonstrated better results.

Findings reported at a 1997 electric vehicle symposium showed newer hybrid buses closing the gap with CNG buses[47], and more recent data show additional gains. Environment Canada performed emissions tests on NYCT's hybrid bus in March 1998. At 0.027 and 10.6 grams per mile, respectively, PM emissions and NOx emissions were virtually the same as they were for the CNG buses tested by WVU.[48] The hybrid bus performed better on CO emissions (0.13 grams per mile, compared to a range of 9.38 to 13.5 grams per mile for CNG).[49] WVU is expected to release its results for a hybrid bus in Winter 1999-2000.[50]

Hybrid buses are more expensive than a standard diesel bus, but they do not involve the full range of capital costs that natural gas buses do. In December 1999, NYCT contracted with Orion to purchase 125 hybrid buses at a cost of $385,500 per bus. This figure well exceeds the price of a standard diesel bus, which costs approximately $270,000, and the latest price for CNG buses, which was $302,000 per bus for a 125-bus order in December 1999. NYCT does not anticipate the price of hybrid buses to approach the cost of diesel buses, but the agency says the price should come down to the level of CNG buses as the technology matures and the volume of orders increases. Critically, no depot modifications are necessary for hybrid diesel-electric buses, which represents a dramatic cost savings over using CNG buses.

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[44] Jason Mark and Laurence R. Davis, ***Shifting Gears: Advanced Technologies and Cleaner Fuels for Transit Buses***, Union of Concerned Scientists, April 1998, p. 25.
[45] Please see footnote 5 on page 6.
[46] ***Shifting Gears***, p. 25.
[47] ***Ibid***.
[48] NYCT Department of Buses, ***Emissions Reduction Strategy,*** January 2000, Appendix A, p. 4.
[49] ***Ibid***.
[50] Personal communication with Dana Lowell and Bill Parsley, NYCT Department of Buses, January 2000.

Table 3: Comparison of Emissions from CNG and Hybrid Diesel-Electric Buses (Grams per Mile)

Bus	PM	NOx	HC	CO
CNG	0.022	14.85	19.30	9.49
Orion V Diesel-Electric	0.372	13.82	N/A	N/A
Orion VI Diesel-Electric	0.027	10.62	0.13	0.13

Sources: ***Emissions Reduction Strategy, Shifting Gears***. (Note: Data were not available for hydrocarbon and carbon monoxide emissions from the Orion V diesel-electric bus.)

Not enough is known at this point to assess fully the operating and maintenance costs of hybrid buses. They do provide more fuel economy than either diesel or CNG buses. The savings are a factor of the smaller combustion engine and the use of the electric drive to power the buses. The fuel economy for the Orion V hybrid bus was 5.46 miles per gallon, compared to 3.57 miles per gallon for the diesel bus against which it was tested.[51] NYCT reports a smaller differential: 2.60 miles per gallon for its hybrid fleet and 2.36 miles per gallon for diesel buses running under similar operating conditions.[52] At 30,000 miles traveled per year, a hybrid bus will provide a modest $942 in savings over a diesel bus, but $4,000 in savings over a CNG bus.

Maintenance costs are an open question. NYCT feels that there will be both cost savings and additional expenses associated with hybrid buses.[53] Hybrid buses do not have transmission systems, which eliminates the need to maintain and rebuild these complicated mechanical devices. Cost savings are anticipated with the braking systems, since the regenerative brakes of the hybrid experience less wear than the brakes of a diesel bus. (Regenerative brakes slow the bus by reversing the magnetic field of the motor; through this process, they generate additional power for the batteries and reduce wear.)[54] NYCT expects that brake life will be doubled as a result. Battery maintenance is a new task that may be required. After a certain amount of time, batteries may need to be replaced, and regular preventive maintenance may be necessary in order to maintain optimal capacity. Batteries may have to be discharged and charged monthly, for example, though NYCT says it may be possible to automate this work. Workers may need to rebuild the diesel engine more times over the lifetime of a hybrid than is required for a standard diesel engine. Whether this

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[51] ***Shifting Gears***, p. 25.
[52] NYCT spreadsheet.
[53] Information on maintenance issues associated with hybrid buses is based on a conversation with Messrs. Lowell and Parsley.
[54] "Lockheed Martin Powers Hybrid Buses to Serve New York," ***Passenger Transport***, October 11, 1999, p. 30.

maintenance will add incremental costs is not certain, since the smaller engine will be less costly to rebuild. Overall, NYCT says that the maintenance costs could be about the same. Not enough data is available to know definitively, however, and more experience is necessary to answer the maintenance question.

Other agencies besides NYCT are showing an interest in hybrid buses, including several large operators. The Massachusetts Bay Transportation Authority in Boston is operating two hybrids, and New Jersey Transit is contemplating using this technology. Other agencies interested in hybrid buses are Metro Transit in Minneapolis, Minnesota, which is in negotiations to buy up to ten buses, and Foothill Transit in Southern California, which is converting its entire fleet of 259 buses to CNG-electric vehicles.[55] Combined with NYCT's recent order of 125 hybrid buses, these initiatives will provide the knowledge base needed to judge whether hybrid technology is a viable alternative to diesel and natural gas buses.

Fuel Cell Buses

The Chicago Transit Authority is testing the one technology that offers the potential for zero emissions: a fuel cell bus. Similar to a hybrid electric bus, a fuel cell bus is powered by an electric drive that receives its energy from a generator. However, the energy to power the electric drive is not derived from an internal combustion engine turning a generator. Instead it is produced by a fuel cell engine that produces electricity directly from the reaction of hydrogen with oxygen at low temperature. The hydrogen can either be stored on board the vehicle as a high pressure gas or derived on-board from a liquid or gaseous fuel that contains hydrogen, such as gasoline, diesel, natural gas, methanol, or ethanol. If the hydrogen is stored and provided as a gas, the only emissions from a fuel cell bus will be water; otherwise, there will be minimal emissions associated with the reforming process that creates the hydrogen from a more complex fuel. In either case, a fuel cell vehicle offers dramatic emissions improvements at the point of use.

The most logical configuration for a fuel cell bus may be to use a fuel other than hydrogen gas as the hydrogen source. Bus depots would have to be converted to accommodate hydrogen storage. This work could present similar challenges as modifying garages to handle natural gas, but at higher costs. The budgeted costs to convert the CTA's depot is $2.9 million for only three buses.[56] The storage tanks on the bus are also bulky and limit the range of the vehicle.[57] Methanol appears to be a viable fuel source for fuel cells. It necessitates only minor modifications to existing fuel cell distribution systems, does not require

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[55] Cliff Henke, "Hybrid Buses Begin to Enter Revenue-Service Stage," ***Metro Magazine,*** May 1998, p. 56.
[56] ***Shifting Gears***, p. 20.
[57] ***Ibid***., p. 19.

large on-board high-pressure storage tanks, and offers a driving range comparable to diesel fuel.[58]

Georgetown University has demonstrated success with a transit bus that uses methanol as the hydrogen source for the fuel cell. The vehicle has a range of 350 miles and has close to no emissions. In tests, it released only 0.01 grams per brake horsepower-hour of NOx and no measurable amounts of particulate matter.[59] The CTA reports that it is satisfied with its program, which is testing the vehicles in revenue service and is now two years old.[60] Other demonstration projects are underway. BC Transit in Vancouver, Canada, is testing three fuel cell buses, and a joint venture of DaimlerChrysler, Ford Motor Company, and Ballard Power Systems has developed a prototype fuel cell bus. The consortium hopes to begin series production of fuel cell buses within the next few years.[61] Automobile manufacturers, including Toyota and General Motors, are developing fuel cell vehicles for the consumer market.[62] Since the challenge has been making fuel cells practical for motor vehicles, advances in this area should help to make the technology commercially viable and bring it to mass production more quickly.

Fuel cell technology has existed since 1839, but until recently, it has been used only for the U.S. space program and for large-scale stationary applications.[63] Through advances in material science and significant reductions in cell size, the technology is now becoming practical for automobiles and buses. However, full-scale production of fuel cell buses is not anticipated for approximately a decade. Once in regular operation, they will solve the emissions problems that today's buses pose.

Low-Sulfur Fuel and Exhaust-Treatment Systems

The EPA has begun to direct its attention to the sulfur content of diesel fuel. In May 1999, it announced its intention to tighten diesel fuel sulfur standards, which now allow up to 500 parts per million (ppm) of sulfur.[64] By contrast, proposed regulations for gasoline will limit sulfur to 30 ppm by 2004.[65] Lowering the amount of sulfur present in diesel fuel would provide important environmental and health benefits.

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[58] Mock, Horst, et al., "From diesel drive to fuel cell: developing buses into 'zero emission' vehicles," ***Public Transport International***, p. 38; Urban Mobility Corporation, "The 'Supercar,'" ***Innovation Briefs***, September/October 1999.
[59] Garrick, Les, "Hybrids and their relatives join the fleet," ***Mass Transit*** 23:5, September/October 1997, p. 61.
[60] "Muddled Picture."
[61] ***Shifting Gears***, p. 20.
[62] "'Supercar.'"
[63] ***Shifting Gears***, p. 19.
[64] ***Federal Register*** 64:92, May 13, 1999, p. 26148.
[65] ***Emissions Reduction Strategy***, p. 7.

Sulfur is a major contributor to emissions pollution. Ambient sulfur compounds, particularly sulfate and sulfur oxide, have been associated with respiratory illness and reduced survival rates in heavily polluted urban areas.[66] Sulfates are a primary component of diesel particulate matter, and diesel engines emit sulfur dioxide.

Low-sulfur diesel fuel would directly reduce these emissions and have an important secondary benefit. Exhaust-treatment systems function better with reduced-sulfur fuel. Sulfur is a contaminant that can reduce the effectiveness of the catalytic systems used in many exhaust emissions reduction devices. In its notice of proposed rulemaking, the EPA cited this characteristic as an important reason for implementing more stringent standards.[67] The EPA estimates dramatic reductions of PM and NOx emissions when low-sulfur fuel is used in combination with exhaust-treatment systems. Diesel engine emissions of NOx and PM could decline by as much as 75% and 80%, respectively.[68] At these levels, emissions from diesel engines would be comparable to emissions from natural gas engines.

Europe is already moving to low-sulfur diesel fuel. The European Union has enacted regulations that will limit the level of sulfur to 350 ppm by 2000 and 30 ppm by 2005.[69] Several European countries are currently using diesel fuel containing no more than 50 ppm of sulfur. All diesel fuel sold in the U.K. will meet this standard, and in Finland, 90% of the diesel fuel used contains less than 50 ppm of sulfur. Japan is considering a 50 ppm standard.[70]

Emissions tests demonstrate that reduced-sulfur diesel fuel can lower the amount of PM, but not to levels comparable with a natural gas bus. The Atmospheric Research and Information Centre in the U.K. reported test results that show a 34 to 84% reduction in PM with low-sulfur fuel. A large diesel engine using fuel with 500 ppm of sulfur had PM emissions of 0.517 grams per kilometer (0.83 grams per mile). A comparable engine using low-sulfur fuel had PM emissions of 0.078 grams per kilometer (0.12 grams per mile).[71] Despite this reduction, the amount of PM is still significantly higher than the levels found in the WVU test (no more than 0.041 grams per mile). NOx emissions were unaffected. They were 10.97 grams per kilometer (17.55 grams per mile) with standard diesel fuel and 10.39 grams per kilometer (16.62 grams per mile) with low-sulfur diesel fuel.[72] These figures exceed the levels reported by WVU for New York City CNG buses, which were approximately 10 grams per mile.

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[66] "British Bus Operator Moves to Ultra-Low-Sulfur Fuel," ***Passenger Transport***, June 21, 1999;[66] ***HEI Communications 8***, p. 5.
[67] ***Federal Register***, p. 26143.
[68] ***Ibid.***
[69] ***Ibid***., p. 26148.
[70] ***Ibid.***
[71] ***ARIC Briefing Note: Alternative Fuel Vehicles***, Atmospheric Research and Information Centre, Manchester, U.K., July 1997. p. 2.
[72] ***Ibid.***

Exhaust-treatment systems are necessary to realize further emissions reductions, and after problems with first-generation technology, several promising products are now being introduced or are under development. One early system that did not perform as anticipated was the particulate trap oxidizer. This device trapped diesel particulates in a filter and then employed a heater to burn, or oxidize, the filtered material. NYCT made extensive use of the traps in the mid 1990s and reports that it was satisfied with the emissions reductions. The system, however, had problems with reliability and with the mechanism by which it burned the particulate. [73] When the manufacturer discontinued production of the traps, NYCT abandoned their use. Since then, advances have been made in diesel exhaust-treatment technology. The EPA anticipates that these systems will provide gains in diesel emissions control comparable to the reductions achieved by the introduction of the automotive catalytic converter in the 1970s.[74]

Two types of systems are being developed, one to reduce PM emissions and one to lower NOx levels. The newest technology aimed at particulate matter is a continuously regenerating trap (CRT) developed by Johnson Matthey. This device contains a filter to trap PM and then uses a chemical agent, or catalyst, to enable the material to burn at engine exhaust temperature. Unlike the trap oxidizers that NYCT used, the regenerative system in the CRT contains no moving parts and is passive. It does not heat the PM, which instead oxidizes naturally after it interacts with the catalyst. Greater success is expected with this simpler technology. The CRT can reduce PM emissions by more than 80% and should sharply lower the amount of particle- and gas-phase toxic compounds.[75] The combination of low-sulfur fuel and the CRT in Europe cut PM emissions to 0.015 grams per mile,[76] comparable to CNG emissions in the WVU tests.

Several technologies are being developed to reduce NOx emissions. The first system to reach the market will be exhaust gas recirculation (EGR). In this process, NOx is redirected back to the combustion chamber, where it is oxidized. Emissions reductions of up to 90% are anticipated[77], and the use of EGR is expected to enable heavy-duty diesel engines to meet the EPA's 2002 combined standard for NOx and non-methane hydrocarbons.[78] This standard requires emissions of no more than 2.5 grams per brake horsepower-hour,[79] a level that is comparable to total NOx and hydrocarbon emissions from a CNG bus. Tests on a CNG engine in 1997 showed respective NOx and hydrocarbon levels of 2.5 and 0.6 grams per brake horsepower-hour.[80]

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[73] ***Shifting Gears***, p. 22.
[74] ***Federal Register***, p. 26147.
[75] ***Ibid***., p. 26150.
[76] NYCT Department of Buses, ***Reducing Bus Fleet Emissions at New York City Transit***, November 1999, p. 18.
[77] ***Federal Register***, p. 26149.
[78] Personal communication with Dana Lowell and Bill Parsley, NYCT Department of Buses.
[79] ***Emissions Reduction Strategy***, Appendix A, p. 2.
[80] ***Shifting Gears***, p. 24.

The other technologies rely on a catalytic process and are not expected to be in use before 2005. Selective catalytic reduction (SCR) uses ammonia and a catalyst to reduce NOx levels. This system can reduce NOx emissions by 70 to 90%, though it poses some challenges. It uses an active process to introduce the ammonia, and as the experience with the trap oxidizers illustrates, active systems are prone to failure. SCR may increase emissions of ammonia, which is a health hazard, and of nitrous oxide, which is a greenhouse gas.[81]

Another technology is a NOx storage catalyst that reduces emissions in a multi-step process. A catalyst converts nitrogen oxide to nitrogen dioxide, which is then stored in a trap. The nitrogen dioxide is then removed from the trap and reduced through a second catalytic process. A NOx storage catalyst could reduce NOx emissions by 50 to 75%.[82]

The last technology is a lean-NOx catalyst, which reduces NOx in an oxygen-rich environment like that of diesel exhaust. Lean-NOx catalysts have not been particularly successful to date, demonstrating emissions reductions of only 15 to 35%. They may be best suited for light-duty engines and then only in combination with another system such as EGR.[83]

Low-sulfur diesel fuel can also be used with hybrid diesel buses. In a 1998 test of a NYCT hybrid bus, PM emissions were 0.002 grams per mile when diesel fuel containing less than 50 ppm of sulfur was used.[84] NOx emissions were high, at 27.66 grams per mile.[85]

The emergence of low-sulfur diesel fuel and exhaust-treatment systems appear to offer a viable approach for reducing emissions. The technologies do present obstacles—more experience with them is needed, and there are additional fuel costs of approximately ten cents per gallon and costs to install the exhaust-cleaning devices—but the strategy would be worth pursuing until hybrid and fuel cell buses are widely available. The incremental costs would be markedly lower than the costs of converting to natural gas technology, tests have demonstrated good results, and the EPA anticipates more gains in the future.

[81] ***Federal Register***, p. 26150.
[82] ***Ibid.***
[83] ***Ibid***, pp. 26149-26150.
[84] ***Emissions Reduction Strategy***, Appendix A, p. 4.
[85] ***Ibid***.

Table 4: Emissions Results with CNG and Alternative Diesel Configurations (Grams per Mile)

Bus	Fuel	PM	NOx	HC	CO
CNG	CNG	0.022	14.85	19.30	9.49
Standard Diesel	Low-Sulfur Diesel	0.120	16.62	N/A	N/A
Standard Diesel	Low-Sulfur Diesel with CRT	0.015	N/A	N/A	N/A
Orion VI Diesel-Electric	Standard Diesel	0.027	10.62	0.13	0.13
Orion VI Diesel-Electric	Low-Sulfur Diesel (<50 ppm)	0.002	27.66	0.00	0.039

Sources: ***Emissions Reduction Strategy***; ***Reducing Bus Fleet Emissions; ARIC Briefing Note:***
(Note: Complete emissions data were not available for the standard diesel buses using low-sulfur diesel fuel and low-sulfur diesel fuel in combination with a CRT.)

Conclusions: Analysis of NYCT's Bus Program

In its 2000-2004 Capital Program, NYCT plans to purchase 1,056 buses. Of this total, 756 will be diesel buses, including 400 articulated buses and 356 over-the-road coaches for express bus service. The remaining 300 will be some combination of CNG and hybrid diesel buses. At the end of the plan, NYCT will have approximately 4,500 buses in its fleet. The composition of the fleet will be 2,578 standard diesel buses, 630 articulated buses, 507 express buses, at least 349 CNG buses, at least 140 hybrid buses, and the mix of 300 new CNG and hybrid buses.

Environmental advocates are dissatisfied with this proposed program. They feel that NYCT should commit itself fully to natural gas buses, beginning with a commitment to buy no diesel buses in the 2000-2004 capital plan. Supporters of CNG buses argue that diesel buses are too dirty and pose too much of a health hazard to City residents. They question the effectiveness of hybrid buses in reducing emissions and doubt that cleaner diesel fuel and exhaust-treatment systems will produce acceptable results. Critics of NYCT feel that natural gas is the only clean-fuel technology with a proven record of reducing emissions.

NYCT counters that it is taking a multi-faceted approach to a cleaner fleet. The Jackie Gleason Depot is equipped to handle CNG fueling, and the Coliseum Depot will open as a CNG facility in 2001. NYCT plans to convert the Manhattanville Depot to CNG operations in the 2000-2004 capital plan. The agency is expanding its hybrid bus program, including a December 1999 contract for 125 more buses, and is confident that low-sulfur fuel in tandem with an exhaust-treatment system will produce appreciably lower emissions. NYCT has discussed doing a demonstration fuel cell project with Plug Power, a New York-based manufacturer of fuel cells. The agency hopes to begin converting its hybrid buses to fuel cell technology within eight years.[86]

NYCT believes that its combined strategy is more effective than a full-CNG policy. Test results have demonstrated the efficacy of other alternatives, and converting to CNG is a complicated, slow, and costly process. The agency says that investing too heavily in CNG technology could actually be counterproductive. Resources would be used more cost effectively on hybrid buses and on low-sulfur fuel and particulate traps, technologies that involve lower capital costs than natural gas buses.

The evidence supports NYCT. Other large transit properties, including LACMTA, have expressed legitimate concerns about the feasibility of natural gas buses. This technology also may not be as clean as its proponents claim. Tests by the New York State Department of Environmental Conservation have

[86] Lueck, Thomas J., "Plan to Add Diesel Buses is Criticized," ***New York Times,*** January 2, 2000, p. 29.

demonstrated that natural gas engines emit a greater number of fine and ultrafine particles than diesel engines. The Harvard Center for Risk Analysis notes that other studies have reached the same conclusion. Emissions of greenhouse gases are higher and the discharge of formaldehyde may be an issue.

Conventionally fueled hybrid buses have done well in tests, with emissions levels comparable to CNG buses. When low-sulfur diesel fuel is used, hybrid diesel technology outperforms natural gas technology. Tests have demonstrated good results for standard diesel buses using low-sulfur fuel and a catalytic particulate trap.

Environmental advocates say that more testing needs to be done on hybrid buses and feel that exhaust-treatment systems will prove to be unreliable. In partnership with the New York State Department of Environmental Conservation, NYCT plans a series of tests that should address these concerns. The program is structured in precisely the way CNG supporters have suggested.

In order to assess the effectiveness of each of its technologies, NYCT will have Environment Canada perform a broad range of emissions tests over the next year. Tests will be conducted on CNG, hybrid, and standard diesel buses, but not on articulated buses and over-the-road express coaches. The hybrid buses will be evaluated with regular diesel fuel and low-sulfur diesel fuel, and the standard buses will be tested using regular diesel fuel, low-sulfur diesel fuel, and low-sulfur diesel fuel in tandem with a continuously regenerating particulate trap (CRT).

Data will be collected for PM, NOx, hydrocarbon, and carbon monoxide emissions, for particle size and distribution, and for emissions of toxic compounds. The latter two tests will provide valuable information on the number of fine and ultrafine particles present in CNG, hybrid diesel, and filtered diesel exhaust, as well as on the toxicity of the exhaust from each vehicle configuration. Subsequent to this series of tests, NYCT will run the CRT-equipped buses in revenue service for a year and bring them back to Canada for further testing. These tests will determine how reliable the CRT technology is.

No decision should be made on converting to CNG buses until the tests are completed. Too many questions need to be answered about the various technologies being evaluated. Committing to an all CNG-policy also would be difficult at this time.

If NYCT agreed to abandon its diesel program, it would have to alter the scope of the 2000-2004 Capital Program to accommodate natural gas bus purchases. More buses would be needed to equal the capacity that the articulated buses and over-the-road express coaches would provide. No CNG version of an articulated bus currently exists; the only available natural gas express coach is the one New Jersey Transit uses. This bus is forty-feet long and costs $500,000 each. NYCT's coach is forty-five-feet long and costs $333,000 from New Flyer and $376,000 from MCI.

NYCT would have to buy 289 more buses in an all-CNG plan, assuming an equivalent of one-and-one-half standard-size buses for each articulated bus and one-and-one-quarter standard-size buses for each forty-five foot express coach. The incremental costs of buying 1,345 CNG buses instead of the programmed mix of 1,056 buses would depend on two factors. One is the price per CNG bus; the other is whether NYCT uses a standard CNG bus or an over-the-road CNG coach to replace the express bus component of the plan. If NYCT buys only standard CNG buses and pays the same $302,000 per bus as it did in its most recent purchase, it would realize savings of $5.3 million. The additional costs could be as high as $96.3 million if NYCT uses the same over-the-road CNG coach as New Jersey Transit does and it pays the same $317,000 per standard CNG bus as it did in its last contract with New Flyer.

In order to accommodate another 1,345 CNG buses, NYCT would need at least six more CNG-equipped depots, assuming that each depot can store 250 buses. With the Coliseum Depot and Manhattanville Depot already programmed for CNG operations, NYCT would have to convert an additional four depots in the 2000-2004 Capital Program to meet this demand. However, the plan only contains funding to build one new depot in Brooklyn and to rehabilitate the East New York Depot.

Financing would be needed for two additional depots and for the incremental costs associated with installing natural gas infrastructure at each garage. The costs could be between $190 and $250 million. Of this amount, $150 million would be for the two additional rehabilitation projects, and between $40 million and $100 million would be for CNG infrastructure. Incremental costs for CNG were estimated at $10 million for the new Brooklyn depot and in the range of $10 to $30 million each for the other three depots.

Schedule would be a factor. In the best-case scenario, the four additional depots would be ready by 2004, since depot design takes approximately one year and construction another two years. However, NYCT probably cannot handle four simultaneous depot renovation projects; with bus storage space already constrained, taking so many garages out of service at one time is not feasible. A more realistic timeframe for completion would be 2006.

Buying only CNG buses in the 2000-2004 Capital Program is not practical considering the probable schedule for converting depots. NYCT would have to defer delivery of a large share of the new buses until the depots are ready. Given the explosive growth in bus ridership since 1996, the agency needs more buses now. In the upcoming capital plan, three-quarters of the bus purchases are planned for 2000 and 2001. Some amount of these procurements would have to

Table 5: Incremental Bus Costs for All CNG Buses in 2000-2004 NYCT Capital Program

Planned Bus Purchases

	2000	2001	2002	2003	2004	2000-2004	Costs
Standard Buses (CNG or Hybrid)	150	150				300	$ 112,200,000.00
Articulated Buses	140	260				400	$ 176,500,000.00
Over-the-Road Express Buses	104		252			356	$ 122,800,000.00
Totals	394	410	252			1,056	$ 411,500,000.00

Bus Program as Full CNG Purchase

	2000	2001	2002	2003	2004	2000-2004
Standard Buses (CNG or Hybrid)	150	150				300
Articulated Buses	210	390				600
Over-the-Road Express Buses	130		315			445
Totals	490	540	315			1,345

Incremental Costs of Full CNG Purchase

	Total CNG Cost	Incremental Costs
At $302,000 per Standard CNG Bus		
If Standard CNGs Replace Express Buses	$ 406,190,000.00	$ (5,310,000.00)
If Over-the-Road CNGs Replace Express Buses	$ 494,300,000.00	$ 82,800,000.00
At $311,000 per Standard CNG Bus		
If Standard CNGs Replace Express Buses	$ 418,295,000.00	$ 6,795,000.00
If Over-the-Road CNGs Replace Express Buses	$ 502,400,000.00	$ 90,900,000.00
At $317,000 per Standard CNG Bus		
If Standard CNGs Replace Express Buses	$ 426,365,000.00	$ 14,865,000.00
If Over-the-Road CNGs Replace Express Buses	$ 507,800,000.00	$ 96,300,000.00

Notes: The price for over-the-road CNG coaches is $500,000 per bus. The $311,000 cost per standard CNG bus is the average of the $302,000 and $317,000 per-bus cost NYCT paid in its last two CNG purchases.

Table 6: Incremental Depot Costs for All CNG Buses in NYCT 2000-2004 Capital Program

Total Depot $ Programmed

	Cost (Millions of $)
Brooklyn (New Construction)	75
Coliseum	N/A
East New York (Rehabilitation)	75
Jamaica (Design Only)	5
Manhattanville (CNG Conversion)	50
Total $ Programmed	205

Note: Coliseum is expected to open in July 2001 and was funded in the 1995-1999 Capital Program.

Incremental Construction Costs (Millions of $)

At $10 million for CNG Infrastructure

	Brooklyn	East New York	Jamaica	Unspecified Location	Total Incremental $
Incremental Construction Costs	0	0	75	75	150
Incremental CNG Costs	10	10	10	10	40
Subtotal Incremental Costs	10	10	85	85	190

At $20 million for CNG Infrastructure

	Brooklyn	East New York	Jamaica	Unspecified Location	Total Incremental $
Incremental Construction Costs	0	0	75	75	150
Incremental CNG Costs	10	20	20	20	70
Subtotal Incremental Costs	10	20	95	95	220

At $30 million for CNG Infrastructure

	Brooklyn	East New York	Jamaica	Unspecified Location	Total Incremental $
Incremental Construction Costs	0	0	75	75	150
Incremental CNG Costs	10	30	30	30	100
Subtotal Incremental Costs	10	30	105	105	250

Note: Since the Brooklyn depot is a new facility, the incremental CNG costs are estimated at $10 million in all scenarios.
Jamaica construction costs are $75 million because no construction money for the depot is budgeted in the Capital Program.

be diesel buses pending conversion of depots, a point that CNG advocates have acknowledged in conversations with the Transit Riders Council.

An all-CNG policy for NYCT's entire fleet would pose substantial obstacles as well. If NYCT were to convert another four depots to CNG operations by 2006, seven of its eighteen depots would be CNG ready. Converting the remaining eleven depots could take until 2014, assuming that NYCT could do three depots at a time and that construction would take two years per depot. (Design work would be done while other projects are underway, enabling NYCT to transition immediately from one set of depots to another.) NYCT would also need to retire many of its diesel buses prematurely and would incur higher operating and maintenance costs with a CNG fleet.

Committing this level of resources to CNG buses is not prudent. Natural gas engines are not fully proven and they are only an interim technology. Fuel cell buses are expected to be widely available by 2014, which would make CNG buses obsolete. Because natural gas can be used as the hydrogen source for a fuel cell bus, the investment in CNG depots would not be entirely wasted. However, it would not be justified. Methanol, which can be handled by existing fuel distribution systems, would be a suitable hydrogen source, and hybrid diesel buses have emerged as a viable alternative to CNG buses.

NYCT's approach is sensible. The agency is assessing a broad range of options, each offering the potential to reduce emissions appreciably. A final decision should be made only when more is known about the entire spectrum of alternative technologies.

Recommendations

The available evidence does not support requiring NYCT to commit fully to compressed natural gas buses. Other technologies, most notably hybrid diesel-electric buses, have emerged as viable alternatives. They provide equal or better emissions performance than natural gas buses. Questions also persist about whether natural gas vehicles are as clean as their supporters say. Emissions of the smallest particulate matter, now considered to pose the greatest threat to human health, may be higher with CNG buses than they are with diesel buses. Natural gas engines release more carbon dioxide and methane, two strong greenhouse gases. Several transit agencies have also abandoned their CNG programs after experiencing problems with the technology. Most critically, with emissions-free fuel cell buses quickly maturing, natural gas is an interim measure. A large commitment of resources to this interim technology is not justified considering the unresolved issues.

For these reasons, the Transit Riders Council recommends the following:

- NYCT should not commit to an all-CNG policy. The agency should instead continue with its multi-faceted approach of testing several alternative technologies to standard diesel buses. These options offer the potential to equal or exceed the emissions performance of CNG buses.

- The EPA, the Health Effects Institute in Cambridge, Massachusetts, and other regulatory and health organizations should continue research into the health effects of small particulate matter. Several studies indicate that natural gas engines may release more fine and ultrafine particles than diesel engines. Even though the natural gas particles are purer, their carbon core may pose a health hazard.

- NYCT should phase out purchases of diesel buses in favor of hybrid diesel-electric buses if the hybrid technology continues to perform well in tests. The results of emissions tests on hybrid buses have been favorable, demonstrating that these vehicles can equal and exceed the emissions reduction of natural gas buses. NYCT should expand the use of hybrid technology to articulated and express buses. While this technology is being developed, NYCT should buy only as many diesel versions of these buses as it needs to meet service requirements.

- NYCT should perform emissions tests on articulated and express buses. These vehicles are not included in the upcoming series of tests because the agency assumes that emissions on a per-passenger basis will be comparable to emissions from standard-size diesel buses. NYCT may be correct, but it should evaluate the larger articulated and express buses to confirm its theory and to see how well they perform with low-sulfur diesel fuel and particulate traps. The results will also provide a baseline that NYCT can use to compare emissions for these vehicles against hybrid buses.

- NYCT should use only reduced-sulfur diesel fuel, which has demonstrated the greatest potential for reducing particulate matter. Negligible levels of particulate matter are released from a hybrid bus using low-sulfur fuel. When operated with reduced-sulfur fuel and a catalytic particulate trap, standard diesel buses have emitted less particulate matter than CNG buses. NYCT's fuel costs would increase modestly since low-sulfur diesel fuel costs about ten cents more per gallon than standard diesel fuel.

- New York State should adopt a stringent sulfur standard in advance of possible EPA action on this issue. The regulations should limit sulfur content to less than 50 parts per million. Applying this standard to all diesel engines would reduce particle emissions from all vehicles, not just NYCT buses.

- NYCT should install catalytic particulate traps on its entire diesel fleet, including articulated and express buses, if this system performs well in the planned tests. The agency should equip its diesel buses with devices to clean nitrogen oxide emissions as these systems emerge and are proven effective.

- NYCT should continue to explore other alternative-fuel technologies, as it is doing with fuel cell buses. The agency has discussed conducting a fuel cell demonstration project with Plug Power of New York and hopes to be running these buses within eight years. Fuel cell buses have the potential for zero emissions, and the Chicago Transit Authority and Georgetown University have demonstrated the viability of this technology for transit buses.

Bibliography

Atmospheric Research and Information Centre. ***ARIC Briefing Note: Alternative Fuel Vehicles***. http://www.doc.mmu.ac.uk/aric/notes/bn26-htm, browsed December 7, 1999.

"British Bus Operator Moves to Ultra-Low-Sulfur Fuel," ***Passenger Transport***. June 21, 1999.

California Air Resources Board. Meeting Summary of the Fuels Subcommittee. http://arbis.arb.ca.gov/toxics/diesel/fs/033199fssum.htm, browsed January 5, 2000.

—— ***Particulate Matter Air Pollution***. http://arbis.arb.ca.gov/html/brochure/pm10.htm, browsed January 10, 2000.

California Energy Commission. ***Clean Diesel Program: Diesel Emissions Reduction Fund***. June 1998.

Campbell, Todd, et al. ***Addressing the Technical and Public Health Issues of Diesel-Electric Hybrid Buses***. April 1999.

"City Could Breath Easier with Natural-Gas Buses," Editorial. ***Newsday***, page A34. January 2000.

Cromwell, Richard. "Clean Fuels: A Good Old Idea Coming Back into Fashion." ***Passenger Transport***, page 56. September 6, 1999.

DieselNet. ***DieselNet Technology Guide: Paper Abstracts.*** http://www.dieselnet.com/tginfo/abstracts.html, browsed November 17, 1999.

—— ***Heavy-Duty Truck and Bus Engines***. http://www.dieselnet.com/standards/us/hd.html, browsed December 23, 1999.

—— ***How Emissions Are Regulated***. http://www.dieselnet.com/standards/intro.html, browsed December 23, 1999.

Control of Diesel Fuel Quality (40 CFR Parts 80 and 86). Federal Register 64:92, pages 26142-26158. May 13, 1999.

Final Report: Analysis of Costs and Emissions Associated with the Replacement of Transit Bus Fleets. Vitetta Group (prepared for the California Transit Association). October 1999.

Fox , Jeanne M. "Diesel Buses Choking City." ***New York Daily News Online***. December 27, 1999.

Garrick, Les. "Hybrids and Their Relatives Join the Fleets." ***Mass Transit*** 23:5, pages 60-62. September/October 1997.

Harvard Center for Risk Analysis, "Fueling Heavy Duty Trucks: Diesel or Natural Gas." ***Risk in Perspective*** 8:1. January 2000.

Health Effects Institute. ***Diesel Exhaust: A Critical Analysis of the Institute's Diesel Working Group***. April 1995.

—— ***HEI Communication 8: The Heath Effects of Fine Particles: Key Questions and the 2003 Review***. http://www.healtheffects.org/Comm8.htm, browsed January 11, 2000.

—— ***Research on Particulate Matter***. May 1999.

Henke, Cliff. "Hybrid Buses Begin to Enter Revenue-Service Stage." ***Metro Magazine,*** pages 52-60. May 1998.

—— "Guess What Vehicle Will (Surprise) Power the Next Century." ***Metro Magazine***. November/December 1999.

Lueck, Thomas J. "Plan to Add Diesel Buses is Criticized." ***New York Times***, pages 27 and 29. January 2, 2000.

"Lockheed Martin Powers Hybrid Buses to Serve New York." ***Passenger Transport***, page 30. October 11, 1999.

Los Angeles County MTA. ***Fuel Strategies for Future Bus Procurements***. August 1999.

M.J. Bradley & Associates, and West Virginia University Heavy Duty Transportable Emissions Lab***. Internal Brief: Comparison of Emissions Performance for Alternative Fueled (CNG) and Conventional Fueled Heavy-Duty Transit Vehicles.*** June 1999.

Mark, Jason, and Davis, Laurence R. ***Shifting Gears: Advanced Technologies and Cleaner Fuels for Transit Buses***. Union of Concerned Scientists, Cambridge, Massachusetts. April 1998.

Metler, Linda. "Alternative Fuels: A Muddled Picture Remains Muddled." ***Bus Ride Magazine***, pages 76-92. December 1999.

Natural Resources Defense Council. ***Statement of the Natural Resources Defense Council on the Federal FY 2000 Capital Improvements Project Request***.

—— ***The Facts on Fumes: Questions and Answers from NRDC's Dump Dirty Diesels Campaign***. October 1999.

—— ***Testimony of the Natural Resources Defense Council on the MTA's 2000-2004 Capital Plan***. November 3, 1999.

New York City Transit Department of Buses. ***Emissions Reduction Strategy***. January 2000.

—— ***Reducing Bus Fleet Emissions at New York City Transit***. November 1999.

—— Spreadsheet: Fuel Costs for CNG, Hybrid, and Diesel NYCT Buses. January 4, 2000.

—— Spreadsheet: Percentage of Clean-fuel Buses in Top 15 U.S. Transit Fleets. December 28, 1999.

New York State Department of Environmental Conservation. ***Diesel Fuel Analysis: Impact on Air Quality***. http://www.dec.state.ny.us/website/dar/bms/diesel.html, browsed January 3, 2000.

New York State Energy Research and Development Authority. ***Alternative Fuels for Vehicles Demonstration Program***. Volume 3: Technical Reports. October 1997.

Office of the New York State Governor George Pataki. ***Governor Announces Initial EPA Approval of State Clean Air Plan***. December 1, 1999.

Skelton, Renee, and Kassel, Richard. ***End of the Line for Dirty Diesels: Why New York City Needs Natural Gas Buses***. Natural Resources Defense Council, New York, New York. September 1993.

U.S. Department of Energy. ***Case Study: Sun Metro - 6.2 Million Miles on Natural Gas***. May 1997.

U.S. EPA. ***Automobiles and Carbon Monoxide*** (EPA 400-F-92-005, OMS Fact Sheet #3). January 1993.

—— ***Automobiles and Ozone*** (EPA 400-F-92-006, Fact Sheet OMS-4). January 1993.

—— ***Clean Fuels: An Overview*** (EPA 400-F-92-008, Fact Sheet OMS-6). August 1994.

U.S. EPA, Air and Radiation, Office of Mobile Sources. ***Proposed Strategy to Reduce Emissions from Heavy Duty Vehicles*** (EPA 420-F-99-034). October 1999.

U.S. EPA, Emissions Inventory Improvement Program. ***Getting Started: PM-2.5 Emission Inventory***. September 1999.

U.S. EPA, Office of Air & Radiation (Office of Air Quality Planning & Standards). ***Fact Sheet: Summary of EPA's Strategy for Implementing New Ozone and Particulate Matter Air Quality Standards***. June 17, 1997.

Watson, John, and Chow, Judith. ***Reconciling Urban Fugitive Dust Emissions Inventory and Ambient Source Contribution Estimates: Summary of Current Knowledge and Needed Research***. Desert Research Institute, Energy and Environmental Engineering Center, Reno, Nevada. Chapter 2. September 1999.

Wolinsky, Julian. "The Next 'New' for New York." ***Bus Ride Magazine***, pages 80-85. September 1999.