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Breathing Clean

Considering the Switch to Natural Gas Buses

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Foreword

There is growing epidemiological evidence that emissions from conventional diesel vehicles are extremely harmful to public health. Against this backdrop, natural gas buses are attracting increasing attention in developing country cities with serious air pollution as policymakers explore alternatives to conventional diesel buses. A number of developing country governments have announced their intention to pursue the expansion of natural gas bus fleets aggressively, including Chile, China, the Arab Republic of Egypt, India and Indonesia.

This report outlines technical, economic and policy issues that affect the success of natural gas bus programs in developing countries. The worldwide experience with natural gas buses is limited, but there are a number of important lessons to be learned in those countries where policymakers have attached a high priority to the promotion of natural gas buses. We hope that these lessons will be studied and integrated into air quality management plans as governments in developing countries consider the option of switching from diesel to natural gas as a fuel for buses.

In many large cities of the world, the transport sector is a significant contributor to deteriorating ambient air quality. One of the most visible signs of urban air pollution is the black smoke coming out of the tailpipes of diesel buses.

One option for effectively eliminating black smoke is to use natural gas instead of diesel. As this report shows, evaluating the costs and benefits of switching from diesel to natural gas for use in buses raises a number of broader policy issues, ranging from inter-fuel taxation to restructuring of the transit bus industry. Merely mandating natural gas buses, as some local governments have done without taking these considerations into account, could endanger the success of the natural gas bus program, seriously tarnishing its image in the eyes of not only the stakeholders in the energy and transport sectors, but also of the public.

We hope that this report will help stimulate further work and systematic data collection, and ultimate assist policymakers to arrive at informed decisions about the viability of natural gas bus programs in their cities.

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Abstract

In response to emerging epidemiological evidence of the toxicity of diesel vehicular emissions, there is growing interest in substituting conventional diesel with much cleaner natural gas in cities where ambient concentrations of particulate matter are markedly higher than what is internationally considered acceptable. This paper compares the performance of natural gas and conventional diesel buses, and outlines the barriers to the adoption of natural gas buses in developing countries.

In the absence of emissions standards that effectively require natural gas, natural gas-fueled buses are unlikely to be adopted because they are more expensive to operate relative to diesel buses. This is partly because diesel is a very cheap fuel in most developing countries—it is lightly taxed or may even be subsidized. Even if diesel were sufficiently taxed, however, it is not obvious that natural gas buses would be cheaper over their life cycle than diesel buses: they cost more to purchase, are less fuel efficient, and are often less reliable.

The above implies that the social case for replacing diesel with natural gas as a fuel for buses rests on environmental grounds. If a local government decides that the reduction in air pollution associated with the substitution of conventional diesel with natural gas for use in buses is worth the cost, then it needs to adopt policies to encourage the switch to natural gas. These policies might include emissions standards for buses, or fuel and vehicle taxes that reflect marginal social costs. In order to do so, the contribution of exhaust emissions from buses to the ambient concentrations of harmful pollutants needs to be quantified so that associated health damage costs can be estimated—the benefits of reducing emissions from buses must be higher than incremental costs incurred. Further, successful implementation of fuel switching requires that a number of additional conditions be met: sufficient incentives for natural gas bus fleet operators, regulatory and administrative arrangements in place to ensure the financial sustainability of transit operators who would be using natural gas, large fleet operations converted to natural gas to exploit economies of scale, proper regulatory framework including enforced safety and performance standards, strong and long-term commitment and involvement of the fleet management, extensive training and education of mechanics and drivers, and regular preventive maintenance and prompt repairs.

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Abbreviations and Acronyms

CARB	California (Environmental Protection Agency) Air Resources Board
CBD	central business district
CCC	CNG Coordination Committee (in New Zealand)
¢/l	cents per liter
CNG	compressed natural gas
CPCB	Central Pollution Control Board (of India)
CRT	Continuously Regenerating Technology (for particulate traps)
EPA	Environmental Protection Agency (in the United States)
EPEFE	European Programme on Emissions, Fuels and Engine Technologies
EU	European Union
g/bhp-h	grams per brake horsepower per hour
g/km	grams per kilometer
g/kWh	grams per kilowatt-hour
ISO	International Organization for Standardization
kg	kilograms
km	kilometers
kWh	kilowatt-hours
LNG	liquefied natural gas
m^3	cubic meters
mg/m^3	milligrams per cubic meter
MJ	megajoules
MTA	Metropolitan Transit Authority
NG	natural gas
NGV	natural gas vehicles
NO_x	oxides of nitrogen
NPV	net present value
NY	New York
NZ$	New Zealand dollars
OBD	on-board diagnostics
OECD	Organisation for Economic Co-operation and Development
OEM	original equipment manufacturers
$PM_{0.1}$	particles smaller than 0.1 microns

$PM_{2.5}$	particles smaller than 2.5 microns
PM_{10}	particles smaller than 10 microns
rpm	revolutions per minute
SAE	Society of Automotive Engineers
SCAQMD	South Coast Air Quality Management District (of California)
SO_x	oxides of sulfur
US$	United States dollars
USAID	United States Agency for International Development
WHO	World Health Organization
wt ppm	parts per million by weight
$\mu g/m^3$	micrograms per cubic meter

Executive Summary

Epidemiological evidence is emerging that shows greater the toxicity of diesel vehicular emissions than previously believed. In response, there is growing interest in substituting diesel with natural gas in cities where ambient concentrations of particulate matter are much higher than what is internationally considered acceptable on health grounds. Are natural gas vehicles an important component of the solution? This report gives an overview of the issues that have to be considered when evaluating natural gas as an alternative to diesel for use in transit buses.

Transit buses constitute one of the cheapest forms of mass transit. Traditionally fueled by diesel, they are also significant emitters of fine particles, which are known to cause premature deaths and illnesses. Urban transit buses are high-usage vehicles that operate in heavily congested areas where air quality improvements and reductions in public exposure to harmful air contaminants are critical. As such, they are good candidates for achieving emission reductions, and substituting natural gas for diesel is one way of reducing emissions of fine particles and airborne toxins dramatically. Particulate and airborne toxin emissions from natural gas vehicles are very low but not nil; the principal source of particulate emissions is the combustion of lubricant. Many natural gas buses in industrial countries are equipped with an oxidation catalyst which reduces some of these emissions further.

Natural Gas Vehicles: Economic and Technical Context

Experience with natural gas buses is limited worldwide. One reason is the relative inter-fuel taxation policies adopted by most governments, which make the end-user price of diesel lower than that of gasoline, and often more competitive than natural gas. As a result, the majority of natural gas vehicles operating in the world today are converted from existing gasoline vehicles. Argentina, which has the largest natural gas vehicle fleet in the world, has in fact no natural gas buses in regular operation. In developing countries, diesel is seen as a social fuel and is taxed little or even subsidized, making it even more difficult to justify conversion to natural gas on commercial grounds without large financial incentives.

Environmental concerns drive the majority of natural gas bus programs today. Another important reason for turning to natural gas in transport is diversification of energy sources. This objective is more easily achieved by targeting gasoline vehicles because of inter-fuel pricing. The United States is a world leader in deploying natural gas-fueled transit buses in cities with serious air pollution. Some Asian countries, such as China, India and the Republic of Korea, are also aggressively pursuing natural gas bus programs. Much technical progress has been made in the heavy-duty natural gas vehicle sector since the early 1990s. Consistent reports show that natural gas buses manufactured in the early 1990s had not only a higher capital cost than their diesel equivalents, but also were about 30 to 40 percent more expensive to maintain and were less reliable (for example, as measured in terms of the mean time between in-service failures, down to half that of diesel vehicles). The latest model heavy-duty natural gas vehicles are much improved, although the engine technology still needs some refinements.

Buses fueled by natural gas may be dual-fuel, running on diesel and natural gas with the combustion of diesel used to ignite the natural gas, or dedicated, running entirely on natural gas. Because of the stop-and-start nature of urban buses, the substitution of diesel with natural gas is limited in dual-fuel buses, and dedicated single-fuel buses are recommended. Diesel engines, which are compression ignition based, are more difficult to convert to dedicated natural gas engines, which are spark ignition based, than gasoline engines. Thus, from the point of view of emissions reduction as well as overall performance, engines and vehicles provided by original equipment manufacturers (OEM) are generally accepted to be superior, even if more expensive, than converted vehicles, and the majority of natural gas buses in industrial countries are OEM vehicles. Natural gas buses are cleaner, quieter, and have less vibrations and odors than their conventional diesel equivalents. The fuel economy of natural gas buses is lower than that of diesel buses on an energy equivalent basis, by at least 10 to 15 percent and typically even more. They have a shorter driving range, often less than two-thirds of diesel, so that if refueling occurs only at depots, bus routes may have to be managed differently. On the whole the experience to date suggests that natural gas vehicles are less reliable than diesel vehicles, although vehicle manufacturers are addressing this. One of the important components of a successful natural gas vehicle program is extensive training of mechanics and drivers, and the availability of qualified engineers for technical support. Training is needed not only for proper maintenance and safe operation of vehicles, but also to dispel misperceptions and build the acceptance and commitment of the operators involved. In Sydney, Australia, for example, drivers had perceptions of lack of acceleration and poor drivability of natural gas vehicles compared to diesel. Comparison trials with diesel buses showed that the drivers were confusing lack of noise from natural gas buses with lack of acceleration.

Considerations for Policymakers

Before embarking on natural gas bus programs, it is important to confirm, even if only order-of-magnitude figures are available, that contributions from diesel vehicle emissions indeed constitute a sizable fraction of ambient particulate concentrations. Wrong assumptions about which sources are responsible for air pollution can lead to choices of measures that are not cost-effective or do not have a measurable impact on air quality. If the relative contribution of road traffic to pollution is actually small compared to other sources—such as refuse burning, emissions from cottage industries in the informal sector, combustion of biomass in households, and small diesel power generators operated by shop owners placed on streets with many pedestrians—then aggressively targeting vehicle exhaust for reduction will almost certainly fail to improve air quality markedly. While it is difficult to identify sources accurately, chemical analysis of particles and other analytical studies go a long way in providing a better understanding of source contributions.

In cities where the contribution of transport to the ambient concentrations of fine particulate matter is deemed to be significant, replacing diesel with natural gas in transit buses could contribute to a measurable improvement in air quality. In these cases, the following observations from worldwide experience with natural gas vehicles, and natural gas buses in particular, are worth considering.

Existence of natural gas pipeline. The volume of gas consumed in the transport sector is not sufficient to justify the construction of natural gas distribution pipelines even in large cities. Without the existence of a network of pipelines for other users of natural gas (industrial, commercial or domestic), a viable natural gas vehicle program would not be possible.

State of the transit bus industry. Transit bus companies in many, if not most, developing countries are cash-strapped. A large number of operators suffer from fare controls that have made it very difficult to provide high-quality service. The emergence of mini-buses in the informal sector—that is, buses in the hands of non-corporate operators, illegal as well as legal—has posed a serious threat to the survival of transit buses, especially in the former Soviet Union and Africa. Because traditional bus operators are often cash-strapped, they do not maintain vehicles, nor can they purchase more expensive natural gas buses, provide extensive staff training on this new technology, and accept the possibility of more repairs to deal with greater frequency of bus breakdowns, at least initially. High emissions from diesel buses are not merely due to the choice of fuel, but are often symptomatic of deeper problems in the transit bus industry in developing countries, and these same problems may condemn natural gas bus programs to failure. If transit operators are in too weak a financial position to switch to natural gas buses without some outside assistance, there should at the least be regulatory and administrative arrangements in place to ensure the operators' financial sustainability when they use natural gas.

Inter-fuel and vehicle taxation policy favorable to natural gas. Natural gas vehicles are more expensive than vehicles powered by liquid fuels: vehicles are more expensive to purchase, refueling stations may have to be established at a significant cost (bus fleet operators set up their own refueling stations in industrial countries), and many natural gas bus operators have found that maintenance costs are also higher. For a natural gas vehicle program to be financially sustainable in the long run, the incremental cost must be recovered in the form of fuel cost savings, possibly supplemented by a large vehicle tax difference in favor of natural gas vehicles. The viability of a natural gas vehicle program therefore rests critically on the fuel and vehicle taxation policy adopted by the government, the first of which determines the relative prices of fuels.

In industrial countries, tax is a large fraction of the final price of liquid fuels, so that it can be adjusted to favor one fuel over another. Because tax collection in general is more efficient, differentiated vehicle taxes—whereby diesel vehicles are taxed more than natural gas vehicles—present a possible option for favoring natural gas. In most developing countries, gasoline carries a high tax rate, but diesel much less. If diesel is taxed little or even subsidized, it may not be possible to have an end-user price difference between diesel and natural gas that is large enough to achieve a reasonable payback period without requiring other subsidies. Because tax collection in general is less efficient, differentiated vehicle taxes may be difficult to implement.

A number of factors need to be taken into account in designing fuel taxes, and they are described in some detail at the end of Chapter 2. Briefly,

- Diesel is an intermediate good, and under a narrow set of conditions, intermediate goods should not be taxed. These conditions, however, are not met, especially in developing countries.
- Goods that are close substitutes should carry comparable tax rates. Gasoline and diesel (for light-duty vehicles), natural gas and fuel oil (in industry and power generation), and natu-

ral gas used in transport on one hand and gasoline and automotive diesel on the other are all close substitutes, certainly in the long run.

- Fuel and vehicle taxes should reflect environmental health risks caused by vehicles. Because diesel emissions are more harmful than gasoline, let alone natural gas, emissions, diesel vehicle owners operating in densely populated areas with serious air pollution should be asked to pay more to reflect the price that society pays in the form of medical costs and productivity loss. However, fuel taxes that are typically set at the national level do not target negative environmental externalities in urban areas well.

Government subsidies. In most countries with successful natural gas bus programs, beginning with the United States, the government has provided significant subsidies. Subsidies were deemed necessary because the inter-fuel price differences were not sufficient to justify natural gas programs purely on economic grounds, particularly given that natural gas buses embody a relatively new technology with all the problems that accompany any new technology. However, unless government subsidies are consistently maintained, the threat of the suspension of government subsidies discourages the growth of the market. Providing heavy subsidies to "kick-start" the industry may also seriously distort the market, while the withdrawal of subsidies after a few years on account of "having given the industry a chance," could lead to the collapse of the market. This occurred in New Zealand, where the new Labor Government withdrew all government support in the mid-1980s. In developing countries, there are many competing and compelling claims on the government budget, including provision of access to clean water, adequate health care, and universal primary education. The relative merits of giving subsidies to the natural gas vehicle industry versus other social needs should be carefully considered.

Regulatory framework. One of the most important roles of the government is to establish a proper regulatory framework—in this case for the natural gas industry and the transport sector—to eliminate market distortions as much as possible, create a level playing field, ensure safe operations, and increase efficiency and quality of service through competition. Internationally acceptable standards for gas cylinders, refueling stations, gas dispensing units, conversion kits, natural gas vehicle and engine manufacture, garages and the quality of gas should be set. Equally important, an adequate monitoring and inspection system to enforce these standards has to be in place. The same applies to the transit bus industry. If poorly maintained diesel buses that are gross emitters are not forced to comply with emission standards, or worse, if there are no emission standards to comply with, then the operating costs of diesel buses are effectively lowered, making it difficult for cleaner but more expensive natural gas buses to compete with diesel buses.

Economies of scale. In order for the operation to be financially viable, a large number of buses should be made to run on natural gas, ideally a whole depot at a time. U.S. and French case studies seem to suggest that a fleet size of tens of buses is desirable, preferably all located at one depot. This in turn may make conversion to natural gas difficult in countries with a large number of small operators, each owning two or three buses.

Mandating natural gas / Emission standards. Emission standards can be made so stringent that only gaseous fuel-powered vehicles, but not conventional diesels, can meet them. For heavy-duty vehicles such as urban transit buses, this would be tantamount to mandating natural gas. In the United States, the California Air Resources Board (CARB) is developing very tight emission standards that conventional diesel cannot meet. In Delhi, India, the Supreme Court banned diesel buses effective 2001. Such steps should be taken only if certain conditions are met: overwhelming evidence that diesel vehicles contribute significantly to ambient concentrations of particulate matter (and oxides of nitrogen, NO_x, in cities where ozone is a serious problem and where NO_x reduction is believed to reduce ozone concentrations); and the incremental cost of switching to natural gas is greatly outweighed by the health benefits accruing from lower emissions of natural gas buses. As mentioned earlier, other important sources of fine particles, including the informal sector and households, may also contribute considerably to worsening air quality in developing country cities.

Technology developments in industrial countries. The greatest competitor to the natural gas vehicle industry in industrial countries today is perhaps the advent of the so-called clean diesel vehicle technology. Using ultra-low sulfur diesel, these vehicles are equipped with catalyzed particulate traps and other advanced controls. The future technology could include selective catalytic reduction or NO_x adsorber traps for NO_x control. There are also advances made and breakthroughs announced in refinery processing technology, potentially making the production of ultra-low sulfur diesel much cheaper in the coming years. If these technologies currently under development are successfully commercialized, the landscape for the clean diesel-natural gas debate may dramatically change. At the same time, the science of assessing the impact of fine particles on public health—more specifically the role of particle size and chemical composition—and of measuring particles from vehicles and in the atmosphere by number and size rather than by mass (as is currently done) is rapidly evolving. These developments will have a large impact on the future of the natural gas vehicle industry in industrial countries, and will also affect the availability of natural gas vehicles in developing countries in the foreseeable future.

A Social Choice

To date, natural gas buses have been at a private economic disadvantage compared with diesel buses unless supported by substantial favorable tax discrimination or subsidies. In the absence of emissions standards that effectively require gaseous fuels, natural gas buses are unlikely to be adopted because they are more expensive to operate relative to diesel buses. This is partly because diesel is a very cheap fuel in most developing countries—it is lightly taxed or may even be subsidized. Even if diesel were taxed much more, however, it is not obvious that natural buses would be cheaper over their life cycle than diesel buses: they cost more to purchase, are less fuel efficient, have a smaller range and are often less reliable. These observations suggest that the social case for replacing diesel by natural gas in buses rests on environmental grounds. In particular, the use of natural gas by heavy-duty vehicles normally fueled by diesel would not be suitable if the diversification of energy sources is the primary objective.

Until such a time as clean diesel becomes widely available on the international market, which is not expected for at least several more years, most developing country cities will have to continue to grapple with a choice between conventional, polluting diesel versus potentially much cleaner natural gas buses. If the government of a city decides that the reduction in air pollution associated with natural buses is worth the cost, then it needs to adopt policies that would encourage the switch to natural gas: either emissions standards for buses, or fuel or vehicle taxes that reflect marginal social costs. Once the decision to switch to natural gas has been made, it is important to check if the conditions for successful implementation of fuel switching are likely to be met: sufficient incentives for natural gas bus fleet operators, the regulatory and administrative arrangements in place to ensure the financial sustainability of transit operators who would be using natural gas, large fleet operations converted to natural gas to exploit economies of scale, proper regulatory framework including enforced safety and performance standards, strong and long-term commitment and involvement of the fleet management, extensive training and education of mechanics and drivers, and regular preventive maintenance and prompt repairs.

Chapter 1

Why Consider Natural Gas Vehicles?

Under the right set of circumstances, mass transit can offer greater sustainability and carrying capacity than private automobiles. Transit buses constitute one of the cheapest forms of mass transit. As such, buses are the backbone of the motorized transport system in most cities in developing countries. However, the sight of poorly maintained buses belching out black smoke is all too common, tarnishing the image of public transport and promoting the perception that buses are the motorized transport mode of last resort. One of the most dramatic responses to the environmental health impact of urban buses is the Indian Supreme Court's total ban, effective 2001, on diesel buses in Delhi. Even in the United States, the California Air Resources Board (CARB) has recently commented that current diesel buses usually emit more pollutants than if the bus riders drove alone in their cars (CARB 1999).

As the Delhi case illustrates, diesel emissions are under increasing attack based on emerging epidemiological evidence. CARB identified particulate emissions from diesel-fueled engines as toxic air contaminants in August 1998 and launched a diesel risk reduction program. The governments of industrial countries have responded to the evidence by tightening diesel emission standards considerably. For example, the diesel emission standards to be implemented in phases in the United States beginning in 2006, and in the European Union (EU) beginning in 2005 and further tightened in 2008, aim to reduce particulate emissions for new vehicles dramatically, by ten-fold compared to the current technology vehicles in the case of the United States. Annex A presents a more detailed discussion of emissions from diesel vehicles and their effects.

In many developing country cities, the toxicity of diesel particulate emissions is of even greater concern—diesel particulate emission levels are much higher than in industrial countries on account of less advanced vehicle technology, poorer vehicle maintenance and poorer fuel quality, while the ambient concentrations of respirable particulate matter (PM_{10}, particles smaller than 10 microns) already far exceed internationally acceptable health-based standards. A large number of studies have linked exposure to elevated levels of respirable particulate matter to premature deaths, hospital admissions and acute and chronic illnesses. There is increasing evidence that the particle size also matters, with health effects worsening as the particle size decreases. Because particles in vehicle exhaust are predominantly in the small, sub-micron range and numerous, and they occur near ground level where people live and work, they cause much greater human exposure in the immediate locality than do emissions from sources such as power plants for which stacks are situated at elevated levels and farther away from dense population centers. Equally disturbing, the threshold level below which health effects are not observable has not been identified, prompting governments in industrial countries to impose increasingly tighter standards—including the introduction of standards for $PM_{2.5}$, particles smaller than 2.5 microns—and the World Health Organization (WHO) to rescind its earlier health-based guideline values for particulate matter (on the grounds that no safe threshold level has been defined).

Particles emitted directly from a source are termed *primary;* particles that are formed within the atmosphere, mainly from the chemical oxidation of atmospheric gases, are termed *secondary.* Diesel is especially prone to high levels of small primary particulate emissions because diesel is heavier than gasoline and hence more difficult to burn. The contribution of traffic to small particle emissions can be illustrated by taking an example from the United Kingdom: a recent study (Airborne Particles Expert Group 1999) concluded that in 1996, road traffic sources were responsible for only 25 percent of PM_{10} but for 60 percent of $PM_{0.1}$ (particles smaller than 0.1 microns). Vehicle exhaust also includes two sources of secondary particles, oxides of sulfur (SO_x) and of nitrogen (NO_x). High levels of sulfur in diesel (for example, close to 1 percent as found in Jordan or Pakistan) would be expected to contribute to significant secondary particle formation. NO_x, the other pollutant of concern found in diesel exhaust, similarly contributes to secondary particles.

In contrast, the ambient concentrations of other pollutants that are elevated in industrial country cities, such as ozone, are typically lower in developing country cities. This is partly because of lesser use of gasoline vehicles, with notable exceptions such as Mexico City and Santiago de Chile that have serious ozone pollution. While there is a drive in industrial countries to limit NO_x emissions, an ozone precursor, to levels that can be achieved only by using emerging technologies that are not yet commercialized, setting stringent NO_x emission standards is not expected to become a priority in the majority of developing countries in the foreseeable future. Instead, the primary focus will remain reducing particulate emissions, and the contribution of NO_x to the ambient concentrations of particulate matter is relatively small.

Against this backdrop, natural gas (NG) has been proposed as a much cleaner alternative to conventional diesel. Consisting primarily of methane and other light hydrocarbons, natural gas does not contain hydrocarbons that form harmful emissions for the most part. In fact, the principal source of particulate emissions from natural gas vehicles (NGVs) is the combustion of lubricant. Many NGVs in commercial production already meet future particulate emission specifications to be imposed in North America and the EU during the latter half of this decade. Therefore, replacing heavy-duty diesel vehicles with natural gas equivalents is one option for reducing vehicular particulate emissions dramatically.

Urban transit buses are high usage vehicles that operate in heavily congested areas where air quality improvements and reductions in public exposure to harmful air contaminants are critical. As such, they are good candidates for achieving both near-term and long-term emission reductions. That many transit buses are centrally kept and fueled makes the introduction of new technologies and alternative fuels more efficient. In fact, natural gas vehicles are ideal for fleet operations, and the natural gas industry is concentrating on high fuel-use commercial vehicles such as transit buses, taxis, airport shuttles, refuse haulers and trucks in its market strategy.

This report gives an overview of the issues that have to be generally considered when evaluating natural gas as an alternative to diesel for use in transit buses. This chapter gives background information on NGVs and associated infrastructure. Chapter 2 gives a broad overview of the development of the NGV industry in select countries. Because the natural gas vehicle industry worldwide consists mostly of light-duty gasoline vehicles converted to run on natural gas, the discussion focuses primarily on this category of vehicles. Chapter 3 then turns to natural gas buses, highlighting advantages and disadvantages over diesel, and drawing lessons from international experience. Chapter 4 concludes with observations and a summary of issues to consider in evaluating the option of purchasing natural gas buses.

Natural Gas Vehicles: Some Basics

Natural gas consists of the lightest hydrocarbons, inert gases (such as carbon dioxide), and negligible sulfur. The octane number of natural gas can exceed the scale's maximum number of 120. To quantify the quality of the natural gas, methane number is used as one measure. It is an experimentally derived number correlating engine performance and fuel composition, dependent primarily on the content of methane and higher hydrocarbons. Pure methane as the most knock-resistant reference fuel is given a value of 100. Similar to the octane number for gasoline, a minimum methane number, which is a function of engine technology, is needed to prevent engine knocking. The minimum methane numbers for the current technology heavy-duty, advanced heavy-duty and light-duty vehicles are about 80, 73 and 65, respectively (CARB 2001).

Another parameter that characterizes the engine behavior is the Wobbe index. The Wobbe index, having the units of energy per unit volume, is a comparative measure of thermal energy flow through a given size orifice. If the Wobbe index remains constant, changes in gas composition will not lead to a change in air-to-fuel ratio and hence gases with the same Wobbe index are interchangeable.

In terms of energy content, 1 kilogram (kg) of NG is equivalent to about 1.3 liters of gasoline and 1.2 liters of diesel. On a volume basis, 1 normal cubic meter (m^3) of NG is equivalent to about 1.1 liters of gasoline and 1.0 liter of diesel. The relative energy efficiencies of engines have to be factored into these figures to arrive at vehicle fuel economy. In order to store sufficient natural gas on board a vehicle to achieve an adequate driving range, natural gas must be stored in high pressure tanks as compressed natural gas (CNG) or as cryogenic liquefied natural gas (LNG) in a highly insulated dewar. The volumetric energy content of the various fuels as stored, expressed in megajoules (MJ) per liter, is shown in Table 1. The advantage of liquid fuels is clear. In the United States, the fuel tank volume of CNG and LNG buses are about five times and twice that of diesel (Watt 2001).

Natural gas as a transport fuel has a number of advantages over diesel:

- Very low particulate emissions
- Low emissions of airborne toxins
- Negligible SO_x emissions
- More quiet operation, with less vibrations and less odors than the equivalent diesel engines.

All of these benefits make NGVs especially suitable in urban areas. In addition, life cycle analysis suggests greenhouse gas emission savings relative to gasoline, and possibly small savings relative to diesel.

The disadvantages of natural gas include the following:

- Greater difficulty in distribution and storage
- Shorter driving range
- Greater weight of the fuel tank (gas cylinder)

Table 1. Energy Content of Liquid and Gaseous Fuels

Fuel	*MJ/liter*	*Relative to gasoline*	*Relative to diesel*
Gasoline	32	1.0	0.9
Diesel	35	1.1	1.0
CNG[a]	10	0.3	0.3
LNG	19	0.6	0.5

a. CNG stored at 200 bar.
Source: Maxwell and Jones 1995.

- Longer refueling time, especially if using a slow fill refueling system
- Backfire in the inlet manifold (which occurs when hot gas from the cylinder escapes into the inlet manifold and ignites the mixture).

Natural gas can be distributed economically in a city only by pipeline. Further, the amount of natural gas used in transport is not sufficient to justify the construction of a pipeline network even in large cities, so that unless pipelines are already in place or are planned for other uses of natural gas (such as for industrial and domestic purposes), NGV programs are not viable. Ballpark figures help to illustrate this point. In the year 2000, CNG and LNG vehicles consumed 385 million m^3 of natural gas in total in the United States. In comparison, a 500-megawatt power plant operating 5,000 hours a year (57 percent utilization) at 50 percent efficiency consumes about 500 million m^3 of gas. That is to say, one 500-megawatt power plant consumes more natural gas than all NGVs in the United States put together.

Because the price of natural gas has to be very low for it to be competitive with liquid fuels (see below), a cheap source of natural gas is needed. A country with domestic production of natural gas is a much more likely candidate for a natural gas vehicle market than a gas-importing country. Storage of natural gas on board a vehicle is costly because it can be stored only as CNG at about 200 bar (200 times the atmospheric pressure) and ambient temperature, or as a liquid (LNG) at –162°C at 2 to 6 bar. LNG vehicles are much less common than CNG vehicles.

In order to store a reasonable amount of gas at 200 bar, large fuel tanks with thick walls are needed, resulting in extra weight added to the vehicle. The use of composite materials can reduce the tank weight considerably, but at a higher cost. One area of research is the storage of natural gas at relatively low pressures by means of adsorption of hydrocarbon molecules onto a structure with a large surface area, such as activated carbon. The extra weight of the gas cylinders currently used commercially increases the fuel consumption of NGVs, and potentially accelerates the tire and brake wear. The extra space taken by the fuel tank is a concern especially in smaller vehicles such as taxis (in which the trunk space is reduced), but much less so for larger vehicles such as transit buses, although the extra weight reduces the passenger carrying capacity.

During refueling, natural gas has to be compressed to a pressure in the neighborhood of 200 bar, typically requiring about 0.2-0.3 kilowatt hours (kWh) of energy per cubic meter of gas. Refueling is one of the least safe moments in the use of natural gas as a transport fuel. In a recent example from Delhi, a car converted to run on CNG exploded during refueling as the gas cylinder failed, injuring five people (Automotive Environment Analyst 2001). The cause was quickly identified to be the poor quality of the gas cylinder.

There are two types of NG refueling systems: *fast fill* and *slow fill*. A fast fill takes only a few minutes. A slow fill costs less to set up but takes half an hour or more to fill a tank. However, a slow fill can be carried out at night when vehicles are not being operated, and gets more gas into the tank than a fast fill. In a slow fill, a second short filling can be done easily to complete the first filling. In Poitiers, France, fast filling was found to result in 15 to 20 percent under-fill. Any under-filling reduces the driving range of the vehicle further. In the United States, typical costs for establishing a refueling station for 200 buses is of the order of US$0.35 million for diesel, US$0.95 million for LNG and US$2.7 million for CNG (Watt 2001).

Because natural gas is lighter than air, it will not lie along the ground if it leaks, and is thus safer in an accident. LNG, on the other hand, forms a liquid pool when spilt. Large accumulations of natural gas vapor can occur, resulting in fire or explosion if an ignition source is nearby. Parking CNG vehicles in an enclosed building can become a problem if any system leakage is present. LNG poses an even greater safety threat. Appropriate roof venting is necessary to ensure that natural gas exits the building. Garages for NGVs must be designed with good ventilation at the ceiling level.

The numbers of NGVs and refueling stations are shown in Table 2. Over 1.5 million vehicles run on natural gas worldwide, fueling at more than four thousand refueling stations. The largest NGV market is Argentina, followed by Italy, Pakistan and the United States. Close to half of total NGVs in the world are in Argentina. Most NGVs are light-duty vehicles converted from gasoline. The number of NGVs in India has increased substantially since information was supplied in August 2000, on account of the Supreme Court decision affecting Delhi. By mid-2001, there were close to 40,000 NGVs in Delhi alone (CPCB 2001). The United States has the largest number of refueling stations, with more than twelve hundred.

When launching a NGV program, one logistical problem is the balance between the number of NGVs and refueling stations. Any imbalance—either in the form of over-supply of refueling stations or a disproportionately greater number of vehicles relative to refueling capacity—would result in either very low returns for refueling station owners, tarnishing the image of the NGV industry in the eyes of investors, or long queues for vehicle drivers, tarnishing the industry's public image. Fleet operators with high usage vehicles may choose to set up their own refueling stations. This is typically the case with transit bus operators in industrial countries that establish filling stations at bus depots. In this case, economies of scale become an important consideration, since there is a minimum number of vehicles that such a filling station should serve to be economic. For NG bus fleet operators, there are also economies of scale in staff training, fuel purchase, vehicle maintenance and service (such as having a service contract for the entire fleet).

There are three types of NGVs:

(1) Bi-fuel, where the vehicle can run either on natural gas or gasoline
(2) Dual-fuel, where the vehicle runs either on diesel only or diesel and natural gas, with the combustion of diesel used to ignite the natural gas
(3) Dedicated, which runs entirely on natural gas.

All three types can be manufactured from the start to use natural gas by original equipment manufacturers (OEM), or converted from vehicles originally manufactured to run on gasoline or diesel only. Either way, there is an incremental cost relative to vehicles using conventional liquid fuels. From the point of view of minimizing emissions, OEM vehicles (that is, vehicles that are manufactured as NGVs at the factory level) are considered more suitable than converted ones, but their higher prices may make it difficult to deploy them on a large scale in developing countries. In 1998, 43 OEMs around the world produced NGVs, and 11 heavy-duty engine manufacturers produced NG engines. Conversion of vehicles in poor condition, as well as poor conversions, are two of the most serious potential problems in developing country cities, and could even defeat the purpose of switching to NG. Impco Technologies, a major supplier of fuel and electronic control systems for natural gas to OEMs, estimates that 50 to 70 percent of vehicles being converted in developing countries will fail a good pre-conversion inspection (Impco Technologies 2000).

Because CNG vehicles are more expensive to purchase than vehicles powered by liquid fuels, for the NGV program to be financially sustainable in the long run, the incremental cost must be recovered in the form of lower operating and maintenance costs. The lower cost in turn typically has to come from a much lower price of fuel per distance traveled. The viability of a NGV program therefore rests critically on inter-fuel pricing, and more specifically, the fuel taxation policy adopted by the government,

Table 2. International Natural Gas Vehicle Statistics

Country	*Vehicles*	*Refueling stations*	*Information as of*
Argentina	668,480	923	May 01
Italy	370,000	355	Mar 01
Pakistan	200,000	200	Jun 01
United States	102,430	1,250	Jan 01
Brazil	80,000	131	Mar 01
China	36,000	70	Jan 00
Venezuela, Republica Bolivariana de	33,586	150	Jun 01
Russian Federation	30,000	202	Sep 00
Egypt, Arab Republic of	24,115	45	Jan 01
Canada	20,505	222	Aug 00
New Zealand	12,000	100	Aug 00
Germany	10,000	146	Jan 01
Colombia	10,000	28	May 01
India	10,000	11	Aug 00
Japan	8,053	138	Jul 01
Bolivia	6,000	17	May 01
France	4,550	105	Oct 00
Trinidad and Tobago	4,000	12	May 01
Malaysia	3,700	18	Oct 00
Indonesia	3,000	12	Aug 00
Australia	2,000	12	Nov 00
Chile	2,000	7	May 01
Sweden	1,500	25	Mar 00
Bangladesh	1,000	5	Aug 00
Great Britain	835	18	Aug 00
Iran, Islamic Republic of	800	2	Aug 00
Netherlands	574	27	Aug 00
Spain	300	6	Aug 00
Belgium	300	5	Aug 00
Mexico	300	2	May 01
Switzerland	270	14	Aug 00
Korea, Republic of	245	3	Jul 01
Turkey	189	3	Aug 00
Thailand	184	1	Mar 01
Austria	83	5	Aug 00
Ireland	81	2	Sep 00
Cuba	45	1	Feb 01
Finland	34	5	Aug 00
Czech Republic	30	11	Aug 00
Nigeria	28	2	Aug 00
Luxembourg	25	5	Aug 00
Poland	20	4	Aug 00
Norway	18	3	Aug 00
Taiwan (China)	6	1	Nov 00
Denmark	5	1	Aug 00
Korea, Democratic People's Republic of	4	1	Aug 00
Total	1,645,705	4,317	

Source: International Association for Natural Gas Vehicles, http://www.iangv.org/html/ngv/stats.html#1 which determines the relative prices of fuels. In Argentina, for example, the retail price of CNG has been historically about one-third of the price of premium gasoline. As a result, car owners who switched from gasoline to natural gas realized 65 percent savings in fuel cost relative to premium gasoline from the beginning of the natural gas vehicle program in 1985, rising to 70 percent savings in 1999. In industrial countries, tax is a large fraction of the final price of liquid fuels, so it can be adjusted to favor one fuel over another. In 1999, tax on gasoline constituted 67 percent, and that on diesel 59 percent, of consumer prices in the countries of the Organisation for Economic Co-operation and Development (OECD) (Bacon 2001). This is also the case in most developing countries with respect to gasoline, but much less so with diesel. As a result, the retail price of diesel has historically been one-half that of gasoline or even lower in countries such as Argentina, India, Indonesia and Sri Lanka.

Natural gas has a much higher auto-ignition temperature than gasoline and diesel, making it safer but also unsuitable for compression ignition, which is used in diesel-fueled vehicles. Most NG vehicles are conversions of existing liquid fuel vehicles. In the case of gasoline (spark ignition) engines, the conversions are generally bi-fuel. The conversion from diesel (compression ignition) to NG is not straightforward. The two main options are dedicated, involving conversion to spark-ignition, and dual-fuel, entailing co-existence of two fuel injection systems and adding to the complexity of the engine.

Reasons for Switching Fuel to Natural Gas

There are two principal reasons for switching to natural gas. One is the significantly lower exhaust emissions, especially of particulate matter. This is the primary reason for the government's promotion of natural gas buses in the United States, as well as the Supreme Court decision in Delhi, India. If exhaust emission reduction is the primary reason, then dual fuel transit buses do not achieve the objective all that well, because the stop-and-start nature of the urban bus driving cycle means that the substitution of diesel by natural gas is limited.

The second reason is diversification of energy sources. This has in fact been the historical reason for switching to natural gas. Worldwide natural gas reserves are more abundant than oil reserves, giving greater potential to the use of natural gas. In 2000, the ratio of proven reserves to production of natural gas was estimated to be 62 years, and that of oil 38 years (bp 2001). A country that imports oil, but has an abundant supply of natural gas, may find it particularly attractive to consider natural gas as a transport fuel in order to reduce its oil import bills. Bangladesh and Indonesia (where crude oil production will cease in less than a decade at the current rate but abundant supplies of natural gas remain) cite this as the reason for wanting to promote NGVs. There are also other ways of using natural gas in transport, such as conversion of natural gas to synthetic fuels (including super-clean diesel, designated by the U.S. government as an alternative fuel in 2000) or to methanol or dimethyl ether. In New Zealand where the government aggressively promoted a NGV program after the oil price shock of the early 1980s, the country's own natural gas resources were used not only directly as a transport fuel but also as a feedstock for making synthetic fuels in the 1980s. The production of synthetic fuels from natural gas—which is not yet economic at the current world price of crude oil and available technologies for converting natural gas to liquid fuels—has been commercially carried out and continues in South Africa and Malaysia today.

There are cases of oil-importing countries with indigenous natural gas reserves where switching to natural gas is not necessarily financially favorable. Pakistan illustrates this point. In Pakistan, as in the rest of South Asia, diesel has historically been priced at one-half that of gasoline. As a result, it is not uncommon to see light-duty gasoline vehicles converted to diesel. Partly as a result of this pricing policy, the consumption of gasoline is less than a fifth of that of diesel. While Pakistan imports the bulk of its diesel, it has recently become a net exporter of naphtha (which is used in gasoline production). Because of Pakistan's inter-fuel pricing, natural gas has displaced only gasoline and not diesel—it is much more attractive for vehicle owners to switch from gasoline to natural gas than from diesel to natural gas—worsening the supply-demand imbalance and forcing the refineries (which are financially supported by the government to some extent) to export even more naphtha at a loss.

Chapter 2

International Experience with Natural Gas Vehicles: Cases of Argentina and New Zealand

The worldwide population of natural gas vehicles grew at an annual rate of about 5 percent between 1994 and 2000. During this period, the number of NGVs grew from 250,000 to 620,000 in Argentina, the largest NGV market, corresponding to an annual growth rate of 16 percent. The growth in Italy, which had the same number of vehicles as Argentina in 1994, was slower, increasing from 250,000 to 320,000. In other countries, the NGV population declined, including New Zealand—once one of the largest NGV markets in the world—and the newly independent states of the former Soviet Union. This chapter reviews the factors affecting the growth or decline of NGV markets through two case studies, Argentina (Francchia 2000) and New Zealand (Harris 2000). While the NGV market in both of these countries has focused exclusively on converting existing gasoline vehicles to run on natural gas, general lessons can be learned to understand the natural gas bus industry.

Argentina

Background

Argentina is endowed with both oil and natural gas. At the end of 2000, the ratio of proven reserves to production was 10 years for oil and 20 years for natural gas (bp 2001). The Liquid Fuels Substitution Program was launched in 1984 to free up more oil for exports (oil is easier to export than natural gas) and to increase fuel taxes on liquid fuels without provoking widespread public protests by offering low price CNG as an automotive fuel. By then, an extensive network of natural gas pipelines reached most cities.

To start the program, two refueling stations were established and a few government vehicles and taxis were converted from gasoline to natural gas. Because of the domestic economic situation, no subsidies could be offered to "get the program off the ground." The incentive for switching to CNG was the very large price difference between gasoline and CNG, ensuring 65 percent savings in fuel cost by switching from premium gasoline to CNG.

Safety, quality and other standards were developed and enforced by the regulatory authorities for gas cylinders, conversion kits, conversion workshops, compressors, dispensers, installation procedures and so on. Internationally well-known certification agencies carried out the certification.

In the late 1980s, the government began to increase the retail price of diesel, aiming in the long run to substitute diesel with natural gas. The primary objective of the Liquid Fuels Substitution Program was in fact the substitution of diesel by natural gas in public transport vehicles. The fiscal policy changes needed to achieve this substitution, however, were not implemented. The retail prices from recent years are shown in Table 3. Diesel has historically been and continues to

Table 3. Representative Fuel Prices

	Premium gasoline (US$/liter)		Diesel (US$/liter)		Natural gas (US$/m³)	
Date	*Total*	*Tax component*	*Total*	*Tax component*	*Total*	*Tax component*
May 1994	0.751	0.369	0.269	0.033	0.256	0.095
December 1998	0.906	0.588	0.403	0.180	0.311	0.106
December 1999	1.044	0.608	0.499	0.211	0.331	0.082

Source: Francchia 2000.

be comparable to CNG in price. After taking engine efficiency into account, the price of diesel was lower than that of CNG in May 1994, comparable to that of CNG in December 1998, and rose above that of CNG only in December 1999, so that diesel has actively competed with CNG in the light-duty vehicle market to replace gasoline. Half of new taxis in Argentina are diesel-powered.

The evolution of the market shares of different fuels in the 1990s is given in Table 4. The market share of gasoline steadily declined, that of CNG increased until 1997, and that of diesel fluctuated until 1997 after which it saw a marked increase at the expense primarily of gasoline, but also of CNG.

Between 1985 and 1999, direct investment in the NGV market totaled US$1.5 billion. The converted vehicles operate as bi-fuel vehicles. In the early years of the NGV program, it took less than two years to pay back the vehicle conversion. The number of months it takes to pay back the conversion cost of US$1,200 as a function of annual kilometers (km) traveled for the premium gasoline and CNG prices effective December 1999 is shown in Figure 1. Today, the NGV industry generates US$0.65 billion worth of business per year. About 1.5 billion m^3 of natural gas is sold annually as a transport fuel, approximately equal to the amount of gas consumed in three 500-megawatt power plants. The number of vehicles converted has stabilized at about 5,000 a month.

In contrast to gasoline vehicles, the economics for converting diesel vehicles to NG are much less favorable even for intensively driven vehicles. Take, for example, a bus driving 120,000 km a year. Assuming a vehicle purchase price difference of US$22,000 and fuel prices as of December 1999, it takes 59 months to recover the incremental vehicle cost based on fuel cost savings, or close to five years. The fuel prices as of December 1998 would have increased the payback period to 29 years, considerably beyond the useful life of the vehicle.

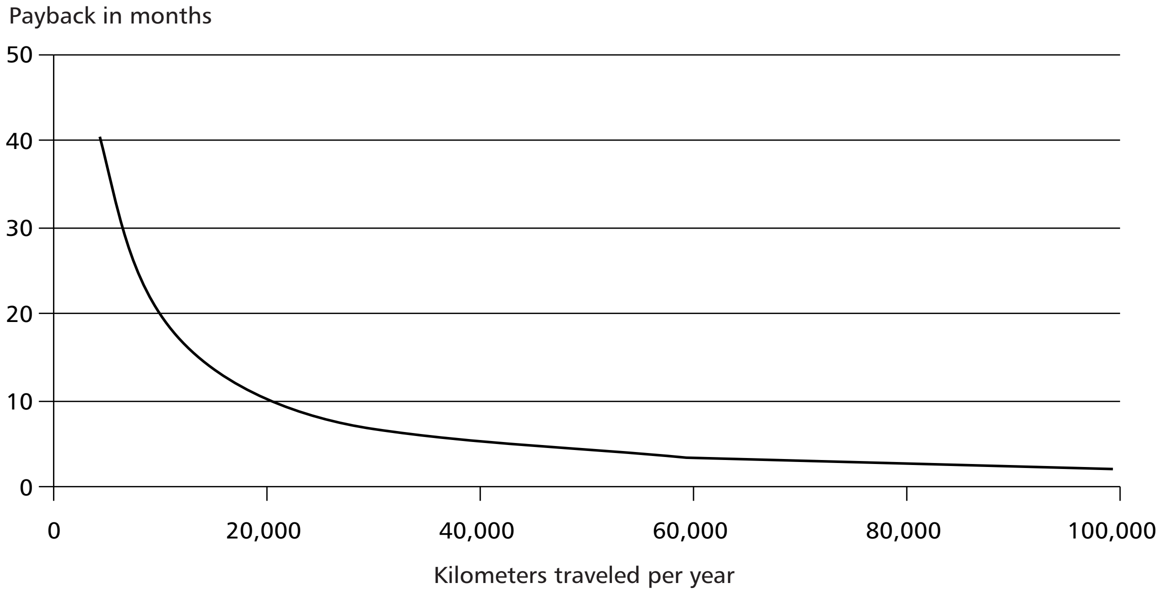
One of the difficulties in launching a NGV program is balancing the numbers of NGVs and refueling stations. Inadequate refueling infrastructure was partly responsible for conversion back to gasoline from CNG in Bangladesh in the 1990s, and long queues at CNG refueling stations in Delhi are a significant source of dissatisfaction among vehicle drivers today. In Argentina, the NGV market has been developed exclusively by the private sector, with many players entering the NGV market—refueling; manufacture of compressors, dispensers and gas cylinders; and manufacture and installation of conversion kits. In setting up the refueling infrastructure, those who had not been previously involved in the fuel retail business opened CNG refueling stations, as did oil companies. The payback period for an independent operator of a refueling station was approximately three years

Table 4. Percent Market Share of Liquid and Gaseous Fuels

Year	*Gasoline*	*Diesel*	*CNG*
1990	42	56	2
1993	40	55	5
1995	37	57	6
1997	35	58	7
1999	29	65	6

Source: Francchia 2000.

Figure 1. Payback for Conversion from Fuel Cost Savings in Months



Source: Francchia 2000 and author's calculations.

in the 1990s. By establishing dual fuel stations (selling both liquid fuels and CNG), oil companies went around the regulation prohibiting refueling stations to be set up within 2 km of each other.

Lessons from Argentina

The NGV program in Argentina is the most successful in the world, measured in terms of NGV population. This program has focused almost exclusively on converting existing gasoline vehicles to CNG, taking advantage of the large price difference between the two fuels. The large price difference in turn is provided by the fuel tax structure. Aside from this indirect support, the government has given no subsidies in the form of financial incentives to the CNG industry, making the CNG program viable in the long run. The CNG industry in Argentina today is exporting ISO 9000 certified compression and dispensing equipment, gas cylinders and conversion kits to other countries in Latin America and Asia. At the same time, the program has made no dent in the automotive diesel market, which is beginning to threaten the CNG market. Heavy-duty public transport vehicles remain entirely diesel fueled. A review of inter-fuel taxation policy as well as vehicle tax policy would be needed if the growth of the automotive diesel market is to be halted in the coming years.

New Zealand

Background

New Zealand was a world leader in CNG vehicles in the middle of the 1980s. The sale of natural gas as CNG peaked in 1985 at close to 150 million m^3 a year. Between 1979 and 1985, the number of NGVs doubled every year. By 1986, CNG represented one-tenth of the fuel used by spark ignition engine vehicles (that is, gasoline engine vehicles) in the North Island—the only island where natural gas is available.

The oil crisis of the 1970s affected New Zealand, which was importing nearly all of its transport fuels, prompting the government to seek alternative forms of energy. A major offshore gas field had been discovered in 1969. While the field was developed for power generation, it became apparent by the late 1970s that demand for power was well below the forecasted levels, requiring much less gas than originally envisaged even though the government had already signed a take-or-pay agreement. The government therefore evaluated CNG as an alternative use of natural gas, and concluded that substitution of gasoline by CNG would help address two economic problems: balance of payments and unemployment. Urban air pollution was not a consideration in the government's decision to launch a NGV program at the time.

The government sponsored extensive investigations into the impact of adopting CNG as a transport fuel starting in 1974. Based on the findings and recommendations, the government in 1979 set a target of 150,000 CNG vehicles by 1985, subsequently revised to 200,000 by 1990. Additional recommendations for the use of natural gas included the construction of a synthetic gasoline plant and a chemical methanol plant, both using natural gas as the feedstock. At the time, there were about 100 gas utility vehicles using CNG and only two refueling stations in New Zealand. Few people had technical expertise. The Ministry of Energy was formed in 1978, and it was not in a strong administrative position to coordinate the implementation of the CNG program in 1979. In response, the government established the CNG Coordination Committee (CCC) to coordinate efforts within the government and the private sector. The Ministry of Energy became the lead agency in 1981, by which time both the CNG program and the ministry were well established.

The government also began to offer financial incentives for vehicle conversion and refueling stations in the form of NZ$200 grants for conversion kits, 25 percent grants for mechanical equipment in refueling stations and loans for refueling stations. The government mounted programs for the implementation of the NGV program: providing training, establishing standards for vehicle conversion and refueling stations, and mounting public awareness campaigns. A major boost to the CNG industry was the decision of the government to require its own fleet to convert to CNG. Within a year, refueling stations became grossly overloaded, and half-hour queues were common. A list of steps taken by the government is summarized in Table 5.

By the middle of 1980, it became clear that a price differential of 50 percent between gasoline and CNG was not sufficient to achieve the conversion target set by the government. At the same time, various technical problems arose, in some cases giving rise to extremely adverse publicity. The rate of conversion fluctuated erratically. A rapid market survey conducted at the end of 1980 convinced the government that further incentives were needed. The package of incentives, announced at the end of 1980, included accelerated depreciation for vehicle

Table 5. Steps Taken by the Government of New Zealand

Year	*Action*
1978	Funding of research and development for evaluating CNG.
1979	Formulation and acceptance of the implementation plan. Setting of targets and incentives. Establishment of CNG Coordination Committee.
1979-1985	Establishment of regulations and standards, and infrastructure for inspection. Various promotional and marketing activities. Conversion of government vehicle fleet to CNG.
1979 onwards	Training programs for installers.
1980	Market survey. Modification of incentives.
1980 onwards	Funding of engine and related research.
1981	Market survey.
1982	Modification of incentives.
1983	100 percent government loans for vehicle conversions.
1984	Market survey. Modification of incentives. Election of new Labor Government.
1985	Target and incentives abandoned by the new Labor Government.

Source: Harris 2000.

conversions (then costing about NZ$1,000 per vehicle) and changed rules for the 25 percent refueling station grant. There was an immediate response, with the rate of conversion nearly doubling between the latter half of 1980 and the first half of 1981. Additional surveys were conducted in 1981 and 1984 to determine the appropriate level of financial incentives needed.

The above incentive schemes were followed in 1982 by the introduction of industry-funded CNG vouchers entitling voucher holders to NZ$300 of free CNG, and in 1983 a 100 percent government loan for vehicle conversions took the place of the accelerated depreciation program described above. Between July 1984 and October 1985, the price of CNG was about 40 to 50 percent that of gasoline on an energy equivalent basis. During that period, the rate of conversion rose sharply, fell, and rose sharply again, challenging the ability of the industry to undertake high quality conversions. By 1985, over 100,000 CNG conversion kits had been sold, nearly all converting gasoline to CNG. Few diesel vehicles were converted. The gross income of the CNG industry in 1984 was approximately NZ$84 million (US$49 million) and net foreign exchange savings amounted to NZ$30 million (US$17 million). Between 1979 and 1985, the net cost to the government of the various incentive schemes and loans was in excess of NZ$20 million (or about NZ$200 per vehicle), in addition to administrative costs such as research and development, promotion and servicing of committees.

A number of implementation issues arose and were handled with varying degree of success.

Technical. A wide range of technical issues related to vehicle conversion and refueling stations were investigated and handled. Some were known from the beginning and required investigation followed by a decision, such as setting the maximum cylinder filling pressure. Others arose as experience with CNG vehicles progressed, and some were unforeseen (for example, the maximum cylinder filling pressure set in 1979 proved to be too low and was later raised). Much of the original technology was imported, especially from Italy and the United States. The constraints faced by New Zealand included the fact that there was (and is) no vehicle manufacturing capacity but only vehicle assembly, nor does New Zealand possess an industry to manufacture major items of CNG equipment.

Institutional. The CNG program was at first greeted with skepticism, if not outright opposition. Against this setting, the chair and executive officer of the CCC effectively became the product champions. The CCC had an influence on almost all the major government decisions related to CNG except the financial incentives. The role of the CCC was initially to lead and cajole various agencies, and after greater acceptance of CNG and cooperation, to promote and market the product. The CCC had no formal legal or administrative status. It relied on persuasion at the beginning. In time, the Ministry of Energy and the industry gave weight to the suggestions made by the CCC.

Setting standards for vehicle conversion and refueling stations became a key activity within the Standards Association of New Zealand. Acceptance of gas cylinders manufactured in Italy by the Dangerous Goods Inspector of the Department of Labor required extensive translation and interpretation of the Italian cylinder design rules. Establishing training courses for mechanics needed action by the Motor Industry Training Board and the Department of Education. The New Zealand Energy Research and Development Committee, a government agency, provided key inputs from the outset. It funded the original technology assessment in 1978 and prepared the implementation plan in 1979. It funded several research projects, especially those directed at how CNG vehicle engines in New Zealand performed.

A small number of government personnel involved with CNG in the beginning stayed with implementation and provided continuity, greatly assisting with progress of the program. Their principal interest was to ensure that New Zealand had a viable alternative to gasoline as a transport fuel. In addition, a small number of people from private sector firms had a similar determination to make CNG a success because of the potential profits the CNG business could bring to their firms. The success of the CNG program can be said to be due in large part to the efforts of these key government and private sector people.

Economic. It goes without saying that, given enough incentives, vehicle owners will switch to CNG. The government of New Zealand introduced a number of financial incentives that persuaded vehicle owners and businesses to convert vehicles and construct refueling stations. The price difference between gasoline and CNG was adequate to give a payback period of 18 months on the investment for vehicle owners spending in excess of NZ$35 per week on gasoline at the time. The industry-funded CNG voucher scheme provided an additional incentive. The capital cost of conversion was covered by a 100 percent government loan. Government grants and loans helped establish refueling stations.

The market survey conducted jointly by the government and the private sector found that the quality of vehicle conversions had not been good, pointing to a need for quality assurance and warranty for vehicle owners. In fact, CNG was seen as a second-rate fuel used only because it cost less than gasoline. Vehicle owners considering conversion weighed the problems and disadvantages of CNG vehicles against the much lower fuel price. Refueling was not seen as a major problem because 450 refueling stations had been established by 1984.

The new Labor Government elected in 1984 adopted an economic policy of deregulation and liberalization, withdrawing the incentives offered for conversion and refueling stations. From 1985, conversions rapidly declined to almost zero and the consumption of CNG fell gradually as existing CNG vehicles ended their normal useful life, as did the number of refueling stations. A little over 10,000 CNG vehicles remained in the national fleet in the year 2000, a significant decline from the peak of 110,000.

Lessons from New Zealand

The CNG program in New Zealand developed against the backdrop of very high international oil prices following the Iranian revolution and an indigenous supply of natural gas with demand not matching the amount that the government had agreed to "take or pay." In response, the government of New Zealand took the lead in promoting the CNG vehicle program aggressively. It sponsored research, prepared the implementation plan, and coordinated the entire program. Most important, it provided generous financial incentives, so that the number of CNG vehicles doubled every year, seriously stretching the ability of the industry to cope. The industry was so preoccupied with meeting the demand for conversion that quality at times became a secondary priority, resulting in a poor perception of CNG vehicles in some quarters.

When the new Labor Government began to deregulate the economy, withdrawing support for the CNG industry in the form of financial incentives, the market essentially died. A CNG program that relies heavily on government subsidies, as in New Zealand, is not likely to be sustainable in the long run. Inter-fuel pricing in New Zealand today suggests that the world oil price must rise above US$30 per barrel before CNG becomes commercially viable without government support. The New Zealand experience suggests that the price of CNG should be no more than half of the retail price of gasoline it is substituting. Further, if the CNG price is 30 percent of the gasoline price, no direct support is necessary, but at 50 percent some government support in the form of financial incentives is believed to be needed.

Other International Experiences

Before the 1990s, many countries turned to natural gas as a means of achieving greater energy self-sufficiency, security of supply or lower fuel import bills. Environmental advantages of NGVs, especially relative to diesel, began to play a prominent role in the 1990s. When gasoline vehicles were converted to natural gas, an unpleasant surprise in industrial countries was that emission tests showed that converted vehicles were more polluting than recent model-year gasoline counterparts. What emerged is that newer vehicles equipped with electronic emissions control packages were less amenable to a successful aftermarket conversion. In fact, the most advanced commercially available gasoline engine vehicles today are extremely clean and NGVs have no obvious emissions advantage over them. However, NGVs do produce lower greenhouse gas emissions over the vehicle's life cycle, which is an increasingly important consideration given the rising contribution of the transport sector to overall greenhouse gas emissions in most countries. In contrast, with older vehicles, or in markets where manufacturers are not required to provide sophisticated electronic and emissions controls, or where leaded gasoline is still extensively used, the conversion to natural gas can provide immediate emissions improvement. One clear-cut example is the conversion of gasoline vehicles running on leaded gasoline to CNG in Pakistan: CNG contains no lead, so switching from leaded gasoline to CNG eliminates lead emissions. As for diesel, particulate emissions from NGVs are much lower than those of conventional diesel, often by a factor of ten or more. Only the so-called clean diesel with sophisticated after-exhaust treatment technology and ultra-low sulfur diesel can begin to match the emission levels of their natural gas equivalents.

In Chile, where tests for converting to CNG have been carried out with taxi fleets, the conversions failed because of a poor choice of aftermarket gasoline-to-CNG conversions; the option of a fully factory-built CNG car would have been more satisfactory. It is very important, when retrofitting existing vehicles, to carry out conversion properly, ensuring customer satisfaction as well as achieving the expected emissions reductions.

The greatest barrier to the expansion of the NGV market has been the high cost of refueling stations, vehicle conversion, and OEM vehicles. In North America and the EU, successful conversions have been difficult and costly because OEM vehicles are generally recognized to be necessary to ensure minimal emissions. As a result, NGVs have been confined mostly to high-usage vehicles.

Role of Government

The cases of Argentina and New Zealand highlight a number of issues related to the role of a government in launching and sustaining a NGV program, and that of government support in particular. The government can assist in a number of ways.

Potential Government Assistance

- *Establishing a proper regulatory framework* is one of the principal roles of the government. The government should ensure that there is a level playing field, players are encouraged to increase efficiency and quality of service and products through competition, and monitoring and enforcement of regulations and standards are adequate.
- *Establishing safety and performance standards* is another important government function. Both Argentina and New Zealand moved quickly to address this aspect, although the maintenance of performance standards was less than satisfactory in the latter.

- *Adopting an inter-fuel taxation policy favorable to automotive natural gas* is necessary if the NGV program is to be viable and sustainable on a commercial basis. In Argentina, gasoline is so heavily taxed that CNG is commercially competitive. In neither country has diesel been taxed to the extent necessary to promote conversion from diesel to CNG. In New Zealand, one of the key incentives for conversion came from government subsidies, so that when the subsidies were withdrawn, inter-fuel price differences alone could not sustain the CNG program. A further question is the extent to which the retail prices should differ. For a given payback period, high-usage vehicles need a smaller price difference than lower-mileage vehicles. If all vehicles including private passenger cars are targeted for conversion, the price difference required would be much greater than if only high-usage commercial vehicles such as taxis and delivery vans are targeted.
- *Providing subsidies* was the policy aggressively pursued by the government of New Zealand. In the early days of a NGV program, the infant industry argument may justify subsidies. For example, to break the logjam in which car owners wait for adequate refueling infrastructure before investing in a fuel switch, while business enterprises wait for a sufficient number of converted vehicles before investing in refueling stations, the government may consider subsidizing startup costs. However, as the case of New Zealand demonstrates, large subsidies are unlikely to be sustainable in the long run, threatening the survival of the NGV program. In the words of Robert Cumming who spoke on behalf of the International Association for Natural Gas Vehicles in Mexico City in 1997, "Governments that believe that all they need is a two- to three-year kickstart are wasting their time and money" (Cumming 1997). It would be preferable to provide modest but consistent support over a long period of time than large subsidies that are reduced significantly or withdrawn altogether after a few years. Heavy subsidies may also lead to serious market distortions, such as over-supply of refueling stations.
- *Providing non-monetary incentives* is another option. Examples include reduced frequency of required emissions inspection tests or the right to drive a CNG vehicle in high-occupancy vehicle lanes or on days when other vehicles are not permitted (as in cities that ban vehicle usage on certain days to reduce air pollution). Such incentives alone would not induce vehicle owners to switch to natural gas, but coupled with other incentives (most importantly fuel cost savings), they could play a useful role.
- *Mandating conversion to natural gas* is not a step that should be taken lightly, especially if financial and logistical (fueling and driving range) burdens are anticipated to be great on vehicle owners. The Supreme Court decision imposed in Delhi for buses is one example. The New Zealand government's decision to convert government fleets to CNG in one sense falls under this category. An indirect way of mandating conversion is to set emission standards that can be met only by NGVs. In the United States, the South Coast Air Quality Management District (SCAQMD) in California has recently banned diesel buses in favor of NG and other alternative fuel engines.
- *Acting as a champion* is a consideration for the government, especially in the early days of the NGV program. The government can publicize the benefits of NGVs, perhaps using prominent senior officials to reinforce the message. It is equally important for the private sector to assume this role.

Designing Fuel Tax

The issue of inter-fuel taxation is a complex one and is beyond the scope of this report. However, a few general principles from tax theory may be outlined here. To devise an optimal tax scheme, which would enable the government to raise sufficient revenues while minimizing the loss of consumers' welfare from the higher prices they would have to pay because of the taxes, the following rule is often taken as the starting point: if a certain set of conditions are met[1], then no intermediate goods should be taxed, and the tax rates on final consumption goods should be inversely proportional to their own price elasticities of demand. Thus, if consumers are likely to cut back consumption markedly in response to a price increase (as in the case of certain luxury goods), that item should not be taxed much, but if consumers are likely to continue to consume only slightly less on account of the price increase (as in the case of such staple food items as rice or maize), then the item should be taxed relatively more. Under these conditions, because diesel used in freight and passenger transport, industry, and agriculture is an intermediate good, diesel for these purposes should not be taxed.

However, the above conditions are not satisfied:

- Vehicles in cities cause congestion, diesel emissions are harmful to public health, and all vehicles, but heavy-duty vehicles consuming diesel in particular, damage roads, so that there is an external cost associated with the use of diesel (for productivity loss due to congestion, additional healthcare costs and expenditures for road maintenance)
- Diesel and gasoline are substitutes for light-duty vehicles in the long run so that taxing diesel little and gasoline much more would result in an automotive fuel switch out of gasoline to diesel
- In many developing countries not all final goods can be taxed, so that taxes on petroleum products, which are relatively easy to collect, become an important source of government finance, especially in low income countries
- A number of markets in developing countries have distortions that impede perfect or even near-perfect competition.

All these trends argue for taxing diesel even when it is an intermediate good. That gasoline and diesel are substitutes in the light-duty vehicle category is a particularly strong argument for making their tax levels comparable, or else the fuel that is taxed less (almost universally diesel) will be consumed more, eroding the tax base and requiring higher tax rates elsewhere to collect the same amount of money.

Yet another consideration in designing tax is equity—items that the poor consume disproportionately more than the rich as a share of their total expenditures (such as food) should be taxed less than the above "inverse elasticity" rule would imply so as to lessen the tax burden on the poor. Conversely, for goods consumed more by the rich than the poor, such as gasoline, the tax rate should be higher. Where the impact of an increase in the price of diesel on household expenditures has been studied, the effects have been found to be regressive—that is to say, the total expenditures of poor households rise more in percentage terms than those of the rich when the price of diesel is raised—although the magnitude of the impact is not large, remaining of the order of a couple of percentage points. This would argue somewhat for not raising the tax on diesel as much as the above factors might suggest. This is one reason why some governments view diesel as a "social" fuel, limiting tax on diesel compared to gasoline, which is seen as a fuel for the rich, since only better-off families can afford to purchase motorized vehicles. Nevertheless, the equity argument alone would not justify keeping the end-user price of diesel at half that of gasoline as seen in a number of countries.

Natural gas used in the transport sector is no different than liquid fuels from the point of view of tax theory with one exception: the environmental externality is lower relative to old technology gasoline vehicles, and considerably lower with respect to conventional diesel. To set the tax level capturing externalities would require a knowledge of contributions of vehicles with different fuels to the overall air and noise pollution, and health and other damages associated with each fuel. This level of information is seldom, if ever, available in most developing country cities.

It is important to note that the incremental tax adjustment to deal with the externality should be applied to that good only—there is no reason to tax complements more heavily or substitutes less heavily independent of their own polluting characteristics. In the case of fuel taxes, this means that government should tax diesel more, and not lower the rate of tax on natural gas. Further, additional considerations include other externalities associated with NGVs—congestion and damage to roads (which would increase because NGVs are heavier)—as well as the fact that natural gas and liquid fuels are close substitutes. Subsidized natural gas is made available in a number of countries. A prime example is natural gas sold to the fertilizer industry. It is important to have market-based natural gas pricing rather than government-determined below-market pricing for the long term viability of the NGV program. Subsidizing natural gas (that is to say, selling it below cost) to promote its use in the transport sector, a position promoted by some, ignores these widely accepted principles of optimal tax theory.

Another important point is that fuel taxation is a poor proxy for an efficient externality charge, because air pollution or congestion is a highly localized phenomenon, while fuel tax is usually set at a national level. From the point of view of taxing environmental health damages, emissions in densely populated areas need to be taxed, which a tax on diesel does not capture well. The option of heavily taxing urban buses fueled by conventional diesel, which may be more targeted, invites other problems: buses are often the transport mode used by the poor, while a heavy tax on diesel buses would result in higher bus fares; and such a vehicle tax scheme may also eliminate transit buses altogether in favor of numerous mini-buses, which may be more difficult to regulate and control for emissions. These issues point to the complexity of setting fuel and vehicle taxes in such a way to minimize distortions and maximize welfare.

Another reason cited for consideration in setting inter-fuel taxation is balance of payments for countries that have indigenous sources of natural gas and that import crude or refined products. However, if the exchange rate is fully determined by market forces so that it reflects opportunity costs, there is no reason to differentiate taxes to save imports. A related issue is diversification of energy sources so as to minimize the impact of possible future price hikes. This may justify differentiated taxation to a degree, although not so much as to give incentives to switch entirely from liquid fuels to NG.

Given that diesel is taxed little or even subsidized in many developing countries, conversion from diesel to natural gas would become economic only if diesel itself or diesel vehicles are taxed much more. While there may be a number of good reasons why the retail price of diesel relative to gasoline should be raised in the long run, there would nevertheless be a significant impact on other uses of diesel—in rail transport, agriculture, and industry, for example. One way of addressing this is to give rebates on the diesel tax to industrial and agricultural users of diesel. In any event, promotion of NGVs is unlikely to play a dominant role in determining diesel taxation. In practice, a combination of a number of instruments are likely to be needed to achieve multiple objectives, including taxing items that cause negative externalities; more uniform taxes across different fuels that are substitutes; tax rebates to industrial users of fuels; higher taxes on diesel vehicles, particularly those used primarily in intracity transport; and targeted subsidies for the poor to compensate for higher expenditures resulting from increased taxes, to mention a few.

Because gasoline is already taxed much more in most developing countries, if CNG has any chance of success on a commercial basis, it is as a gasoline substitute. A large price difference between gasoline and CNG is currently achieved by taxing CNG much less. Several issues need to be considered in this case:

- If gasoline is effectively the sole source of tax revenue from refined products (because all other fuels are taxed little or subsidized), the government may not welcome a successful CNG program whereby consumers shift from relatively heavily taxed gasoline to essentially untaxed CNG. This would be particularly a concern in low-income countries where tax revenue from hydrocarbons accounts for a significant fraction of the government's total tax take.
- If the CNG program is so successful that a sizable portion of the gasoline market is replaced by CNG while the automotive diesel market is untouched, the resulting product slate (with a very low gasoline-to-diesel ratio) will be difficult to manage for countries with refineries.
- If taxing CNG little does not provide sufficient financial incentives for conversion, the government might consider increasing the tax on gasoline further (which in turn could further reduce the gasoline-to-diesel ratio for demand), or reducing the tax on CNG, or both. If the tax difference between CNG and gasoline is to be widened at all, it would probably make sense to target high-usage vehicles only. Leakage—diversion of CNG to users not targeted by the government—is unlikely to be a serious concern for two reasons. First, unlike liquid fuels, natural gas is much more difficult to transport, so that diversion to non-automotive users from refueling stations would not be simple. Second, since the tax scheme would target the price difference between CNG and gasoline to be at the level that would make conversion to CNG financially attractive only for high-usage vehicle owners, lower mileage vehicle owners would not benefit from converting to CNG to take advantage of the price difference.

Note

1. The conditions are that the economy is perfectly competitive, so that tax changes will be passed on fully to consumers; there are no externalities associated with the consumed goods (such as air pollution or congestion); all consumers are identical; all final consumption goods can be taxed; and the items taxed at different rates are not substitutable (such as butter and margarine).

Chapter 3

Comparison of Natural Gas and Diesel Buses

The conventional diesel engine is very energy efficient and reliable. One of the goals of heavy-duty NGVs is to have diesel-like efficiency and reliability. There are consistent reports that the performance of the generation of NG buses from the early 1990s was less than satisfactory. The latest model heavy-duty NGVs are much improved, but the engine technology still needs some refinements.

Comparison of heavy-duty NG and diesel vehicles is made difficult by the fact that both are evolving technologies. In the area of energy efficiency and reliability, conventional diesel vehicles have reached a mature stage and the majority of the current development efforts focus on reducing exhaust emissions. NGVs start with an inherently lower emissions base, and development efforts have focused just as much on improving its fuel economy and reliability.

In comparing NG and conventional fuel vehicles, it is important to clarify what is being compared. Comparing the state-of-the-art NGVs with conventional diesels, or vice versa, could favor one over the other. While comparison of the latest NG and diesel technologies may be of primary interest in North America, EU and other industrial regions of the world, this comparison may not be relevant to policy discussions in developing countries. Unfortunately, nearly all published data are from industrial countries, making it difficult to draw conclusions for developing countries. Another important consideration for developing countries is the emissions and performance characteristics of vehicles as they age, especially in countries that have poor cultural acceptance of regular maintenance. This information is not widely available for NGVs, as many published studies have measured emissions from relatively new vehicles.

Performance

There are two types of engines, compression ignition and spark ignition. All diesel engine vehicles have compression ignition, while gasoline and dedicated NGVs have spark ignition. Compression ignition engines rely on self-ignition upon injection into hot, high pressure compressed air, and enjoy a number of advantages over spark ignition engines, which ignite a homogeneous and compressed pre-mixed mixture of fuel and air with a spark. These advantages include lower fuel consumption, longer life and safer operation. Compression ignition engines run “lean,” or at a high air-to-fuel ratio, so that combustion occurs in the presence of excess air. In contrast, spark ignition engines typically run “stoichiometric,” meaning that the air-to-fuel ratio is adjusted so that the amount of oxygen in the air is exactly that needed to combust all hydrocarbons in gasoline. Vehicles with three-way catalytic converters must use a stoichiometric mixture. The compression ratios of diesel engines at 15-to-1 to 20-to-1 are much higher than those of gasoline engines at 8-to-1 to 10-to-1. Compression ignition engines do not have throttle, thereby reducing pumping losses. The lean-burn characteristics, the lack of a throttle and a high engine compression ratio help to increase the efficiency of a diesel engine, leading to superior fuel economy. Because dedicated NGVs have to use spark ignition, all these advantages of diesel engines have to be sacrificed to some extent, although the high octane number of natural gas compensates for some of the engine compression ratio loss in going from compression to spark ignition in the case of OEM vehicles. Dual-fuel NGVs use a compression ignition.

Compression ignition engine components are typically more robust than corresponding spark ignition engine components, increasing engine life before overhaul or replacement significantly. The lean burn characteristics of diesel engines provide cooler exhaust temperatures, helping to decrease engine wear. Because compression ignition engines do not have ignition systems, there are no spark plugs or other ignition system components to clean and replace. However, the high pressure fuel injection system does require maintenance.

There are two options for the air-to-fuel mixture ratio of heavy-duty NG vehicles: lean or stoichiometric. Cummins—the world's largest designer and manufacturer of diesel engines which also offers the most widely fitted proprietary CNG engines in Europe—is committed to lean burn NG engine technology for fuel economy reasons. Others, such as Fiat-Iveco, have been developing stoichiometric NG units. In industrial countries, heavy-duty NGVs operate either with stoichiometric mixtures and three-way catalysts, or with lean mixtures and oxidation catalysts. Stoichiometric units enable reducing emissions to extremely low levels and give better drivability. The benefits of operating in the lean-burn mode include greater engine durability, higher fuel economy and higher power output if turbocharging is used. Lean-burn operation, however, has higher NO_x and methane emissions, is more sensitive to gas composition variations, and can also lead to faster erosion of the spark-plug electrodes, needing replacement as frequently as 300 hours (Nylund and Lawson 2000) as opposed to a durability of 48,000 km required in the United States for gasoline engines.

The maximum efficiency of a NG engine is some 10-15 percent lower than that of a good diesel engine. In practice, the difference may be even greater. The energy consumption of a heavy-duty vehicle is estimated to increase, in most applications, by 20-35 percent after conversion from diesel to natural gas. (Nylund and Lawson 2000). Old conversion technologies decrease fuel economy by as much as 25-40 percent. The fall in fuel economy arises from lower compression ratios and throttling losses of NGV engines, and the additional weight of gas cylinders for fuel storage. The thermal efficiency is 39 percent for a typical lean burn NG engine. As a comparison, new truck and bus diesel engines in the EU achieve thermal efficiencies of around 46 percent.

The driving range of NG buses is smaller than that of diesel buses. There is a trade-off between cylinder weight and the desired range: the lower the cylinder weight for a given material of construction, the higher the fuel economy, but also the lower the range. The driving range of CNG buses is often less than two-thirds of diesel buses. In the United States, driving ranges are of the order of 400 km for CNG and over 650 km for diesel buses. This has presented problems to some bus operators who have had to arrange mid-day fueling (Montgomery County Transit, Maryland) and take other steps to ensure that buses do not run out of fuel. (Greater Cleveland Regional Transit Authority in Ohio reports that NG buses have suffered out-of-fuel problems.) Similarly, TransAdelaide in Adelaide, South Australia, found that the range of NG buses was 11 hours against their daily shifts of 15 hours, requiring the organization of mid-shift refueling.

Diesel buses could complete the shift without refueling. In contrast, buses for the Bangkok Mass Transit Organization in Thailand travel about 220 km a day on two routes, so that the driving range is not a critical issue.

Emissions

The most visible and familiar emission from diesel engines is the smoke trail produced when the vehicle operates under load. Consisting of solid particles and liquid droplets, smoke from diesel engines can be blue-white or gray-black in color. Blue smoke is typically caused by the combustion of lubricant found in the combustion chamber due to poor piston ring sealing or valve guide wear. NGVs are also a source of particulate emissions, although at a much lower level. White smoke is generated when the combustion temperature during fuel injection is too low, which happens typically during transient operation when starting, especially during cold weather or at high altitudes. White smoke can also be produced when the injection timing is overly retarded or when the compression ratio is too low. Gray-black smoke, consisting of carbon particles, is generated when the engine is operating at or near full load and too much fuel is injected or when the air intake is partially obstructed (for example, if the air filter is dirty). Gray-black smoke results from poor maintenance of air filters and fuel injectors, or from improper adjustment of the fuel injection pump. Excessive smoke from diesel engines usually suggests a loss in thermal efficiency, power output and fuel economy (Maxwell and Jones 1995).

Dedicated NGVs can enjoy a considerable exhaust emissions advantage over conventional diesel engine vehicles. In particular, visible smoke is virtually eliminated. A comparison of emission test results of comparable diesel and dedicated CNG buses is shown in Table 6. The reductions in emissions in going from conventional diesel to dedicated OEM CNG buses are

Table 6. Emissions Benefits of Replacing Diesel with CNG Vehicles

Fuel	*CO*	*NO_x*	*PM*
Diesel	2.4 g/km	21 g/km	0.38 g/km
CNG	0.4 g/km	8.9 g/km	0.012 g/km
% reduction	84	58	97

Note: Diesel engines certified to the 1997 U.S. federal emission standards. The numbers are averages of three vehicles in each fuel category. All were equipped with oxidation catalysts except one CNG bus.
Source: Frailey and others 2000.

dramatic. The emission characteristics of dual-fuel vehicles depend in part on the extent to which diesel is substituted by natural gas over the engine operation range. As mentioned in Chapter 1, the stop-and-start nature of urban transit buses limits the amount of natural gas substituting diesel, significantly reducing the environmental advantage of switching to natural gas.

It is important to bear in mind that emission levels are a function of a number of parameters—engine, after-exhaust treatment technology, the "reference" fuel quality (the quality of the fuel to be used in the tests) and driving cycles. Engines that have been optimized to give low emissions at steady-state do not necessarily have low emissions in transient (meaning continually varying speed) driving cycles, which are more representative of real life service. This has led the EU to require a new transient test cycle starting with the Euro III emissions regulations. Unlike light-duty vehicles where the entire vehicle is driven on a chassis dynamometer for emission certification, heavy-duty vehicles are tested by running engines in engine dynamometers. Transient engine testing is very expensive to carry out, and for this reason the EU and Japan have been using only steady-state testing for emissions certification of heavy-duty vehicles. In the United States, a transient cycle has been used for heavy-duty engines since 1985.

The importance of driving cycles was highlighted in a recent court case in the United States concerning charges of "cycle beating." A number of diesel vehicle manufacturers were accused of carefully optimizing the emissions control exactly under the conditions that matched the specified test driving cycle. Outside of the test conditions, the vehicle would be configured to maximize fuel economy rather than emissions control in real-life driving, resulting in much higher emissions. All the engine makers were fined heavily for contravening the spirit, if not the letter, of U.S. emissions legislation.

Governments in North America and the EU are in the process of introducing much tighter emission standards for vehicles, including heavy-duty diesel vehicles, to be fully enforced by the end of this decade. The so-called Tier 2 emission standards for heavy-duty vehicles, which will be phased in beginning with the 2007 model year (that is, in the autumn of 2006) in the United States, will lower particulate and NO_x emission levels by 90 and 95 percent, respectively. The EU is introducing progressively tighter standards in 2005 and 2008. The evolution of standards for new heavy-duty diesel vehicles is shown in Table 7. The limits are shown both in grams per kilowatt-hour (g/kWh) and grams per brake horsepower per hour (g/bhp-h) for the U.S. standards, the latter being the original numbers. Tier 2 emission standards in particular are sufficiently stringent that it is not immediately obvious that NGVs will have significant emissions advantages over the so-called "clean" diesel.

The clean diesel technology, however, requires not only advanced and sophisticated vehicle technology and emissions controls, but also dramatic reductions in diesel sulfur. The need for what is known as ultra-low-sulfur or sulfur-free diesel arises from the deactivating impact of sulfur on state-of-the-art exhaust control technologies. Compliance with Tier 2 in North America requires a sulfur reduction to 15 parts per million by weight (wt ppm). The EU is requiring a reduction to 50 wt ppm by 2005, and is seriously considering a 2011 deadline for limiting maximum sulfur in diesel to 10 wt ppm sulfur in all diesel. Finland, Sweden and Germany are already granting tax incentives to introduce diesel with 10 wt ppm. In all developing countries, the level of sulfur in diesel is much higher than that in ultra-low sulfur diesel. Only a handful of countries, such as Mexico and Thailand, have a sulfur limit of 500 wt ppm, still a level too high to meet Tier 2 or Euro IV and V emission standards. Several developing countries have a diesel sulfur limit as high as 10,000 wt ppm (or 1 percent by weight). Deploying clean diesel vehicles would require not only manufacturing or importing the best available technology vehicles, but also either importing ultra-low sulfur diesel or investing heavily in refinery modifications to reduce sulfur in diesel drastically. Massive refinery investment to lower diesel sulfur is unlikely to be a high priority in the near future, especially in countries that have a policy of maintaining a low retail price of diesel.

NGVs may be equipped with an oxidation catalyst to oxidize (that is, burn completely) residual carbon monoxide and hydrocarbons, such as lubricant but also methane. Methane is thermodynamically the most difficult hydrocarbon

Table 7. Heavy-Duty Diesel Emission Standards
(in g/kWh, with g/bhp-h in parentheses)

Pollutant	*USA* 1990	*USA* 1998	*USA Tier 2* 2007+	*Euro I* 1993	*Euro III* 2000[a]	*Euro IV* 2005[a]	*Euro V* 2008[a]
Particulate matter	0.80 (0.6)	0.13 (0.10)	0.013 (0.01)	0.36	0.16	0.03	0.03
NO_x	8.0 (6.0)	5.4 (4.0)	0.27 (0.20)	8.0	5.0	3.5	2.0
Hydrocarbons	1.7 (1.3)	1.7 (1.3)	0.19 (0.14)[b]	1.1	0.78[b]	0.55[2]	0.55[b]

a. European transient cycle.
b. Non-methane hydrocarbons.
Source: http://www.dieselnet.com/standards.html.

to oxidize and requires a specialized catalyst, but catalyst deactivation has been a problem. Sulfur based odorant (tetrahydrothiophene) at 10-15 milligrams per cubic meter (mg/m^3) can have a detrimental effect on oxidation catalyst conversion efficiency. Because methane is inert, its release is essentially harmless from the point of view of local air pollution, but methane is a powerful greenhouse gas. While U.S. emissions regulations distinguish between methane and non-methane hydrocarbons, those for light-duty vehicles in the EU do not, posing an additional challenge to the manufacturers of NGVs.

As mentioned earlier, particulate emissions from NGVs originate primarily from the lubricant; excessive oil consumption could lead to non-negligible particulate emissions from NGVs. An oxidation catalyst can lower particulate emissions some. Although not yet a concern in most developing country cities, it is worth noting that a NG engine that is not optimized can have much higher NO_x emissions than a conventional diesel engine. The reported NO_x emission of current heavy-duty NG engines varies from 0.5 to 3.5 g/kWh. Multi-point fuel injection and closed-loop control systems are instrumental in assuring low emissions in transient driving. Conversion of Mercedes buses to NG in Brazil is reported to have resulted in higher emissions of a number of pollutants.

By 2004, on-board diagnostic (OBD) monitors will have to be active on all fuels in the United States. OBD systems, which monitor emission control components for any malfunction or deterioration that cause an excess in emission limits, alert the driver of the need for repair via a dashboard light when the diagnostic system has detected a problem. In 2005, European OBD compliance will be required on alternative fuels. This could be a major impediment to the growth of alternative fuel vehicles. OBD calibration is very expensive, and each engine type has to be calibrated. If the number of vehicles sold is small, the cost of calibration cannot be economically amortized. Certification and OBD II (generation two) issues have severely curtailed aftermarket alternative fuel conversions in North America.

Stringent Euro IV and V and Tier 2 emission standards that may require particulate traps and a (not yet commercially available) "lean deNO_x" catalyst system for reducing NO_x may possibly work in favor of CNG vehicles. Depending on future technological developments, these factors may make natural gas competitive in North America and the EU.

Recently, emissions data were obtained on CNG buses (1996, 1998 and 1999 model year) equipped with oxidation catalysts and diesel buses (1999 model year) fueled by ultra-low sulfur diesel containing 30 wt ppm sulfur and equipped with Johnson Matthey's Continuously Regenerating Technology (CRT™) filter system for reducing particulate emissions. The results from the central business district (CBD) and New York (NY) bus cycles are shown in Table 8. CNG buses had an advantage over diesel for NO_x but not for particulate emissions. The much higher hydrocarbon emissions of CNG buses are due primarily to greater methane release. CNG buses were also found to have higher carbonyl emissions. The data in Table 8 should be interpreted with caution, however, since the measurements were taken at three different test sites.

It would be useful to reinforce the observation about gasoline vehicle emissions. Absent catalytic converters, switching from gasoline to a gaseous fuel often meant reduced exhaust emissions. Today, advanced technology gasoline vehicles with three-way catalysts are so clean

Table 8. Comparison of CNG and "Clean Diesel" Buses *(g/km)*

	CBD cycle		*NY bus cycle*	
Pollutant	*CNG*	*Diesel*	*CNG*	*Diesel*
Particulate matter	0.011	0.015	0.044	0.023
NO_x	15	16	32	45
Total hydrocarbons	10	0.01	42	0.038

Source: 2001, Interim report: Emissions Results from Clean Diesel Demonstration Program with CRT™ Particulate Filter at New York City Transit, http://www.epa.gov/OMS/retrofit/documents/ny_crt_presentation.pdf.

that the fuel itself (that is, whether liquid or gas) plays a minor role, especially for the regulated emissions. Under these circumstances, converting an advanced gasoline vehicle to gaseous fuel could even increase rather than decrease emissions.

Fuel Quality

The quality of the fuel affects emissions and vehicle performance. In the case of diesel, the need to lower sulfur for clean diesel technology has been noted. Natural gas quality may vary with the proportion of light hydrocarbons in the gas (especially methane), water, oil and dust. The quality of natural gas in the United States is typically consistently high, with a methane content of 95 or even 98 percent not unusual. Even so, Sun Metro, the public transportation authority of El Paso, Texas, selected LNG for its natural gas-fueled mass transit fleet because the natural gas quality could not be guaranteed at 98 percent methane. In Europe, natural gas quality is more erratic, in particular the methane content of U.K. supplies. This is said to be adding to the difficulties of meeting future emissions standards in the EU.

If a mechanical fuel metering system without any kind of feedback control is used, the engine has to be tuned for a specific gas. To compensate for even small changes in gas composition, a closed-loop fuel metering system with an exhaust gas oxygen sensor is needed.

The NG bus program in Bangkok, Thailand, encountered problems initially on account of the methane content varying from 60 to 85 percent. More specifically, the buses manufactured by MAN with Lambda 1 technology experienced operational problems. Today, blending is used to reduce the amount of gas quality variation. As a result, the variation of the methane content has been narrowed to between 72 and 83 percent.

International Experience

The international experience with NG bus operation is limited compared to other types of vehicles. The world leader is the United States, where 80 transit authorities operated some 3,500 NG transit buses in over half of the 50 states as of January 2000 (Watt 2001). Over a quarter of the transit authorities had 50 or more NG buses. In Delhi, India, some 1,600 NG buses were in operation by mid-2001 (CPCB 2001). Another leader is China, with over 1,300 NG transit buses in Beijing alone. Other countries with over 200 NG transit buses in operation include Australia (492 buses), Canada (367), France (350), Sweden (320), Japan (259) and Germany (220 in 1996). The Republic of Korea has an ambitious plan to put 5,000 NG transit buses in circulation in eight cities for the 2002 World Soccer Cup. Interestingly, two world leaders in the NGV market, Argentina and Italy, have few NG transit buses: Italy has about 170, and Argentina has none operating regularly.

Among other developing countries, the United States Agency for International Development (USAID) has provided funds to purchase a number of NG transit buses to combat air pollution in Cairo, Egypt. Fifty-seven new dedicated NG buses operated in Egypt in early 2001. The government of Indonesia announced recently that all new buses and taxis will need to be powered by CNG. The regulations will be introduced first in Jakarta and surrounding cities. Most of Jakarta's 10 million inhabitants rely on buses for transport. No timetable has been proposed for the implementation of the regulations. The government of Thailand wants to replace 10 percent of total oil use in the transport sector with natural gas in the next five years through a program estimated to cost 959 million baht (US$23 million). The extent to which NG buses will be promoted is not yet clear.

A detailed description of the international experience with NG transit buses can be found in Watt (2001). Several countries where substantive data are available are discussed briefly below.

United States

The United States has the most extensive experience with urban natural gas buses. As of January 2000, an estimated 44,300 transit buses operated in the United States, of which 3,535 were reported to be fueled by natural gas, CNG as well as LNG. NG buses accounted for 18 percent of new bus orders and 28 percent of potential orders. The principal driving force for switching to NG in the United States is low emissions, and hence NG buses are deployed in cities with serious air pollution. All full-size transit bus manufacturers in the United States offer NG buses. There are 1,200 CNG and close to 70 LNG refueling stations throughout the country, with over 70 stations serving transit bus fleets.

The federal government heavily subsidizes the purchase of transit buses, and transit bus fleets do not have to rely entirely on local funding. For example, the Federal Transit Administration subsidizes up to 83 percent of the cost of a new NG transit bus. Air quality funds offset most of the differential capital and some of the infrastructure costs. The federal government supports NGVs by imposing lower highway tax on CNG and LNG: highway taxes are 6.3 U.S. cents per liter (¢/l) for diesel, 4.7 ¢/l for gasoline, 3.0 ¢/l for LNG and 1.5 ¢/l of gasoline equivalent for CNG. The federal government also gives grants of up to US$50,000 per heavy-duty vehicle and up to US$100,000 per refueling station, and allows tax deductions for NG vehicle owners. Some 32 state governments support NGVs through tax credits, grants and other incentive schemes. In one of the most successful CNG/LNG transit bus programs, run by Sun Metro in Texas, the payback period for the cost of switching from diesel to NG (including fueling infrastructure) before government grants is said to be 4.5 years, reduced to 0.9 years after receiving grants.[1]

The capital cost of NG transit buses is 10 to 25 percent higher than their diesel equivalents, which cost upwards of US$200,000, resulting in a cost increase of up to US$50,000 per bus. Refueling, maintenance and bus storage infrastructure is also expensive. Different transit authorities report significantly different incremental operating costs. Two examples illustrate this point. In the first case, two northern California public transit agencies that replaced old diesel buses with new CNG buses in 1994 conducted a three-year study. The agencies found that the incremental capital cost of bus purchase (excluding the incremental cost of establishing the CNG infrastructure) was recovered in about seven years (Finley and Daly 1999). In the second case, the Los Angeles County Metropolitan Transportation Authority, which operates the largest fleet of NG buses in the country, reports that the fuel cost for NG buses per distance traveled has been 27 percent higher than diesel when compression costs are taken into account and that NG buses have had a much greater defect rate. Several other agencies have reported higher operating costs for NG buses; some have decided to stay with natural gas despite the economic disincentives purely on environmental grounds. One has concluded that NGVs are as reliable as gasoline vehicles in light-duty applications, but are inferior to diesel in heavy-duty applications, and recommended a moratorium on further expansion of the NG bus program but continuation with light-duty CNG vehicle purchase.

Fleet operators found it particularly difficult to recover the incremental costs of mounting a NG bus program in the early days of NG buses, when they experienced many mechanical and other problems. Comments submitted by the American Public Transit Association to the Department of Energy in July 1998 highlighted these concerns. The key issues to be overcome to increase the presence of transit NG buses in the market were said to be:

- higher capital and startup costs: bus purchase, fueling station, training for maintenance and operators, garage retrofit
- higher operating costs: fuel station maintenance, bus maintenance (lower engine reliability, reduced brake life, more expensive parts due to lower volumes), fuel costs, reduced range.

Box 1 shows an example calculation illustrating the inter-fuel price difference needed to make conversion from diesel to CNG economic.

NG bus programs experienced some setbacks in the 1990s, attributed to the cost and reliability problems of the early generations of buses. Some cities reversed their plans to purchase NG buses. There are consistent reports that the generation of NG buses from the early 1990s were not only more expensive to purchase than their diesel equivalents, but also were about 30 to 40 percent more expensive to maintain and had considerably reduced reliability (such as shorter mean distance between in-service failures and higher defect rate with parts).

Recent announcements to purchase CNG buses include that by the New York City Metropolitan Transportation Authority (MTA), which plans to expand CNG bus operations between 2000 and 2004 by adding 300 more CNG buses to the fleet and converting 2 depots to CNG. During the same period, the MTA also plans to retire all two-stroke engine diesel buses by 2003 and adopt clean diesel technology for 3,500 buses by retrofitting them with catalyzed particulate trap filters. The MTA's experience with CNG buses between 1995 and 2000 was not all positive, however. CNG buses were found to be only 50 to 75 percent as reliable as diesel buses, although the difference is narrowing. CNG buses were also found to be 40 percent less energy-efficient in urban service and significantly more expensive to operate (Department of Buses 2000).

CARB is a strong proponent of NG transit buses. It is developing a proposal for low-emission transit buses that includes a particulate emission standard of 0.00 (that is to say, less than 0.005) g/bhp-h and a NO_x standard of 0.1

Box 1. An Example of the Economics of CNG Buses in the United States

What is the price difference between diesel and natural gas needed to make fuel switching economic for a fleet operator? The following example gives order-of-magnitude estimates.

The assumptions made in this example are given below.

- There are 100 buses in the fleet.
- Each bus travels 80,000 km a year.
- The fuel economy falls by 15 percent upon switching to natural gas.
- The refueling station costs US$750,000 to establish and US$30,000 annually to maintain.
- Electricity costs $0.08/kWh.
- An additional $350,000 is required for building modifications.
- The incremental cost of NG buses is US$40,000 per bus.
- The cost of natural gas before compression is US$0.40 per gallon diesel equivalent.

The net present value (NPV) of this NG bus program was calculated over a time period of 20 years at a discount rate of 8 percent. The NPV became positive at a diesel price of US$0.88 per gallon, or more than twice the price of CNG. If the incremental cost of NG bus purchase is assumed to be US$30,000 per bus, then the break-even diesel price falls to US$0.81, still remaining above twice the price of CNG. In reality, if the life of a bus is shorter than 20 years (typical life of diesel buses is taken as 12-15 years in economic calculations), the break-even price would be even higher.

Source: King and Hutton 2000.

g/bhp-h by 2008–2012. Originally designed to mandate alternative fuel technology including natural gas, the current proposal gives flexibility by not dictating the choice of fuel. However, the current clean diesel technology cannot meet these emission standards, so that a technological breakthrough followed by successful commercialization will be needed if diesel technology (as opposed to diesel-electric hybrid technology) is to be used. California's SCAQMD approved regulations in June 2000 that mandated fleet operators with more than 15 buses to use non-petroleum alternative fuels, effectively banning clean-diesel technology. A recent survey by CARB has shown, however, that outside of the SCAQMD, 17 of 22 northern California transit agencies have chosen the clean diesel path, including virtually the entire San Francisco Bay area.

The experience with transit NG bus operators in the United States seems to suggest the following lessons:

- If the overall operating and maintenance costs are higher for NG buses, there is no hope of recovering the incremental cost of bus purchase and establishing the NG infrastructure. The operating and maintenance costs can be higher for a combination of reasons—significantly lower fuel economy for NG, insufficient price difference between natural gas and diesel, frequent breakdowns by NG buses, and fewer kilometers traveled on account of increased downtime and shorter driving range (making management of bus routes difficult in some cases if buses are refueled only at their depots). In a 1999 document, CARB concludes that even after overcoming these problems to a considerable extent, operating costs of new NG fleets in the future are estimated to be slightly higher than that of new diesel fleets, and the capital costs for NG fleets—initial bus purchase price and the refueling and facility modification costs—will continue to be higher than that for diesel fleets (CARB 1999).
- A large number of buses should be made to run on natural gas to take advantage of economies of scale, ideally at least a whole depot.
- Long-term commitment, support and active involvement by management are crucial.
- Financial capability must be in place.
- Extensive training of drivers and mechanics must be undertaken, and qualified and experienced engineers made available to provide competent support for smooth operation and maintenance, as well as to ensure safety. Having trained operators and maintenance staff who can catch and report problems or changes in the buses while in operation and during preventive maintenance is very important (Box 2).
- Government mandates/regulations alone are insufficient, and incentives are needed to encourage conversion from diesel to natural gas. In the United States, grants are available from the federal and state governments to switch to natural gas.
- The fleet operators should recognize that there will be additional costs and inconvenience during transition. Some have had to struggle with more frequent breakdowns requiring repairs for a number of years.
- No significant regulatory hurdles should have to be overcome.

Australia

The Government of Australia has introduced a number of measures to support alternative fuels. The package of federal government programs providing a strong incentive to switch to alternative fuels, especially natural gas, include

- *CNG Infrastructure Program* providing funding up to 50 percent of the cost of installing in excess of 20 public refueling facilities
- *Alternative Fuels Conversion Program* funding up to 50 percent of the additional cost of conversion or purchase of new NGVs with a

Box 2. Phoenix Transit

Phoenix Transit in Arizona operates 411 buses, of which 157 are fueled by LNG. The LNG buses are of 1998, 1999 and 2000 model year vintages equipped with catalytic converters. They travel about 80,000 km a year, averaging fuel economy of about 0.80 km per liter diesel equivalent, compared to diesel buses achieving 1.3 km per liter. Carbon monoxide and non-methane hydrocarbon emission levels are a little lower than for a diesel engine of the same age; NO_x at idle is significantly higher, and NO_x under load is considerably lower, than diesel. Data on particulate emissions are not available. There have been no significant differences in road call incidents between diesel and LNG buses of the same age.

The views of Phoenix Transit about how they have managed the transition to LNG underscore the importance of training and winning the support of every person in the organization:

> "The main challenge is to have trained operators and maintenance staff that can observe and report changes in the buses while in operation and during preventive maintenance. The next challenge is to have bus manufacturers and component manufacturers working in partnership with the service and maintenance contractors. The bus, bus fueling system, refueling system, transmission and engine have all been a challenge but the problems have not kept the buses out of service and each problem as it occurs is being resolved to make the bus better.
>
> The bottom line is *training, training and more training*. Phoenix Transit initially met resistance from the operators, mechanics, fuelers, and subsequently the union. They trained everybody from top management to bus washers. A little 'LNG 101' goes a long way, provided you have the answers to conciliate the resistance."

Source: Watt 2001.

gross vehicle weight of over 3.5 tons (which include urban transit buses)

- *Diesel and Alternative Fuels Grants Scheme* ensuring that the fuel price advantage of natural gas over diesel is maintained
- *Alternative Fuels Grants Scheme* applying exclusively to urban buses and offering a grant of 12.1 Australian cents per cubic meter of natural gas, improving the price advantage of NG over diesel by approximately 10 percent.

The response to NG buses in Australia from fleet owners has been positive on the whole, certainly much more so than in Canada (see below). Many achieved economic savings relative to diesel. Emissions advantages of CNG buses have been demonstrated time and again. Reliability has been a problem, as well as backfiring. Vehicle manufactures have worked closely with fleet operators and given considerable technical support. The importance of training and education of drivers was highlighted when drivers in Sydney, Australia, spoke of lack of acceleration and poor drivability of natural gas vehicles compared to diesel. Comparison trials with diesel buses showed that the drivers were confusing lack of noise from natural gas buses with lack of acceleration. CNG buses are about US$20,000 more expensive than their diesel counterparts. The Scania NG buses purchased by Sydney Buses have given a payback period of about seven years.

Canada

The CNG program in Canada was launched in 1983 with a series of economic incentives. A payback period of about two years was deemed necessary to encourage owners to switch to NG, and the federal government, some provincial governments and the natural gas utilities developed incentive packages. The environmental advantages of CNG did not become a factor until about 1992. The use of NG buses has been motivated primarily by consideration for emissions improvement. While Canada was active in the development and use of NG buses in the early 1990s, the purchase rate declined considerably in 1998 and has come virtually to a halt, in sharp contrast to the NG transit bus market in the United States. The difference between the two North American countries is attributed to the lack of equivalent Canadian and provincial government policies regarding the need to improve air quality. Two major NG bus operators in Canada—Coast Mountain Bus Company and the Toronto Transit Commission—are expressing concerns about the operational problems and maintenance costs of NG buses and have been reported as being inclined to switch out from natural gas to other alternative fuels. This perception of NG buses is believed to arise from the disappointing performance of the buses purchased in the early 1990s. Some NG buses in Canada have even been converted back to diesel.

One unintended consequence of operating new NG buses and older diesel buses in parallel is the increased use of diesel buses on account of the higher downtime and lower passenger carrying capacity of NG buses, as Coast Mountain Bus Company in British Columbia has found. Although the company achieved fuel cost savings of 47 percent in 1999, the savings were offset altogether by the 49 percent higher operating costs.

France

One new bus out of three is fueled by natural gas in France today. A quarter of all new buses ordered are NG buses, selected primarily for environmental reasons. The NG buses are "low floor" with composite material cylinders located in the roof. The buses travel about 40,000 km a year on urban routes. Most filling stations use slow fill. NG buses cost about US$28,000 to US$35,000 more than their diesel counterparts. The financial break-even point relative to diesel is generally achieved for fleets of 20 buses or more. Fleet managers report that they are generally satisfied with NG buses. No significant maintenance or operational problems have been encountered. Operation during cold periods has been somewhat problematic, necessitating a wait of 15 to 20 minutes before the engine functions properly and upgrades to reduce the number of breakdowns. A survey conducted in May 2000 found that 90 percent of passengers believed that NG buses improved air quality, and 96 percent stated that NG buses are superior to diesel buses.

The government lowered taxes on gas for NG buses between 1998 and 1999 by giving a tax exemption for 24,000 m^3 per year per bus. During the same period, the market price of diesel increased, and in addition the government increased taxation on diesel. In Poitiers, the break-even point relative to diesel was achieved for a fleet operator when the monthly gas consumption reached 45,000 m^3, or for 16 buses driving more than 4,700 km per month.

Transit Bus Industry in Developing Countries

Any assessment of fuel switching for transit buses in developing countries must take into account the evolving public transport sector in the individual countries. Transit bus companies in many, if not most, developing countries are cash-strapped. A large number of operators suffer from fare controls that have made it very difficult to provide high-quality service. The emergence of mini-buses in the informal sector—that is, buses in the hands of non-corporate operators, illegal as well as legal—has posed a serious threat to the survival of transit buses, especially in the former Soviet Union and Africa. Where they operate illegally, these informal sector buses save costs by minimizing payments to the government in the form of taxes and license fees. In some parts of Central Asia, the tax paid by traditional (formal sector) bus operators is estimated to be an order of magnitude higher than that paid by informal operators, giving a considerable advantage to the latter. Because informal sector buses are in the hands of a large number of owners, even when they operate legally, they may be more difficult to bring under control for the purpose of monitoring and enforcing regulations (such as vehicle registration, and safety and emission standards).

As governments attempt to reduce emissions from buses, they must face that traditional bus operators are cash-strapped, in part because of fare controls, and have little money left to maintain their vehicles properly, and that bus operators in the informal sector are difficult to regulate. In part because they are cash-strapped, bus operators do not maintain vehicles, resulting in high emissions as manifested by black smoke belching out of diesel buses. For the same reason, they would not be in a position to purchase more expensive NG buses, provide extensive staff training on this new technology, and accept the possibility of more repairs to deal with greater frequency of bus breakdowns, at least initially. That even U.S. bus operators have faced considerable mechanical challenges with NG buses, resulting in higher operating costs in a number of cases, is a cause for concern, especially given the much smaller number of technically qualified mechanics to service NGVs in developing countries. In the informal sector, bus operators are not likely to own a large number of vehicles. Even if they are operating legally, they are not likely to be able to exploit economies of scale in maintenance, training and refueling, making it difficult to switch to NG.

Under the current circumstances, the transit bus industry in a number of countries is not sustainable in the long run—fare control will eventually have to be lifted to bring in new types of service, or else the formal sector may disappear altogether and be replaced by the informal sector. That is to say, high emissions from diesel buses are not merely because of the choice of fuel, but are symptomatic of deeper problems in the transit bus industry in developing countries, and these same problems may condemn NG bus programs to failure even if inter-fuel pricing is adjusted to favor NG much more at the expense of diesel. While mini-buses have a proper role to play, large transit buses are ideal for segregated busways in congested situations where the reservation of well-functioning rights-of-way for buses is often the only affordable solution for mass transit. They are also the road vehicle of choice where passenger volumes are high and public transport vehicles constitute a high percentage of traffic in congested or near-congested streets.

Some governments, such as the United States and Australia, have offered considerable financial incentive packages to promote NG transit buses. Especially when these incentive packages have been combined with tough emissions regulations, NG bus programs have been successful. However, the level of subsidies offered in these countries are unlikely to be sustainable in developing countries.

Experience in developing countries with NG transit buses is limited. The extent to which experience and lessons—especially with respect to mechanical reliability, drivability, maintenance and other issues—from industrial countries can be transferred is not clear. The NG buses now being purchased in industrial countries are all OEM buses, costing some US$20,000 to US$50,000 more than their diesel counterparts, up to as much as US$300,000 per bus. Most developing countries pay US$100,000 or less for each bus. Reliability and increased repair frequency have been one of the major issues in the past, even with OEM NG buses. The data needed to establish whether NG buses offered at dramatically lower prices in developing countries such as China have comparable, more, or fewer operational and maintenance problems will become available only in a few years' time.

Finally, there is the question of what happens to NG buses if they are neglected as much as conventional diesel buses in developing countries. This is an interesting question for cities such as Delhi, which has mandated conversion from diesel to NG. How the poor cultural acceptance of, as well as inability to pay for, regular maintenance affects the life of the NG bus, its fuel economy, frequency of complete breakdown (so that it cannot be operated on the road), and emissions is an important question that should be monitored closely as developing country cities launch NG bus programs.

Note

1. However, this analysis by Sun Metro has been criticized for not comparing like with like, and therefore projecting more favorable economics for NG buses (Watt 2001).

Chapter 4

Looking to the Future

This report has shown that NGVs are a relatively new and rapidly evolving technology. As such, while there are useful lessons to be learned from other countries' experience, some of them may no longer be directly applicable—for example, experience relating to the poor performance of NG buses manufactured in the early 1990s compared to those manufactured more recently.

To date, NG buses have been at a private economic disadvantage compared with diesel buses unless supported by substantial favorable tax discrimination or subsidies. In the absence of emissions standards that effectively require gaseous fuels, natural gas buses are unlikely to be adopted because they are more expensive to operate relative to diesel buses. This is partly because diesel is a very cheap fuel in most developing countries—it is lightly taxed or may even be subsidized. Even if diesel were taxed much more, however, it is not obvious that CNG buses would be cheaper over their life cycle than diesel buses: they cost more to purchase, are less fuel efficient, have a smaller range and are often less reliable. These observations suggest that the social case for replacing diesel by CNG in buses rests on environmental grounds. In particular, the use of natural gas by heavy-duty vehicles normally fueled by diesel would not be suitable if the diversification of energy sources is the primary objective.

Developments in the clean diesel technology are expected to have a direct impact on the future of the NGV industry and market in industrial countries. The environmental concerns directing research and development in the auto industry in industrial countries are not the same as those in developing countries. Severe NO_x emissions control, which is not yet a priority in most developing country cities, presents a significant technical challenge to vehicle manufacturers in industrial countries who have turned to sophisticated technical solutions based on ultra-low sulfur diesel (preferably below 10 wt ppm sulfur). For controlling particulate emissions, catalyzed particulate traps appear to be successful in reducing emissions dramatically, but they too require ultra-low sulfur diesel. Cummins cited quirks of Euro III emission standards (including the limit on exhaust methane) and subsequent certification test cycles as the primary reasons for its earlier decision to withdraw its natural gas engines from the European market when Euro III truck and bus emissions legislation was originally scheduled to come into force for all new vehicles in October 2001[1]. That is to say, the evolution of the NGV market and manufacturing industry in industrial countries is influenced to a significant extent by considerations that are often not priority issues in developing countries. And yet because the bulk of product development occurs in industrial countries, what happens there will have an impact on the availability of NGVs in developing countries in the foreseeable future. To take an extreme scenario, if the NGV industry in industrial countries were to die (for example, as a result of clean diesel replacing natural gas), it could become much more difficult for developing country cities to implement a NG bus program.

A closely related factor is developments in the refining industry. More specifically, given the future mandated reductions in sulfur in diesel, there has been extensive research and development to lower the cost of diesel hydrodesulfurization technologies. Breakthroughs have been announced and demonstrated at the pilot scale, including the announcement of a novel sulfur extraction technology that could radically reduce the cost of both diesel and gasoline desulfurization while efficiently saturating aromatics and boosting cetane—the cost of virtually eliminating sulfur in high-sulfur diesel is estimated to be on the order of 0.7 U.S. cents per liter (Hart's Diesel Fuel News 2001). Successful commercialization of such processing technologies could dramatically alter the landscape for the clean diesel–natural gas debate.

However, until such a time as "cheap" clean diesel becomes widely available worldwide, which is not expected for at least several more years, most developing country cities will continue to grapple with a choice between conventional, polluting diesel versus potentially much cleaner natural gas buses. If the government of a city decides that the reduction in air pollution associated with CNG buses is worth the cost, then it needs to adopt policies that would encourage the switch to CNG: either emissions standards for buses, or fuel or vehicle taxes that reflect marginal social costs.

The type of analysis that could be carried out to determine whether CNG buses should replace conventional diesel buses would include

- comparing the lifecycle costs and emissions of a new conventional diesel bus and a CNG bus, using a net of tax price for diesel fuel, CNG and their respective vehicles, or
- comparing the cost of retrofitting a diesel bus with a CNG engine and estimating the resulting change in emissions over the remaining life of the bus (also using net of tax fuel and vehicle prices).

The first is applicable to the case where a new bus purchase is being considered, and the second to the case of converting existing diesel buses (which is not normally recommended). These calculations would give an idea of how the options compare on economic grounds. Repeating the above calculations using gross of tax fuel and vehicle prices would indicate how much more fleet operators would have to bear to achieve target emission levels. By making assumptions about exhaust emission factors, it would also be possible to compute a cost per ton of particulate matter reduced, although this might be misleading in view of the fact that other pollutants are being reduced at the same time.

Many unknowns in the above calculations introduce large uncertainties in the final results. The relative operating costs of diesel and NG buses have been reported to vary over a wide range, even in the United States where data collection has been rigorous. Little is known about the experience of converting existing diesel buses to CNG, other than that such conversions typically do not make happy customers. The reliability of CNG buses in developing countries is one of the greatest unknowns. However, carrying out calculations using the most optimistic as well as more pessimistic assumptions could give order-of-magnitude estimates. For example, if even the most optimistic of assumptions cannot justify CNG buses, then switching to CNG is unlikely to be sustainable.

An added consideration is the cash-strapped state of the transit bus industry in developing countries. Lack of an adequate operating budget is one of the reasons for the poor maintenance of diesel buses, resulting in gross emissions. Since operating NG buses incurs higher upfront costs—for purchasing buses, setting up refueling stations and training mechanics and drivers—transit bus fleet operators in poor financial condition are not in a position to take on a NV bus program successfully. While lack of proper maintenance may not necessarily lead to black smoke emitted by tailpipes in the case of NG buses, it could easily result in more frequent breakdowns and other operational problems, as well as higher emissions of other pollutants that may become an issue in the long run. NG buses tend to be less reliable than their diesel equivalents even in the best of circumstances. Reports of continual operational problems with NG buses are certain to invite a backlash from bus operators, seriously harming the future of the NGV industry. Some of the more negative experiences in developing countries include that in Jakarta, Indonesia, where of the 40 dedicated CNG buses, only 20 are operating owing to maintenance problems.

Lastly, because natural gas buses have higher upfront costs that require some type of government support (for example, in the form of higher diesel fuel or vehicle taxes) to recover, and hence emissions reductions from switching to natural gas come at a price, this cost for reducing particulate emissions should be compared to that for other sources—for example, industry, households and the informal sector. In order to make this comparison, the contributions of various sources to ambient concentrations have to be understood. While it is difficult to identify sources accurately, chemical analysis of particles and other analytical studies go a long way in providing a better understanding of source contributions. At the same time, such numerical findings need to be tempered by the growing evidence that diesel particulate emissions are indeed very toxic, and exhaust emissions fall predominantly in the particle size range that seems to have the most health impact (namely below 1 micron).

In summary, the following are some of the questions that should be posed in considering the choice of fuel for transit buses.

- *What is the financial position of the transit bus operators?* If they are cash-strapped, is this because distortions in the policy framework need to be corrected? If fare control is the primary reason for the bus operators' poor financial state, how much would the fares need to rise before the financial health of the operators is recovered? If fares are to be raised, are there provisions to protect low-income bus riders who may not have alternatives?
- *Is automotive diesel priced much above natural gas for transport?* If not, switching to natural gas will not be economic, and hence not commercially sustainable in the long run. Are there pricing distortions today that may be corrected in the future, and that may have an adverse impact on relative prices of the two fuels (for example, a heavy subsidy for natural gas)? If so, economic calculations should be based on long-run marginal cost of natural gas rather than the current low price. Is the price difference between natural gas and diesel (possibly combined with higher vehicle tax on diesel vehicles) adequate for recovering the incremental costs? Is the payback period reasonable? Does the government have a plan to support the price difference in times of falling international price of diesel and rising price of natural gas?
- *Is emissions reduction in transport, and more specifically targeting buses, likely to be cost-effective compared to emissions reductions in other sectors?* If, on the contrary, informal refuse burning, combustion of biomass in urban households, wood and coal burning in cottage industries in the informal sector, and two-stroke engine gasoline motorcycles and three-wheelers turn out to contribute the majority of ambient concentrations of particulate matter, targeting diesel buses aggressively will not reduce particulate air pollution markedly.
- *How will large-scale substitution away from gasoline to NG affect the government's finances?* Assuming the price of diesel is below the price of gasoline, setting the tax rate on NG that makes it economically attractive to switch from diesel to NG will make it even more attractive to switch from gasoline to NG. Will a successful NGV pro-

gram require adjustments to inter-fuel taxation later on, making NG less attractive? Will there be serious imbalances in petroleum product consumption patterns, such as a very low gasoline-to-diesel ratio? Such imbalances may not be a problem for a country that imports nearly all of its fuel demand, but they would constrain the ability of refineries to remain profitable.

- *Are subsidies (such as capital subsidies provided by the U.S. government) needed to justify conversion to natural gas on economic grounds?* If diesel tax is not raised, should CNG buses even be considered? Is there room for subsidies as the United States has provided for capital? If so, based on order-of-magnitude calculations, does it appear that the benefits of switching to natural gas in terms of health impacts justify the subsidies? Or can the government save more lives and reduce illnesses by using the same amount of money elsewhere, such as on clean water or health care? If subsidies seem justified, is the government committed to providing subsidies in the long run to avoid the repeat of the New Zealand NGV experience?
- *Is the regulatory framework for NGVs in place*, including safety regulations and standards for equipment? Is there an adequate monitoring and enforcement mechanism?
- *Is the quality of natural gas consistent and does it meet minimal requirements for vehicles*, or does it tend to fluctuate over a wide range so that certain vehicle technologies may not be used without processing the gas further (such as by blending)?
- *How many buses could be converted to natural gas at one depot?* Is there a sufficient number to exploit economies of scale?
- *Is there a realistic and workable plan to train maintenance staff and drivers?* Are there enough qualified trainers and engineers to support the program?
- *Are the transit fleet managers considering NG buses very much committed to the fuel switch* and ready to get involved themselves?

The decision to switch from diesel to natural gas for use in buses is not straightforward. At a minimum, the regulatory and administrative arrangements should be in place to ensure the financial sustainability of transit operators who would be using natural gas, and vehicle taxes should reflect marginal social costs of health damage from air pollution. If these conditions are satisfied, cities in countries with abundant supplies of domestic gas, gas pipelines already in place, and with transport emissions contributing substantially to serious urban air pollution may consider this fuel option. The conditions outlined above would present a serious challenge even in industrial country cities, and certainly in nearly all developing country cities.

The temptation to mandate NG buses under the circumstances may be strong, but mandating what would otherwise be commercially unsustainable in the long run cannot be a viable solution. If municipal governments are serious about wanting to promote NG for transit buses, broader issues facing the public transport sector, such as examination of the fare structure and how to create a level playing field for all bus operators including regulation of informal sector buses, will need to be addressed. Once transit bus operators are on their way to a more sound financial footing, the question of how best to recover the incremental cost of switching to NG—such as fiscal incentives reserved only for fleet operators so as not to increase the fiscal burden on the government—may be explored. Lastly, as a growing number of developing country cities experiment with NG buses, systematic collection and exchange of information could be invaluable in guiding policymakers as they consider this new fuel system.

Note

1. In January 2001, the EU decided to delay implementation of Euro III rules for gas engines by two years. In response, Cummins has put on hold its decision to withdraw from the European gas engine market.

Annex A

Emissions from Diesel Vehicles

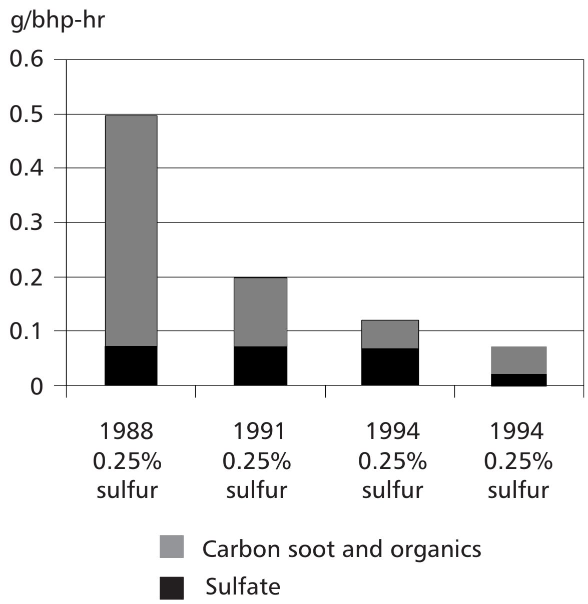
The pollutants of concern found in diesel exhaust are particulate matter, oxides of nitrogen (NO_x) and hydrocarbon toxins such as polynuclear aromatics. *Primary* particles are emitted directly by vehicles; *secondary* particles, in contrast, are formed from the chemical oxidation of atmospheric gases. Oxides of sulfur (SO_x) and of nitrogen (NO_x) are precursors for secondary particles; reducing sulfur in diesel lowers the amount of sulfate-based particles. NO_x is in addition an ozone precursor. Ozone pollution is not yet a serious problem in most developing country cities, but ambient concentrations of ozone and NO_x are on the rise.

There is a growing consensus that diesel exhaust poses a cancer risk. The advisory board to the U.S. National Toxicology Program has recommended that diesel exhaust particles be listed as "reasonably anticipated to be a human carcinogen." The California Air Resources Board (CARB) has officially recognized that some elements of emissions from diesel engines are carcinogens. CARB, in fact, points to several studies that have shown that the cancer risk from diesel particles is greater than the risk from all other identified toxic air contaminants combined. Japanese scientists claim that they have found 3-nitrobenzanthrone to be one of the most carcinogenic substances ever discovered; emissions of 3-nitrobenzanthrone increase markedly when a diesel engine is operating under high load. This suggests that diesel particulate emissions are especially harmful to public health—a matter for concern, since the consumption of diesel far exceeds that of gasoline in many developing countries.

A series of extensive studies, mainly in the United States, has shown clear associations between small changes in a wide range of health indicators—mortality, hospital admissions, emergency room visits, time off school or work, respiratory symptoms, exacerbation of asthma and changes in lung function—and ambient particulate concentrations. Of the various health indicators, the measurement of mortality has been particularly well studied. The actual adverse impact of fine particulate matter on public health may be considerably greater in developing countries than existing data indicate: most studies have been carried out on urban populations in industrial countries who receive high-quality medical care and who do not spend as much time outdoors as some segments of the population in developing countries do.

Historically, carbonaceous contributions to diesel particulate emissions have far exceeded sulfate contributions. Figure A1 shows the reduction in the carbon soot and organics portion of particulate matter that was achieved by improving heavy-duty diesel engine design between 1988 and 1994 in the United States. The sulfate portion is due to sulfur found in diesel and lubricant. In 1988, carbon soot and organics

Figure A1. Particulate Emissions from New Vehicles in the United States



Source: McCarthy 1994.

constituted the majority of particulate emissions. As a result of steady refinements in the engine technology, the sulfate contribution was greater than the carbonaceous contribution by 1994. The engine manufacturers would not have been able to meet the 1994 particulate emission limit of 0.1 grams per brakehorse power per hour (g/bhp-hr) without reducing sulfur in diesel from 0.25 percent to 0.05 percent. Therefore, the decision of the U.S. Environmental Protection Agency (EPA) to lower the limit on sulfur in diesel to 0.05 percent for the 1994 model year was justified and should serve as a model for future regulatory action—vehicle technology and fuel quality improvements should be consistent and coordinated.

Certain fuel parameters have been linked to diesel emissions. One of the most extensive studies conducted to date is the European Programme on Emissions, Fuels and Engine Technologies (EPEFE). Representing an unprecedented collaboration between the European motor and oil industries, EPEFE was undertaken as part of the European auto-oil program, the objective of which was to identify measures for improving urban air quality based on sound science and cost-effectiveness as primary criteria. EPEFE found that the relationships between vehicle and fuel technologies were complex, so that those measures that reduced emissions from light-duty vehicles sometimes increased emissions from heavy-duty vehicles, and vice versa. For example, reducing diesel density decreased NO_x emissions from heavy-duty diesel engines, but increased NO_x from light-duty engines. Some measures were effective for all diesel engines tested: decreasing polynuclear aromatics in diesel reduced NO_x and particulate emissions, and increasing cetane number decreased hydrocarbon and carbon monoxide emissions, from both heavy- and light-duty vehicles. However, increasing cetane number increased particulate emissions from light-duty vehicles. Overall, the following measures were found to decrease particulate emissions:

- reducing density for light-duty engines
- reducing polynuclear aromatics for both light- and heavy-duty engines
- decreasing the temperature at which 95 percent of diesel evaporates, for light-duty engines.

The health impact of diesel emissions appears to be especially serious for those close to the sources of emissions, such as school children riding buses, traffic police and vehicle riders following diesel vehicles. As a striking example, one study in Los Angeles, United States, found that concentrations of elemental carbon (which constitutes a relatively high fraction of diesel particulate emissions) inside vehicles with windows closed were about 5 micrograms per cubic meters ($\mu g/m^3$) without any vehicles in front; 15 $\mu g/m^3$ when following a diesel truck with a high, vertical exhaust pipe or a diesel passenger car; 50 $\mu g/m^3$ when following a diesel truck with a low exhaust pipe; and as high as 130 $\mu g/m^3$ when following an urban transit bus making frequent stops (Fruin and others 2000). These concentrations would be expected to be even higher in developing countries where emission levels are generally higher than in California.

While there are growing concerns about the environmental health risks of conventional diesel vehicles as studies continue to shed new light on the adverse health impact of particulate emissions, the markedly higher efficiency of diesel engines compared to gasoline has made diesel popular. For example, in Europe, one out of every three cars sold in 2001 is forecast to be diesel-fueled. The EU and the United States have steadily tightened emission standards, requiring engine modifications as well as diesel quality improvements. The challenge facing vehicle manufacturers is the trade-off between NO_x and particulate emissions: measures that reduce the peak flame temperature, such as injection timing retard, decrease NO_x emissions but increase particulate emissions that arise from incomplete combustion, and hence fuel consumption.

Oxidation catalysts are used to reduce gaseous hydrocarbons and the soluble organic fraction of particles in the diesel exhaust. Oxidation catalysts are especially effective for two-stroke engine diesel vehicles. In the Urban Bus Retrofit/Rebuild Program finalized by the U.S. EPA in 1993, oxidation catalysts are extensively used to reduce particulate emissions. The program is limited to 1993 and earlier model-year urban buses operating in metropolitan areas and applies at the time of engine rebuild or replacement. A key aspect of the program is the certification of retrofit/rebuilt equipment, which often includes an oxidation catalyst as one of the components. The use of oxidation catalysts calls for low (but not necessarily ultra-low) sulfur diesel, namely diesel with a sulfur content of 0.05 percent or lower.

For dramatic reductions of particulate emissions, catalyzed particulate filters and continuously regenerating particulate traps have been shown to be effective. A continuously regenerating particulate trap can reduce particle number counts by one to two orders of magnitude as well as the mass of particles. To use these particulate filters, however, ultra-low sulfur is needed for durability. In response, the European Commission proposed during the first half of 2001 that sulfur-free diesel (meaning diesel with sulfur below 0.001 percent by weight, or 10 parts per million) be made available in all EU countries by 2005.

In the United States, in-use diesel vehicles are tested for smoke opacity in eight states. The U.S. EPA has not mandated opacity tests for diesel vehicles because of concerns about correlation between opacity measurements and particulate emissions. While loaded dynamometer tests are reasonably correlated with mass particulate emissions to a degree, lowering smoke opacity does not necessarily guarantee a reduction in particulate emissions, and vice versa. The correlation between opacity measurements under snap acceleration[1] (which is the test used even in the United States) on one hand and mass particulate emissions during transient operation is much weaker. This poses a considerable challenge for designing an effective diesel vehicle inspection and maintenance program.

Note

1. The vehicle engine, with the transmission in neutral, is accelerated at full throttle from a raised idle revolutions per minute (rpm) to a maximum governed rpm.

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