INFORM
Strategies for a better environment

Bus Futures

New Technologies for Cleaner Cities

James S. Cannon
Chyi Sun

INFORM, Inc.
120 Wall Street
New York, NY 10005-4001

Tel 212 361-2400
Fax 212 361-2412
Site www.informinc.org

Gina Goldstein, Senior Editor
Emily Robbins, Production Editor

Printed in the United States of America

ISBN #0-918780-748

INFORM wishes to express appreciation to the many transit agencies, bus manufacturers, fuel providers, and officials at the US Departments of Energy and Transportation — who are identified in the notes to the report — for sharing their data and experiences and providing input and technical review of this study. While their involvement was essential, INFORM bears full responsibility for the report's final content and conclusions.

We also extend our thanks to the Alida R. Messinger Charitable Lead Trust, the Compton Foundation Inc., the Helen Sperry Lea Foundation, the Overbrook Foundation, the Philanthropic Collaborative, and the US Department of Energy for support that made the preparation and publication of this report possible.

INFORM, Inc., is a national non-profit organization that identifies practical ways of living and doing business that are environmentally sustainable. INFORM is supported by individual, foundation, government, and corporate contributions, and by book sales. All contributions are tax-deductible.

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Foreword

This new INFORM report brings good news about alternatives to the conventional diesel bus — alternatives that have the potential to meet the travel needs of millions of Americans in and around our urban centers while protecting air quality and human health. *Bus Futures* is the eighth major report published as part of INFORM's ongoing transportation research program, which, since 1986, has sought to clarify for government and business leaders, and for the general public, the steps we can take to move toward environmentally sustainable forms of transportation. It is intended as a guide for public officials, transit agencies, and community leaders involved in decision-making about where they can best invest their resources in new bus procurement, both now and in the immediate future.

Over the past decade, concern has been growing among government, environmental, health, and community leaders about the price we are paying for our reliance on diesel-fueled buses. Emissions from these vehicles are polluting our environment and damaging the health of millions of urban Americans. Diesel exhaust irritates the lungs and is a key aggravating factor in soaring rates of asthma nationwide — especially among children in poor and minority urban neighborhoods. Recently, the effects of the many toxic chemicals contained in diesel exhaust have also come into clearer focus — about half are known or suspected of being carcinogenic. Exhaust from heavy-duty diesel vehicles is considered a probable human carcinogen by the National Institute for Occupational Safety and Health, the World Health Organization, and the International Agency for Research on Cancer.

However, INFORM's research shows that there are many promising alternative bus technologies now under development. *Bus Futures* assesses the commercial availability, costs, and emissions performance of each, from cleaner diesel buses, to conventional compressed natural gas (CNG) buses, to electric-diesel and electric-natural gas hybrids, to hydrogen fuel cell buses. Its conclusion tells the best news of all: One alternative — the conventional natural gas bus — is available here and now. It is today's best choice.

CNG buses are fully commercial *and* they are clean, healthy, and safe. The top five US bus manufacturers accounted for 80 percent of all urban buses sold in 1998. Four of these companies make significant numbers of natural gas buses, and could immediately step up production to meet greater demand. In light of CNG's benefits, transit agencies are well positioned to turn their backs now on conventional diesel buses.

The major obstacle to expanded use of CNG buses is the costs involved in establishing the infrastructure needed for refueling. Investing in this infrastructure, however, can be worthwhile for transit agencies both now and in the longer term. It enables a domestically plentiful fuel to be used today — a fuel that is less susceptible to the price and availability fluctuations of imported fuels. And while communities enjoy the immediate health and environmental advantages of clean CNG bus technology, transit agencies interested in conducting demonstrations of electric hybrids can use natural gas to fuel these buses, avoiding the pollution controls and low-sulfur fuel that hybrids powered by diesel will probably need to meet emissions standards. Nor will these agencies have to worry about toxic emissions, since natural gas is virtually toxic-free. That these benefits are becoming increasingly clear is reflected in the use of natural gas buses by 65 transit agencies throughout the US.

Looking ahead, moving to natural gas buses now can facilitate the transition to the hydrogen fuel cell buses of the future. Depots and refueling systems adapted for natural gas today will easily be able to handle hydrogen — another gaseous fuel — tomorrow. And transit agencies with a CNG infrastructure already in place will be able to fuel their fuel cell buses themselves, with hydrogen obtained from natural gas, its most efficient source.

In the next decade, more than $10 billion in public funds will be spent to purchase more than 75,000 new buses. But the decisions that transit agencies and local communities make now are not just a matter of technology and economics. They are a matter of our priorities. How important is it to safeguard human health and especially the health of our children, who are the ones most vulnerable to environmental contaminants? How important is it to address the undue impacts of pollution on poor and minority urban communities? What example do we want to set for millions of travelers from abroad, whose own priorities may be influenced by the choices they see being made in the cities they visit here? For those to whom these are important concerns, *Bus Futures* points the way to a future of dependable transportation, cleaner air, and better health for communities throughout the United States.

Joanna D. Underwood
President
INFORM, Inc.

I INTRODUCTION

Across the country, transit authorities are looking with fresh eyes at the fuels and bus technologies they will choose to meet the needs of riders in the decades ahead. Both passengers and the residents of communities in which transit buses operate are demanding cleaner vehicles, for the benefit of both air quality and the health of themselves and their children.

Community demands for cleaner buses have grown in response to increasing information about the health and environmental hazards of diesel exhaust from trucks and buses. In particular, the link between rising rates of asthma in urban centers and emissions of particulate matter and nitrogen oxides from diesel-burning vehicles has provoked widespread concern. In 1997, there were over 30,000 hospitalizations for asthma in New York City alone, where hospitalization rates for the disease increased 22 percent between 1988 and 1997. The largest increase, of more than 60 percent, was seen in children from low-income communities.[1] Diesel exhaust also contains toxic air contaminants that are carcinogenic or suspected of being carcinogenic.

Until very recently, there was only one bus choice — the conventional diesel bus.* Increasingly, however, competition from cleaner fuel options and more efficient engines is growing. For some transit agencies and their governing boards, the conventional diesel bus is becoming a thing of the past.

A Shift in Technology

The new fuel and engine options now emerging are clearly part of a major shift in the transportation sector. The zero-sum game of trying to wring yet more pollution reductions from vehicle emissions already subject to rigorous environmental controls has led to a decade-long search for alternative environmental protection strategies. Foremost among these is the use of natural gas, which can be used today in conventional vehicles powered by slightly modified internal combustion engines. Hence, while many transit agencies see hydrogen as the ultimate pollution-free fuel option and low-sulfur diesel as a way to reduce emissions from conventional diesel buses in the short term, an immediate shift can be made right now, from conventional diesel to cleaner compressed natural gas.

* A conventional vehicle is one in which an internal combustion engine provides power directly to the wheels.

In the next few decades, there will clearly be a significant transition in engine technology for transit buses and other vehicles...a shift from the internal combustion engine to more efficient alternatives such as hybrid electric and, ultimately, fuel cells. New electric propulsion technologies with profound environmental advantages are already beginning to enter the marketplace. Electric vehicle drivetrains use energy much more efficiently than conventional mechanical drivetrains, thereby reducing energy use and the potential to pollute. The electricity to run an electric drivetrain can be generated by a wide variety of fuels, including fossil and alternative fuels, or by an on-board generator. This range of innovative options for electrical generation, combined with the energy efficiency and fuel flexibility of these engine technologies, creates enormous opportunities for dramatically reducing urban air pollution. Both hybrid electric and fuel cells are currently being demonstrated by a number of transit agencies across the United States.

To ensure that the buses of the future perform as expected, training is especially critical. These technologies involve components with which transit agencies have little or no experience thus far — such as advanced high-voltage battery packs and gaseous hydrogen. Transit personnel will need to be trained in the proper use and maintenance of these vehicles, and new infrastructure may also have to be built.

Overview and Methodology

With fuels and technologies changing so quickly, it is often not clear to transit agencies exactly what is available today and what they can plan for the foreseeable future. The choice of technologies most often cited includes conventional diesel buses, conventional diesel buses equipped with control technologies and using low-sulfur diesel, conventional natural gas buses, hybrid electric buses, and fuel cell buses.

To assist transit agencies and policy makers in making their bus purchase decisions, this report provides an overview of bus technologies, their emissions performance, and their commercial availability. It focuses specifically on today's two mainstream technologies — natural gas and diesel buses; fuel cell buses are also briefly discussed because of the great interest that has been taken in this option by both transit agencies and the general public. The report includes a discussion of the health effects of air pollution, as well as information on the costs of different vehicles and their associated infrastructure. Finally, it addresses the operational and maintenance experience of transit agencies around the country, which varies widely depending on local conditions and needs.

Research for this report involved an extensive review of reports, conference presentations, newsletters, and other publications on vehicle technologies and alternative fuels from transit agencies, federal and state agencies, government research institutes, industry associations, and nonprofit organizations. In addition, numerous interviews were conducted with transit agency personnel and industry experts.

2 FINDINGS

INFORM's survey of bus and fuel options produced five major findings, summarized below.

1 Until recently, there was only one commercial bus option available to transit agencies: the conventional diesel bus. Today, with conventional natural gas buses commercial and road-ready, there are two.

- Of the buses running on US roads, 93 percent are diesel buses, with which transit agencies have more than 50 years of experience. Their closest competitor is compressed natural gas (CNG) technology, which has matured rapidly over the last decade. Conventional CNG buses are now a viable alternative to conventional diesel buses.

- The trend away from diesel and toward natural gas buses is growing. In 1998, natural gas buses accounted for 21.9 percent of the 4225 buses built. This is much more than the 6.2 percent share of the total existing bus fleet represented by natural gas buses.

- Many transit agencies are relying significantly on natural gas buses. Since 1998, the total number of transit agencies that operate natural gas buses has grown by 14 percent, from 57 to 65. In 1999, 31 transit agencies had 20 percent or more of their fleets powered by natural gas, and more than 30 percent of planned bus orders were for CNG.

- Four out of five of the top US bus manufacturers build significant numbers of natural gas buses. Some companies have a much larger stake in the natural gas bus business than others. At the high end, in 1998, natural gas buses accounted for 57.3 percent of all buses built by North American Bus Industries; at the low end, 12.7 percent of all buses built by New Flyer were natural gas.

- A number of transit fleets have made a commitment to purchase only clean natural gas buses and no new diesel buses. These include the Los Angeles, Sacramento, and Atlanta transit authorities, SunLine Transit Agency in Thousand Palms, California, and New York City's Department of Transportation.

2 As study after study confirms, the evidence is overwhelming that CNG buses emit significantly fewer pollutants than diesel buses.

- The results of nine studies comparing emissions from conventional diesel and CNG buses show that CNG buses emit 40 to 86 percent less particulate matter and 38 to 58 percent less nitrogen oxide (NO_x) than diesel buses.

- CNG is virtually toxic-free, while diesel exhaust contains more than 40 toxic chemicals, about half of which are known or suspected carcinogens.

- A study conducted by the Northeast Advanced Vehicle Consortium, published in February 2000, showed mixed emissions results for hybrid electric-diesel buses compared with conventional CNG buses. Particulate emissions from hybrid electric buses powered by conventional diesel fuel were six times higher than emissions from conventional natural gas buses. Particulate emissions from hybrid electric buses powered by low-sulfur diesel and using particulate trap technology were comparable to those of conventional natural gas buses. However, average emissions of NO_x from these hybrid electric-diesel buses were 20 to 30 percent higher than emissions from conventional natural gas buses. This study did not address toxic air pollutants ("air toxics"), an important but unregulated source of air pollution. Diesel-burning vehicles are major contributors to emissions of air toxics, while vehicles powered by natural gas emit virtually none.

- While more research is required, greenhouse gas emissions from CNG buses appear to be similar to those from diesel buses on a total fuel cycle basis, even though they emit more methane. Natural gas buses have inherently lower carbon dioxide emissions than diesel buses.

- Because natural gas is inherently cleaner than diesel and is virtually toxic-free, hybrid electric buses powered by natural gas are likely to be cleaner than those powered by diesel.

- As state and federal emissions standards grow more stringent, transit agencies will find it increasingly difficult to continue relying on conventional diesel buses.

3 While CNG buses compared to conventional diesel buses are more expensive to buy — and, for most transit agencies, to operate — an accurate cost picture requires analysis of societal costs and the costs of infrastructure investment in both the short and long terms.

- CNG buses cost about $30,000 to $50,000 more than diesel buses (about $320,000 compared to $270,000), but the cost difference between CNG and diesel buses has declined in recent years and is expected to decline further as commercial production expands.

- Transit authorities provide a mixed report on the costs of buying, fueling, and maintaining CNG buses compared to diesel. However, agencies such as SunLine Transit and Sacramento Regional Transit, which have large numbers of CNG vehicles in their fleets, report operating costs comparable to or lower than those of diesel buses. They attribute their success with CNG to high levels of worker training, extensive experience with CNG buses, and lower maintenance costs resulting from CNG's cleaner combustion process. Hybrid electric and fuel cells, however, are only now in the testing and demonstration phase; once they become fully commercial, it is unclear what the operational and maintenance costs of these buses will turn out to be.

- Shifting from diesel to natural gas requires significant infrastructure changes, and these are costly when viewed in the short term. Diesel bus depots need to be retrofitted to accommodate CNG buses and refueling facilities have to be built. CNG infrastructure costs cover a wide range; according to a survey conducted by the US General Accounting Office, transit agencies report refueling station costs at $950,000 to $5 million and depot modification costs at $320,000 to $15 million (depending on what these costs include).

- The overall costs of establishing a CNG infrastructure are determined by five key factors: space, climate, cost of materials, fire safety and building construction codes, and cost of labor.

- The costs of building an infrastructure for CNG must be weighed against the costs of vehicle-related air pollution and its effects on human health. For example, medical costs associated with asthma, to which vehicle emissions are a well-established aggravating factor, are currently $11 billion in the United States.

- Natural gas is the fuel with the greatest application to future engine technologies. It can be used on its own in conventional internal combustion engines, it can power hybrid electric engines, and it is the most efficient feedstock for obtaining hydrogen — a potential fuel in fuel cells. The switch to a hydrogen-based transportation system will require diesel depots to convert their infrastructure, but the refueling infrastructure required for CNG is largely compatible with that of hydrogen.

- The ultimate price of low-sulfur diesel fuel (sulfur content of 15 parts per million) is uncertain, but fuel refiners have estimated that it will cost at least 10 cents more per gallon than conventional diesel.

- New particulate traps now being demonstrated cost between $6000 to $9000 each in today's production quantities.

4 While many transit agencies want to continue relying on diesel buses, neither the new particulate trap technologies nor the low-sulfur diesel fuel that will be required to adequately control diesel bus emissions is available commercially nationwide.

- Second-generation particulate traps combined with low-sulfur diesel fuel are being evaluated as a means of reducing the emissions of conventional diesel buses and hybrid electric-diesel buses. These traps, used in thousands of vehicles throughout Europe, have not been used extensively in the United States. To function properly, the traps require the use of low-sulfur fuel.

- US transit agencies have just begun to use the new particulate traps and low-sulfur fuel in demonstrations to assess their durability and emissions reduction potential. However, it cannot be assumed that this technology can be adopted without any technical difficulties.

- Low-sulfur diesel fuel is not commercially available everywhere in the United States. The US Environmental Protection Agency recently proposed emissions standards for diesel fuel that would reduce sulfur levels to 15 parts per million, but these standards are facing strong industry opposition and would not take effect until June 2006. It is also unclear whether current diesel delivery systems can be used for low-sulfur fuel or what the costs of the changeover may be.

- Currently in the United States, technologies to control nitrogen oxide emissions are not being tested or used in buses.

5 Hybrid electric and fuel cell buses are exciting and promising new technologies, but they are not yet sound commercial options.

- Hybrid electric and fuel cell bus technologies are still in the demonstration and testing stage. These buses will require several years to a decade or more of expensive experimentation and refinement before they are sufficiently reliable to go into revenue service.

- Fewer than 50 hybrid electric buses are currently running in the United States. These buses are powered by natural gas, diesel, propane, or gasoline. In 2000, fewer than five fuel cell buses will be operating in the US at one time.

- Given their complex engineering systems, these new technologies will undoubtedly encounter technical challenges. As small numbers of hybrid electric and fuel cell buses are tested and their problems identified, changes will be made and new rounds of testing will be carried out. In the case of CNG buses, this process of research, testing, and demonstration produced a fully commercial product very rapidly — in just over a decade. In the case of hybrids the testing process is just beginning, and it is not clear how long it will take. At this stage, reliance on large numbers of these buses to serve core public transport needs would probably not be prudent for any transit agency.

- Successful commercialization of hybrid electric-diesel buses and the retrofit of conventional diesel buses will depend not only on the refinement of diesel bus technology but also on pollution control technologies and low-sulfur diesel fuels that are just now being developed or demonstrated in the United States.

3 CONCLUSIONS

While many new technologies are in the development stage, transit agencies have to meet their communities' long-term transport needs through procurement decisions made today. How can they decide the best path to pursue? The answer may be found by looking at the options available and the long-term implications of steps taken now.

1 **For transit agencies deciding what buses to purchase now and in the near term, conventional CNG buses are clearly the best choice.** CNG buses are commercial vehicles that can be counted on to serve the needs of riders. Natural gas vehicle emissions are virtually toxic-free, so CNG buses can make a significant contribution to reducing the health problems associated with diesel exhaust. Studies show that emissions of particulate matter and nitrogen oxides from CNG buses are up to 86 percent and 58 percent lower, respectively, than those of diesel buses. Moreover, as transit agencies become more experienced with CNG buses in their own fleets and as their overall number grows, the operating and maintenance costs of CNG buses are expected to decline.

2 **Diesel technologies that are not yet commercial should not be a significant component of a transit agency's emissions reduction strategy.** Reducing the emissions of conventional diesel buses through new pollution control technologies and low-sulfur diesel may be possible, but this option – while capitalizing on existing infrastructure – relies on technologies that are only now being used on a demonstration basis by a few transit agencies. At this point, it is not known how they will perform over time and what issues may arise in the course of their commercialization. In contrast, conventional natural gas buses, while requiring significant changes in infrastructure, are the cleanest buses commercially available today.

3 **Because riders count on the buses they use to perform reliably, transit agencies are ill advised to procure large numbers of buses still in the testing and development phase for their in-service fleet.** The argument commonly marshaled against a full-scale shift to CNG buses is the ability of hybrid electric buses, fueled by low-sulfur diesel and equipped with the latest pollution controls, to achieve levels of particulate emissions comparable to those of conventional CNG buses.

Unlike these technologies, however, CNG buses are commercially available now. Hybrid electric buses have only begun to be tested (fewer than 50 are are in operation) and cannot be expected to be immediately road-ready and able to perform to the same standard as conventional buses. Moreover, very little emissions testing has been done on these buses and their performance over time is unclear. Fuel cell buses (of which only five will be demonstrated in 2000) are also far from being commercial.

At the same time, while it is unwise to dedicate a large percentage of an agency's fleet to hybrid electric or fuel cell buses, transit operators can play a valuable role in accelerating the development of these vehicle technologies by participating in demonstration projects, sharing the results, and helping to prioritize further research needs.

4 Investing in conventional natural gas buses, and in the infrastructure they require, lays the groundwork for steady progress toward a future of cleaner buses and cleaner air. With natural gas plentiful and widely available throughout the United States, transit agencies can take immediate advantage of proven CNG bus technology, while also conducting tests and demonstrations of hybrid electric buses powered by natural gas. Agencies that operate light- and medium-duty vehicles in addition to buses can maximize use of their natural gas infrastructure by converting vans, paratransit, and motor pools to CNG as well. Ultimately, when hybrid electric technology becomes commercial, these agencies — with CNG depots and infrastructure already in place — will need to make no further investments in low-sulfur fuel and new emission controls, since natural gas is intrinsically cleaner than diesel. Nor will they have to worry about toxic emissions, since natural gas is virtually toxic-free.

Further in the future, the transition to compressed-hydrogen fuel cell buses will require not just new vehicle purchases but also the establishment of an infrastructure to provide the hydrogen fuel and accommodate the buses. Depots not equipped to handle gaseous fuels will have to be modified and retrofitted with equipment that can detect and ventilate hydrogen in the event of leaks. Unlike diesel bus depots, CNG depots are already equipped to handle gaseous fuels and already have detection and ventilation systems in place. Finally, transit agencies with an established CNG infrastructure will be able to fuel their fuel cell buses themselves, with hydrogen obtained from natural gas. SunLine Transit Agency, for example, will begin demonstrating a fuel cell bus this summer and is producing hydrogen by a number of methods, including from natural gas.

4 TRANSPORTATION EMISSIONS, AIR POLLUTION, AND HEALTH

The transportation sector overall is the major contributor to air pollution in the United States. A component of transportation-related pollution is pollution from motor vehicles, to which the US population of approximately 74,500 transit buses stands out as a particularly troubling contributor in urban areas. This is partly due to their concentration within cities and within the most densely populated, and often the poorest, neighborhoods. It is also due to the long distances – up to 350 miles per day – an individual bus tends to be driven. Most of all, however, it is due to the high levels of pollution emitted by each individual bus.

Before the late 1970s, when a series of increasingly strict government regulations designed to reduce pollution from diesel buses began to be passed, a single smoke-belching bus could generate polluting emissions equivalent to those of several hundred automobiles. Even today, research shows that new diesel transit buses are still emitting 80 times the nitrogen oxides and 60 times the particulate matter generated by today's gasoline-powered vehicles, even though they easily pass current environmental standards.[2]

The large quantity of pollutants emitted by diesel buses is a primary concern because of the health impacts of these substances on the communities in which the buses operate. Diesel exhaust contains fine particulates that irritate the respiratory system, as well as toxic chemicals considered to be carcinogens, probable carcinogens, or reproductive toxicants by the US Environmental Protection Agency (EPA) and the California Air Resources Board. These toxic constituents are currently not regulated by the federal government.

Transportation's Role in Air Pollution

According to the EPA, over 100 million Americans, including 35 million children, are breathing air that fails to meet air quality standards established to protect public health.[3] The combined exhaust from the more than 210 million motor vehicles now traveling US roads is arguably the largest single source of air pollution in the nation. On the basis of total tonnage, vehicles account for more than half the emissions of four out of six of the so-called criteria air pollutants regulated under the national Clean Air Act by the EPA. In 1997, on-road and off-road motor vehicles accounted for 77 percent of the total carbon monoxide (CO) emissions in the US, 49 percent of the nitrogen oxides (NO_x), 24 percent of particulates in the larger PM_{10} category, and 40 percent of the hydrocarbons.[4] High levels of these emissions are currently the cause of pollution that exceeds federal public health standards, called the National Ambient Air Quality Standards (NAAQS), in many parts of the country.

The Clean Air Act originally required all regions of the United States to comply with NAAQS by December 31, 1982. As of the end of 1998 – some 16 years after this deadline was set to protect public health – the EPA still categorized more than 100 air quality districts, mostly major cities and densely populated metropolitan areas, as nonattainment zones. Air quality in these areas, which varies in level of nonattainment, still exceeds national standards for at least one of the pollutants emitted in large quantities by motor vehicles.

National statistics on the contribution of transportation sources to the national inventory of pollution discharges indicate the importance of reducing automotive pollution. However, the real impact of automotive pollution, especially on human health, is far greater than nationwide totals imply. This is partly because pollution from vehicles is concentrated at ground level and in densely populated urban areas. Thus, a large percentage of the population in these areas is routinely forced to breathe vehicle exhaust directly, before it has a chance to mix with cleaner air or degrade into less hazardous by-products.

The concentration of motor vehicle exhaust in urban areas is clear from a comparison of pollution statistics in metropolitan areas and nationwide. According to air pollution emission inventories maintained by the EPA, motor vehicles account for more than 90 percent of the total carbon monoxide emissions in many major cities – including New York, Chicago, and Atlanta – even though their contribution to CO emissions nationwide is only 77 percent. Similarly, about two-thirds of the smog in Los Angeles and Denver results from automotive pollution, even though vehicles account for less than half the total emissions of hydrocarbons and nitrogen oxides – the two main precursors of smog – nationwide. In New York City, 53 percent of all emissions of particulate matter come from diesel exhaust, more than twice the contribution of particulates to the nationwide inventory. One California study found the average concentration of particulate matter in the air around Los Angeles to be 10 times higher than the typical concentration in sparsely populated rural areas.

Even a focus on metropolitan areas, however, understates the health impacts of motor vehicle emissions. There are areas within cities where vehicle exhaust is even more concentrated than in the city at large, and where natural mixing with cleaner air is even more restricted. Short-term or peak exposures to pollution in such settings are usually higher than monthly or annual average concentrations. For example, researchers have shown that "street canyons" can concentrate diesel exhaust levels in the confined air between a city's high buildings to as much as 8.8 micrograms per cubic meter.[5] This is four times the average concentration of diesel exhaust from all sources in California in 1995.

Poor, often minority, neighborhoods are another urban pollution “hotspot,” raising important issues of environmental justice. High levels of pollution in these communities are frequently due to their location near major urban highways and to the concentration within them of polluting industries and diesel bus depots. In New York City, for example, six out of eight diesel bus depots in Manhattan are located above 96th Street, where some of the city’s poorest neighborhoods are located. Because buses are continually being driven into and out of these depots for maintenance and repairs, higher levels of pollution from diesel exhaust have been measured in these neighborhoods than in most other parts of the city.

A final consideration raises perhaps the most troubling concern of all. None of the pollution statistics mentioned so far reflects the large contribution of motor vehicle emissions to the growing problem of toxic air pollutants (commonly referred to as air toxics). Air toxics from motor vehicles are not regulated by the Environmental Protection Agency, although the agency estimates that transportation sources generate 21 percent of the total national inventory of these chemicals.[6] Both gasoline- and diesel-burning road vehicles are major contributors of air toxics from transportation sources. In fact, motor vehicles are the largest source of the three toxic air pollutants emitted in the largest quantities — benzene, formaldehyde, and 1,3-butadiene. Vehicles powered by natural gas emit virtually no air toxics.

Vehicle Emissions and Health

While buses are clearly a major contributor to urban air pollution, it is difficult to measure exactly how much air pollution comes from buses or from any other type of motor vehicle. What is known is that emissions from the diesel fuel burned in buses contain large quantities of air pollutants harmful to human health. The pollutants emitted in the largest quantities are particulate matter, nitrogen oxides, and toxic air contaminants.

Particulate Matter

Particulate matter is a general term for any solid matter or liquid droplet found in the atmosphere. It ranges in size from large particles, such as visible dust, soot, and smoke, to very fine particles 2.5 microns in diameter (one ten-thousandth of an inch, which is 100 times thinner than a human hair) or smaller. Diesel vehicles are estimated to emit 0.5 million tons of this fine particulate matter ($PM_{2.5}$) each year, accounting for about one-sixth of total emissions of $PM_{2.5}$ in the United States. Since most diesel emissions occur in urban areas, diesel vehicles are by far the main preventable source of $PM_{2.5}$ in US cities. Half of the approximately 3 million tons of $PM_{2.5}$ (excluding natural dust) generated annually in the US are the result of forest fires and the burning of wood and waste in rural areas.[7]

The EPA currently regulates emissions of particulate matter 10 microns in diameter or smaller (PM_{10}); its proposed standard for $PM_{2.5}$ is currently under court challenge but is ultimately expected to go into effect.

Research suggests that particulates smaller than 50 nanometers (0.05 micron) in diameter, known as nanoparticles or ultrafine particles, also pose a serious health risk. Equipment limitations make it difficult to measure the quantity of nanoparticles contained in bus exhaust and there is no accepted testing method. At this point, the validity and implications of studies examining these particles in vehicle exhaust are unclear. More research will therefore be needed before the health impacts of nanoparticles are characterized and fully understood.[8]

What is known is that particles larger than 2.5 microns in diameter serve as adsorption and condensation nuclei for nanoparticles. Thus, because modern diesel engines emit less of the larger particles than their older counterparts, they are likely to emit more nanoparticles than diesel engines of the past.[9] In contrast, natural gas is inherently lower in particulate emissions than diesel. The particulate matter in natural gas vehicle exhaust comes largely from oil lubricants, not the fuel itself.

In addition to reducing visibility in many parts of the United States, particulate matter from diesel engines has seriously adverse effects on human health. These include aggravation of existing respiratory and cardiovascular disease, alterations in the body's defense system against foreign matter, damage to lung tissue, carcinogenesis, and premature death. Particulate matter also serves as a carrier for a variety of toxic metals and compounds.

Asthma rates, thought to be exacerbated by particulate matter, have doubled in the United States in the past decade. According to a recent study at Mount Sinai Hospital, asthma hospitalization rates for children in New York City's poor, minority communities are up to 21 times higher than for children in more affluent neighborhoods. As stated earlier, six out of eight of the city's diesel bus depots are located in these areas.

Nitrogen Oxides

Approximately 11.6 million tons of nitrogen oxides are emitted annually from transportation sources in the United States, accounting for 49 percent of total NO_x emissions nationwide.[10] Both gasoline- and diesel-burning engines are major sources of NO_x pollution, but diesel engines account for a disproportionately larger share. Although diesel-powered vehicles account for less than 20 percent of all vehicles on the road, they are responsible for over one-third of the NO_x from motor vehicles.

Nitrogen oxides make up a class of poisonous and highly reactive air pollutants. These gases irritate lung tissue and lower resistance to respiratory infections such as influenza. Most NO_x results from the fusion of nitrogen and oxygen in the air when fuel is burned at high temperatures. The principal component of NO_x pollution is nitrogen dioxide, a suffocating, brownish gas. When NO_x mixes with water in the air, it forms a type of acid rain. Moreover, when NO_x reacts with hydrocarbon pollutants in the air, they form a third pollutant known as ozone, or smog.

Ozone is a poisonous form of oxygen that damages lung tissue, reduces lung function, and sensitizes the lungs to other irritants. These effects can produce respiratory inflammation, chest pain, coughing, nausea, and pulmonary congestion. A study conducted by the American Lung Association found that ground-level ozone was linked to between approximately 10,000 and 15,000 hospital admissions for respiratory conditions in 13 US cities during the high-ozone season (April to September) of 1993 or 1994.[*] In addition, 30,000 to 50,000 emergency room visits were linked to high ozone levels.[11] Ozone pollution also causes billions of dollars annually in crop damage and has serious impacts on other plant and animal life as well.

Air Toxics

A large percentage of the toxic air pollutants in the United States are emitted by motor vehicles. Growing evidence suggests that the highest burden of air toxics is contained in diesel exhaust. These substances are regulated separately from the criteria air pollutants regulated under the Clean Air Act. The EPA has designated a total of 188 air pollutants as toxic (i.e., hazardous) pollutants under Section 112 of the act. The California Air Resources Board (CARB) has identified 41 constituents of diesel exhaust as toxic air contaminants. In 1998, CARB designated the particulate matter contained in diesel exhaust as a toxic air pollutant.

According to the definition established by the California Air Resources Board, an air toxic is "an air pollutant which may cause or contribute to an increase in mortality or in serious illness, or which may pose a present or potential hazard to human health." The precise effects of air toxics vary from pollutant to pollutant, but in all cases they are grave. About half, for example, are known or suspected of being carcinogenic — including the three major toxic air pollutants contained in motor vehicle exhaust. Among the other health effects of air toxics are blood disorders, birth defects and other reproductive problems, impairment or destruction of the immune system, interference with the endocrine system, and tissue irritation.

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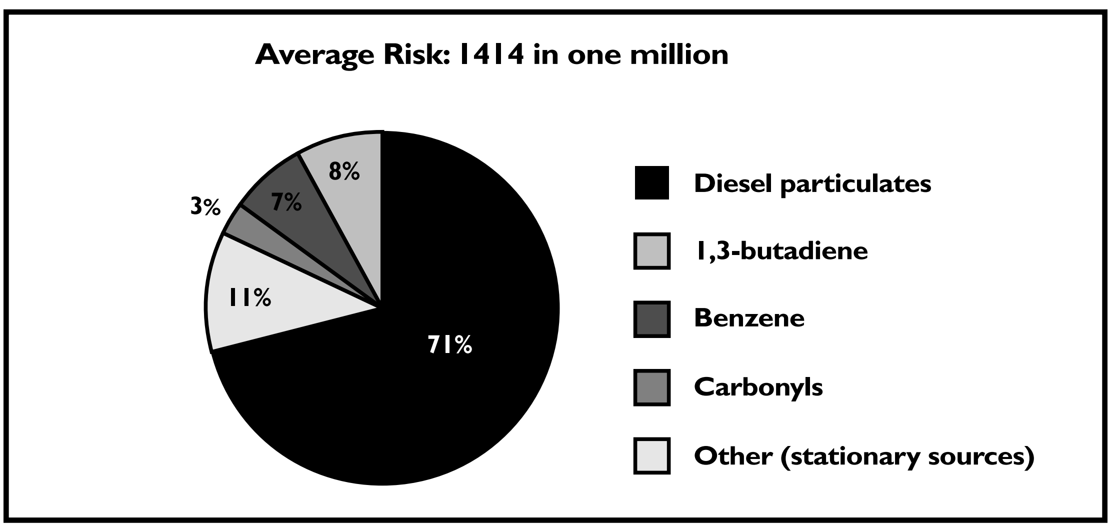
* Admissions data were for four cities during the high-ozone season of 1993 and nine cities during the high-ozone season of 1994.

The serious public health risk posed by air toxics from motor vehicles is suggested by the findings of a March 1999 report, "Exposure to Hazardous Air Pollutants in Los Angeles," which concluded that motor vehicles are the largest source of hazardous air pollution in that city.[12] Nine of the ten hazardous air pollutants analyzed for this study were detected at levels above the health goals set in the Clean Air Act. These included all the major air toxics emitted by motor vehicles. When added together, the total lifetime risk from exposure to the 10 compounds studied in the ambient air of Los Angeles could be as high as 426 additional cancer cases per million exposed individuals, a risk that is more than 400 times higher than the health protection goal established for air toxics in the Clean Air Act.

Another study of urban toxic air pollution in the Los Angeles area, published in late 1999, identified motor vehicles, particularly diesel vehicles, as the dominant source of cancer-causing air pollutants in the region. The report, known as the *Multiple Air Toxics Exposure Study II*, was prepared by the South Coast Air Quality Management District (AQMD).[13] The AQMD calculated the cancer risk from diesel particulates based on a method for estimating diesel particulates in air samples and a cancer potency factor determined by the state. The results are shown in Figure 1. The AQMD found that that diesel soot accounted for 71 percent of the cancer risk. Other pollutants posing a risk for cancer were found to include three substances emitted primarily by motor vehicles: 1,3-butadiene (accounting for 8 percent of the cancer risk); benzene (accounting for 7 percent of the risk); and carbonyls, including formaldehyde (accounting for 3 percent of the risk).[14] Pollutants emitted primarily from stationary sources were found to account for only 11 percent of the cancer risk.

Figure 1. Transportation Sources of Cancer Risk in Los Angeles



Source: South Coast Air Quality Management District

Since air toxics contained in bus emissions are currently not regulated by federal or state agencies, emissions tests of buses powered by different fuels do not include measurements of these chemicals. To allow for emissions comparisons, air toxics emission tests should be done not only for diesel buses, but also for natural gas and hybrid electric buses, and for all buses using new fuels or engine technologies. As noted earlier, natural gas is virtually free of the toxic chemicals that diesel contains, so such tests would demonstrate further its inherently clean-burning qualities.

Emissions Standards

In response to high levels of air pollutants nationwide — especially particulate matter and nitrogen oxides — the EPA began regulating emissions specifically from bus engines in 1976. Since then, the EPA and the State of California (which has set its own, more stringent motor vehicle emissions standards, as permitted under the Clean Air Act) have repeatedly tightened standards for bus engines. The history of federal and California bus emissions standards is shown in Table 1.

Table 1. Federal and California Emissions Standards for Heavy-Duty Bus Engines (g/bhp-hr)

Standard	Particulate Matter	Nitrogen Oxides	Carbon Monoxide	Total Hydrocarbons	Nonmethane Hydrocarbons
Federal Standards					
Pre-1976	None	None	None	None	None
1984-1987	None	10.7	15.5	1.3	None
1988-1989	0.60	10.7	15.5	1.3	None
1991-1993	0.25	5.0	15.5	1.3	None
1994-1995	0.07	5.0	15.5	1.3	1.2
1996-1997	0.05	5.0	15.5	1.3	1.2
1998-2003	0.05	4.0	15.5	1.3	1.2
California Standards					
1991-1993	0.25	5.0	15.5	1.3	1.2
1994-1995	0.07	5.0	15.5	1.3	1.2
1996	0.05	4.0	15.5	1.3	1.2

Source: EPA and CARB Emission Standard Databases

In order to comply with these standards, bus engines are tested on an engine dynamometer in a laboratory. The measurements are taken as grams of pollution emitted per brake horsepower hour (g/bhp-hr) of engine power output. Engine manufacturers must demonstrate that emissions will not increase over the engine's lifetime, but no tests are required for engines actually used in an operating vehicle.

As shown in Table 1, allowable particulate emissions for transit buses under federal regulations have been cut from 0.60 to 0.05 g/bhp-hr, a 91 percent reduction since 1988. New particulate standards for heavy-duty engines proposed by the EPA in May 2000 would reduce these emissions further, to 0.01 g/bhp-hr beginning in 2007. Allowable emissions of NO_x have dropped 62 percent since 1984, from 10.7 to 4.0 g/bhp-hr. Beginning in 2004, federal NO_x emission standards for urban bus engines will fall again, to approximately 2.0 g/bhp-hr. Moreover, because of a settlement agreement between the EPA and the Department of Justice and the heavy-duty diesel engine industry, manufacturers of these engines will be required to meet the 2004 NO_x standard by October 2002.*

New standards, adopted by California in February 2000, will further limit NO_x and particulate emissions from transit buses. In 2004, new urban buses purchased by transit agencies that do not have 85 percent of their fleets powered by alternative fuels will be required to reduce particulate emissions to 0.01 g/bhp-hr. However, diesel engine manufacturers have agreed to meet that standard in 2002. Fleets that choose the alternative fuel path, and have 85 percent of all leased and purchased buses running on alternative fuel, are not required to meet the 0.01 g/bhp-hr standard until 2007. In 2007, California's NO_x emission standard for transit buses will fall to 0.02 g/bhp-hr.

While New York has not adopted new emissions standards for buses, it is establishing an emissions performance benchmark for new bus purchases. Based on in-use tests (see the following section) set at the level achieved by modern buses fueled by compressed natural gas, the standard will take into account in-use emissions of particulate matter, criteria pollutants, and toxics, as well as engine deterioration rates. The standard will be revised periodically to reflect changes in technology.[15]

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* In October 1998, the US Environmental Protection Agency and the Department of Justice announced an $83.4 million penalty against seven major diesel engine manufacturers, the largest civil penalty ever levied for violation of environmental law. The EPA alleged that these companies sold engines containing illegal "defeat devices" that allowed engines to pass EPA emissions tests but then stopped operating during highway driving, causing them to emit twice as much NO_x. Engines containing the defeat devices were being sold as early as 1988. As a result of the settlement, engine manufactures agreed to pay penalties, to eliminate the control devices in future engine models, to produce engines that meet 2004 federal emissions standards by October 2002, and to fund environmental projects. The latter include developing new emission control technologies and funding the purchase of natural gas buses by transit authorities.

Emissions Testing

Vehicles being compared in emissions tests are operated in identical patterns of acceleration, cruising, and braking. For transit bus emissions, the "central business district" cycle is used to simulate acceleration, constant-velocity driving, deceleration, and stopping in congested urban areas. There are two types of emissions tests: "in-use" and engine certification, each costing tens of thousands of dollars to perform.

Studies that examine emissions from operating vehicles are called in-use analyses. These tests are generally performed on a chassis dynamometer with the vehicle remaining stationary while the wheels move on rotating rollers. Emissions from the tailpipe are captured as the vehicle moves through the simulated driving conditions and analyzed. As stated earlier, New York is establishing an emissions performance benchmark for new bus purchases based on in-use tests.

The principal advantage of in-use studies is that they closely approximate the actual levels of air pollution emitted by vehicles during everyday driving. Emissions data from in-use analyses are most helpful in assessing actual human exposures to motor vehicle pollutants. Unfortunately, however, there are still disparities between the results of chassis dynamometer tests and real-world emissions. For example, a vehicle operated in mountainous terrain or under extensive stop-and-go conditions may emit vastly different quantities of pollution than the same vehicle tested on a dynamometer at sea level in a driving pattern that highlights moderate speeds. In-use studies can be difficult to perform because fleet and vehicle owners are often reluctant to give up their vehicles for testing.

Emissions can also be compared using measurements taken during engine certification procedures. These tests form the basis of compliance with federal pollution control standards and the tighter automotive standards now in place in California and a few other states. Engine certification tests usually involve an engine dynamometer, which consists of a test stand holding only the engine and some related equipment. A number of testing procedures have been developed by government testing agencies. The principal test for medium- and heavy-duty vehicles is the heavy-duty federal test procedure (HD-FTP).

The advantage of engine certification tests is that the data they provide reflect emissions under nearly identical operating conditions, facilitating "apples-to-apples" comparison of emissions from different vehicles and fuels. The disadvantage is that pollution discharged by vehicles when operated on the road often differs significantly from the emissions recorded during the engine certification process. Part of the reason for this is that the testing protocols do not accurately mirror actual driving conditions. Most certification tests have been found to under-state the amount of pollution actually emitted under real-world conditions. Certification results are therefore limited in their ability to predict actual pollution levels from operating vehicles in the ambient environment.

5 COMMERCIAL BUS TECHNOLOGIES: CONVENTIONAL NATURAL GAS AND DIESEL BUSES

About 4000 urban buses are manufactured annually in the United States, many of which are replacements for older buses that are being retired. However, the US bus population is rising steadily, from approximately 68,000 in 1994 to more than 74,500 in 1998. Roughly 93 percent of the current fleet is powered by conventional diesel engines. About 6 percent run on natural gas, a figure that has been increasing throughout the past decade.

Conventional diesel and natural gas buses are the only fully commercial options available today, accounting for about 99 percent of all buses on the road. The diesel bus industry is a mature industry and has been providing buses to the nation's transit agencies for many decades. Although natural gas buses have only been on the commercial market for a little more than a decade, growth in their sales has been robust, and a surprising variety of models are already available for purchase.

Some of the most important factors to consider when planning a bus purchase are commercial availability, costs, emissions, safety, and refueling capability. Emissions are especially important because of the threats posed by bus exhaust to human health. Costs include the cost of both buying and operating a vehicle and need to be considered in the context of a technology's immediate and long-term benefits.

Reports from transit agencies on the subject of costs are mixed. Some have reported the costs of buying and operating natural gas buses to be higher that those of diesel. However, agencies that have large numbers of natural gas buses in their fleets and extensive experience in their maintenance and operation have reported operating costs comparable to, if not lower than, those of diesel buses. The long-term benefits of natural gas buses include savings in community health costs from using a less polluting fuel than diesel, avoided environmental cleanup costs from leaking underground diesel storage tanks, and creation of a refueling and bus depot infrastructure compatible with the infrastructure required for hydrogen fuel cells.

Natural Gas Fuel

Natural gas is in gaseous form at room temperature and is approximately 90 percent methane, a simple molecule containing one atom of carbon and four atoms of hydrogen. Natural gas is a naturally occurring fossil fuel often found in underground reservoirs in conjunction with oil, but sometimes found in separate deposits. Like oil, it is produced from wells drilled at the surface. Unlike oil, however, natural gas does not require extensive refining prior to marketing. An inherently cleaner resource, it requires only minimal processing to remove contaminants before it is ready for use as a fuel.

Although natural gas, like other fossil fuels, is a limited resource, its supply picture is more promising than that of oil. According to the US Energy Information Administration's *Energy Review 1998*, nearly 90 percent of the natural gas consumed in the United States is from domestic sources, compared to less than 50 percent of oil. Most US imports of natural gas are from Canada, not from the volatile Middle East. US production of natural gas has increased in the past decade, while domestic oil production has been dropping steadily for more than 20 years.

Natural gas is cheaper than oil products and not as susceptible to price fluctuations. At the pipeline delivery point, natural gas costs about half as much as wholesale gasoline. Despite its low cost, natural gas is a high-quality fuel and an excellent substitute for gasoline and diesel in automobiles and buses.* For example, natural gas has an octane rating of 130, which is significantly higher than the rating of gasoline brands on the market today.

Of natural gas buses on US roads, 80 percent carry the fuel in compressed form. Cylinder tanks are generally filled with the gas to pressures of 3000 to 3600 pounds per square inch. Even at these high pressures, a compressed natural gas (CNG) storage system takes up between three and four times the space of a conventional gasoline fuel tank and weighs from two to three times as much. Thus, CNG transit buses weigh several thousand pounds more than diesel buses, although new tanks made of composite carbon fiber are lighter than the older metal tanks.

For the 20 percent of natural gas buses fueled by liquefied natural gas (LNG), temperatures of about –250° F are needed to liquefy the gas. Then, to keep it from warming and returning to its gaseous form, LNG must be stored in specially designed insulated containers that look and function like large thermos bottles. The advantage of LNG is that it contains much more energy

* The composition of pipeline natural gas varies by geography. For example, in certain areas the gas utility blends refinery stack gas into pipeline gas, thus reducing the amount of natural gas in the pipeline. Since natural gas engines are designed for specific concentrations of the fuel, it is important for transit agencies to make sure that their natural gas supplier can deliver the quality needed.

per pound or per unit of space than compressed natural gas. However, because the handling of super-cold LNG involves special procedures and training, its use is currently limited to heavy-duty truck and bus fleets, which generally have their own refueling equipment and trained staff. LNG is also not readily available in all cities. Since natural gas in the compressed form continues to be the prevalent choice for transit agencies that operate natural gas buses, the remaining discussion will focus on CNG.

Many transit authorities own and operate their own CNG refueling stations, while others have formed partnerships with their local utility or natural gas fuel supplier. In the latter case, long-term fuel supply agreements usually include ongoing maintenance and operation of the compressor station. Refueling stations equipped with direct fast-fill systems can refuel a bus in the same amount of time it takes to refuel with diesel.[16] The only on-site gas storage is in the form of aboveground “buffer tanks” containing approximately 500 gallons equivalent of natural gas.

Leaks of CNG fuel raise fewer environmental concerns than diesel leaks. When released, CNG dissipates quickly into the air. In contrast, an uncontained diesel leak can pool and contaminate the ground or drinking water and release toxic fumes into the air. Diesel bus facilities typically store more fuel on site (about 100,000 gallons) than CNG facilities,[17] so a leak from a diesel tank can release tens of thousands of gallons over time. New York City Transit recently publicized a 95,000 gallon underground diesel spill from its depot in Jamaica, Queens, which began in 1991; in 1998, the agency notified residents near its Flatbush Avenue depot of a 19,000 gallon leak that began in 1992.[18]

Commercial Availability of Natural Gas Buses

The commercial availability of natural gas and diesel bus technology is reflected in manufacturing and delivery statistics for 1998, the latest year for which comprehensive data are available from the American Public Transit Association (APTA).

Manufacturers

According to the APTA’s *1999 Transit Vehicle Data Book*, 4225 buses seating 30 or more passengers were built and sold in the United States in 1998 (approximately 550 smaller buses capable of seating fewer than 30 passengers were also built, but the commercial availability of these shuttle-type buses was not examined by INFORM).*

* More than 90 percent of the 4225 buses sold in 1998 were over 27.5 feet in length; about 88 percent were over 37.5 feet in length. Articulated buses — two-section buses usually 55 feet or more in length linked by a flexible, accordion-like partition — accounted for 174 of the buses sold in that year. Of the buses sold in 1998, 1272 could seat between 30 and 39 passengers and 2953, including the articulated buses, could seat 40 or more. A decade ago, a total of only 2782 buses were built. Thus, the bus industry has grown about 50 percent in the past decade, primarily in the 30-to-39-seat category.

As shown in Table 2, diesel-powered buses are the backbone of the bus manufacturing industry, accounting for 77 percent of all buses built in 1998 and 80.7 percent of the orders for new buses pending as of January 1, 1999.

Table 2. US Bus Sales by Fuel Type, 1998

Fuel	Built in 1998		On Order, Jan. 1, 1999	
	Number	% of Total	Number	% of Total
Diesel	3253	77.0%	6709	80.7%
Natural Gas	924	21.9%	1201	14.5%
Electric	32	0.8%	272	3.3%
Gasoline	4	0.1%	1	0.0%
Propane	0	0.0%	71	0.9%
Other	12	0.3%	56	0.7%
Total	**4225**	**100.0%**	**8310**	**100.0%**

Source: American Public Transit Association

Natural gas buses accounted for 21.9 percent of the 4225 buses built in 1998. These included 550 buses fueled by CNG and 374 fueled by LNG. The rapid growth in the role of natural gas buses in the nation's transit system is reflected in the disparity between the large percentage of natural gas buses built in 1998 and their small (6.2 percent) share in the existing US bus fleet. Moreover, orders for 1201 additional natural gas buses have been filed by transit operators for delivery between 1999 and the end of 2001. These buses account for 14.5 percent of all new bus orders.

As shown in Table 3, four out of the top five US bus manufacturers, which accounted for 80.3 percent of all urban buses built and sold in 1998, make significant numbers of natural gas buses. The largest bus builder, with 24 percent of the total market, is Novabus Inc. (headquarters in Roswell, New Mexico); of the 1012 buses it manufactured in 1998, 147 run on natural gas. Orion Bus Industries, Inc. (Oriskany, New York), New Flyer Industries, Inc. (Manitoba, Canada), and North American Bus Industries (Moorpark, California) also build natural gas buses. Among these major producers, only Gillig did not manufacture any natural gas buses in 1998. Another manufacturer, Neoplan, is the only one to offer articulated CNG buses.

Table 3. Top Five US Bus Manufacturers, 1998

Company	Built in 1998				On Order, Jan. 1, 1999	
	Total No. of Buses	% of Total Market	Total No. of Natural Gas Buses	% of Total Market	No. of Buses	% of Total Market
Novabus	1012	24.0%	147	4.33%	1352	16.3%
Gillig	764	18.1%	0	0.0%	1752	21.1%
Orion	655	15.5%	140	4.13%	731	8.8%
New Flyer	620	14.7%	79	2.33%	2127	25.6%
North American Bus	342	8.1%	196	5.78%	919	11.1%
Top 5 Total	**3393**	**80.3%**	**562**	**16.56%**	**6881**	**82.8%**

Source: American Public Transit Association

Some companies have a much larger stake in the natural gas bus business than others. At the high end, natural gas buses accounted for 57.3 percent of the 342 buses built by North American Bus Industries in 1998. At the low end, natural gas buses accounted for just 12.7 percent of New Flyer's production of 620 buses. In the middle, natural gas buses made up 14.5 percent of the 1012 buses manufactured by Novabus and 21.3 percent of the 655 buses manufactured by Orion in 1998.

Natural Gas Bus Use by Transit Agencies

While close to 200 transit agencies in the United States operate diesel buses only, 65 others use natural gas as well as diesel. Since 1998, the total number of transit agencies that operate natural gas vehicles has grown by 14 percent, from 57 to 65. As shown in Table 4, 31 of those 65 agencies now have 20 percent or more of their fleets operating on natural gas, and 10 have more than 100 natural gas buses.

From a population of zero in 1983, the number of operating alternative-fuel buses in the United States now exceeds 3600 and will jump to nearly 5000 when pending orders for new buses are filled. Table 5, based on statistics from the American Public Transit Association's *1999 Transit Fact Book*, shows the steady growth in the use of all types of alternative-fuel buses, from 597 in 1993 to 3643 as of January 1, 1999 — more than a sixfold increase.

Table 4. Largest Natural Gas Bus Fleets in the United States

Transit Agencies with More than 20% Natural Gas Buses

Phoenix, Arizona (two agencies)
Tempe, Arizona*
Tucson, Arizona
Bakersfield, California
Culver City, California
Davis, California
Los Angeles, California
Monterey, California
Oxnard, California
Riverside, California
Sacramento, California
San Bernardino, California
San Diego, California (San Diego Metro Transportation Development Board)
San Diego, California (San Diego Transit Corp.)
Thousand Palms, California*
Norwalk, Connecticut
Boise, Idaho
Port Huron, Michigan
Garden City, New York
Akron, Ohio
Cleveland, Ohio**
Grand River, Ohio
Youngstown, Ohio
State College, Pennsylvania
El Paso, Texas
Fort Worth, Texas
Houston, Texas
Laredo, Texas
Tacoma, Washington
Kenosha, Wisconsin

Transit Agencies with More than 100 Natural Gas Buses

Phoenix, Arizona
Los Angeles, California**
Sacramento, California**
Atlanta, Georgia**
Garden City, New York
New York, New York (New York City Dept. of Transportation)**
Cleveland, Ohio**
Dallas, Texas
Houston, Texas
Tacoma, Washington

* Agencies with 100 percent natural gas buses. ** Agencies with a no-diesel policy.

Table 5. Alternative-Fuel Buses in the United States, 1993-1999

Year	Natural Gas	Ethanol	Electricity	Propane	Methanol	Total
1993	305	86	18	28	160	597
1994	640	86	31	28	351	1136
1995	1035	82	37	31	399	1584
1996	1421	82	41	29	396	1969
1997	1909	347	24	25	63	2368
1998	2494	395	33	12	19	2953
1999	3204	375	38	9	17	3643
1999 as a Percentage of Total	**6.2%**	**0.7%**	**0.1%**	**<0.1%**	**<0.1%**	**7.0%**

Source: American Public Transit Association

Testing of the nation's first natural gas bus began in 1986 in Orange County, California, followed two years later by demonstrations of two other vehicles in New York City. Additional demonstration buses followed and, by 1992, more than 100 CNG and LNG buses were operating in the United States. APTA figures show that the number of natural gas buses increased tenfold between 1993 and January 1, 1999, from 305 to 3204. Of the current fleet of 3204 natural gas buses, 2494 are powered by CNG and 710 by LNG. CNG and LNG buses account for 87.9 percent of all alternative-fuel buses and for 6.2 percent of the 51,608 urban buses included in the APTA survey. Moreover, transit operators have placed orders for 1201 additional natural gas buses, most to be delivered by the end of 2001.

Transit companies are not just buying natural gas buses, they are increasingly relying on them. The growth in natural gas consumption far outstrips the proliferation of natural gas buses themselves. As shown in Table 6, from 1992 to 1998, the use of natural gas in buses increased 28 times, to 34,161 thousands of gallons equivalent, more than twice the growth rate for natural gas buses.

Table 6. Alternative-Fuel Consumption by US Transit Buses (thousands of gallons equivalent)

Year*	Natural Gas	Propane	Methanol	Other**
1992	1200	2487	1583	12
1993	2053	2098	4975	197
1994	6285	1871	12,269	492
1995	12,976	3686	11,174	865
1996	17,954	5235	7268	4353
1997	27,936	5150	965	7771
1998	34,161	5112	783	2865

*Figures for 1998 are preliminary. **Ethanol and electricity are the major fuels in this category.
Source: American Public Transit Association.

In 1998, CNG bus orders grew 26 percent (from 890 to 1125) compared to the previous year, while LNG bus orders declined by more than 5 percent (from 422 to 102). Of potential orders specifying a fuel type (i.e., those planned for which no contract has yet been awarded), CNG buses accounted for 16 percent (2100 buses) in 1998 and 31 percent in 1999 (4079 buses).

The trend toward increasing use of natural gas buses has been driven primarily by their clean air and health benefits. A number of large transit agencies, such as the Los Angeles County Metropolitan Transit Authority, the Greater Cleveland Regional Transit Authority, Metro Atlanta Regional Transit Authority, and the New York Metropolitan Transit Authority's Long

Island Bus Co., are committed to purchasing *only* alternative-fuel buses. SunLine Transit Agency, in Thousand Palms, California, replaced all of its diesel buses in 1994 (it was one of the first transit agencies to do so) and since then has run a 100 percent CNG fleet.

Transit agencies are also under increasing regulatory pressure to reduce bus emissions. In February 2000, California's Air Resources Board passed a resolution requiring transit agencies to use either alternative fuels or cleaner diesel technology to reduce the public's exposure to diesel exhaust.[19] There are already 1300 transit buses operating on alternative fuels in California, with 750 more on order.[20] Agencies in Los Angeles, Orange, Riverside, and San Bernardino counties may have to go even further than those in the rest of the state. California's South Coast Air Quality Management District has proposed a rule that, in the interest of reducing emissions of air toxics and criteria pollutants, would require public transit fleet operators to acquire only alternative-fuel heavy-duty vehicles.[21] Similarly, a new emissions performance standard in New York State will require all new buses to perform at the level achieved by a modern CNG bus.[22] The new regulation is to include air toxics, which may further discourage future purchases of diesel buses.[23]

The growth in alternative-fuel bus purchases by transit fleets reflects the increasing awareness by transit agencies and their boards of rising public concerns about the health effects of diesel. For example, the decision by New York's Metropolitan Transportation Authority (reflected in its capital plan for 2000 to 2004) to move toward cleaner-fuel buses was in large part due to pressure from environmental, health, and community groups to reduce pollution from the agency's New York City Transit bus fleet. New York's Governor Pataki has emphasized the need to balance public transit priorities with reductions in vehicle emissions.[24] In Ohio, the board of directors of the Greater Cleveland Regional Transit Authority, after weighing the environmental and social costs of bus emissions, decided to continue purchasing CNG buses, even though their operating costs were higher than those of diesel buses.[25]

Despite the growth in alternative-fuel use in buses this decade, diesel is still the dominant fuel used by transit operators. Diesel-powered buses account for about 92.6 percent of the bus fleet surveyed by the American Public Transit Association (gasoline is used in a mere 0.4 percent of buses). However, the number of diesel buses operating in the United States actually declined 5.9 percent between 1993 and 1999, from 50,989 to 47,965.

Transit Bus Costs

One reason for the continued commercial dominance of diesel-powered buses is their lower cost compared to that of natural gas buses. Bus costs fall into three main categories: procurement costs; refueling, maintenance, and storage infrastructure costs; and operating and maintenance costs.

Often, a transit agency can avoid bearing the full capital costs associated with acquiring buses and modifying the infrastructure. The Federal Transit Administration (FTA) will pay up to 80 percent of the costs of new bus procurement, facility modernization, and related improvements. Other funding sources apply specifically to clean-fuel buses. For example, eligible projects under the FTA's Clean Fuels Formula Grant Program include purchasing or leasing clean-fuel buses (such as CNG buses) and retrofitting existing facilities to accommodate them. Fleets operating in areas that are in violation of federal standards for ozone, PM_{10}, and carbon monoxide are eligible for Congestion Mitigation and Air Quality Improvement Program funds to purchase clean-fuel buses.

Because transit buses have a direct impact on the health and environment of the communities in which they operate, any examination of costs must include more than those addressed in a transit agency's capital and operating budgets. Costs such as those associated with environmental cleanup and the health effects of diesel emissions also need to be considered. For example, US medical costs associated with asthma, to which vehicle emissions are a well-established aggravating factor, were $6 billion in 1990 and are currently $11 billion. Some transit authorities are already including such factors in their decision-making.

At this point, there are no reliable comparisons of transit agency costs. Such comparisons are difficult to make because there is so much variation among agencies and their operations. Existing studies have produced differing results, with some agencies reporting lower and some reporting higher costs. Moreover, none of these studies examines or even addresses possible future costs once mass production of alternative-fuel buses has begun, once an established refueling infrastructure for alternative-fuel vehicles is in place, and once the impact of more stringent emissions standards on diesel buses is known.

One study that did attempt to survey a limited number of transit agencies resulted in the report entitled "Mass Transit: Use of Alternative Fuels in Buses," published by the US General Accounting Office (GAO) in December 1999. This report focuses on the experience of 12 transit agencies, eight of which maintain fleets of natural gas buses. Six of the transit operators surveyed plan to acquire additional diesel buses in the near future, five plan to purchase natural gas buses, and one plans to buy more of both bus types. The remainder of this section includes some data from the GAO study.

Procurement Costs

Information obtained from transit operators and other sources, such as bus manufacturers, confirms that natural gas buses cost between 15 and 25 percent more than conventional diesel buses. A typical bus powered by CNG costs between $290,000 and $318,000, while a typical diesel bus costs between $250,000 and $275,000. This price disparity stems in part from the lack of economies of scale in the manufacture of CNG buses and from manufacturers' need to recover development, certification, and warranty service costs for their small production volumes of vehicles and engines.[26] As production of CNG buses expands, however, the price differential between CNG and diesel buses is expected to decline.

Infrastructure Costs

To operate natural gas buses, transit agencies must invest in fast-fill refueling stations and gas compressor equipment. A natural gas refueling station can cost from a few hundred thousand dollars to several million dollars. The Federal Transit Administration estimates that a typical refueling station for a fleet of 200 natural gas buses costs about $1.7 million.

Refueling station construction costs cited by transit operators in the GAO report covered a wide range. Pierce Transit Authority spent $950,000 on its refueling facility in Tacoma, Washington, while the Greater Cleveland Regional Transit Authority (GCRTA) spent $3 million for one of its facilities in Ohio. New York City Transit (NYCT) and the Los Angeles County Metropolitan Transportation Authority (LACMTA) each spent $5 million on their refueling facilities.[27]

Some transit agencies are finding alternatives to the large capital outlay involved in establishing their own refueling stations. For example, the Los Angeles County Metropolitan Transit Authority recently entered into the nation's first public/private partnership to finance a CNG bus refueling station. Instead of owning the station, LACMTA will lease it from Trillium, USA. Trillium will own, operate, and maintain it, and Los Angeles will make monthly lease payments and pay the costs of fuel over 10 years. LACMTA expects to save $1 million in costs and between 6 and 12 months in design and construction time.[28] In Georgia, Atlanta Gas Light Co. provided the Metropolitan Atlanta Rapid Transit Authority with its CNG compressor station, which the utility operates and maintains for a flat (per gallon) fee included in the monthly gas cost.

Transit operators that switch to natural gas must modify their existing bus maintenance and storage facilities to include proper ventilation, leak detection, and other monitoring systems. According to FTA estimates, about $600,000 is needed to modify a typical maintenance garage for natural gas. However, facility modification costs, like construction costs, vary widely. While SunLine Transit in Thousand Palms, California, spent $320,000 to retrofit its facilities, Pierce

Transit spent $645,000, GCRTA spent $750,000, and LACMTA spent $1 million. Again, the highest costs were reported by NYCT, which spent $15 million on a single facility.[29]

The great variation in natural gas infrastructure costs is due to the large number of factors that differ from location to location. Moreover, the costs involved in constructing or modifying facilities for natural gas are not always necessitated by the buses themselves. For example, in addition to meeting local fire and construction codes, upgrades to older buildings may have to meet nonfuel-related standards that did not exist when the building was originally constructed. Key questions that can impact costs include the following:

- How many buses must be accommodated, how much land is available, how many stories will the facility contain, and what type of refueling equipment is required to meet depot needs?
- Will the buses be stored indoors or outdoors? (If they are stored inside, more electrical, gas detection, and ventilation work will be required. If they are stored outside, upgrades will be required for maintenance facilities only.)
- Is an existing facility being modified or is a new facility being built?
- What level of safety is required by local fire safety and building construction codes?
- What are the local labor costs?

Indoor facilities for bus storage and maintenance require monitoring and ventilation systems to detect leaks and prevent gases from accumulating. Natural gas is lighter than air and will rise in the event of a leak. Outdoors, it will dissipate into the air. Indoors, when allowed to collect at concentrations of 5 to 15 percent, it will burn if it comes into contact with an emission source. Gas detection systems measure the amount of methane (the main component of natural gas) in the air and shut off the flow of gas automatically if it builds up beyond a certain level. Ventilation fans help dissipate the gas and are linked to the detection system.

A number of organizations, such as the Federal Transit Administration and the National Fire Protection Association (NFPA), have published guidelines for natural gas facilities. For example, the NFPA code for CNG maintenance garages prohibits the use of obvious ignition sources such as open-flame heaters and requires some ventilation and gas detection capability. The latest edition of the NFPA code for parking garages, however, includes no special requirements for accommodating CNG vehicles. This is because existing carbon monoxide ventilation systems in conventional vehicle garages are sufficient to reduce the risk of a natural gas release. Because of the variation in bus storage facilities and locations, compliance with these guidelines is a matter of interpretation. At most facilities, however, leak detection systems, ventilation systems, and spark-proof electrical equipment (such as light fixtures and heaters) are standard.

Other equipment includes automatic roll-up doors, panic buttons, and automatic fire department notification.

The operation and maintenance of refueling stations involve additional costs. Some agencies have taken out service contracts for equipment such as compressors and fuel dispensers. Energy is required to compress the natural gas, and depending on how this is done, there are additional electricity or natural gas costs to consider. Finally, compressor stations may need to be overhauled periodically because of the limited lifetime of some components. On the other hand, diesel refueling stations are not maintenance-free either. Diesel pumps and dispensers require regular maintenance and periodic replacement of parts. EPA regulations have also required underground diesel tanks to be replaced. In California, this cost the Los Angeles County Metropolitan Transit Authority millions of dollars.[30]

Although there are startup costs associated with establishing a CNG infrastructure, the investment may have long- as well as short-term benefits. Agencies that operate light- and medium-duty vehicles in addition to buses (such as vans, motor pools, and paratransit for the elderly or disabled) can maximize use of their CNG facilities by converting these vehicles to natural gas as well. Moreover, CNG can be used not only in conventional natural gas buses but also in hybrid electric buses. And through a simple process known as steam reforming, it can be used as a feedstock to produce pure hydrogen for fuel cells (see chapter 7). Natural gas can also be mixed with hydrogen to produce Hythane fuel, which, when burned in a conventional CNG bus, generates much lower emissions than CNG alone. Finally, since CNG is a gaseous fuel like hydrogen, the refueling, storage, and maintenance infrastructure for CNG buses is compatible with that required by fuel cell-powered vehicles.[31] Thus, both CNG and the infrastructure it entails are building blocks for the transportation technologies of the future. In contrast, it is unlikely that diesel fuel will be used as a feedstock for hydrogen; thus, the infrastructure for diesel is only applicable to two technologies: conventional diesel and hybrid electric buses.

Operating and Maintenance Costs

Transit agencies report differing operating and maintenance costs for CNG buses compared to diesel buses. Agencies that report lower costs attribute their success to three factors: geographical location, amount of experience with CNG buses, and worker training.

Fuel costs are dependent on fuel price and the vehicle's fuel economy. The GAO report found that fuel costs depend on location, on the cost of compressing the gas, and on any special pricing arrangements made with the natural gas provider.[32] In the GAO report, three of the six transit agencies that provided fuel costs reported higher prices for natural gas compared to diesel, two reported lower prices for natural gas, and one reported equivalent prices for both fuels.

The agency's survey covered only six of the 65 US transit operators that use natural gas in their fleets and was conducted at a time when diesel prices were much lower than they are now (in the first half of 2000). Nationwide, the US Energy Information Administration reports that the average price of diesel fuel in 1999 was 25 percent higher than the average price of natural gas, on an equivalent energy basis. The average price of diesel was $7.91 per million British thermal units (Btu), while that of CNG was $6.31 per million Btu.

An alternative-fuels cost analysis performed by the Greater Cleveland Regional Transit Authority in May 1999 included a fuel price sensitivity test. The analysis concluded that changes in fuel price do affect the overall economic viability of using CNG as a fuel for transit buses.[33] When diesel prices doubled, the cost of operating CNG buses became comparable to the cost of operating diesel buses. Diesel prices are expected to rise again in the future, when low-sulfur diesel is introduced. In California, natural gas prices paid by the Sacramento Regional Transit District declined when the industry was deregulated. Deregulation in other states could likewise result in lower natural gas prices.

The amount of fuel used also affects a transit agency's fuel costs. The FTA reports that natural gas buses are 20 to 40 percent less fuel-efficient than diesel buses, thus requiring more fuel per vehicle. The lower efficiency of CNG buses is the result of less efficient engines and the additional weight of the CNG fuel tank. CNG engine technology is still evolving, however, and efficiency gains are likely. The use of lighter composite materials for tanks and body parts may also improve the fuel efficiency of CNG buses.

Maintenance costs, like fuel costs, vary from agency to agency. Some, such as the Los Angeles County Metropolitan Transit Authority and New York City Transit, report lower mean miles between failure for CNG buses than for diesel buses. Higher failure rates can lead to additional costs for labor and parts (these agencies reported that parts for CNG vehicles are more expensive than diesel parts).[34] CNG buses have also been found to require extra engine tune-ups and fuel-line repairs.[35] However, these problems are expected to diminish in the latest CNG engine systems, which have no spark plug wires. It should also be noted that some of the failures reported by LACMTA and NYCT were caused not by engine or fuel system problems but by "out of fuel" calls. Since CNG buses have a shorter travel range than diesel buses — 240 to 323 miles compared to more than 400 miles for diesel buses — transit authorities need to take this limitation into account when determining the routes and schedules of their CNG fleets.

Other agencies have found the maintenance costs for CNG buses to be the same as or less than those of diesel buses. Pierce Transit in Washington reports the costs of maintenance to be nearly equal for its diesel and CNG fleets.[36] In contrast, SunLine Transit Agency and the Sacramento Regional Transit District (SRTD) report savings of $200,000 and $1 million, respectively, for their CNG buses compared to their diesel buses over the course of a year.[37] These diesel buses are all older than their CNG counterparts, but the savings continued after the agencies' CNG bus warranties expired. SunLine and SRTD were able to extend the interval between oil changes to between 10,000 and 12,000 miles and reported that their CNG engines showed no signs of needing a midlife rebuild. (In Arizona, Phoenix Transit has been able to extend the interval between spark plug replacement to 18,000 miles.[38]) Since CNG is an inherently cleaner fuel, CNG buses run cleaner than diesel, reducing wear on the engine.[39] Neither SunLine nor SRTD has experienced a significant number of system-related road calls for their CNG fleets.[40]

The agencies that report reduced maintenance costs for their CNG buses attribute the savings to better engine wear, extensive worker training, and extensive experience with CNG buses. As personnel become more experienced with CNG buses, maintenance costs tend to decline. Over time, these costs can be expected to fall further as the technology matures and more transit agencies invest in CNG buses, resulting in lower costs for CNG bus parts and the buses themselves.

Some costs related to diesel bus maintenance simply do not pertain to CNG buses. Because CNG engines do not generate heavy particulate matter, they do not require steam cleaning — which in California creates hazardous waste that needs to be carried away for disposal. As a result, SunLine's hazardous waste disposal costs have decreased 72 percent since the agency switched to an all-CNG fleet.[41] Less cleanup is also required in CNG bus maintenance and parking areas. And unlike diesel fuel, which can leak thousands of gallons from underground storage tanks, natural gas has no associated environmental cleanup costs.

Emerging Diesel Pollution Reduction Technologies

Some transit agencies are hoping to use low-sulfur diesel fuel and the latest generation of emissions control technologies to reduce their diesel bus emissions. This option is attractive because it will allow them to continue using diesel buses and existing infrastructure instead of purchasing new alternative-fuel buses and making changes in their facilities and daily operations. However, these technologies are still in the demonstration stage in the United States. At this point, it is still unclear how they will perform with different types of diesel buses and what their costs and durability will be.

Low-Sulfur Diesel

The US Environmental Protection Agency proposed new sulfur emission standards for diesel fuel in May 2000. These would sharply reduce sulfur levels by 97 percent, from 500 to 15 parts per million (ppm), starting in 2006.[42] According to refiners, who want sulfur levels to be capped at 50 ppm, low-sulfur diesel meeting the 15 ppm standard could cost at least 10 to 12 cents more per gallon because of the technology required to produce it.[43] It is also unknown whether the current delivery infrastructure, which uses the same pipelines and trucks to deliver both diesel and heating oil, can be used to deliver low-sulfur diesel and what the costs of changing over to low-sulfur diesel may be.

In an effort to reduce the public's exposure to diesel exhaust, the California Air Resources Board (CARB) is requiring urban transit fleets to begin using low-sulfur diesel capped at 15 ppm beginning on July 1, 2002.[44] (Currently, the average sulfur content of CARB diesel is 120 ppm.) In December 1999, Atlantic Richfield Co. (ARCO, now part of BP Amoco) began offering low-sulfur fuel to transit agencies in southern California that operate urban buses retrofitted with catalytic exhaust control technology.[45] ARCO's EC-Diesel has a maximum sulfur content of 15 ppm. The Los Angeles County Metropolitan Transportation Authority is testing the fuel and Johnson Matthey's continuous regenerating technology particulate traps (see the following section) on 12 of its buses as part of a one-year program.[46] Tests comparing the emissions of buses running on CARB diesel (average 120 ppm), on ARCO's EC-Diesel (15 ppm), and on EC-Diesel with the CRT particulate traps will be performed by CARB.

New York City Transit is committed to using low-sulfur diesel in all of its buses by 2003 and is hoping to do so by 2001.[47] In this case, low-sulfur diesel is defined as 30 ppm. The agency is currently demonstrating low-sulfur diesel and Johnson Matthey's particulate traps on 50 buses. At two points during the demonstration, emissions tests will be performed on a number of buses by Environment Canada. The diesel fuel is being supplied by Equilon, a Shell–Texaco joint venture, and was made especially for the demonstration. Because no low-sulfur diesel is produced on the East Coast of the United States, it may be as cost-effective in the short term to purchase it from Europe as from the West Coast.[48]

Diesel Emission Controls

Diesel emission control technologies are designed to reduce emissions of nitrogen oxides (NO_x) and particulate matter from buses. These technologies can be used to retrofit an existing bus or they can be incorporated into future buses. The only commercially available technologies currently available in the United States are retrofit technologies: diesel particulate traps and diesel oxidation catalysts. These reduce particulate emissions only; technologies to reduce NO_x and toxic emissions from diesel buses are currently not available. Both particulate and NO_x reduction technologies (once they become available) can also be used in CNG buses, where they may actually be more effective. Since natural gas contains almost no sulfur, after-treatment systems for CNG will not have the durability issues associated with diesel fuel.

Diesel particulate traps reduce emissions of particulate matter by filtering them out of the exhaust stream and cleaning the filter using oxidation catalysts. This "regeneration" of the filter avoids the problem of clogging that plagued the first generation of particulate traps. The oxidation catalysts oxidize nitrogen oxide to nitrogen dioxide, which destroys the soot trapped in the walls of the filter. The traps are expected to reduce particulate emissions by at least 80 percent to more than 90 percent, with similar emissions reductions for carbon monoxide and hydrocarbons as well.[49] They require the use of low-sulfur fuel to function properly.

The US companies Johnson Matthey and Englehard Corp. both manufacture these traps. Johnson Matthey's traps, based on its trademark continuous regenerating technology (CRT), have been used successfully in Europe on trucks and buses for several years. They are being used in the United States for the first time in emissions tests being conducted by transit agencies such as the Los Angeles County Metropolitan Transportation Authority and New York City Transit.

In the case of both LACMTA and NYCT, these tests of CRT particulate traps are occurring because the agencies are either required or committed to using after-treatment technology to reduce particulate emissions from their transit buses. Fleets in California are also testing traps from Englehard in conjunction with ARCO's EC-Diesel. These demonstrations and tests are intended to determine the traps' durability and particulate reduction potential before NYCT's (30 ppm) low-sulfur deadline and CARB's (15 ppm) low-sulfur deadline take effect in 2001 and 2002, respectively. The NYCT demonstration program will also test toxic emissions.

It is important to bear in mind that the performance of diesel particulate traps may vary depending on the age of the engine. Since older engines may not present ideal operating conditions, tests need to be performed in both modern diesel buses and their older, more polluting counterparts. Also, although the cost of these traps is unknown, estimates range from $6000 to $9000 given today's production quantities.[50]

Diesel oxidation catalysts reduce particulate emissions by oxidizing carbon monoxide, gaseous hydrocarbons, and liquid hydrocarbons adsorbed onto carbon particles in diesel exhaust. They have proven effective in reducing particulate emissions in older buses. Five manufacturers have oxidation catalysts certified by the EPA (under its Urban Bus Rebuild/Retrofit Program*)

* This program requires bus operators in metropolitan areas with populations of 750,000 or more to ensure that their buses meet emission standards for particulate matter when engines are replaced or rebuilt.

to reduce particulate emissions by 25 percent.[51] However, meeting the particulate emission standards proposed by the EPA for 2007 and by CARB for 2002 will require the use of particulate traps; oxidation catalysts will not be able to reduce emissions to the levels required.

Technologies to reduce NOx emissions are also under development. They include cooled exhaust gas recirculation, selective catalytic reduction systems, and NO_x adsorbers, none of which is commercial as yet.

- Cooled exhaust gas recirculation (EGR) minimizes combustion temperatures, thereby reducing NO_x emissions.[52] However, without the proper balance of gas recirculation and low temperature, EGR can increase emissions of particulate matter; thus, there can be an emissions reduction tradeoff between the two pollutants. It is expected that engine manufacturers will begin integrating EGR into their engines by 2002.

- Selective catalytic reduction (SCR) systems use ammonia or urea to convert NO_x into nitrogen and oxygen. They are commonly used in stationary sources, such as power plants, to reduce NO_x emissions. Since these systems are not yet commercial for vehicles, no tests of them in buses have been performed in the United States. Their retrofit costs are expected to be high because of extensive electrical and engineering requirements.

- NO_x adsorbers are currently being tested on engines and will not be available until 2007.[53]

Like particulate controls, NO_x controls require the use of low-sulfur diesel to function efficiently. NO_x technologies can also be used in natural gas buses to make them even less polluting.

When these NO_x reduction technologies are introduced to the market, they will have to be tested by transit agencies to determine how they perform under real-world conditions. In all likelihood, transit agencies that retain their diesel fleets and rely on after-treatment technologies to reduce pollution will have to invest in a combination of particulate and NO_x controls to meet increasingly stringent emissions standards. Moreover, low-sulfur diesel will have to be used in addition to the reduction technologies themselves.

6 EMISSIONS COMPARISONS: CONVENTIONAL NATURAL GAS AND DIESEL BUSES

Nine studies comparing emissions from diesel and natural gas engines and buses consistently show that emissions of particulate matter and nitrogen oxides (NO_x) from natural gas vehicles, regardless of vehicle type, are significantly lower than emissions from diesel vehicles. NO_x reductions range from 38 to 58 percent, and particulate reductions range from 40 to 86 percent. Results of emissions studies comparing natural gas and diesel trucks and school buses illustrate the reduction possibilities for other heavy-duty vehicles. The first five studies reviewed in this section are based on emissions tests; the findings of the remaining, slightly older studies are calculated from actual emissions results. The latter studies are of interest because their results are consistent with those of the more recent studies, underscoring the fact that natural gas buses are less polluting than diesel buses.

The GRI Study

Analysis of more than 40 studies of transportation fuels, published in the December 1999 report *The Cleaner Choice: Natural Gas as a Substitute for Diesel*, found strong evidence that substituting natural gas for diesel in heavy-duty trucks and buses significantly reduces the health risks of diesel exhaust. The study was sponsored by GRI (formerly known as the Gas Research Institute) of Chicago, Illinois, and was conducted by Engine, Fuel, and Emissions Engineering Inc., located in Sacramento, California. It examined research studies published by the US Environmental Protection Agency, the National Renewable Energy Laboratory, the California Air Resources Board (CARB), and other organizations.

The study's comparison of emissions certification data for heavy-duty engines of comparable size using compressed natural gas (CNG) and diesel showed clear environmental benefits from the use of CNG (Table 7). Five separate engine comparisons were made, involving the best-selling CNG and comparable diesel engines manufactured by two of the largest US heavy-duty engine companies, Cummins Engine Co. and Detroit Diesel Corp. The side-by-side comparisons showed that use of natural gas reduces emissions of particulate matter between 71 and 80 percent compared to emissions from comparably sized engines running on diesel. Reductions of NO_x ranged from 44 to 56 percent. These results are intended to reflect an engine's performance over its entire useful life.

Table 7. Emissions Certification Data for Heavy-Duty Diesel and CNG Engines (g/bhp-hr)

Engine Model and Fuel	Particulate Matter	Nitrogen Oxides
Cummins ISB215 diesel	0.07	3.4
Cummins B5.9G CNG	0.02	1.8
	% Change with CNG	
	– 71.4%	– 47.1%
Cummins ISC250 diesel	0.09	4.0
Cummins C8.3G CNG	0.02	1.8
	% Change with CNG	
	– 77.8%	– 55.0%
Detroit Diesel ES50BUS diesel	0.04	4.0
Detroit Diesel Series 50G CNG	0.01	2.2
	% Change with CNG	
	– 76.2%	– 44.4%
Detroit Diesel Series 60 diesel	0.10	3.9
Detroit Diesel Series 60G CNG	0.02	2.0
	% Change with CNG	
	– 80.0%	– 48.7%
Cummins ISC280 diesel	0.05	3.9
Cummins C8.3, 275G CNG	0.01	1.7
	% Change with CNG	
	– 80.0%	– 56.4%
	1998 EPA Bus Standard	
	0.05	4.0

Source: GRI

The GRI study found that heavy-duty natural gas engine manufacturers conform to or are pursuing certification to CARB and/or EPA ultra-low-emission vehicle (ULEV) standards. These engines will easily meet the EPA's heavy-duty ULEV standards when they become effective in 2004.

In addition, some heavy-duty natural gas engines have been certified to even lower NO_x levels under California's emissions credit program. For example, the most recent models of heavy-duty CNG pickups and vans have been certified to the state's standard for super-ultra-low-emission vehicles (SULEVs), with NO_x emissions under 0.3 gram per mile and nonmethane organic gas emissions under 0.06 gram per mile. These emissions are less than those of most light-duty gasoline vehicles.

The GRI study also found new data showing that diesel buses in operation on the road consistently exceed certification standards for particulate emissions. Data from a series of tests conducted by the National Renewable Energy Laboratory (NREL) and the US Department of Energy (DOE) showed that deterioration in particulate emissions is a problem found only in diesel buses — not in natural gas buses, which burn an inherently cleaner fuel. The transit buses were tested on the central business district cycle. Results showed that natural gas buses easily meet the 1994 and 1998 federal particulate emission standards of 0.07 and 0.05 gram per brake horsepower hour (g/bhp-hr), respectively, even at higher mileage. In contrast, average particulate emissions from diesel buses (0.13 g/bhp-hr) exceeded the standards.

NO_x emissions from CNG buses were also below emission standards (except in a few cases that could be attributable to incorrect air–fuel ratio settings), while diesel buses had higher emissions. The study also found that diesel trucks with engines certified to the current particulate standard of 0.1 g/bhp-hr had average in-use particulate emissions of 0.23 g/bhp-hr, more than twice the standard. Many trucks were emitting particulate matter in quantities of 0.4 to 0.6 g/bhp-hr by the time they accumulated 200,000 miles. The NREL/DOE data showed that actual average engine emissions of CNG vehicles in use are well below the 1998 standard, at 0.016 g/bhp-hr for both buses and trucks.

CIFER/WVU Bus Tests

In 1998, the Regional Transportation District in metropolitan Denver, in cooperation with the GO Boulder transportation planning agency, purchased 18 transit buses as part of the "Skip" demonstration program. The 26-foot buses — 15 operating on diesel and three on natural gas — were to run along a route in downtown Boulder.

The Skip program included emissions comparisons of the three CNG buses with three of the diesel buses. The buses were all 1997 models powered by 5.9 liter engines built by Cummins Engine Co. Tailpipe emissions tests were performed by two laboratories and compared to ensure accuracy. The laboratories were the Colorado Institute for Fuels and High Altitude Engine Research (CIFER) and the alternative-fuels testing center at West Virginia University (WVU).

The results of the emissions analyses, shown in Table 8, showed dramatically lower levels of pollution from the natural gas buses across the board. In the CIFER tests, emissions of particulate matter dropped from 0.7 gram per mile in the diesel buses to less than 0.1 gram per mile in the CNG buses, a decline of more than 86 percent. NO_x emissions dropped by 39 percent with the shift from diesel to natural gas. The WVU laboratory findings generally agreed with those from CIFER, with particulate and NO_x reductions of 74 and 58 percent, respectively.

Table 8. Medium-Duty Diesel and CNG Bus Chassis Dynamometer Data (grams/mile)

Pollutant	Diesel	CNG	% Change with CNG
CIFER Lab			
Particulates	0.7	0.1	– 86%
NO_x	18.4	11.2	– 39%
WVU Lab			
Particulates	0.38	0.1	– 74%
NO_x	20.6	8.87	– 58%

Source: CIFER and WVU data reported in N. Clark *et al*., Society of Automotive Engineers, Paper 1999-01-1469.

The California Energy Commission

The California Energy Commission (CEC) recently completed an analysis of the emissions from over 30 vehicles, mostly buses. The results were presented at the Intertech Clean Fuels 2000 conference held in February 2000 in San Diego. The study included nine different school bus models – three fueled by CNG, five fueled by diesel, and one fueled by pure methanol – in addition to transit buses, intercity buses, and large Class 8 trucks (the type used to haul semitrailers). Emissions testing was done at the Los Angeles County Metropolitan Transportation Authority emissions test facility. Nearly 400 test cycles were performed using the central business district test cycle.

Chassis dynamometer test results for the natural gas buses showed consistently lower particulate emissions than the diesel vehicles, mostly below 0.1 gram per mile. These excellent levels were especially notable in the urban transit buses, but were found in the school buses as well. NO_x levels for the natural gas buses were also generally lower than for the diesel vehicles, but they exhibited a broader range of emissions. The CEC believes, however, that additional testing of these vehicles in use is needed to confirm the long-term advantage of natural gas compared to diesel vehicles with respect to NO_x emissions.

School buses showed the most variation in NO_x level. The vehicles that had been converted to dual-fuel use — meaning they could burn either diesel alone or natural gas and diesel simultaneously — showed generally higher emissions than the dedicated natural gas vehicles. This indicates the emission compromises associated with dual-fuel use, although the CEC believes that further emission reductions might be possible with better pollution control catalysts.

There was a strong correlation between pollution level and vehicle age in the diesel fleet. The older diesel buses (1975 to 1977) emitted nine times more particulate matter than the 1997 diesel intercity bus. On the other hand, particulate emissions from the newest diesel bus approached the low levels achieved by some of the natural gas buses. This illustrates the closing gap between natural gas and diesel with respect to particulate emissions. NO_x levels from the diesel vehicles were stable within a narrow band found at the high end of emissions from the CNG buses.

CARB and EPA Engine Certification Data

In addition to the GRI study, a number of comparisons of emissions certification data have been published for various models of natural gas and diesel engines commonly used in buses. Table 9 shows emissions results for two types of Cummins heavy-duty engines frequently used in large (40 foot and longer) buses. The first data set shows emissions from a diesel-powered version of the Cummins M11 engine and from a CNG version of the company's L10 engine, as reported in CARB's "1998 Model Year Heavy-Duty On-Road Certification Listing." The second data set lists certification data for earlier versions of these engines reported in 1997.

Table 9. California Certification Data for 1997 and 1998 Heavy-Duty Diesel and CNG Engines (g/bhp-hr)

Pollutant	M11 Diesel Engine	10 Liter CNG Engine	% Change with CNG
	Cummins 1998		
Particulates	0.04	0.02	– 50%
NO_x	4.0	1.4	– 65%
	Cummins 1997		
Particulates	0.05	0.03	– 40%
NO_x	4.0	2.5	– 38%

Source: CARB Emission Certification Database

In both data sets, emissions of particulate matter and NO_x were significantly lower in natural gas than in diesel engines. In the 1998 engines, particulates and NO_x dropped 50 and 65 percent, respectively, in the CNG engine compared to the diesel engine. In the older engine, emissions dropped 40 and 38 percent with natural gas.

Another comparison appears in Table 10. It shows EPA certification results for the 1999 5.9 and 8.3 liter engines built by Cummins Engine Co. The data show that when the 5.9 liter engine (which is used in school buses, hybrid electric buses, and shuttle buses) burned natural gas, emissions of particulate matter were reduced by 82 percent compared to diesel. Combined emissions of NO_x and non-methane hydrocarbons dropped 55 percent when the engine was operated in the CNG mode. Natural gas brought significant emissions reductions in the 8.3 liter engine as well. Compared to emissions from the diesel-burning version, the CNG engine reduced particulates by 54 percent and NO_x/hydrocarbons by 51 percent.

Table 10. EPA Certification Data for 1999 Diesel and CNG Engines (g/bhp-hr)

Pollutant	Diesel	CNG	% Change with CNG
	5.9 Liter 1999 Cummins Engine		
Particulates	0.102	0.018	– 82%
NO_x and hydrocarbons	4.04	1.8	– 55%
	8.3 Liter 1999 Cummins Engine		
Particulates	0.076	0.035	– 54%
NO_x and hydrocarbons	3.92	1.90	– 51%

Source: EPA Emission Certification Database

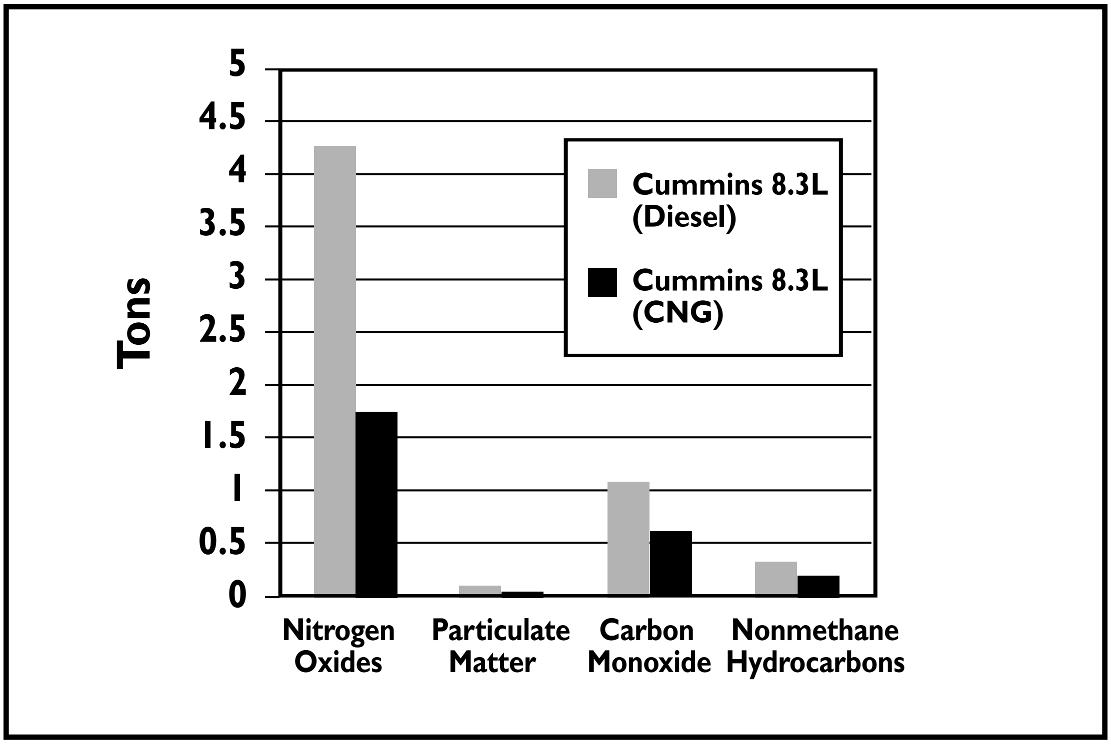
The Coalition for Clean Air

The Coalition for Clean Air (CCA), an environmental organization located in Los Angeles, examined emissions from school buses and concluded that these vehicles pose a significant health risk to the children who ride them. The CCA's analysis appears in a report published in November 1999 entitled *Failing the Grade: How Diesel School Buses Threaten Our Children's Health*.

According to the CCA, over 69 percent of the 24,372 school buses in California run on diesel fuel. Only 3 percent are powered by cleaner-burning alternative fuels such as natural gas. These 640 buses are distributed among the state's 60 school districts. The report cites South Coast Air Quality Management District data showing that the average diesel bus generates 223.5 times more toxic air emissions than a new CNG school bus. The worst polluters are older diesel buses, which, according to CARB, emit more than three times the nitrogen oxides and four times the particulate matter of a CNG bus.

Figure 2 shows the total lifetime emissions of school buses powered by 8.3 liter natural gas and diesel engines from Cummins Engine Co. According to the CCA's analysis, use of natural gas will reduce lifetime emissions of NO_x to 1.75 tons, compared to 4.3 tons for a diesel bus. Moreover, the organization estimates that CNG will reduce emissions of particulate matter to virtually nothing.

Figure 2. Lifetime Diesel and CNG School Bus Emissions



Source: Coalition for Clean Air

Natural Resources Defense Council

In April 1998, the Natural Resources Defense Council (NRDC) published "Exhausted by Diesel: How America's Dependence on Diesel Engines Threatens Our Health," which included a comparison of emissions from diesel- and natural gas-burning buses.

The NRDC analysis presented certification data for two common bus engines: the Cummins M11-330E diesel engine and the Cummins L10-300G CNG engine. The emissions data were obtained from CARB's "1998 Model Year Heavy-Duty On-Road Certification Listing." The study projected actual in-use emissions from buses equipped with these engines using conversion factors developed by CARB.

The results of this analysis are shown in Table 11. Engine certification data showed that the CNG engine reduced emissions by 52 percent for particulate matter and 67 percent for NO_x. Based on its calculations, NRDC concluded that the lifetime emissions benefits of operating a single CNG-powered bus instead of a new diesel transit bus are equal to 130 pounds of particulate matter and 15,900 pounds of NO_x. The reduction in particulate emissions from a bus using

CNG rather than diesel would be equivalent to removing 17 passenger cars from the road; NO_x savings are equivalent to removing 55 cars from the road.

Table 11. NRDC Analysis of Diesel and CNG Bus Emissions (grams/mile)

Pollutant	Diesel	CNG	% Change with CNG
Particulates	0.172	0.082	– 52%
Nitrogen oxides	17.20	5.74	– 67%

Source: Natural Resources Defense Council

The Union of Concerned Scientists

In April 1998, the Union of Concerned Scientists (UCS), another environmental organization, published *Shifting Gears: Advanced Technologies and Cleaner Fuels for Transit Buses*, which included a comparison of the emissions from diesel- and natural gas-burning buses.

Like NRDC, the UCS presented engine certification data from the Cummins M11-330E diesel engine and the Cummins L10-300G CNG engine. However, rather than relying on the 1998 CARB certification inventory, the UCS used emissions data reported in 1997. It then projected actual in-use emissions from buses equipped with these engines using conversion factors developed by CARB.

The results of this analysis are shown in Table 12. Like NRDC, the UCS projected emissions reductions from using CNG for both particulate matter and NO_x. Projected reductions were estimated at 45 percent for particulates and 40 percent for NO_x. Based on its calculations, the UCS concluded that the lifetime emissions benefits of operating a single CNG-powered bus instead of a new diesel transit bus are equal to 140 pounds of particulate matter and 9600 pounds of NO_x. The reduction in particulate emissions from using CNG rather than diesel would be equivalent to removing 18 passenger cars from the road; NO_x savings are equivalent to removing 33 cars from the road.

Table 12. UCS Analysis of Diesel and CNG Bus Emissions (grams/mile)

Pollutant	Diesel	CNG	% Change with CNG
Particulates	0.22	0.12	– 45%
Nitrogen oxides	17.20	10.30	– 40%

Source: Union of Concerned Scientists

Engine, Fuel, and Emissions Engineering, Inc.

Reducing air pollution through the use of alternative-fuel vehicles may have economic value as well as helping to protect human health. Under emissions reduction credit programs, vehicle fleet operators that reduce pollution more than they are required to do under the law can "sell" the excess portion to other fleet operators. The buyers can then apply these emissions reductions toward the pollution control targets required for their own operations.

In late 1996, Engine, Fuel, and Emissions Engineering, Inc. (EFEE) completed a study examining the pollution reduction credits that may be available from various weight classes of natural gas vehicles compared to their gasoline- or diesel-powered counterparts. This analysis compared emissions from CNG vehicles based on engine certification data with emissions from diesel vehicles based on the EPA's MOBILE5B mobile source emissions model, which was introduced in September 1996. Calculated NO_x emissions for diesel- and CNG-fueled vehicles are shown in Table 13.

Table 13. NO_x Emissions from Simulated Diesel and Actual CNG Vehicles (grams/mile)

Vehicle Class	Diesel	CNG	% Change with CNG
	NO_x Emissions		
Heavy-duty bus	11.87	7.31	– 38%
Heavy-duty truck	11.02	5.08	– 54%
Medium-duty truck	8.28	4.94	– 40%
Medium-duty school bus	5.96	3.55	– 40%
Light-duty truck	3.39	0.83	– 76%

Source: Engine, Fuel, and Emissions Engineering, Inc.

The study compared emissions from two types of heavy-duty vehicles — large Class 8 trucks (the type used to haul semitrailers) and urban transit buses. In both cases, the CNG data were based on emissions from vehicles equipped with L10G engines built by Cummins Engine Co. In the bus, use of CNG was found to reduce NO_x emissions by 38 percent compared to diesel.

The EFEE study also analyzed a medium-duty truck and school bus and a light-duty truck. The CNG-fueled vehicles in these weight classes were equipped with either a Cummins C8.3 or B5.9 engine. The school bus and medium-duty CNG truck (14,000 to 33,000 pounds gross vehicle weight) were assumed to be equipped with the C8.3 engine; the light-duty truck (8500 to 14,000 pounds gross vehicle weight) was assumed to be equipped with the B5.9 engine. In the tests involving the C8.3 engine, use of CNG was found to reduce NO_x emissions by 40 percent compared to the diesel-fueled school bus and medium-duty truck.

Northeast States for Coordinated Air Use Management

In May 1997, the Northeast States for Coordinated Air Use Management (NESCAUM), an association of state government air pollution officials, completed a study entitled "Heavy-Duty Engine Emissions in the Northeast." This report contains a detailed assessment of heavy-duty vehicle emissions inventories in the Northeast as well as recommendations for obtaining pollution reductions from these sources. NESCAUM concluded that alternative-fuel vehicles, and natural gas vehicles in particular, could play an important role in providing emission reductions. For example:

- Switching from diesel to CNG can reduce both NO_x and particulate emissions from trucks and buses.
- By 2010, widespread use of natural gas vehicles (compared to no use of these vehicles at all) could reduce total heavy-duty vehicle particulate inventories in the region by 7 percent and NO_x inventories by 9 percent.
- Within the bus market, use of natural gas buses could reduce total bus emission inventories of particulate matter by 18 percent and NO_x by 11 percent.

7 DEVELOPING BUS TECHNOLOGIES: HYBRID ELECTRIC AND FUEL CELLS

Hybrid electric and fuel cell technologies are both in the early stages of commercial development. Research and development for application in buses has been under way for many years in the United States, but few functioning vehicles have been built and field-tested. Consequently, data on actual emissions from these vehicles are scant. Nonetheless, the results of field testing to date, combined with information on the few commercial sales of hybrid electric buses, show that both these technologies have a potentially important role to play in the nation's transit fleets and in reducing urban air pollution.

Through field testing, manufacturers gather information on the performance of developing products and their components outside the laboratory and use this information to make improvements. Transit agencies are interested in testing hybrid electric and fuel cell buses to understand the operating and maintenance issues associated with these vehicles and to gain some experience in their use. Demonstrations also raise awareness of these technologies among the public.

The existence of demonstration programs, however, does not necessarily mean that these buses are problem-free and widely available for purchase. Hybrid electric and fuel cell systems are complex technologies that still present engineering, operational, and technical challenges. Moreover, even when a new technology begins to be commercialized, it is continually being refined and products are often available on only a limited basis. It has taken a little more than a decade for natural gas buses to become fully commercial, and electric hybrids and fuel cells may well require an equivalent amount of time.

It is unclear at this point what the operational and maintenance costs of these buses will be, or even what operational and maintenance issues will arise. Demonstration costs do not necessarily reflect the cost of the buses themselves, since field-tested buses are sometimes unique and built specifically for individual demonstration programs. Moreover, using and maintaining these vehicles are likely to generate costs associated with worker training in new tools and skills.

Both hybrid electric and fuel cell buses are expected to produce lower emissions than diesel buses. However, hybrid electric is generally viewed as an intermediary technology to be used until emissions-free fuel cell buses become available. While the existing infrastructure for diesel buses can accommodate hybrid electric vehicles, hydrogen fuel cell buses have distinctly different fuel storage and depot requirements than either conventional diesel or hybrid electric-diesel buses. In contrast, the infrastructure for compressed natural gas (CNG) and hybrid electric-CNG buses is compatible with hydrogen fuel cells. Thus, transit agencies with no natural gas infrastructure in place will eventually have to either retrofit their existing depots and refueling stations or build new facilities to accommodate buses powered by compressed hydrogen.

Hybrid Electric Technology

A hybrid electric vehicle (HEV) uses both an engine (powered by gasoline, diesel, an alternative fuel such as natural gas, or a turbine) and an energy storage system (such as batteries, a flywheel, or an ultracapacitor). While there are many hybrid system concepts, the most common links an internal combustion engine (ICE) to a battery pack. In a conventional vehicle, the chemical energy of the fuel burned in the engine is converted directly into mechanical energy, which turns the wheels. In an HEV, the engine runs a generator that produces electricity. The electricity from the generator is stored on board the vehicle — in a battery, for instance — and is used to power motors that turn the vehicle's wheels. This arrangement allows the engine to run at a constant speed — typically the speed at which it is most efficient and generates the least pollution.

HEVs are able to operate approximately twice as efficiently as traditional ICE vehicles. They do this by minimizing energy losses. In an ICE, the energy contained in the fuel is released when the fuel is burned in the engine. The released energy is used to move the driveshaft, which turns the wheels. This two-step process is inefficient because only about 16 percent of the fuel's energy is used to accelerate the vehicle; most of the rest becomes waste heat. In contrast, an HEV uses regenerative braking, lightweight composite materials, and special aerodynamic body shapes to minimize energy losses, making as much energy available as possible to propel the vehicle.*

Because HEVs use energy more efficiently than conventional ICE vehicles, they can use smaller engines. A smaller engine reduces the weight of the vehicle, thereby reducing overall energy consumption.[54] Lower energy consumption decreases the amount of fuel that has to be stored on board, so hybrid electric-CNG buses require fewer tanks than conventional CNG buses.

* In a conventional vehicle, braking energy turns into heat and is lost to the atmosphere. Regenerative braking saves this energy and uses it instead to help power the vehicle. Any vehicle that uses electric motors to drive the wheels can be made to recapture the energy dissipated during braking by turning the motors into electric generators. In an HEV, this electricity can then be used to recharge the batteries. Vehicles operated under extensive stop-and-go conditions have the most to gain from regenerative braking. The use of lightweight composite materials can reduce fuel consumption. Research is under way on composites made from glass, polymers, and carbon fibers.

(The use of regenerative breaking also partly offsets the weight of the CNG fuel tanks.) Since today's batteries have low specific energies (i.e., a low density of watt-hours per kilogram of weight), however, relatively large ICEs are still needed to maintain performance. The development of batteries with high specific energies is therefore crucial to maximizing the efficiency of hybrid electric buses.

There are two basic approaches to building the electric and fuel systems for an HEV: a parallel or a series configuration. Like a conventional vehicle, an HEV in a parallel configuration has a direct mechanical connection between the power unit and the wheels, but an electric motor is also available to drive the wheels. Because both the engine and the motor can supply power to the wheels simultaneously, parallel hybrids tend to have more power than series hybrids. However, they also require a larger engine, which cannot always run at the most efficient and least polluting speed. The benefits of a parallel over a series HEV are:

- It can use the power generated by the ICE for highway driving and the power generated by the electric motor for city driving and for added power during acceleration.
- It uses a smaller battery pack, reducing both the weight and expense of the batteries.

In a series HEV, there is no mechanical connection between the power unit and the wheels; it uses the ICE exclusively with the generator to supply energy to the battery pack and electric motors. At medium speeds on level roads, all the engine power is transferred by the batteries to the drive motors. When the vehicle is running downhill or at low speeds, excess power is used to charge the batteries. During acceleration, high-speed, or uphill driving, engine power and power stored in the batteries combine. While series HEVs require a smaller engine than parallel HEVs, they also require a larger, heavier, and more expensive battery pack. The benefits of a series over a parallel HEV are:

- The engine never idles, which reduces vehicle emissions.
- The engine drives a generator, ensuring optimum efficiency and emissions performance.
- The technology allows for a variety of options when mounting the engine and vehicle components.
- Some configurations do not need a transmission.

Hybrid electric vehicles are just beginning to enter the commercial marketplace. The world's first modern HEV, the Toyota Prius, has been marketed in Japan since late 1997. More than 30,000 of these five-passenger sedans have been sold so far, and the company plans to begin selling the Prius in the United States by mid-2000. The Honda Insight, a two-passenger vehicle, became the first commercial HEV to be offered for sale in the US beginning in December 1999. Both the Prius and the Insight are parallel hybrids.

Fuel Cells

Fuel cells are an efficient, emissions-free means of generating electricity for both transportation and stationary-source use. A fuel cell generates electricity by combining hydrogen with oxygen from the air. Because there is no combustion to generate the high temperatures that lead to the formation of nitrogen oxides, fuel cell-powered electric vehicles offer the cleanest way of using hydrogen: they are zero-emission vehicles.[55] When pure hydrogen is used in a fuel cell, the only by-product is water. Compared to an ICE, which can dissipate over 80 percent of the energy contained in the fuel, energy losses from a fuel cell are only 40 to 60 percent.[56]

Hydrogen for a fuel cell can be obtained from a number of sources, including natural gas, gasoline, diesel, methanol, ethanol, landfill gas, and biomass. Most hydrogen produced today is made from natural gas in a process called steam reforming.[57] It can also be made using renewable energy sources, such as solar and hydropower, which generate electricity that splits water molecules into hydrogen and oxygen. Hydrogen can be produced on site or it can be brought on site, although the hydrogen distribution system is limited.

Like CNG, hydrogen can be stored under pressure in tanks on board the vehicle. The weight and volume of hydrogen fuel storage systems are comparable to the weight and volume of storage systems for CNG. The weight of hydrogen storage will be further reduced by new tanks made of composite materials. Hydrogen can also be generated by an on-board reformer from water and hydrocarbon fuels such as methanol, methane, or natural gas, eliminating the need for tanks altogether. However, reformers increase the cost, bulk, and complexity of the fuel cell system.[58]

The technology and infrastructure needed to store, produce, and distribute hydrogen for transit use are very similar to those required by CNG. For storage in tanks, the same high-pressure compressors already available at CNG refueling stations can be used for hydrogen. Natural gas can also be used for on-site production of hydrogen. Fast-fill CNG refueling technology can be adapted for fuel cell vehicles, and ventilation and methane detection systems at CNG depots can be adapted for hydrogen gas.[59]

Research and Demonstration Initiatives

As of January 1, 2000, there were fewer than 50 hybrid electric buses operating in the United States. These were roughly evenly split between buses powered by diesel and buses powered by natural gas. However, several hundred hybrid buses are on order, likewise split between natural gas and diesel models.

Encouraged by the results of early demonstration projects, several companies have moved rapidly to commercialize hybrid electric buses and a number of transit agencies have placed additional orders. For example, hybrid electric-natural gas buses have been ordered in Denver and in Tempe, Arizona, and transit agencies in New York City and Tampa, Florida, recently placed orders for hybrid electric-diesels. The choice of fuel to power hybrid buses often depends on which fuel the current infrastructure supports.

Demonstrations of fuel cell buses are not as advanced as for hybrid electric buses. As of January 1, 2000, fewer than five fuel cell buses were operating in the United States.

Current private and public sector demonstration initiatives are described in the following sections. Since these are new and/or ongoing, performance results are not readily available.

Manufacturer/ Program	Description
Hybrid Electric-Natural Gas Buses	
Advanced Vehicle Systems, Inc.	22-foot bus in field tests since 1997 by Chattanooga Area Regional Transportation Authority 31 22-foot LNG buses to be delivered to Tempe, AZ, by February 2001; the order includes a pooled purchase option for an additional 169 buses
Transportation Techniques LLC	Shuttle bus debuted by Regional Transportation District (RTD) of Denver in January 1999 RTD has contracted for 26 buses with an option to purchase 10 more at a future date
ISE Research Corp.	Six prototype hybrid powertrains using the company's ThunderVolt technology have been built for use in delivery trucks, refuse collection trucks, transit buses, and airplane tows
Advanced Transportation Technology Bus program (FTA)	Six 40-foot buses built and tested by the Los Angeles County Metropolitan Transportation Authority and the Metropolitan Transit Authority of Harris County, TX
Demonstration Utilization of Electric Transportation Systems (DUETS) program (FTA and DARPA)	First prototype bus began road tests in New Mexico in March 1997

Manufacturer/ Program	Description
Hybrid Electric-Diesel Buses	
Orion Bus Industries, Inc.	40-foot hybrids being demonstrated by New York City Transit (NYCT) and the Massachusetts Bay Transportation Authority in Boston 125 additional buses ordered by NYCT in December 1999, the largest order ever placed for any type of hybrid bus
Novabus Inc.	Converted hybrid delivered to NYCT in May 1999 Another five retrofit buses ordered for delivery in the first half of 2000
Advanced Vehicle Systems, Inc.	Ten 22-foot hybrid buses ordered by Florida Transit Association (Tampa, FL) in September 1999, for delivery within 2 years; the order includes a pooled purchase option for an additional 80 buses
ISE Research Corp.	Three gasoline-powered electric hybrids to be delivered to the San Bernardino (CA) transit agency in 2000 Four propane-powered hybrids in service at the Los Angeles Dept. of Transportation and another four to go into service soon
APS Systems, Inc.	A 40-foot propane-powered hybrid bus tested by transit agencies in the East San Francisco Bay area and in Orange County
Fuel Cell Buses	
Ballard Power Systems/EXCELLSIS Fuel Cell Engines, Inc.	Testing of three hydrogen fuel cell buses completed by Chicago Transit in March 2000; the buses operated for two years and logged over 30,000 miles
California Fuel Cell Partnership	More than 50 fuel cell buses and cars to be placed on the state's roads between 2000 and 2003; the first bus to be delivered to SunLine Transit (Thousand Palms, CA) in the summer of 2000
Georgetown University Fuel Cell Bus Program (FTA)	Five fuel cell buses demonstrated since 1994: a full-sized Novabus RTS model bus powered by a proton-exchange membrane fuel cell and four methanol fuel cell buses (three 30-foot and one 40-foot) powered by phosphoric acid fuel cells

Natural Gas Hybrids

In January 2000, RP Publishing released a catalog of commercial vehicles powered by alternative fuels. *Advanced Vehicle 2000* lists 183 models of alternative-fuel vehicles available worldwide from more than 60 manufacturers. It identifies nine commercially available hybrid trucks and buses powered by alternative fuels. Six of these are natural gas-powered buses marketed in the United States by three companies, as shown in Table 14. A number of other demonstration and commercial hybrid electric-natural gas buses have been built as part of government-sponsored test programs.

Table 14. Commercial Hybrid Electric-Natural Gas Buses

Manufacturer	Bus Model
Advanced Vehicle Systems, Inc.	AVS-22-foot shuttle bus AVS-30-foot bus AVS-35-foot bus AVS-40-foot bus
Transportation Techniques LLC	Specialty 45-foot transit bus
ISE Research Corp.	ThunderVolt TB-30H bus

Source: RP Publishing

Advanced Vehicle Systems, Inc. (AVS), of Chattanooga, Tennessee, is the largest manufacturer of hybrid electric and battery-powered electric buses in the United States. In 1996, the company completed construction of the world's first hybrid electric bus to burn natural gas in a turbine engine. By mid-1999, this 22-foot bus had completed two years of testing by the Chattanooga Area Regional Transportation Authority (CARTA).

The vehicle's turbine system was designed and built by Capstone Turbine Corp., which has been modifying jet engine technology for use in electrical generation applications since 1988. More than 37 Capstone MicroTurbine systems have been field-tested around the world since 1994.

The CARTA bus is a modified AVS-22 electric bus. Its construction as a battery-powered electric bus was 95 percent complete when the Capstone MicroTurbine became available. Some structural changes were made to the bus's rear portion to incorporate the turbine, turbine controller, and high-voltage distribution and fusing system. Since the turbine is powered by compressed natural gas, the rear compartment had to be completely redesigned to accommodate two CNG storage cylinders. Subsequent redesigns will allow the bus to accommodate a larger number of roof-mounted tanks or to carry the gas in a liquefied state. Either redesign will greatly increase driving range.

The CARTA bus was placed in transit service in June 1997. Since then, it has accumulated over 22,000 miles and been demonstrated at transportation exhibitions around the country. Compared to a conventional bus powered by diesel, the CARTA bus shows improved efficiency and reduced emissions. Less quantitative improvements include quieter and vibration-free operation.

In August 1999, the municipal government of Tempe, Arizona, ordered 31 hybrid electric-natural gas buses to be delivered by February 2001. This represents the largest single order for natural gas-powered hybrid electric buses in the world. The 22-foot buses will be powered by liquefied natural gas stored in on-board cryogenic tanks. The Tempe order also includes a pooled purchase option that allows other cities and transit agencies in Arizona to apply federal transit funding to the purchase of up to 169 additional hybrid buses at the price negotiated by Tempe. This brings the total potential order to 200 hybrid electric-natural gas buses.

AVS is currently expanding its bus manufacturing facility in Tennessee to handle future orders of electric and hybrid electric buses. The company is also developing larger hybrid buses, which it plans to commercialize over the next few years. These buses, powered by either natural gas or diesel, will come in 30-, 35-, and 40-foot models.

Transportation Techniques LLC (TransTeq) and the Regional Transportation District (RTD) of Denver, which provides transit service throughout the metropolitan area, debuted a hybrid electric-CNG bus in January 1999. The state-of-the-art shuttle bus, designed for use in Denver's 16th Street Mall, is expected to eventually replace the mall's entire 16-year-old shuttle fleet. TransTeq (also of Denver) built the bus under a $15 million contract with RTD that stipulated delivery of 26 buses in the first phase of commercialization, with an option to purchase 10 more at a future date.

The shuttle bus has four passenger doors (compared to three in the older buses), low floors (14 inches above street level) for easy passenger access, a fast-operating wheelchair ramp, insulation for interior/exterior noise, and a durable, stainless steel frame. The free shuttle currently serves about 39,000 customers daily. TransTeq's buses can accommodate 116 passengers (compared to 70 passengers in the older buses). It was designed for 12 years of nearly maintenance-free service under the slow (15 mile per hour), stop-and-go conditions of the 16th Street Mall.

The new bus underwent extensive testing in 1999, including certification by the Federal Transportation Administration (FTA) at the Pennsylvania Transportation Institute. In January 2000, RTD's board of directors directed TransTeq to move forward with the construction of the remainder of the 26 buses included in the first phase of the project.

ISE Research Corp., of San Diego, California, is a research, development, and manufacturing company specializing in efficient and nonpolluting powertrains for use in heavy-duty vehicles, including buses. Since 1994, ISE has been developing its ThunderVolt series of hybrid electric drivetrains. These are high-performance drivetrains that can be customized to meet specific requirements, including fuel source and vehicle size. To date, ISE has built six prototype hybrid powertrains for use in delivery trucks, refuse collection trucks, transit buses, and airport tow tractors. Compared with vehicles powered by conventional drivetrains, ISE ThunderVolt hybrid systems have so far proven to offer the following advantages:

- They are 25 to 50 percent more fuel-efficient.
- They reduce emissions of most pollutants between 50 and 95 percent.
- They reduce vehicle maintenance costs by 10 to 20 percent.
- They provide faster acceleration and a smoother ride.

The Advanced Transportation Technology Bus (ATTB) program was initiated by the FTA to develop a lightweight, low-floor, low-emission transit bus utilizing hybrid electric drivetrain technology.

The research, development, and testing phases of the $51.2 million ATTB project, which began in 1992, are near completion. The first bus was completed in October 1996. A total of six prototypes, all developed, produced, and tested under contract with Northrop Grumman Corp., have been delivered to the Los Angeles County Metropolitan Transportation Authority. The buses, which are powered by compressed natural gas, are now undergoing tests and are not for sale commercially. As part of the program, the Metropolitan Transit Authority of Harris County, Texas, is also testing a hybrid electric-CNG bus. Testing is expected to be completed by the end of 2001.

Demonstration Utilization of Electric Transportation Systems (DUETS) is an $8 million program sponsored jointly by the FTA and the US Defense Department's Advanced Research Projects Agency (DARPA). Its objective is to demonstrate the technical capability and commercial potential of three major subsystem technologies in urban transit buses: a natural gas-powered hybrid electric drivetrain, an integrated vehicle management and communication system, and an advanced, semiactive rear suspension for improved pitch control and better ride characteristics. In March 1997, the first prototype DUETS bus — equipped with a unique rotary natural gas-powered combustion engine and a 100-kilowatt electric generator — began road tests in New Mexico.

Diesel Hybrids

Hybrid electric-diesel buses are being developed largely by Orion Bus Industries, Inc., and Novabus Inc. in response to two demonstration programs in New York City. Smaller development projects are being conducted by other companies and additional buses will be field-tested at other locations in the near future.

Since 1996, New York City Transit (NYCT) has been leading an effort to develop and commercialize full-size (40 foot) hybrid electric-diesel buses for use in its fleet. The agency has pursued two projects. The first uses hybrid technology incorporated into new buses manufactured by Orion. The second converts conventional diesel buses built by Novabus into hybrid electric-diesels. Other transit agencies are also beginning to test hybrids, but they are doing so with only a few vehicles rather than the hundreds being demonstrated by NYCT.

Orion Bus Industries, Inc., of Oriskany, New York, built its first diesel hybrid in 1996, as part of a $6.5 million project. The hybrid technology for the bus, which was based on the company's Orion V model, was developed by General Electric at its research and development center in Schenectady, New York.

The company's second-generation hybrid electric-diesel is based on its Orion VI model bus. NYCT placed an order for 10 of these buses, the first five of which were delivered in September 1998. Equipped with the HybriDrive hybrid propulsion system manufactured by Lockheed Martin Control Systems at its facility in Johnson City, New York, the bus is twice as fuel-efficient as a comparable bus operating on diesel. The remaining five buses are scheduled for delivery in early 2000.

In December 1999, New York City Transit ordered an additional 125 hybrid electric-diesel buses from Orion for $385,500 each. This is by far the largest order ever placed for any type of hybrid bus, and producing such a large number may be a challenge. The bus will be based on the company's Orion VII model and the hybrid technology will again be provided by Lockheed.

The Massachusetts Bay Transportation Authority is also testing two of Orion's hybrid electric-diesel buses on 39 lines in Boston. These low-floor buses are equipped with global positioning system, voice automation system, and wheel-chair ramp access. Evaluation of the technologies is expected to be complete by August 2000 (West Virginia University has performed tests on these buses, but they have not yet been released).[60]

Novabus Inc., of Roswell, New Mexico, delivered the first of its converted hybrid diesels to New York City Transit in 1999. In this effort, a group led by General Motor's Allison Transmission Division retrofit a Novabus RTS model bus with a hybrid powertrain incorporating a battery system adapted from the drivetrain used in GM's S-10 electric pickup truck.

NYCT has ordered five more retrofit diesel hybrids from Novabus for delivery in the first half of 2000. Unlike the first bus, these will be equipped with Lockheed's HybriDrive system.

Advanced Vehicle Systems, Inc. (see the section on natural gas hybrids for more on this company) received an order in September 1999 from the Florida Transit Association (Tampa) for 10 diesel-powered 22-foot hybrid electric buses to be delivered within two years. Like the company's deal with the city of Tempe, Arizona, for natural gas hybrids, the Tampa order includes a pooled purchase option whereby other cities in the region can buy up to 80 additional hybrid electric-diesel buses at the same price.

Other Hybrid Electric Bus Development Projects

ISE Research Corp. (see the section on natural gas hybrids for more on this company) is outfitting buses destined for use in two California demonstration projects with its ThunderVolt hybrid powertrain.

As part of a $1.5 million hybrid electric transit bus demonstration program managed by the San Bernardino transit agency OMNITRANS, ISE was awarded a $219,000 California Technology Investment Partnership grant to support further development and commercialization of its hybrid vehicle technology. The company is incorporating the ThunderVolt drivetrain into three New Flyer buses powered by a gasoline engine in combination with electric motors and batteries. The buses will feature an advanced on-board recharging system that enables the batteries to be recharged by the gasoline engine, as well as by plugging the vehicle into standard electrical outlets. The buses are to go into service in San Bernardino early next year.

ISE is also installing its ThunderVolt technology in eight propane-powered hybrid buses. The first four of these 30-foot vehicles, based on an El Dorado National bus body, are currently in service at the Los Angeles Department of Transportation. The other four — one of which will be a low-floor prototype — will use Capstone MicroTurbines. The drivetrain includes a 100-kilowatt Siemens electric motor and an 80-kilowatt Fisher electric generator powered by a 5.7-liter GM engine converted to run on propane. The bus has a range of about 150 miles when running on propane and about 20 miles when running solely on electricity stored in its batteries.

APS Systems, Inc., of Oxnard, California, is another company active in hybrid bus technology. In 1998, it completed a 40-foot hybrid electric transit bus powered by propane. This bus has been operated in a test program by AC Transit, which serves communities in the East San Francisco Bay area, and by the Orange County Transportation Authority in southern California.

Fuel Cell Buses

Development of fuel cells and fuel cell vehicles has been undertaken by partnerships of fuel cell developers and transit agencies. Demonstrations of fuel cell buses have so far occurred on a very limited basis in the United States, in Chicago and Washington, DC. The Chicago demonstration is complete and the Washington program, which is sponsored by the federal government, is ongoing. Other demonstrations are expected to begin in California soon.*

Ballard Power Systems and ***EXCELLSIS Fuel Cell Engines, Inc.*** (respectively of Burnaby and Vancouver, British Columbia), in cooperation with the Chicago Transit Authority, concluded the world's first demonstration and testing of a fuel cell bus in March 2000, after two years in operation. The three buses, powered by hydrogen fuel cells from Ballard, logged more than 30,000 miles and more than 5000 hours of service. Data from the demonstration program will be used to develop and design the next generation of fuel cells. A similar field trial in Vancouver is scheduled for completion in the summer of 2000. Ballard believes that a commercial fuel cell bus engine will be available in two years.[61]

The California Fuel Cell Partnership is a collaborative effort between private and public entities to demonstrate fuel cell vehicles. Partners include automakers, fuel cell manufacturers, oil companies, state agencies, transit agencies, and the US Department of Energy. The partnership intends to place more than 50 fuel cell buses and cars on the road in California between 2000 and 2003.

The first bus will be demonstrated by SunLine Transit Agency (Thousand Palms) beginning in the summer of 2000. The bus is a 40-foot low-floor New Flyer with an EXCELLSIS fuel cell engine. It will be tested for 13 months in simulated route service.[62] Funding for the tests is provided by the FTA and EXCELLSIS. Two other fuel cell buses will be tested by SunLine beginning in mid-2002. AC Transit, of San Francisco, also plans to test two fuel cell buses in the future.

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* In Europe, DaimlerChrysler plans to offer 20 to 30 hydrogen fuel cell buses for sale to transit operators over the next three years. The first vehicles are planned for delivery by the end of 2002. The buses will be made in Germany by EvoBus, a subsidiary of DaimlerChrysler, and will be powered by Ballard fuel cells.

SunLine has an on-site hydrogen production facility and is producing hydrogen by a variety of methods. Solar power and electricity from the grid are used to convert water into hydrogen and oxygen; a wind-powered generator may also be tested as another renewable energy source. Since SunLine's buses all run on natural gas, the agency is able to capitalize on its CNG infrastructure and use steam reforming to produce pure hydrogen from natural gas.

Georgetown University Fuel Cell Bus Program has demonstrated five fuel cell buses since 1994 under a grant from the FTA. In 2000, a full-sized, wide-front-door Novabus RTS model bus powered by a proton-exchange membrane fuel cell was placed into service. Hydrogen for the fuel cell is extracted from methanol using an on-board reformer. The bus uses batteries to provide surge power and regenerative braking to recover energy. It has a range of 350 miles before refueling is required. The program has also demonstrated four methanol fuel cell buses (three 30-foot and one 40-foot) powered by phosphoric acid fuel cells.

8 EMISSIONS COMPARISONS: NATURAL GAS AND HYBRID ELECTRIC-DIESEL

Hybrid electric vehicles are an emerging industry. Few vehicles exist and those that do have been in operation only briefly. These vehicles do not yet perform optimally and with high reliability, so components are frequently being added, removed, or replaced with alternative designs. At this point, no comprehensive analyses are available of hybrid electric vehicle emissions, including emissions of toxic air pollutants and ultrafine particulates. The few partial analyses that do exist represent the results of tests on one-of-a-kind vehicles from which it is difficult to extrapolate the emissions of future commercial designs.

This chapter presents the findings of three studies that do address emissions from hybrid buses. Most of the comparisons are between conventional diesel buses, conventional natural gas buses, and hybrid electric-diesel buses; none of the studies presents data on natural gas hybrids. The studies provide important information about the performance of these bus technologies and fuels, but they do not provide “apple to apple” comparisons of comparably sized natural gas and hybrid electric-diesel buses.

Northeast Advanced Vehicle Consortium

In 1999, the Northeast Advanced Vehicle Consortium (NAVC) of Boston initiated a program comparing the energy efficiency and emissions performance of hybrid electric buses powered by diesel with the performance of conventional buses powered by diesel or compressed natural gas (CNG). Funded by the US Defense Department’s Advanced Research Projects Agency, this study provides the most thorough independent comparison of the environmental performance of these technologies based on real-world demonstration conditions.

An independent team of engineers and scientists directed the evaluation, including personnel from the consulting firm of M.J. Bradley & Associates and the alternative-fuels testing center at West Virginia University (WVU). Project participants included the two operators of the tested vehicles, the Massachusetts Bay Transportation Authority and New York City Transit. A draft report of the project’s findings, “Hybrid-Electric Drive Heavy-Duty Vehicle Testing Project,” was published in February 2000.

Six bus models were tested:

- A hybrid electric Orion VI bus from Orion Bus Industries, equipped with Lockheed Martin power plants
- A hybrid electric RTS model bus from Novabus, equipped with an Allison hybrid drive system
- Three conventional CNG buses manufactured by Neoplan, New Flyer, and Orion
- One conventional diesel bus built by Novabus.

Each of the vehicles was equipped with some sort of exhaust after-treatment system: oxidation catalysts for the conventional diesel and natural gas buses and particulate traps for the hybrid electric buses.

The study included a significant amount of urban bus testing, primarily on the central business district emissions test cycle. The buses were also evaluated over six different emissions test cycles at average speeds of 3 to 17 miles per hour and at duty cycles from 4 to 18 stops per mile.

The WVU emissions laboratory measured nitrogen oxides (NO_x), carbon monoxide, carbon dioxide, organic compounds, and particulate matter (emissions testing for air toxics was not performed). In addition, fuel economy for each vehicle was calculated on a mile-per-gallon basis. Fuel economy for natural gas buses was converted into diesel gallons equivalent so direct comparisons could be made.

Four fuel variations were evaluated to determine how various levels of sulfur affected particulate emissions. These included conventional diesel fuel — known as D1 distillate auto diesel — which has a sulfur content of about 0.03 percent (i.e., 300 ppm), ultralow city diesel with a sulfur content of less than 20 ppm, synthetic diesel fuel (Mossgas) with a sulfur content of essentially zero, and natural gas.

Table 15 summarizes the emissions of the six buses tested on the central business district cycle. Particulate emissions from the natural gas buses, powered by Detroit Diesel Corp. Series 50G engines, were consistently around 80 to 90 percent lower than from the conventional diesel bus powered by the diesel version of the same Series 50 engine and running on conventional D1 fuel. Emissions from the hybrid bus burning conventional D1 diesel were six times higher than emissions from the CNG buses, although these were significantly lower than the emissions from the conventional diesel bus. The hybrid diesel buses using the low-sulfur and Mossgas fuels, however, showed low particulate emissions comparable to the natural gas buses.

Table 15. NAVC Emissions Comparisons for Diesel, Hybrid Electric-Diesel, and Natural Gas Buses (grams/mile)

Bus Type*	Fuel	Particulate Matter	Nitrogen Oxides
Orion VI electric-diesel hybrid	D1 diesel	0.12	19.5
Orion VI electric-diesel hybrid	Mossgas	0.02	18.5
Novabus electric-diesel hybrid	Low-sulfur diesel	Below detection	27.7
Novabus conventional diesel	D1 diesel	0.24	30.1
Novabus conventional diesel	Mossgas	0.09	32.2
Neoplan AN440	CNG	0.02	25.0
New Flyer 40LF	CNG	0.02	14.9
Orion V	CNG	0.02	10.8

*Conventional diesel and CNG buses were equipped with oxidation catalysts; hybrid electric-diesel buses were equipped with particulate traps.

Source: Northeast Advanced Vehicle Consortium

NO_x emissions from the Orion hybrid buses fueled with D1 diesel were 30 to 40 percent lower than those from the conventional diesel vehicle. NO_x emissions from the CNG buses were 50 to 60 percent lower, on average, than emissions from the conventional diesel bus. Overall, average NO_x emissions from the diesel hybrid buses were higher by roughly 20 to 30 percent compared to emissions from the natural gas buses.

The results of this program demonstrate that hybrid electric-diesel vehicles offer reduced drive-cycle emissions compared to conventional diesel buses. However, the low emissions of the hybrid electric-diesels were due in part to the use of low-sulfur fuels, which are not available commercially, and to the use of particulate traps, which were not installed on the CNG buses. The study did not address air toxics, an important but unregulated source of pollution. Diesel-burning vehicles are major contributors to emissions of air toxics, while vehicles powered by natural gas emit virtually none.

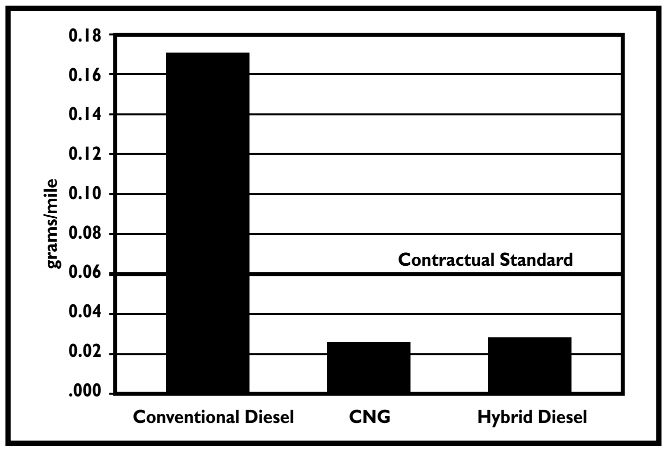
New York City Transit

New York City Transit (which is operated by the state-run Metropolitan Transportation Authority) has been the principal agency testing hybrid electric-diesel buses in New York. In addition to the data from these buses reported in the NAVC study, the results of individual bus emission analyses are from time to time released by New York City Transit. The agency reported the results of one such test in a presentation at the North American Electric Vehicle and Infrastructure conference held in Atlanta, Georgia, in November 1999.

The analysis compared emissions of particulate matter and NO_x from three buses in the New York City transit fleet: a conventional diesel bus, a conventional CNG bus, and an Orion VI hybrid diesel bus. The results appear in Figures 4 and 5. The line marked "contractual standard" indicates the emissions target for the buses the agency plans to buy in the future.

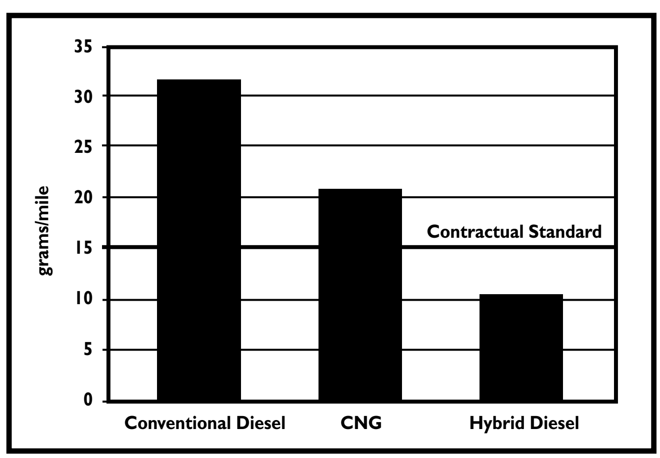
As shown in Figure 3, particulate emissions from both the conventional CNG bus and the hybrid diesel bus were more than 80 percent lower than those from the conventional diesel bus, with the CNG bus burning slightly cleaner than the hybrid diesel. Both vehicles were well below the agency's particulate emissions target. The conventional CNG and hybrid buses likewise achieved reductions in

Figure 3. Emissions of Particulate Matter from Diesel and Natural Gas Buses



Source: Metropolitan Transportation Authority

Figure 4. Emissions of Nitrogen Oxides from Diesel and Natural Gas Buses



Source: Metropolitan Transportation Authority

NO_x emissions, as shown in Figure 4. For this pollutant, however, the hybrid diesel bus was cleaner than the conventional natural gas bus. Emissions from the CNG bus were above the agency's target for NO_x emissions.

Union of Concerned Scientists

The Union of Concerned Scientists (UCS) examined the emissions of conventional and hybrid electric buses in its 1998 report, *Shifting Gears: Advanced Technologies and Cleaner Fuels for Transit Buses*. The UCS compared emissions from a typical several-year-old diesel-powered bus with those from a new conventional diesel bus equipped with improved pollution controls. It then presented emissions data for a typical new conventional CNG bus and a hybrid electric-diesel version of an Orion V bus.

Table 16. UCS Emissions Comparisons for Diesel, Hybrid Electric-Diesel, and Natural Gas Buses (grams/mile)

Bus Type	Particulate Matter	Nitrogen Oxides
Older conventional diesel	1.32	25.3
New conventional diesel	0.22	17.2
Orion V hybrid electric-diesel	0.37	13.8
New conventional CNG	0.12	10.3

Source: Union of Concerned Scientists

The results of the UCS analysis are shown in Table 16. New conventional diesel bus technology represents an improvement over older diesel buses for both particulate and NO_x emissions. Further reductions in NO_x were achieved by the hybrid diesel bus. On the other hand, particulate emissions increased by over 50 percent in the diesel hybrid bus. The conventional natural gas bus registered the least amount of pollution for both particulate matter and NO_x. Particulate emissions were 67 percent lower in the natural gas bus compared to the diesel hybrid. NO_x emissions dropped 25 percent in the natural gas bus.

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