TRANSIT COOPERATIVE RESEARCH PROGRAM

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TCRP Report 38

Guidebook for Evaluating, Selecting, and Implementing Fuel Choices for Transit Bus Operations

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TRANSIT COOPERATIVE RESEARCH PROGRAM

Report 38

Guidebook for Evaluating, Selecting, and Implementing Fuel Choices for Transit Bus Operations

ARCADIS GERAGHTY & MILLER, INC.
Mountain View, CA

Subject Area

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TRANSIT COOPERATIVE RESEARCH PROGRAM

The nation's growth and the need to meet mobility, environmental, and energy objectives place demands on public transit systems. Current systems, some of which are old and in need of upgrading, must expand service area, increase service frequency, and improve efficiency to serve these demands. Research is necessary to solve operating problems, to adapt appropriate new technologies from other industries, and to introduce innovations into the transit industry. The Transit Cooperative Research Program (TCRP) serves as one of the principal means by which the transit industry can develop innovative near-term solutions to meet demands placed on it.

The need for TCRP was originally identified in *TRB Special Report 213—Research for Public Transit: New Directions,* published in 1987 and based on a study sponsored by the Urban Mass Transportation Administration—now the Federal Transit Admini-stration (FTA). A report by the American Public Transit Association (APTA), *Transportation 2000*, also recognized the need for local, problem-solving research. TCRP, modeled after the longstanding and successful National Cooperative Highway Research Program, undertakes research and other technical activities in response to the needs of transit service providers. The scope of TCRP includes a variety of transit research fields including planning, service configuration, equipment, facilities, operations, human resources, maintenance, policy, and administrative practices.

TCRP was established under FTA sponsorship in July 1992. Proposed by the U.S. Department of Transportation, TCRP was authorized as part of the Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA). On May 13, 1992, a memorandum agreement outlining TCRP operating procedures was executed by the three cooperating organizations: FTA; the National Academy of Sciences, acting through the Transportation Research Board (TRB); and the Transit Development Corporation, Inc. (TDC), a nonprofit educational and research organization established by APTA. TDC is responsible for forming the independent governing board, designated as the TCRP Oversight and Project Selection (TOPS) Committee.

Research problem statements for TCRP are solicited periodically but may be submitted to TRB by anyone at any time It is the responsibility of the TOPS Committee to formulate the research program by identifying the highest priority projects. As part of the evaluation, the TOPS Committee defines funding levels and expected products.

Once selected, each project is assigned to an expert panel, appointed by the Transportation Research Board. The panels prepare project statements (requests for proposals), select contractors, and provide technical guidance and counsel throughout the life of the project. The process for developing research problem statements and selecting research agencies has been used by TRB in managing cooperative research programs since 1962. As in other TRB activities, TCRP project panels serve voluntarily without compensation.

Because research cannot have the desired impact if products fail to reach the intended audience, special emphasis is placed on disseminating TCRP results to the intended end users of the research: transit agencies, service providers, and suppliers. TRB provides a series of research reports, syntheses of transit practice, and other supporting material developed by TCRP research. APTA will arrange for workshops, training aids, field visits, and other activities to ensure that results are implemented by urban and rural transit industry practitioners.

The TCRP provides a forum where transit agencies can cooperatively address common operational problems. The TCRP results support and complement other ongoing transit research and training programs.

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The members of the technical advisory panel selected to monitor this project and to review this report were chosen for recognized scholarly competence and with due consideration for the balance of disciplines appropriate to the project. The opinions and conclusions expressed or implied are those of the research agency that performed the research, and while they have been accepted as appropriate by the technical panel, they are not necessarily those of the Transportation Research Board, the National Research Council, the Transit Development Corporation, or the Federal Transit Administration of the U.S. Department of Transportation.

Each report is reviewed and accepted for publication by the technical panel according to procedures established and monitored by the Transportation Research Board Executive Committee and the Governing Board of the National Research Council.

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The Transportation Research Board, the National Research Council, the Transit Development Corporation, and the Federal Transit Administration (sponsor of the Transit Cooperative Research Program) do not endorse products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to the clarity and completeness of the project reporting.

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FOREWORD

By Staff
Transportation Research Board

This guidebook and its accompanying cost-model spreadsheet (*FuelCost 1.0*) will be of interest to transit managers, policymakers, operations and maintenance professionals, and others considering the deployment of, or conversion to, alternative fuel buses. They are intended for individuals who, while being quite knowledgeable about the transit industry, may not be familiar with alternative fuels and implementation issues. The guidebook and *FuelCost 1.0* provide tools to simplify the process of developing an alternative fuel strategy by clearly identifying the issues, and the costs and benefits associated with the conversion to various available alternative fuel technologies.

The Federal Transit Administration has sponsored a number of alternative fuel projects over the past several years under the Clean Air Program. These projects have included CNG, LNG, methanol, biodiesel, propane, battery-powered, and other vehicles. Each transit system experimenting with alternative fuels has experienced various levels of ease or difficulty in implementation and operation. Although numerous alternative fuel projects have been completed or are currently underway, there has not been an attempt to synthesize all the available information into a guide to assist transit managers in the assessment, selection, and implementation of alternative fuel options for transit buses.

Under TCRP Project C-8, research was undertaken by ARCADIS Geraghty & Miller, Inc. (formerly Acurex Environmental Corporation) to develop (1) a guidebook to assist transit managers in the assessment, selection, and implementation of alternative fuel options for transit buses and (2) a spreadsheet-based computer tool to assist in the quantification of costs associated with the potential conversion to alternative fuels.

To achieve the project objectives, the researchers conducted an extensive assessment of the state of alternative fuels in transit systems. This assessment included a literature search of data reported and summarized in trade journals, technical publications, technical presentations, and project reports; site visits with key transit agencies that have had experience in implementing major alternative fuel programs to obtain the latest available cost information, along with insights on the problems, successes, and failures of their programs, and their recommendations for those who may be contemplating conversion to an alternative fuel; a survey of engine and vehicle manufacturers to determine up-to-date understanding of product plans, and their assessment of trends in the alternative fuel market; a survey of fuel providers and fueling equipment suppliers to obtain information concerning future pricing and availability of transportation fuels; and an evaluation of requirements and interests that may influence a transit agency's choice of fuel, including current and future emissions standards, and policies to encourage the use of non-petroleum fuels. This information was then used as the basis for developing the guidebook and the inputs to the *FuelCost 1.0* cost model.

The guidebook starts with a review of current and expected developments in diesel engine technology and emission performance, as diesel represents the baseline for evaluating the performance and cost of alternative fuels. For each of the five most commonly used alternative fuels

- compressed natural gas (CNG)
- liquefied natural gas (LNG)
- methanol
- ethanol
- liquefied petroleum gas (LPG)

information is provided concerning engine and vehicle technology, vehicle performance, fueling station design, maintenance facility modifications, safety considerations, and fuel availability and cost. Key issues and prospects are provided for other important alternative fuel technologies as well, including hybrid electric, battery electric, fuel cell, and biodiesel. Comparative information illustrating the current market status of each alternative fuel, including market share and trends, is also provided. Case studies of three transit agencies that are successfully converting to alternative fuels—Sun Metro, El Paso, Texas (LNG); Sacramento Regional Transit District (mild-climate CNG); and Greater Cleveland Regional Transit Authority (cold-climate CNG)—are also included. Finally, the guidebook summarizes available fuel options, and issues to consider in evaluating fuels and vehicle technologies.

The accompanying cost-model spreadsheet—*Fuelcost 1.0*—enables the user to conveniently estimate and compare the cost impacts of the available fuel options with a user-friendly spreadsheet in Microsoft Excel 5.0 format. *FuelCost 1.0* uses data provided by the user (with default values if the user does not have fleet-specific data) and some predefined data to perform a life-cycle cost analysis of alternative fuels, as well as a cash-flow analysis that compares costs for different fuel options during each calendar year. This allows the user to see not only how fuel options compare over the long term, but also how they may affect the year-to-year operating cash flow for a transit agency. *FuelCost 1.0* reflects uncertainty in calculating costs by including median-, low-, and high-cost cases. It can be used to analyze a single procurement or a wholesale conversion to an alternative fuel over several years. *FuelCost 1.0* is intended to assist transit agencies with scoping-level planning. Documentation for *FuelCost 1.0* is provided in a user's guide, which is included as an appendix to this guidebook, and is also available in electronic fashion on the disk containing the *FuelCost 1.0* spreadsheet. The user's guide and disk also include examples of the use of *FuelCost 1.0* for 10-, 50-, and 200-bus applications.

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ARCADIS Geraghty & Miller's Principal Investigator was Richard Remillard. Other primary authors of this Guidebook were Daniel R. Luscher and Elizabeth A. Devino. ARCADIS Geraghty & Miller's subcontractors on this project, Rich Davis and Steven Barsony of Davis & Associates, provided valuable expertise regarding transit operations and FTA transit funding policies, and performed the site visits that provided the basis for the case studies in Chapter 13.

The authors would like to thank the TCRP Project Officer, Christopher Jenks, for his valuable guidance throughout the project. In addition, the TCRP Project Panel offered useful and constructive comments on various work products during the course of this study. Cameron Beach (Sacramento Regional Transit District), Gino Chavez (Sun Metro), and Anthony Russo (Greater Cleveland Regional Transit Authority) provided critical information for the Chapter 13 case studies.

CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION

This *Guidebook for Evaluating, Selecting, and Implementing Fuel Choices for Transit Bus Operations* is the result of the Transit Cooperative Research Program's (TCRP) Project C-8, entitled "A Framework for Evaluating Fuel Options for Transit Buses." The objective of this study was to provide transit managers with tools to simplify the process of developing an alternative-fuel strategy by clearly identifying the issues, costs, and benefits associated with converting to one or more of the various available alternative-fuel technologies. In addition to the *Guidebook*, a Microsoft Excel spreadsheet model, named *Fuelcost 1.0*, was developed that enables the user to conveniently estimate and compare the cost impacts of the available fuel options. Documentation for *Fuelcost 1.0* is contained in *Fuelcost 1.0 User's Guide,* which provides instructions for using the model, an explanation of its assumptions and methodology, and sample outputs. The *User's Guide* is provided as an Appendix to this *Guidebook* and is also available in electronic format (Microsoft Word 6.0) for viewing and/or printing on the enclosed diskette containing the *FuelCost 1.0* spreadsheet model.

Two principal objectives underlie policy makers' efforts to convert vehicular fleets to alternative fuels: emission reductions and energy security.

Research and development programs involving heavy-duty engines that use alternative fuels have demonstrated that, compared with conventional diesel engines, these engines are capable of substantially reduced emission rates of some regulated pollutants. (Table 1 summarizes the important air pollutants and their effects.) In particular, the alternative-fuel engines have demonstrated low levels of nitrogen oxides (NO_x) and particulate material (PM). Heavy-duty fleets are a major source of these pollutants. NO_x emissions lead to the formation of ozone in the atmosphere, which is one of the most severe and intractable urban air pollutants in North America (Table 1). Federal and state legislation calls for major reductions in public exposure to atmospheric ozone, which in some parts of the United States can be accomplished only through large reductions in the NO_x emission inventory from motor vehicles. Diesel PM is also of concern, because it most likely is a human carcinogen.

Domestic production of petroleum in the United States peaked in the 1970s and declined in subsequent years. This trend reflects the depletion of domestic reservoirs of easily produced petroleum after 60 years of intensive exploitation. Comparatively low-cost petroleum is still abundantly available from foreign sources. As increasing production costs have made domestic petroleum less competitive, the market share of imported petroleum products in the United States has increased dramatically in recent years (Figure 1). Increasing reliance on imported petroleum has potentially adverse effects on the U.S. economy. To maintain a balance of trade, exports must increase, which makes the economy more vulnerable to petroleum price shocks and supply restrictions that might arise from foreign political instability.

Most experts believe that the natural gas resources in the United States are very large. Almost all the demand for natural gas in the United States is met by domestic sources, although importation from Canada is growing.[1] U.S. producers of methanol, compressed and liquefied natural gas, and about 60 percent of the liquefied petroleum gas market utilize North American natural gas for feed stock. Ethanol is produced almost entirely from domestic agricultural sources (fermentation of plant sugars). Under existing economic conditions, conversion of heavy-duty fleets from diesel to any of these fuels would tend to diversify the transportation fuel market away from petroleum imports and toward North American fuel sources. Many experts believe that this would promote U.S. economic security.

1.2 ORGANIZATION OF THE *GUIDEBOOK*

This *Guidebook* provides information on the current status of diesel and alternative-fuel technologies as they apply to transit bus operations. It also suggests considerations or criteria to employ while evaluating fuel and engine technology choices. Chapter 2 reviews current and likely development in diesel engine technology and emission performance,

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[1] *Natural Gas Annual 1994*, U.S. Department of Energy, Energy Information Administration (Nov. 1995). Available from the Energy Information Administration's World Wide Web Site: http://www.eia.doe.gov.

TABLE 1 Air pollutants associated with vehicular emissions

Pollutant	Source	Environmental and Health Effects
Hydrocarbons (HC)	Unburned or partially burned fuel	Certain hydrocarbon species are carcinogenic or otherwise toxic. Hydrocarbons are also ozone precursors. With sufficient sunlight, reactive hydrocarbon species react with nitrogen dioxide in the atmosphere to produce ozone (O_3). Methane, the principal HC constituent in CNG engine exhaust is a powerful greenhouse gas.
Carbon monoxide (CO)	Product of incomplete combustion of carbonaceous fuels	Hazardous in high concentrations because it binds with hemoglobin in the blood, impairing its ability to transport oxygen.
Carbon dioxide (CO_2)	Product of complete combustion of carbonaceous fuels	Promotes greenhouse effect by increasing atmospheric absorption of infrared radiation as its concentration in the atmosphere increases.
Nitrogen oxides (NO_x) (includes NO and NO_2)	Reactions between oxygen and nitrogen in air at high temperatures	As emitted directly from the tailpipe, NO_x consists mainly of NO (90% NO + 10% NO_2). NO is non-toxic and does not promote formation of ozone. However, NO is rapidly converted to NO_2 in the atmosphere. NO_2 is an oxidizing gas which in concentrations higher than 0.2 ppm, irritates and damages lung tissue. NO_2 also combines with water to form nitric acid. Deposition of nitric acid is damaging to plants in forests and lakes.
Ozone (O_3)	Reactions between HC oxygen and NO_2, when stimulated by sunlight	Strongly oxidizing gas which is naturally present in the unpolluted atmosphere at a concentration of 0.04 ppm. At concentrations greater than 0.12 ppm, causes decreased lung function and damages lung tissue. Also damages plants.
Sulfur oxides (SO_x)	Combustion of sulfur in fuel	SO_x reacts with atmospheric water to form sulfuric acid. Subsequent reactions convert the sulfuric acid to an extremely fine solid sulfate aerosol, which impairs visibility. Deposition of this acidic material is damaging to plants.
Particulate matter (PM)	Product of combustion in diesel engines. Also produced by tire wear. PM is also produced by conversion of NO_x and SO_x into aerosols in the atmosphere.	Scatters light, reducing visibility. Particulate material finer than 10 microns in diameter (PM10) is absorbed by the lungs and causes lung damage. Diesel particulate consists entirely of PM10, and has been classified as a carcinogen by the California Air Resources Board. Particulate formed by atmospheric processes converting NO_x and SO_x into solid aerosol is considered the major source of acidic deposition (also called "acid rain").

inasmuch as diesel engines continue to represent the standard for evaluating the performance and costs of the alternative fuels. Chapters 3 through 7 of this report review the status of the five most commonly used alternative fuels: compressed natural gas (CNG), liquefied natural gas (LNG), methanol, ethanol, and liquefied petroleum gas (LPG), respectively. Each chapter addresses the fuel's principal impacts on transit operations. These effects include the following:

- Engine and vehicle technology,
- Vehicle performance,
- Fueling station design,
- Maintenance facility modifications,
- Safety considerations, and
- Fuel availability and cost.

Chapters 8 through 11 discuss key issues and prospects for other important alternative-fuel options, including hybrid electric, battery electric, fuel cell, and biodiesel technology. Chapter 12 presents comparative information that illustrates the current market status of each alternative fuel, including market share and sales trends. Because of the importance of emission performance as a transit bus market driver, emission trends for buses powered by the various available fuels are also reviewed. This analysis is based on the extensive base of chassis-dynamometer emission data that have been

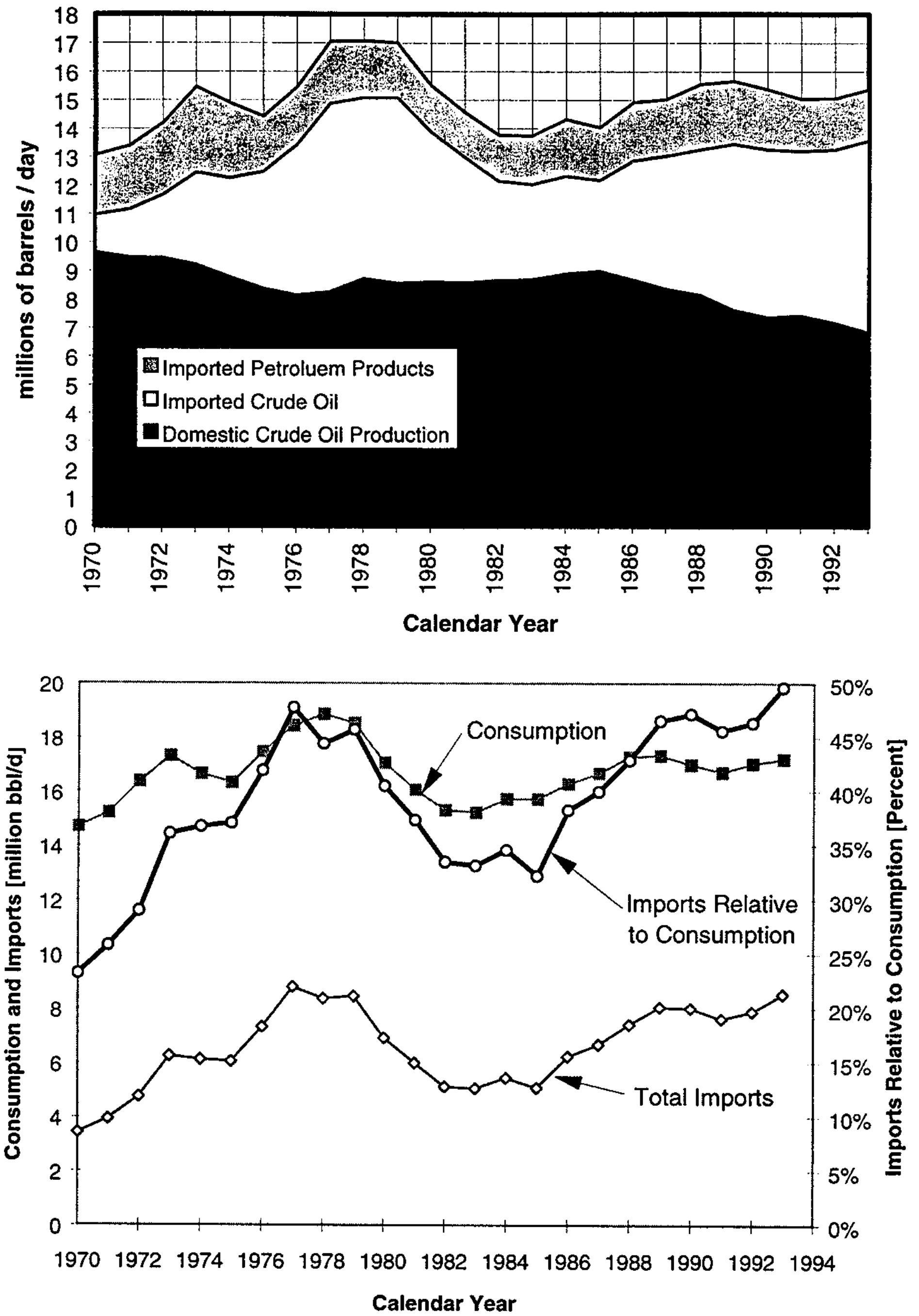

Figure 1. Trends in U.S. petroleum production, imports, and consumption. Based on data from Monthly Energy Review, U.S. Department of Energy, Energy Information Administration (March 1994).

developed for transit buses over the past few years. Chapter 13 is devoted to case studies of three transit agencies that are converting all or a portion of their fleets to alternative fuels: Sun Metro, in El Paso Texas, which is converting to LNG; Sacramento Regional Transit District, an early adopter of CNG, located in a mild climate; and Greater Cleveland Regional Transit Authority, which pioneered CNG bus operations in a cold climate where indoor parking and fueling are practiced.

Finally, Chapter 14 summarizes the available fuel options along with considerations for evaluating fuels and vehicle technologies.

For reference, Table 2 summarizes key properties of liquid and gaseous alternative fuels and automotive diesel fuel.

TABLE 2 Alternative transportation fuel data summary

Property	Unit	Fuel							
		Diesel No. 2	**Automotive Gasoline**	**Methanol**	**Ethanol**	**LPG (Propane)**	**CNG**	**LNG (Methane)**	**Biodiesel**
Appearance and Phase at Storage Conditions		Amber liquid	Yellowish liquid	Clear liquid	Clear liquid	Colorless gas	Colorless gas	Clear cryogenic liquid	Amber liquid
Water Soluble?		No	No	Yes	Yes	No	No	No	No
Higher Heating Value (60°F liquid)	Btu/lb	19,400 av	20,100 av	9,751	12,770	21,489	22,179	23,890 (g)	
	Btu/gal	138,700 av	125,000 av	64,732	84,532	90,830	140	84,242	
(Gas at 60°F & 1 Atm)	Btu/scf			867		2,516	1,050	1,010	
Lower Heating Value (LHV) (60°F liquid)	Btu/lb	18,300	18,900	8,559	11,531	19,757	20,476	21,501 (g)	16,000
	Btu/gal	128,700	117,180	56,819	76,331	83,509	124	75,818	119,200
(Gas at 60°F & 1 Atm)	Btu/scf			766		2,315	930	909	
Heat of Vaporization (at boiling pt.)	Btu/lb	90	150	463	359	183	(gas)	219	189
Charge Cooling Effect Heat of Vaporization/LHV		0.49%	0.81%	5.40%	3.11%	0.93%		1.02%	1.18%
Density:									
Liquid at 60°F, except methane	lb/ft^3	52.7	46.4	49.7	49.5	31.6		23.6[a]	55.7
	lb/gal	7.05	6.2	6.64	6.62	4.23		3.16[a]	7.450
Gas at 60°F & 3000 psig	lb/ft^3						10.6	10.5	
Vapor or Gas at 60°F & 1 Atm	lb/ft^3	0.30 - 0.45	0.15 - 0.30	0.084	0.121	0.116	0.0454	0.0423	
Vapor or Gas Relative to Air	%	400% - 600%	200% - 400%	111%	159%	152%	60%	55%	
Storage Volume Relative to Diesel		100%	110%	228%	170%	154%	445%	190%[a]	108%
Reid Vapor Pressure (100° F)	psia	0.02 - 0.2	7-14	4.63	2.31	189	(gas)	n/a	1.50E-04
Boiling Temperature at 1 Atm	°F	350-650	80-437	148	173	-43.8	(gas)	-258.9	536
Flammability Limits (by Volume)	lower	0.60%	1.40%	5.50%	3.28%	2.00%	5.00%	5.00%	
	upper	5.50%	7.60%	44.00%	19.00%	9.50%	15.00%	15.00%	
Flame Luminosity re gasoline	%	100%	100%	0.03%	3.00%	60.00%	60.00%	60.00%	
Autoignition Temp.	°F	480	495	867	793	919	999	999	482
Cetane Number		40 to 51	8 to 14	0 to 4	5 to 15	-5 to 0	-10	-10	
Octane Number (R + M)/2			85 - 95	99	100	106	116	118	47-52

[a] LNG conditioned for pumpless on-board storage tanks (saturated liquid with a vapor pressure of 80 psi).

Notes: Properties for non-pure fuels are for typical compositions.

Compiled from *Engineering Data Book,* 10th Ed., Gas Processors Suppliers Association, Tulsa, Okla. (1987); *Properties of Alternative Fuels,* FTA Report No. FTA-OH-06-0060-94-1 (March 1994); and other sources.

CHAPTER **2**

DIESEL FUEL

2.1 DIESEL ENGINE TECHNOLOGY

Diesel engine technology used in transit buses has been evolving rapidly in recent years. This has occurred in response to three driving influences:

- The dramatic tightening of emission standards,
- Major advances in understanding the diesel combustion process, and
- Development of low-cost digital electronic engine control systems.

For many years, two-stroke diesel engines had been the mainstay of the North American transit bus market. These engines offered high performance coupled with mechanical simplicity. However, two-stroke diesel engines have inherently higher lubricating oil consumption than four-stroke engines, which also results in higher PM emission rates. Two-stroke engines proved unable to meet the 1993 PM standard of the U.S. Environmental Protection Agency (EPA) (0.10 g/bhp-hour) unless they were equipped with particulate trap oxidizers in their exhaust systems. In contrast, modern four-stroke diesel engines were capable of meeting this standard **without exhaust aftertreatment.** Trap oxidizer systems proved to be expensive, complex, and unreliable in transit bus demonstrations. As a result, two-stroke automotive diesel engines are no longer sold in the United States and Canada. Over the past several years, diesel engines have realized substantial improvements in reliability, durability, and fuel economy even though their emission rates have been greatly reduced. These developments must be remembered when comparative performance data between diesel and alternative-fuel engines are being reviewed. This is particularly true with emission performance.

2.1.1 Emission Performance Trends in Diesel Engines

In the past few years, emission rates from new automotive diesel engines have decreased significantly, mainly in response to legislated emission standards. Because the diesel engine represents the standard for evaluating the emission benefits of alternative fuels in transit buses, any objective analysis of alternative fuels for transit must comprehend these trends in diesel engine emission performance. Various types of air pollutants are formed during the operation of internal combustion engines. The types of pollutants and their effects are summarized in Table 1. In the late 1970s and early 1980s, stringent emission standards were legislated for light-duty vehicles for the purpose of reducing urban smog. During this time, emission standards for heavy-duty vehicles remained comparatively lax. For example, a meaningful NO_x emission standard for heavy-duty engines did not exist in California until 1977 (Table 3) and did not exist nationally until 1979 (Table 4). This situation led air-quality regulators to project that heavy-duty vehicles would account for an increasingly larger portion of the emission inventory over time, as older high-emitting light-duty vehicles were replaced by low-emitting models. In addition, numerous studies indicated that diesel particulate is quite injurious to human health and very likely is a human carcinogen. Recognition of the need to apply more stringent emission standards to heavy-duty engines culminated in the strengthened standards enacted with the 1990 Federal Clean Air Act Amendments (CAAA).

Research institutions and engine manufactures have conducted, and are continuing, an intensive effort to better understand diesel combustion processes, in order to develop means of reducing diesel exhaust emissions enough to comply with the increasingly stringent emission standards. Regulated pollutants from automotive engines include hydrocarbons (HCs), carbon monoxide (CO), NO_x, and PM. Because of the rather complete combustion of fuel they achieve, diesel engines produce inherently low levels of HCs and CO. However, their high combustion temperatures tend to produce high concentrations of NO_x, and they tend to emit PM at much higher rates than spark-ignited engines. Although the heavy-duty NO_x standards set by 1990 CAAA were considered to be reasonably attainable by diesel engines, the PM standards for transit bus engines are very challenging. They specified PM rates of not more than 0.05 g/bhp-hour by Model Year 1996 (Table 4). Diesel PM was unregulated as recently as 1986. PM rates from unregulated engines were typically between 0.8 and 1.0 g/bhp-hour, so this standard represented an emission reduction of as much as 95 percent.

Many experts believed that diesel engines could not meet the 1996 EPA PM standard unless they were equipped with exhaust aftertreatment devices to trap or otherwise destroy the PM. Between 1988 and 1993, several manufacturers of auto-

TABLE 3 California emission standards for heavy-duty diesel engines and alternative-fuel engines derived from heavy-duty diesel engines

Model Year	Pollutant (g/bhp-hr)					
	HC	CO	NO_x	HC+ NO_x	PM	Test Procedure
All Heavy-Duty Diesel Engines						
Prior to 1973	—	—	(9-12[a])	—	(0.9-1.2[a])	(Transient cycle)
1973-74	—	40	—	16	—	13-mode steady state
1975-76	—	30	—	10	—	
1977-79	1.0	25	7.5	—	—	
1980-83	1.0	25	—	6.0	—	
1984-86	1.3	15.5	5.1	—	—	Transient Cycle
1987-90	1.3	15.5	6.0	—	0.6	
Transit Bus Engines						
1991-93	1.3	15.5	5.0	—	0.10	Transient Cycle
1994-95	1.3	15.5	5.0	—	0.07	Transient Cycle w/CARB-spec. low sulfur diesel fuel
1996-97	1.3	15.5	4.0		0.05	
1998 and later	1.3	15.5	4.0		0.05	Transient Cycle w/USEPA-spec. low sulfur diesel fuel

[a] Values represent emission test data typical of uncontrolled engines of the time.

motive catalytic converters attempted to develop practical particulate trap systems. These systems generally accumulated PM over several thousand miles, accompanied by an increase in exhaust restriction. When the exhaust restriction became sufficiently severe, electric heating elements in the trap were activated to ignite and burn away (or oxidize) the accumulated particulate. This operation was termed "regeneration." A number of buses equipped with trap oxidizers were demonstrated in transit service. Their control systems were complex and unreliable, and it was difficult to accomplish complete regeneration.

Engine researchers also worked to reduce particulate formation **in the combustion chamber** by improving the diesel combustion process. This approach proved to be more successful than trap oxidizers. Diesel PM has two major constituents: (1) a nucleus of solid carbonaceous material that is formed by incomplete combustion of the injected fuel droplets, and (2) lubricating oil and unburned products of combustion that adsorb onto the surface of the solid material. Solvents can be used to extract the second constituent from the solid nucleus and is accordingly called the **soluble organic fraction** (SOF). In addition to these major constituents, diesel PM contains less sulfuric acid, which is derived from sulfur in the fuel. Researchers have developed a number of techniques to control one or more of these PM components. These techniques are summarized in Table 5.

Manufacturers' efforts to reduce diesel PM were aided in October 1993, when the EPA established standards for automotive diesel fuel quality that substantially reduced the allowable sulfur content. Before this standard, average sulfur content was about 3 percent. The new standard limits sulfur content to less than 0.05 percent. This gives a direct benefit in reduced sulfuric acid PM emissions. Burning low sulfur EPA-specification fuel, modern diesel engines using in-cylinder PM control techniques can typically achieve engine-out PM rates as low as 0.07 g/bhp-hour. This is sufficient to meet the 0.1 g/bhp-hour legislated for heavy-duty truck engines but not the 0.05 g/bhp-hour standard for transit bus engines. Exhaust aftertreatment by oxidation catalytic converters (which do not trap diesel particulate) has been found to be effective in reducing the mass of diesel PM. The converters apparently work by burning a portion of the SOF. Although they do not act on the solid carbonaceous portion of the PM, they reduce the SOF mass enough to enable modern engines to meet the 0.05 g/bhp-hour PM standard. Because sulfur is poisonous to catalytic converters (rendering them inactive), the new diesel fuel standard also has the indirect benefit of promoting the durability of catalytic converters, making them far more practical for exhaust aftertreatment of PM. All the diesel engines currently certified for transit bus applications are equipped with oxidation catalysts.

The 1990 CAAA continued the State of California's authority to set automotive emission standards that are more stringent than the U.S. national standards. As of Model Year 1996, the NO_x emission standards set by the California Air Resources Board (CARB) for transit bus engines have become more stringent than the EPA standard. CARB has reduced the allowable NO_x rate from 5 g/bhp-hour to 4 g/bhp-hour. EPA will similarly reduce the NO_x limit for all heavy-duty engines in 1998. Therefore, the emission performance of

TABLE 4 Federal emission standards for heavy-duty diesel engines

Model Year	Pollutant (g/bhp-hr)					Test Procedure
	HC	CO	NO_x	$HC+NO_x$	PM	
1970-1973	—	—	—	—	—	13-mode steady state
1974-1978	—	40	—	16	—	
1979-1984	1.5	25	—	10	—	
1985-1987	1.3	15.5	10.7	—	—	Transient Cycle
1988-1989	1.3	15.5	10.7	—	0.60	
1990	1.3	15.5	6.0	—	0.60	
1991-1992	1.3	15.5	5.0	—	0.25	
1993	1.3	15.5	5.0	—	0.25 truck 0.10 transit bus	
1994-1995	1.3	15.5	5.0	—	0.10 truck 0.07 transit bus	Transient Cycle using low sulfur (<0.05% S) diesel fuel
1996-1997	1.3	15.5	5.0	—	0.10 truck 0.05 transit bus	
1998 and later	1.3	15.5	4.0	—	0.10 truck 0.05 transit bus	

TABLE 5 In-cylinder diesel PM control techniques

Control Technique	PM Component(s) Affected	Mode of Operation
Low Sac Injection Nozzles	Carbonaceous Particulate and SOF	Reduces leakage of fuel into the combustion chamber after the fuel injector closes
High Injection pressures (20,000-28,000 psi)	Carbonaceous Particulate and SOF	Achieves finer atomization of fuel and more efficient fuel/air mixing, resulting in more complete combustion of fuel
Electronic Injection control	Carbonaceous Particulate and SOF	Improves combustion through more precise control of fuel injection timing, and of air/fuel ratio
Turbocharging and aftercooling of intake air	Carbonaceous Particulate and SOF	Increases air density, thereby improving combustion
Optimized geometry of intake passages and combustion chamber; multi-valve heads	Carbonaceous Particulate and SOF	Increases and optimizes air swirl to promote better fuel/mixing, thereby improving combustion
Design of piston ring pack, cylinder hone pattern and valve stem seals optimized for minimizing leakage of lubricating oil into the combustion chamber	SOF	Reduces amount of lubricating oil available for absorption into the solid particulate material
Conversion from two-stroke to four-stroke cycle	SOF	Substantially reduces flow of lubricating oil into the combustion chamber
Low sulfur (<0.05%) diesel fuel formulation	Sulfuric acid	Reduces the amount of sulfur available for conversion into sulfuric acid by the combustion process

TABLE 6 Certification emission rates of Model Year 1996 transit bus engines certified by CARB

Manufacturer	Engine Model	Fuel	Emission Controls	Pollutants (g/bhp-hr)					
				THC	NMHC	CO	NO_x	PM	CO_2
Cummins	C8.3G	CNG	PCM, TC, CAC, HO2S, OC		0.10	1.10	2.60	0.01	519
Cummins	L10-280G	CNG	PCM, TC, CAC, OC	0.15		0.36	1.65	0.02	613
Cummins	L10-300G	CNG	PCM, TC, CAC, HO2S, OC		0.47	5.89	2.43	0.03	540
Cummins	M11	DSL	PCM, TC, CAC, OC	0.18		0.47	3.97	0.04	543
DDC	6V-92TA	E95	ECM, PCM, TC, CAC, OC	1.30		3.00	3.30	0.05	
DDC	Series 50	DSL	ECM, PCM, TC, CAC, OC	0.01		1.00	4.00	0.05	594
DDC	Series 50G	CNG	ECM, PCM, TC, CAC	0.74		2.48	2.73	0.05	462

DEFINITIONS:

Emission Controls		Fuels	
PCM	Electronic Power Train Control Module	CNG	Compressed Natural Gas
ECM	Electronic Engine Control module	DSL	CARB Reformulated Diesel
TC	Turbocharger	E95	95% Ethanol w/5% unleaded gasoline
CAC	Charge Air Cooler		
HO2S	Heated Oxygen Sensor		
OC	Oxidation Catalyst		
TWC	Three-Way Catalyst		

Pollutants	
THC	Total Hydrocarbon
NMHC	Non-methane Hydrocarbon
CO	Carbon Monoxide
NO_x	Nitrogen Oxides
PM	Particulate Material
CO_2	Carbon Dioxide

Note: Diesel engines were emission tested with fuel formulated to CARB's diesel fuel quality standards. CARB's standards call for a lower aromatic hydrocarbon content than those of the USEPA. Therefore these engines would likely exhibit slightly higher NO_x and PM emission rates when using USEPA-specification diesel fuel.

CARB-certified transit bus engines gives an indication of the likely performance of engines that will be offered nationally during 1998 to 2003. Certification emission rates of Model Year 1996 transit bus engines certified by CARB are shown in Table 6.[2] These data indicate that, with the exception of NO_x, emission rates of all regulated pollutants from natural gas and diesel engines are now similar. NO_x rates of diesel engines are close to the legal limit of 4 g/bhp-hour, whereas gas engines can be calibrated to achieve NO_x rates of approximately 2 g/bhp-hour.

2.1.2 Emission Performance of Diesel Engines in the Future

Air-quality modeling studies are used by regulatory agencies to predict the amount of emission reductions needed in a region for it to attain the national ambient air-quality standards (NAAQS) required by the Clean Air Act. These studies indicate that the 1998 federal NO_x standard of 4.0 g/bhp-hour for heavy-duty vehicles is not stringent enough to bring some regions (such as southern California) into compliance with the NAAQS. In 1995, the EPA and CARB held discussions with the heavy-duty engine manufacturers about the appropriateness and feasibility of additional emission reductions after 1998. These discussions culminated in a Statement of

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[2] CARB Executive Orders, information provided by T. Chang, Air Resources Engineering Associates, California Air Resources Board, Mobile Source Division.

Principles[3] that was signed in July 1995 by all the parties involved. The signatories agreed that more stringent NO_x and HC standards for heavy-duty engines were both desirable and technically feasible. The Statement of Principles calls for the emission standards shown in Table 7 to take effect as of Model Year 2004. In June 1996, the EPA issued a Notice of Proposed Rulemaking to establish regulations requiring heavy-duty engines to meet the emission levels recommended in the Statement of Principles. EPA adopted these standards in 1997. (See Federal Register, *Control of Emissions of Air Pollution from Highway Heavy-Duty Engines,* Final Rule, 40 CFR Parts 9 and 86. Vol. 62, No. 203, p. 54694 [October 21, 1997].)

As the EPA and CARB have worked diligently to develop a consensus with the engine manufacturers before proposing regulations to enforce these emission standards, it is likely that they will be adopted with little modification. Current diesel engines are already emitting HCs at rates below the rate specified in Option 2 (Table 7); hence, the effect of the standards will be to reduce NO_x rates to between 2.0 and 2.3 g/bhp-hour. These NO_x rates are very similar to those now being achieved by state-of-the-art natural gas engines (Table 6).

The proposed NO_x standard entails a 50 percent reduction in NO_x rates relative to those of the most highly emissioncontrolled models currently produced. Engine manufacturers are investigating several techniques for achieving this NO_x reduction by diesel engines. NO_x is formed by reactions between oxygen and nitrogen in the intake air, which are stimulated by high temperatures. In-cylinder NO_x control techniques work by both reducing peak combustion temperatures and reducing the duration of high combustion temperatures.

Specific diesel NO_x control techniques and their commercialization status are summarized in Table 8. Engine manufacturers are generally reluctant to divulge the details of development programs that could affect the competitive position of their products. Nevertheless, their agreement to the Statement of Principles is widely interpreted to mean that the engine manufacturers have well-developed techniques to enable diesel engines to meet the proposed emission standards for the year 2004. In addition to refining the NO_x control techniques already in use, exhaust gas recirculation (EGR) very likely will be widely incorporated to achieve the necessary NO_x reductions. Subsequent commercialization of lean NO_x catalysts may then allow the standards to be met with little or no use of EGR.

In conclusion, it appears that the dramatic improvements in the emission performance shown by diesel engines over the past decade will continue into the next. These developments are eroding the formerly significant advantages in emission performance that alternatively fueled heavy-duty engines offered over diesel engines.

TABLE 7 Proposed EPA emission standards for 2004 and subsequent model heavy-duty engines

Option	NMHC + NO_x (g/bhp-hr)	NMHC (g/bhp-hr)
Option 1	2.4	No explicit limit
Option 2	2.5	0.5

Notes: NMHC refers to nonmethane hydrocarbons.

CO and PM emission limits would remain unchanged from those of 1998-2003.

Implementation dates and emission limits could be modified following a feasibility review to be conducted in 1999.

2.2 DIESEL VEHICLE PERFORMANCE

Transit buses have become heavier in recent years. Curb weights have increased as features such as air conditioning and wheelchair lifts have become standard equipment. Chassis and suspension components also have become heavier to retain adequate durability while supporting the weight of this equipment. Air conditioning also represents a surprisingly large accessory power load. To maintain adequate acceleration and gradability with heavier vehicles equipped with air conditioning, engine ratings have increased as well; 180 bhp was typical of the two-stroke engines widely used in the early 1980s. In the mid-1980s, larger engines were introduced, with ratings between 230 and 250 bhp. The combination of increased weight accompanied by the widespread introduction of air conditioning and higher engine ratings has led to decreased fuel consumption compared with that in the early 1980s at most transit agencies. The recent conversion of the transit industry to four-stroke engines equipped with turbochargers, air-to-air aftercoolers, and electronically controlled fuel injection has tended to reverse this trend. For example, the four-stroke DDC Series 50, which has supplanted the two-stroke 6V-92, has been commonly observed to deliver 15 to 20 percent better fuel consumption than similarly equipped buses powered by 6V-92s operating over similar routes.

Fuel is a major contributor to the cost of operating a transit bus fleet. Obtaining accurate fuel cost comparisons against diesel baseline is an important element of any evaluation of alternative-fuel options. As the above discussion indicates, diesel baseline fuel consumption can vary widely, depending on several factors:

- Presence or absence of air conditioning,
- The engine's horsepower rating,
- Downtown (frequent stop, low speed) versus suburban or express service cycle,
- Curb weight and representative passenger loadings, and
- Four-stroke versus two-stroke engines.

These factors should be considered when fuel consumption data from other agencies are used to predict in-service fuel consumption and fuel cost with alternative-fuel buses.

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[3] *Heavy-Duty Engine Emission Standards for Highway Trucks and Buses,* U.S. Environmental Protection Agency, Office of Mobile Sources Environmental Fact Sheet (June 1996).

TABLE 8 Diesel NOx control techniques

Technique	How it works	Development Status
Delay (retard) timing of beginning of fuel injection	Reduces the time over which the intake charge is exposed to high temperatures. Also limits time available for combustion of fuel — too much retardation increases PM, HC and CO.	Employed almost universally in current automotive engines
High Injection pressures (20,000 to 28,000 psi)	Increases the rate of fuel delivery and improves atomization, allowing for greater injection timing retardation before PM becomes excessive.	Widely employed in current heavy duty diesel engines
Electronic Injection control	Gives better control of injection timing and fuel quantity, allowing for greater retardation of injection timing than with mechanical injection control.	Becoming almost universally employed in heavy duty automotive diesel engines
Turbocharging and aftercooling of intake air	Increases the amount of unburned air, which dilutes the heat of combustion. Aftercooling also reduces temperature of the intake charge. Both effects reduce peak combustion temperature.	Almost universally employed in heavy duty automotive diesel engines
Air-to-air aftercooling, instead of aftercooling with engine coolant	Ambient air is used to cool the intake charge after it is compressed by the turbocharger. Technique is more effective than using engine coolant, since ambient air is much cooler than engine coolant.	Becoming universally employed in heavy duty automotive diesel engines
Variable geometry turbochargers	Variable geometry turbochargers are more effective than models with fixed geometry, because they efficiently boost the intake air pressure across a wider range of engine speeds and loads.	Prototype models are being demonstrated. Variable-geometry turbochargers are nearing commercialization.
Exhaust gas recirculation (EGR)	Products of combustion (CO_2 and H_2O) in exhaust are inert in the sense that they cannot support additional combustion. EGR reduces combustion temperature by diluting combustible gases (oxygen and fuel) with additional inert gases. Too much EGR increases PM emissions and increases engine wear.	While widely used in light duty gasoline engines, EGR has been rarely employed to date in heavy duty diesel engines. Likely to be adopted in some engine models to meet heavy duty NO_x standards proposed to take effect in 2004
Improved diesel fuel quality: reduced aromatic and sulfur content along with a higher minimum cetane standard	USEPA may adopt diesel fuel quality standards similar to those currently required by CARB. Reducing aromatic hydrocarbon and sulfur content tend to reduce PM emissions, allowing greater injection timing retardation before PM becomes excessive. Higher cetane fuels experience less ignition delay (time between injection and beginning of autoignition), which also allows for increased injection timing retardation.	Has been suggested as a means of easing the difficulty of modifying diesel engines to meet the proposed 2004 NO_x standards. USEPA has not proposed rulemaking to enhance diesel fuel quality standards.
Lean NO_x catalytic converters	Diesel exhaust contains a substantial percentage of unburned or "excess" air, making conventional 3-way catalytic converters ineffective for exhaust NO_x aftertreatment. Certain zeolite catalysts have been found to reduce NO_x even with excess air.	Catalyst manufacturers have been conducting an intensive research and development program to commercialize lean NO_x catalytic converters for diesel vehicles. Progress has been slower than originally hoped. Not likely to be commercially available by 2004.

CHAPTER 3

COMPRESSED NATURAL GAS

3.1 OVERVIEW

Natural gas is a fossil fuel with greater domestic availability and frequently lower cost than petroleum. A pipeline network covering much of the United States supplies natural gas for home heating, electrical generation, and industrial processes. Pipeline natural gas is primarily methane plus minor amounts of heavier HCs and inert gases, such as nitrogen and carbon dioxide. Because of its low cost, domestic availability, and clean combustion characteristics, natural gas is also a potential alternative to gasoline and diesel fuel as a motor vehicle fuel. Methane is a small molecule in the gaseous state at room temperature and pressure, where it has a very low energy density. To boost its energy density enough to make it a practical transportation fuel, natural gas must be either highly compressed or liquefied by refrigeration. CNG vehicle technology is discussed in this chapter. LNG vehicles are discussed in Chapter 4.

From the comparative listing of chemical and physical properties of CNG and other fuels in Table 2, several properties deserve notice. Table 9 summarizes several key properties of CNG that affect its use as a transportation fuel.

Section 3.2 presents the current state of technology including the impacts of CNG fueling on engine and vehicle performance and transit buses currently in operation using the technologies identified. Sections 3.3 and 3.4 discuss potential issues related to CNG use in fueling and maintenance facilities. Section 3.5 describes safety considerations. Section 3.6 identifies fuel availability and price issues. Section 3.7 discusses potential cost implications including general capital and operating costs.

3.2 ENGINE AND VEHICLE TECHNOLOGY

3.2.1 Engine Technology

Diesel engines are technically defined as compression-ignition engines. The fuel is injected into the combustion chamber and autoignites in the hot compressed air charge—no spark plugs are used. The ease with which a fuel can be ignited in this fashion is characterized by its cetane number. Unlike diesel fuel, natural gas has a very low cetane number, and therefore it is difficult to compression-ignite. Although direct injection and ignition of natural gas by a glow plug has been demonstrated in laboratory engines, the process entails very high injection pressures [4,000 pounds per square inch (psi)] to achieve sufficiently rapid fuel/air mixing, and proper mixing and gas penetration at all loads are technically difficult to ensure. Another approach is pilot ignition or fumigation—the diesel injection system is left in place, and it is used to ignite a gas-air charge created by a mixer or gas injector. In practice, it has been difficult to achieve low NO_x emission rates in pilot ignition engines. The most successful design approaches for heavy-duty natural gas engines to date involve spark ignition of a uniform air/fuel mixture. Conversion of heavy-duty diesel engines is fairly straightforward: the diesel fuel system is removed, spark plugs and ignition system are installed, and a carburetor or electronic fuel metering system is installed in the intake manifold along with a throttle valve.

Maintaining tight control of the air/fuel ratio is critical for achieving low emission rates and high fuel economy in a spark-ignited natural gas engine. Almost all commercially available heavy-duty automotive natural gas engines are designed to maintain very lean mixtures under most conditions. The presence of excess air (i.e., more air than is needed to completely burn the fuel) has several beneficial effects:

- It dilutes the heat of combustion, thereby lowering the flame temperature, which greatly inhibits the formation of NO_x and promotes long engine life;
- It greatly reduces the formation of CO; and
- It lowers flame speed, which reduces the tendency of spark-ignition engines to knock, allowing higher torque ratings.

Knock behavior represents a crucial difference between the diesel engine and spark ignition engines. With spark ignition, a flame front propagates spherically from the spark through the uniformly ignitable mixture. At the same time, the heated, expanding products of combustion compress the remaining unburned mixture. Knock occurs when the heating due to compression is strong enough to cause the unburned mixture in front of the flame to detonate. In the diesel engine, knock is inherently avoided. This follows from the fact that the fuel must evaporate and diffuse from the surface of a liquid droplet before it can burn. The combustion rate is thereby limited by the rate of evaporation,

TABLE 9 Summary of key properties of CNG versus diesel fuel

Property	Diesel Fuel	CNG	Implications for CNG Vehicles Versus Diesel
Relative storage volume	100%	445%	Requires much more fuel storage volume for equivalent range.
Cetane number	40 to 51	-10	Difficult to compression ignite, CNG is much more suitable for spark-ignition. Spark ignition entails a 20-40% fuel efficiency penalty.
Octane number	(<0)	116	
Phase at storage conditions	Liquid	Gas	Must be highly compressed for adequate energy density.
Relative vapor density (air = 1)	4 to 6	0.6	Natural gas is lighter than air. Leaking fuel will pool near ceilings of enclosed structures and potentially ignite.
Reid Vapor Pressure	0.02 to 0.2	(gas)	CNG leaks need to be dispersed quickly (using adequate ventilation) to prevent ignition. Diesel fuel at room temperature has a very low vapor pressure; diesel leaks will not form flammable vapors.
Flammability limits in air (volume %)	0.6 to 5.5	5 to 15	

even at extremely high pressures and temperatures. Compression ratio and turbocharger boost pressure, and hence torque, are not knock limited. The performance of diesel engines is limited mainly by thermal loads imposed on the piston. The practical result is that spark-ignited natural gas engines are knock limited to torque ratings approximately 25 percent lower than those of geometrically similar diesel engines.

Furthermore, a high-torque natural gas engine designed for lean calibration can be quickly damaged by knock if its mixture is allowed to drift rich. This has occurred in transit buses owing to two principal causes:

- Poor air/fuel ratio control caused by defects or design limitations of the onboard fuel-metering system, and
- Perturbations in the composition of pipeline gas, especially in regions where stored propane is used to meet wintertime peaks in gas demand.

Natural gas liquids, such as ethane and propane, have considerably higher heating values per unit volume than methane; they also have much lower knock resistance. Therefore, if the pipeline gas composition shifts too far in the direction of more natural gas liquids and less methane, knock-related engine damage is likely to occur. Engine designers are forced to limit performance of natural gas engines in order to provide a margin of safety against the wide variations in composition that can occur in pipeline gas. This compositional variation makes it difficult for the engine designer to calibrate the engine for optimum emission performance as well, particularly with respect to NO_x.

The most recent versions of heavy-duty natural gas engines offered by Cummins and DDC are equipped with electronic control systems, which should offer the engine greater protection against the effects of variable fuel quality and other problems occurring in fleet service. These control systems incorporate sensors to measure the mass flow rates of air and fuel as well as exhaust gas oxygen sensors that monitor the actual air/fuel ratio. Using the signals from these sensors, the electronic control system can precisely adjust the fuel flow rate to compensate for variations in fuel composition, fuel pressure (due to fuel filter clogging, poor pressure regulation, or other causes), and intake air density (due to elevation changes or air filter clogging).

Although electronic fuel control systems are well proven in diesel engines, they have been introduced in heavy-duty natural gas engines only recently, so design and durability defects may surface in the future.

Diesel engines have excellent fuel economy. This is largely the result of two design features: (1) the compression ratio is not knock limited, so very high compression ratios (14:1 to 17:1) may be used; and (2) the intake air is not throttled, so pumping losses are low.

Conversion to spark ignition entails installation of a throttle valve and a reduction in the compression ratio. These modifications are observed to result in reductions in fuel economy of between 20 and 40 percent in transit service when natural gas engines are used in place of similar diesel engines in similar service.

Most of the U.S. diesel engine manufacturers are currently conducting heavy-duty natural gas engine research and development, prototype engine demonstration, and commercial sales of certified engines. In addition, various other companies offer equipment and services to convert existing diesel engines to natural gas engines. Most of these conversions result in pilot ignition (i.e., dual-fuel) natural gas engines, although a few are conversions to dedicated natural gas sparkignition operation.

Four companies (Cummins, DDC, Hercules, and Tecogen) currently offer commercialized heavy-duty natural gas engines for transit buses. All are spark-ignition engines. DDC and Cummins are also demonstrating prototype high-horsepower (hp) (about 350 hp) spark-ignition natural gas engines in large Class 8 trucks. In addition, Caterpillar is developing direct-injection natural gas engine technology. DDC had been developing direct injection of natural gas for the 6V-92 (two-stroke cycle) but suspended work in this area when they shifted from two-stroke to four-stroke diesel engines for transit applications.

3.2.2 Vehicle Performance

The performance and drivability of a CNG bus can be made equal to those of a diesel bus. However, some increase in rated speed or displacement may be needed to offset the CNG engine's lower torque capability.

The size and weight of CNG tanks is an issue for virtually all CNG vehicles. Because the tanks are necessarily cylindrical, they cannot be custom fit into tight areas. Tanks are much larger than energy-equivalent diesel tanks because of the lower energy density of the fuel. Vehicular CNG tanks are manufactured from steel, fiberglass-reinforced steel, fiberglass-reinforced aluminum, or all-composite construction. They are designed for working pressures of 3,000 or 3,600 psi. Thick wall sections are needed to guarantee sufficient strength to contain these high pressures, which causes CNG tanks to be heavier than diesel fuel tanks with similar energy capacity. For example, Los Angeles County Metropolitan Transportation Authority (LACMTA) has reported a weight penalty of 3,000 pounds (lb) versus diesel buses for its CNG buses fitted with fiberglass-reinforced aluminum CNG cylinders. This weight penalty can reduce legal passenger capacities in bus models that already have high curb weights in the diesel versions. The newest generation of lightweight CNG cylinders use plastic liners wrapped by fiber-reinforced composites. These all-composite tanks are about one-half as heavy as those that use aluminum liners, which greatly mitigate CNG's weight penalty.

As noted in Section 3.2.1, CNG transit buses have experienced a fuel economy penalty of between 20 and 40 percent compared with diesel buses in similar service.

The simple chemistry of the methane molecule and the combustion properties of natural gas combine to enable engineers to achieve lower exhaust emissions with natural gas engines than with diesel engines. In particular, natural gas engines are able to simultaneously achieve low particulate and low NO_x emissions, which is difficult for diesel engines to achieve. For example, the 240-hp natural gas Cummins L-10G has been certified at 2.0 g/bhp-hour NO_x and 0.02 g/bhp-hour particulate. For comparison, new diesel engines are typically certified at approximately 4 g/bhp-hour NO_x and 0.05 g/bhp-hour particulate. However, in-use testing of CNG buses indicates that NO_x emissions can be significantly higher, and these emissions are highly sensitive to engine tuning.[4] Comparative emission data for alternativefuel and diesel transit buses are presented in Chapter 12.

3.2.3 Vehicles Currently in Use

CNG is by far the most popular alternative to diesel in transit bus applications. A growing number of transit agencies operate CNG buses. Table 10 lists these agencies and the vehicles they operate. Forty-seven transit agencies currently use CNG, and an additional 14 agencies have CNG buses on order. Seventeen agencies currently using CNG buses have additional ones on order. Note that the number of buses on order (1,072) is only somewhat less than the number currently in use (1,388), indicating that the market share for CNG buses is growing rapidly. Figure 2 shows a CNG bus at Pierce Transit in Tacoma, Washington.

3.3 FUELING FACILITY IMPACTS

3.3.1 CNG Fueling Approaches

There are four general fueling station design approaches for CNG vehicles. These four approaches are direct fast fill, fast fill from storage, slow (or time) fill, and fast/slow fill.

The cost of a gas compressor increases with its design capacity. Fleet fueling operations can vary greatly in terms of available time to fuel a vehicle and the number of vehicles fueled per day. Proper selection of the fueling approach allows fleet operational requirements to be met and also minimizes the capacity and cost of the compressor station. The following sections briefly describe these fueling approaches.

3.3.1.1 Direct Fast Fill

Of the four basic CNG fueling approaches, direct fast fill most closely resembles current liquid fueling practices. The objective is to fill the CNG tanks as quickly as diesel, in 3 to 10 min. Figure 3 shows the principal elements of a direct fast fill station. Gas is supplied by the local utility via underground pipeline. To minimize the cost of the compressor station and the energy needed to compress the gas to the design storage pressure, it is desirable that the gas be provided at the highest possible pressure. The gas line must also be sufficiently large in diameter to deliver gas at the high rate demanded by the station. Unless the bus garage's design and construction anticipated CNG bus fueling, the gas line to the garage will likely have to be upgraded to meet the demand of the fueling station.

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[4] *Compressed Natural Gas Project Monitoring and Reporting*, Acurex Environmental, for Yolo County Transit Authority (March 1995).

TABLE 10 CNG-fueled full-size transit buses in use and on order

Transit System	City	No. In Use	No. On Order	Chassis Mfr.	Chassis Model	Length (ft)	Engine Mfr.
1 Albuquerque Transit Dept.	Albuquerque, NM		40	Neoplan			Cummins L10G
2 MARTA	Atlanta, GA	118		New Flyer Ind.	D40LF	40	DDC Series 50G
3	Akron, OH		18	Flxible		40	DDC Series 50G
4 Capital Metropolitan Trans. Auth.	Austin, TX	34		TMC	RTS 08	40	Cummins L10G
5 Mass Transit Admin. of Maryland	Baltimore, MD	8		Flxible		40	Cummins L10G
6 BCT	Binghamton, NY	50		Orion Bus Ind.	Orion 5.501	40	
	Binghamton, NY	3		Orion Bus Ind.	Orion 5.501		Cummins L10G
7 BJCTA	Birmingham, AL		12	Flxible			
8 Boise Urban Stages	Boise, ID	20		Orion Bus Ind.	Orion 5.501	33	Cummins L10G
Boise Urban Stages	Boise, ID		16	El Dorado-National	Transmark	30	Hercules GTA5.6
9 Brazos Transit System	Bryan, TX	8	100	El Dorado-National		30	Hercules GTA5.6
10 Niagara Frontier Trans. Auth.	Buffalo, NY	5		Orion Bus Ind.	Orion 5.501	40	Cummins L10G
11 Greater Cleveland Regional Transit Auth.	Cleveland, OH	60		Flxible	Metro 40102-4D-1	40	DDC Series 50G
Greater Cleveland Regional Transit Auth.	Cleveland, OH	20		Flxible	Metro 40102	40	Cummins L10G
Greater Cleveland Regional Transit Auth.	Cleveland, OH	1					Cummins C8.3G
13 Dallas Area Rapid Transit	Dallas, TX	2		Flxible	Metro 40102	40	Cummins L10G
14	Davis, CA	15		Orion Bus Ind.	Orion 5.501		Cummins L10G
15 Denver Intnl. Airport	Denver, CO	4		Neoplan			Cummins L10G
16 Sun Metro	El Paso, TX	20		Orion Bus Ind.	Orion 5.501	40	Cummins L10G
17 Fort Worth Trans. Auth.	Fort Worth, TX	55		Flxible	Metro 40102-6C-1	40	Cummins L10G
18 MTA Long Island Bus	Garden City, NY	35	125	Orion Bus Ind.	Orion 5.501	40	Cummins L10G
19 LAKETRAN	Grand River, OH		13				

The gas is compressed to approximately 4,500 psi at the compressor outlet. At this high pressure, water and heavier HCs in the gas condense. Liquids in the onboard fuel system's regulators and tanks adversely affect their performance. Therefore, the gas is normally conditioned by a dryer to remove water from the feed stock gas before it enters the first stage of the compressor. The dryer contains a sorbent material, which must be periodically regenerated by heating. Condensable HCs and compressor oil are then removed by a coalescing filter, which is located at the compressor outlet, and in some designs it is at the outlet of each compressor stage. Liquids collected in the filter receptacles must be drained at regular intervals.

CNG compressors usually compress the gas to storage pressures in three or four stages. The compression ratio across each stage is usually between 3:1 and 4:1. The gas is heated as it absorbs the work of compression; it is desirable to maximize the density of the gas and to reduce the work of compression by minimizing the associated increase in temperature. This is accomplished by routing the gas through finned, air-cooled heat exchangers between each stage. Each stage consists of a piston reciprocating in a cylinder, with gas exchange controlled by valves. A crankshaft drives the cylinders via connecting rods. The piston-cylinder interface is sealed by compression rings, with the cylinder wall generally splash lubricated by specially formulated lubricating oil. (Compressors that do not use oil are available from some manufacturers.) Overall construction is analogous to that of an automotive engine.

The compressor delivers the gas to a buffer/receiver tank with a typical storage capacity of 30,000 standard cubic feet (scf). This allows the compressor to continue delivering gas while the dispensers are disconnected from the buses. This arrangement gives two benefits: (1) on/off cycling of the compressor (which causes wear) is minimized; and (2) the average gas delivery rate is increased.

A hose and nozzle assembly dispenses gas through a quick disconnect coupling, which mates with a receptacle on the bus. The dispenser's appearance and function usually resemble those of a diesel dispenser. Metering natural gas delivery is complicated by the wide variation in pressure, temperature, and density that occur as the onboard tanks are filled. Good accuracy has been obtained with vibrating tube mass flow meters; however, these meters are fairly expensive.

TABLE 10 *(continued)*

Transit System	City	No. In Use	No. On Order	Chassis Mfr.	Chassis Model	Length (ft)	Engine Mfr.
20 Hamilton Street Railway Company	Hamilton, ON		25	New Flyer Ind.	D40LF	40	DDC Series 50G
	Hamilton, ON	29		Orion Bus Ind.	Orion 5		Cummins L10G
	Hamilton, ON	1		Orion Bus Ind.	Orion 5		Cummins C8.3G
21 Kenosha Transit	Kenosha, WI	10	2	TMC	T80 208	40	Cummins L10G
22	Kitchener, ONT		23	New Flyer Ind.			DDC Series 50G
23	Laredo, TX		12	Flxible			DDC Series 50G
24 Los Angeles County Met. Transportation Authority (LACMTA)	Los Angeles, CA	10		Flxible	Metro 40102-6C-1	40	Cummins L10G
Los Angeles County Met. Transportation Authority (LACMTA)	Los Angeles, CA	294		Neoplan	AN-440-A	40	Cummins L10G
25 Los Angeles Department of Transportation	Los Angeles, CA	56		El Dorado	RE-29 & Transmark	29	Hercules and Cummins L10G
Los Angeles Department of Transportation	Los Angeles, CA	20				40	DDC6V-92 PING
26	Lubbock, TX		36	Flxible			DDC Series 50G
27 Metro-Dade Transit Agency	Miami, FL	5		Flxible	Metro 40102-6C-1	40	Cummins L10G
28 Nassau-Libus	Mineola, NY	27		Orion Bus Ind.	Orion 5		Cummins L10G
	Mineola, NY	1		Orion Bus Ind.			Cummins C8.3G
29 Mississauga Transit	Mississauga, ON	11	11	Orion Bus Ind.	Orion 5.501	40	Cummins L10G
30 Monterey-Salinas Transit	Monterey, CA		9	Orion Bus Ind.		35	DDC Series 50G
31 Montgomery County Transit Services	Rockville, MD	3		Orion Bus Ind.	Orion 1.507	35	Cummins L10G
32 MTA New York City Transit	New York, NY	33		Orion Bus Ind.	Orion 5.501	40	Cummins L10G
33 NYCDOT	New York, NY	52		TMC	T80 208	40	Cummins L10G
NYCDOT	New York, NY		174	Orion Bus Ind.		40	DDC Series 50G
34 New Jersey Transit Corporation	Newark, NJ	5		Flxible	Metro 40102-6C-1	40	Cummins L10G
35 North San Diego Transit Corp.	Oceanside, CA	6		Flxible	Metro 40102-6C-1	40	Cummins L10G
36	Oklahoma City, OK		3	Novabus	RTS	40	DDC Series 50G

3.3.1.2 Compression Heating

Despite the use of interstage cooling, the compressor station commonly delivers gas to the bus's tanks at temperatures as high as 190°F to 200°F (87.7°C to 93.3°C). Assuming that the tank is filled to 3,600 psi at these temperatures, the pressure will then fall substantially when the tanks' contents cool to ambient temperature (at which point it has reached its "settled pressure"). The tank is thereby effectively underfilled, as it is designed to sustain settled pressures of 3,600 psi, which produce a more dense fill than the same pressure at elevated temperatures. To avoid underfilling associated with compression heating, the dispenser's controller may be designed to overfill the bus's tank enough that it will be filled to 3,600 psi when it cools to ambient temperature. This process subjects the tanks to pressures on the order of 4,000 psi before settling. Experience suggests that this is the most likely time for a defective or damaged tank to fail.

Compressing natural gas to 4,500 psi at the high flow rates needed for transit fueling operations requires substantial power. For example, to fill a 150-bus division in 8 hours, a station with a compression capacity of 2,400 scf/min is usually needed. Approximately 670 shaft hp are needed to deliver gas at 2,400 scf/min, with an inlet pressure of 150 psi.[5] Compressor drive is normally provided by three-phase AC induction motors, using a 480-volt (V) AC sup-

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[5] Keder, J., and Darrow, K., Energy International Inc., *An Assessment of Gas Engine Drives for CNG Compressors at NGV Fueling Stations.* GRI-95-0163, Gas Research Institute, Chicago, Ill. (June 1995) p. 10.

TABLE 10 (continued)

Transit System	City	No. In Use	No. On Order	Chassis Mfr.	Chassis Model	Length (ft)	Engine Mfr.
37 Orange County Trans. Auth.	Orange, CA	2		Gillig	Phantom 40TB96	40	Cummins L10G
38 LYNX	Orlando, FL	10		New Flyer Ind.			DDC Series 50G
39 South Coast Area Transit	Oxnard, CA	26		Flxible	Metro 35102-4D-1	35	DDC Series 50G
South Coast Area Transit	Oxnard, CA		9	Orion Bus Ind.	Orion 5		DDC Series 50G
40 City of Phoenix	Phoenix, AZ	23	6	El Dorado-National	Transmark	30	
41 Port Auth. of Allegheny County	Pittsburgh, PA	5		Orion Bus Ind.	Orion 5.501	40	Cummins L10G
42 Berks Area Reading Trans. Auth.	Reading, PA	1		Orion Bus Ind.	Orion 5.501	40	Cummins L10G
Berks Area Reading Trans. Auth.	Reading, PA		5	New Flyer Ind.		40	DDC Series 50G
43 Riverside Transit Authority	Riverside, CA	18		Flxible		40	Cummins L10G
44 Rochester-Genesee Regional Trans. Auth.	Rochester, NY	5		Orion Bus Ind.	Orion 5.501	40	Cummins L10G
45 Sacramento Regional Transit District	Sacramento, CA	95	40	Orion Bus Ind.	Orion 5.501	40	Cummins L10G
46 Utah Transit Auth.	Salt Lake City, UT	5		Orion Bus Ind.	Orion 5.501	40	Cummins L10G
47 Omnitrans	San Bernardino, CA		24	Orion Bus Ind.			Cummins L10G
Omnitrans	San Bernardino, CA		7	Neoplan			Cummins L10G
48 San Diego Met. Transit Develop. Board	San Diego, CA	4	51	New Flyer Ind.	D40	40	DDC Series 50G
	San Diego, CA	6		Flxible			Cummins L10G
San Diego Transit Corp.	San Diego, CA		29	New Flyer Ind.			DDC Series 50G
49 San Luis Transit	San Luis Obispo, CA	2		Orion Bus Ind.		40	Cummins L10G
50 Sonoma County Transit	Santa Rosa, CA		15	Orion Bus Ind.	Orion 5.501	40	DDC Series 50G
51 Bi-State Development Agency	St. Louis, MO	2		Flxible	Metro 40102	40	Cummins L10G
Bi-State Development Agency	St. Louis, MO		49	Neoplan	AN-440-A	40	Cummins L10G

ply Assuming that the motor is 85 percent efficient, an electrical load of

$$\frac{670\ sHP \cdot \left(\frac{1\ kW}{1.341\ sHP}\right)}{0.85} = 590\ kW \qquad (1)$$

would result. This is a large load, which may require upgrading the electrical service to the garage. The compression load would likely be distributed across a minimum of three 800-scf/min compressors operating together, with each compressor powered by a 200-kilowatt (kW) motor. To protect the operation from breakdown of a compressor, and to minimize wear by distributing the work across a greater number of compressors, it is advisable to install a fourth, redundant compressor.

Direct fast fill is normally used when a fleet of 100 or more buses must be fueled within an 8-hour shift. Installation costs can vary, depending on several design variables. These include the following:

- The gas line pressure available;
- The flow rate desired;
- How extensively the gas is dried and filtered; and
- How much compressor redundancy is specified for purposes of reducing the wear rate of each compressor, or to guard against a compressor failing.

Total installed costs reported for recent CNG fueling stations for transit bus operations have been between $1.5 million and $3 million. A common rule of thumb for estimating compressor station capital costs is to assume that the cost will be between $800 and $1,000 per scf/min of capacity. For example, the cost of a 2,000-scf/min station would be between $1.6 million and $2 million.

3.3.1.3 Fast Fill from Storage

Fast fill from storage is similar to direct fast fill except that large storage capacity allows the use of a much smaller compressor. Figure 4 illustrates the fast fill from storage option. Buses are fueled from storage tanks. To efficiently utilize a given gas storage capacity, the storage tanks are usually connected in a "cascade" fashion. A bus is initially filled from a low-pressure storage tank, and then from a storage tank at a

TABLE 10 (continued)

Transit System	City	No. In Use	No. On Order	Chassis Mfr.	Chassis Model	Length (ft)	Engine Mfr.
52 Centre Area Trans. Auth.	State College, PA		4	New Flyer Ind.		40	Detroit Diesel
53 Central New York Regional Trans. Auth.	Syracuse, NY	8		Orion Bus Ind.	Orion 5.501	40	Cummins L10G
Central New York Regional Trans. Auth.	Syracuse, NY		25	Novabus	RTS		Cummins L10G
54 Pierce Transit	Tacoma, WA	58	18	Orion Bus Ind.	Orion 5.501	40	Cummins L10G
Pierce Transit	Tacoma, WA		15	Orion Bus Ind.			DDC Series 50G
55 Hillsborough Area Regional Transit Auth.	Tampa, FL		5	Blue Bird	Bus	30	Cummins L10G
56	Stratford, Ont.	25		Orion Bus Ind.			Cummins L10G
57 Sun Line Transit	Thousand Palms, CA	32		Orion Bus Ind.	Orion 5.501	40	Cummins L10G
Sun Line Transit	Thousand Palms, CA	2		Orion Bus Ind.			Cummins C8.3G
58 Toronto Transit Commission	Toronto, ON	25	50	Orion Bus Ind.	Orion 5	40	Cummins L10G
Toronto Transit Commission	Toronto, ON		50	Orion Bus Ind.	Orion 6	40	Cummins L10G
59 City of Tucson Mass Transit System	Tucson, AZ	3		Neoplan	AN-440-A	40	DDC Series 50G
City of Tucson Mass Transit System	Tucson, AZ		26	New Flyer Ind.	D40LF		DDC Series 50G
60 BC Transit — Vancouver Regional Transit	Vancouver, BC		25	New Flyer Ind.	D40	40	DDC Series 50G
61 Yolo County Transit	Yolo Co., CA	7		Orion Bus Ind.			Cummins L10G
	TOTALS	1388	1072				

Compiled from American Public Transit Association 1996 Transit Passenger Vehicle Fleet Inventory, and data provided by Mr. Clark Ahrens, Cummins Engine Co. and Mr. Patrick Scully, Detroit Diesel Corporation.

medium pressure, and finally the bus is "topped off" from a storage tank that is at a pressure slightly above the desired maximum pressure of the onboard fuel tanks.

The CNG storage volume must be at least 3 times (often up to 4 times) the fill requirement of the bus to achieve fast fill. Also, the gas delivery piping, hose, fueling nozzle, and all the piping on the bus must be designed large enough for the fueling time desired. If on-site CNG storage is not large enough then the bus will not be capable of being completely filled. If the piping is too small in any part of the delivery system, complete refueling may be achieved, but the fueling time will be unacceptably long.

Figure 2. CNG bus at Pierce Transit (Tacoma, Washington).

The compressor system operates over a time period longer than the bus fueling window (up to 24 hours per day in some cases) to fill the storage tanks, and therefore its capacity can be considerably less than that required for direct fast fill. The amount of gas storage required depends primarily on the number of buses to be fueled and the quantity of fuel required by each bus. It also depends on the compressor size and the fueling window. The pressure in the storage tanks obviously decreases as the pressure in the bus tank increases. Therefore, the storage tanks need to be charged to a pressure higher than the maximum bus fuel tank pressure. If all the storage tanks were interconnected so that they were at the same pressure, it would be impossible to completely fill the bus tanks when the storage pressure drops below the maximum bus tank pressure.

Fast fill from storage is ideally suited for small fleets or fleets that fuel at various times throughout the day (instead of all at once during a fueling window). For large fleets where all the vehicles must be fueled within a given fueling window, a very large storage capacity may be required, and this can be even more expensive than the large compressors required for a direct fast fill system.

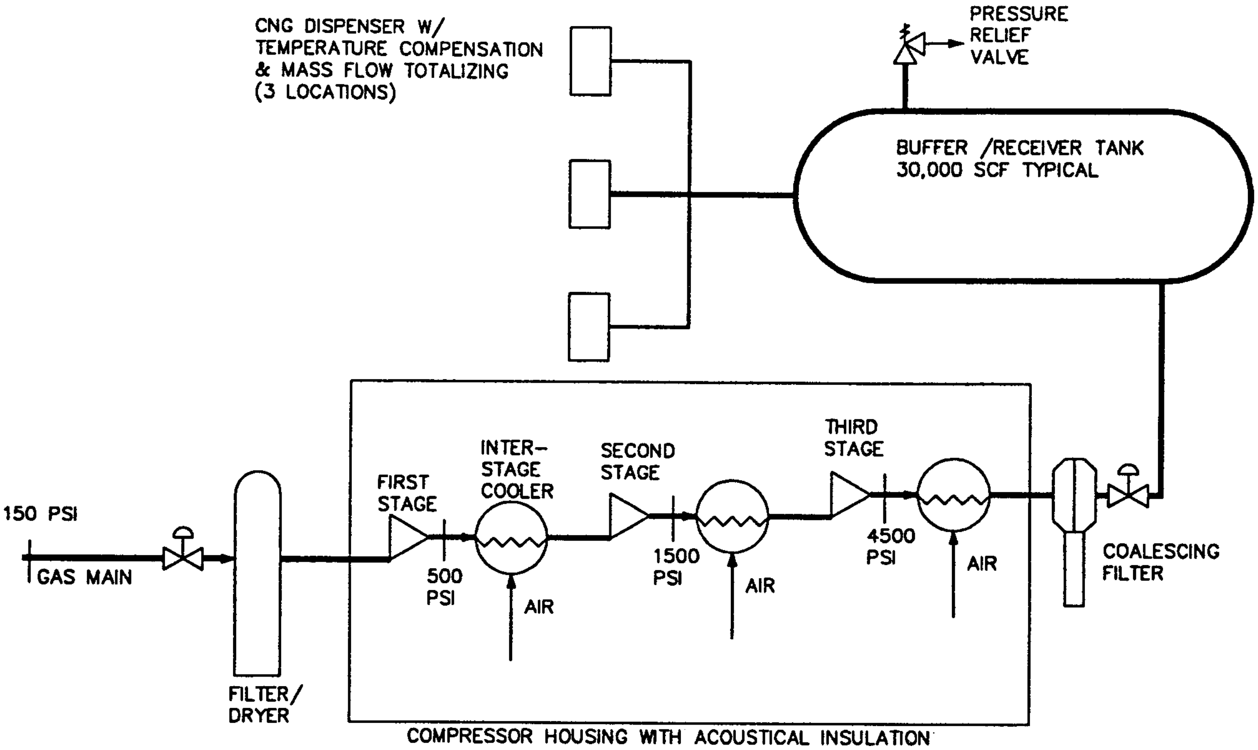


Figure 3. Direct fast fill CNG fueling station.

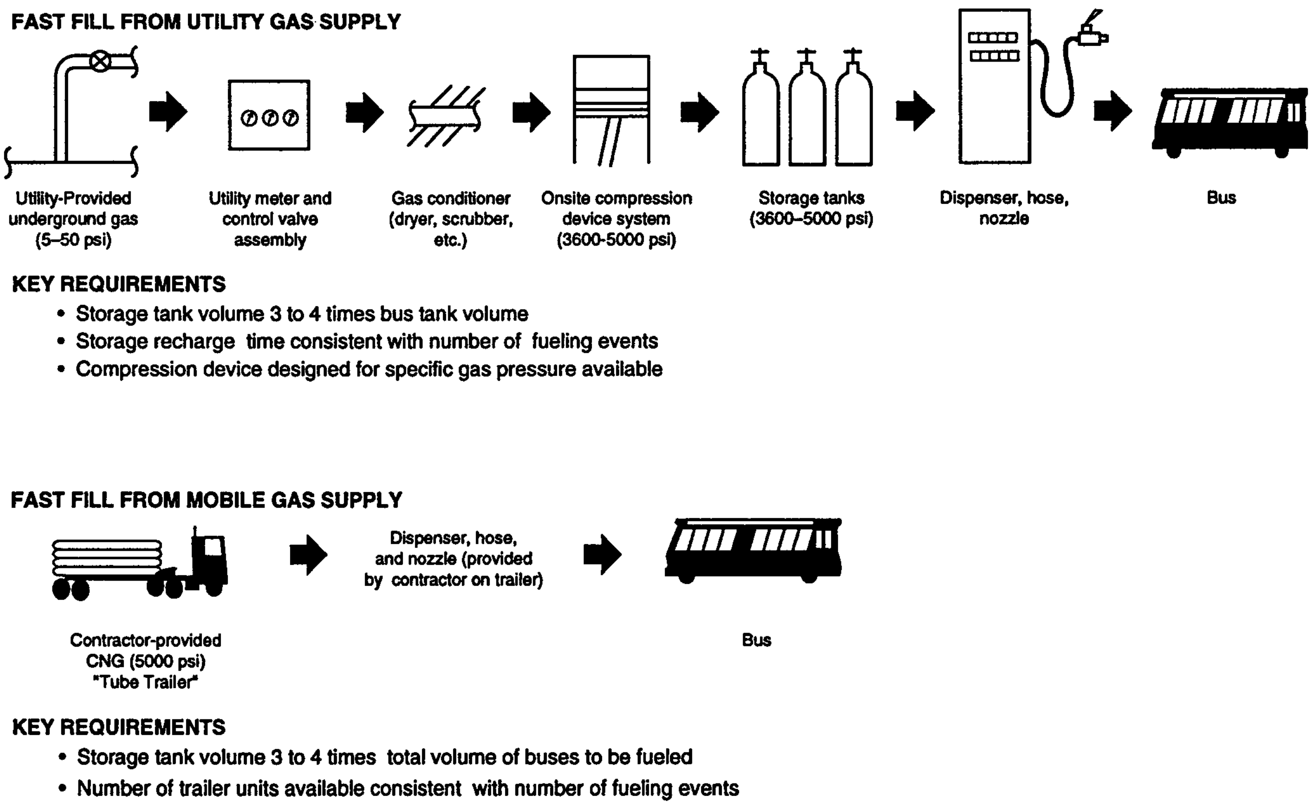
Mobile fueling (also illustrated in Figure 4) is another option. Vehicles are fueled directly from trailer-mounted gas storage tanks. The trailer is transported to a compressor station to be refilled. No compressor or permanent gas storage is required at the fueling site. Fueling trucks are available that can off-load at approximately 800 cubic ft/min (cfm) and can off-load at a rate of 117 thousand cubic ft (Mcf) or 129 Mcf depending on the vehicle. A small (10-bus) fleet requires only about 80 Mcf per day, so these trucks can supply a sufficient quantity of gas with one delivery for its daily use. This strategy is being promoted as an interim fueling scenario. As fleet sizes increase beyond 10 or 12 vehicles, the fuel required for one day's use could not be delivered in one truckload. Multiple daily deliveries would be required to adequately fuel larger fleets.

3.3.1.4 Slow (Time) Fill

The slow (time) fill approach is the most simple, inexpensive, and relatively common approach for light-duty CNG vehicles, but it has not been applied extensively to transit buses. The objective of slow fill, shown in Figure 5, is to fuel many vehicles at once over a long period, typically overnight. The compressor is sized for fueling the whole fleet simultaneously over 12 hours or more. A manifold piping system distributing high-pressure gas through multiple flexible hoses and individual nozzles brings the fuel to the buses. Storage tanks are not required; instead, a small receiver is included for system control. Generally, a dispenser is not useful for such systems because all vehicles are fueled at once with no need for determining fuel usage on an individual basis. Fuel flow to each vehicle is automatically shut off when sufficient back pressure is reached. For fleets of more than 40 vehicles, the compressor flow rates needed for slow fill stations become approximately equal to those associated with fast fill designs. Therefore, slow fill systems are normally applied only to fleets of 40 or fewer vehicles.

3.3.1.5 Fast/Slow Fill

The fast/slow fill approach is illustrated in Figure 6. This system combines the features of both the fast and slow fill approaches. Regular fueling is done with a slow fill system similar to that described previously. Additional storage is provided onsite to allow for small-scale fast fill capacity such as that required for "topping off" a limited number of vehicles. The storage tanks are recharged by the compressors when they are not being used for slow fill fueling. This approach could be applicable to an agency with a few buses, smaller support vehicles, and smaller transit vehicles.



KEY REQUIREMENTS

- Storage tank volume 3 to 4 times bus tank volume
- Storage recharge time consistent with number of fueling events
- Compression device designed for specific gas pressure available

KEY REQUIREMENTS

- Storage tank volume 3 to 4 times total volume of buses to be fueled
- Number of trailer units available consistent with number of fueling events

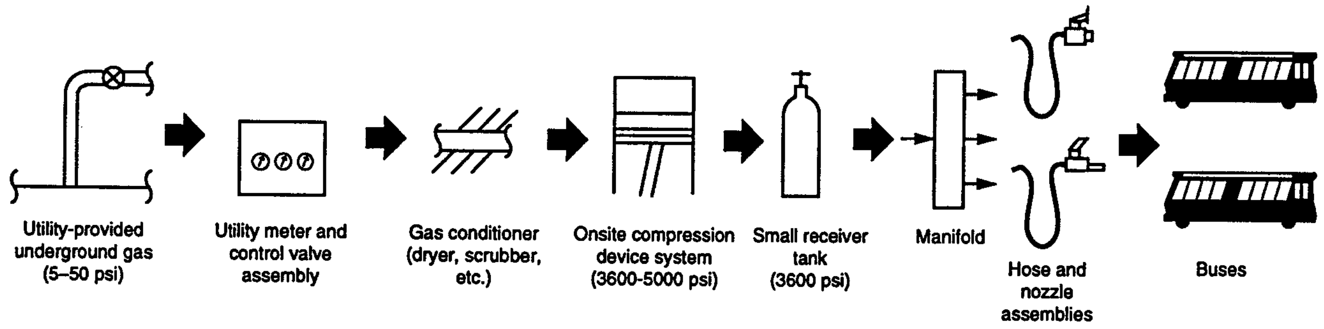
Figure 4. Fast fill from storage.

3.3.2 Other Fueling Facility Design Considerations

A CNG fueling station presents potential hazards due to fire and due to the high pressures it employs. Accordingly, many design requirements govern the CNG fueling facility. National Fire Protection Association (NFPA) Standard 52 (*Standard for Compressed Natural Gas Vehicular Fuel Systems,* 1995 Edition) is used by most fire officials to delineate the requirements for CNG equipment. Discussion with the Fire Marshall is an essential step in the planning of any new CNG fueling station, in order to satisfy any local requirements that the officials may impose beyond those of NFPA 52. CNG typically is stored in cylinders designed for working pressures between 3,000 and 4,800 psi. All devices designed to store or transmit CNG must be capable of withstanding from 1.5 to 4 times the maximum working pressure of the gas and must be designed for natural gas service, using appropriate standards. Labeling requirements apply to devices such as cylinders, valves, hoses, regulators, and filters. NFPA 52, Section 2-8.4, states that cast iron, plastic, galvanized aluminum, and copper alloys exceeding 70 percent copper are not approved for CNG service, because these materials lack the necessary strength or resistance to corrosion required for such service. Stainless steel is the material of choice for CNG piping and components because of the corrosive nature of water and sulfur compounds that may be found as contaminants in CNG.

Large stationary CNG tanks of the type used for fueling facilities are typically manufactured from steel and are qualified under American Society of Mechanical Engineers (ASME) pressure vessel code, Section VII, Division I and Appendix 22. These pressure vessels are rated as high as 4,900 psi. Earthquake restraints are needed for cylinder storage in California.

The work of compression represents a significant operating cost for a CNG fueling station. This cost is normally higher if electric motors are used for compressor drive instead of natural gas engines. If a large, high-capacity compressor station is installed and operated while the CNG fleet is still small, electrical demand charges can be very high relative to gas throughput. The pressure in gas lines falls from 150 to 200 psi to about 25 psi, as it moves from large transmission lines to local distribution lines. To reduce the cost of compression, it is desirable to supply the compressor station with gas at the highest possible pressure. Transit agencies investigating the installation of CNG compressor stations should contact their gas utility company to determine whether high-pressure lines are available near the fueling station site.



KEY REQUIREMENTS

- **Compression device sized for inlet pressure available and flowrate required for overnight fueling of all vehicles simultaneously**
- **No storage tanks, no totalizing dispenser**
- **Gas distributed to regular vehicle parking spaces**

Figure 5. Slow fill.

3.3.3 CNG Compressor Maintenance

Proper design and maintenance of both compressors and filter/coalescers are necessary to preclude the introduction of water or compressor lubricating oil into the vehicle fuel systems. The large, positive-displacement compressors used in fast fill stations are constructed much like an automotive engine: they have pistons working in cylinders, piston rings, and lubricating oil to seal the piston-ring interface, and poppet valves to control the flow of gas. They work hard and are subject to some of the same types of failure as engines: wear of rings, cylinders, and crank bearings, and valve and cam failures. A leading manufacturer of reciprocating natural gas compressors reports 10,000 hours between overhauls and guaranteed ring life of 6,000 hours.[6] This is equivalent to 2.5 years in a fully operational direct fast fill station. Filters and compressor oil must be replaced periodically to prevent premature wear. Agencies considering CNG should be aware that fueling station maintenance requirements for CNG are much more rigorous (and costly) than those for other fuels. An industry rule of thumb is to assume that compressor station maintenance costs will be 3 percent of plant value per year.

For readers who are interested in additional details of CNG transit bus fueling station siting, design, construction, and maintenance considerations, the Gas Research Institute (GRI) recently published the *CNG Transit Fueling Station Handbook,*[7] which provides a clear and comprehensive treatment of the subject.

3.4 MAINTENANCE GARAGE IMPACTS

Diesel fuel has a very low vapor pressure at room temperature. Combustible vapors do not normally form above diesel fuel spills; this property makes the fuel comparatively resistant to ignition, and few precautions are needed for ensuring fire safety in a garage designed for diesel vehicles. In contrast, fuel leaks from CNG vehicles can be very rapid, such as when a pressure relief device opens. Leaked CNG fuel will spontaneously mix with air. Common belief holds that CNG leaks are less dense than air and that the leaked fuel will rise. Recent work has pointed out that because of the tremendous expansion cooling effect, the leaked gas will be extremely cold and dense. Emerging as a supersonic jet, the leak will also mix rapidly with the surrounding air. The resulting dilute natural gas/air mixture will not be very buoyant, even when the gas warms to ambient temperature. Its rise toward the ceiling may be slow. Natural gas is ignitable at concentrations in air between 5 and 15 percent, although a fairly hot ignition source is needed.

Estimating the extent and cost of the modifications needed to safely convert diesel garages to CNG is made uncertain by the absence of definitive codes applicable to CNG. NFPA 88B, Standard for Repair Garages, and NFPA 70, the National Electric Code, may be broadly applied to CNG garages with considerable interpretation. In parti-cular, the requirements for electrical system safety in CNG bus garages are not available in any national code.[8] How-ever, informal standards have begun to emerge. For example, the

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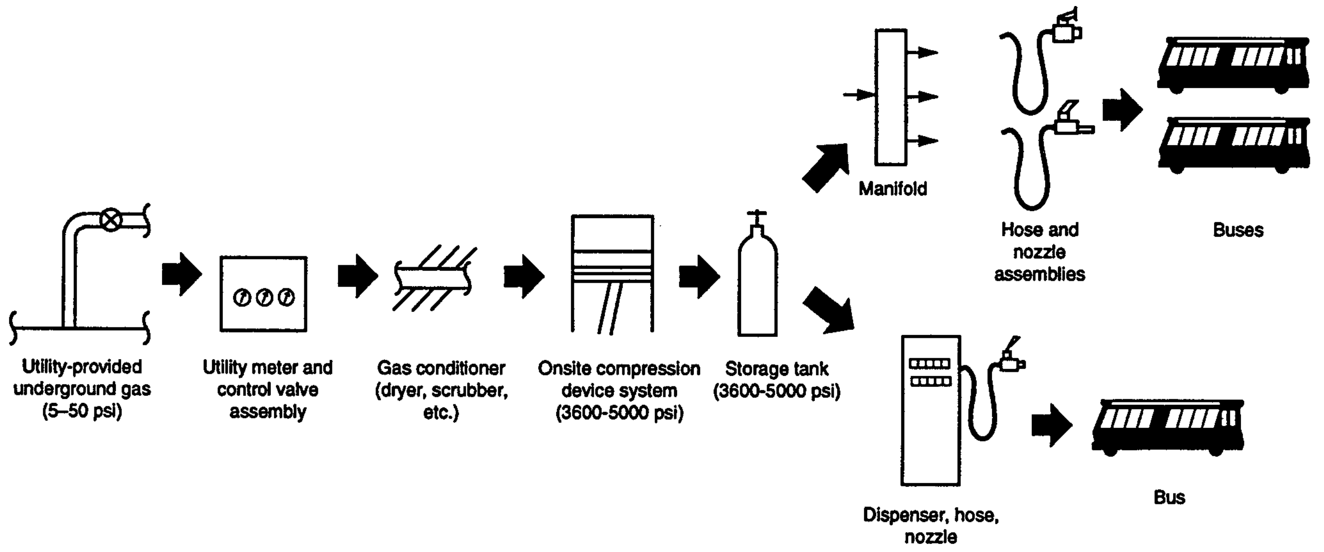
[6] *Natural Gas Fuels* (Nov. 1966) p. 19.

[7] Wilson Technologies, Inc., and the Marathon Compressor Company, *CNG Transit Fueling Station Handbook.* Report No. 97/0092. Gas Research Institute, Chicago, Ill. (Feb. 1997).

[8] *Facility Design Guidelines for Alternative Fuels: A Reference Handbook,* Technology and Management Systems (July 1995).



KEY REQUIREMENTS

- **Storage tank volume 3 to 4 times volume of one bus tank**
- **Storage recharge time consistent with number of fast fill fueling events and volume of gas required to slow fill balance of fleet overnight**
- **Compression device designed for specific gas pressure available**

Figure 6. Fast/slow fill.

Federal Transit Administration (FTA) has recently published *Design Guidelines for Bus Transit Systems Using Compressed Natural Gas as an Alternative Fuel,*[9] which provides a comprehensive summary of applicable building and design code provisions, as well as design practices which are emerging from the transit industry's experience with CNG.

The primary objective in modifying maintenance garages for CNG vehicles is to ensure that ventilation rates are high enough to rapidly disperse and dilute potential leaks. This follows from the fact that methane at concentrations below 5 percent is not ignitable. In the CNG garage, a basic ventilation rate equivalent to 6 room air exchanges per hour is needed. Methane leak detectors are installed in or above the service bays. Upon detection of a leak, the ventilation rate is increased to 12 air exchanges per hour, all doors are automatically opened, and an alarm may sound. To eliminate ignition sources, the fire protection system may automatically shut off all nonemergency electrical systems at some methane concentration well above the detection limit. Because CNG vapors are eventually lighter than air, they will ultimately accumulate near the ceiling. Roof ventilators are desirable to dissipate any natural gas that may be released in the maintenance area. To satisfy the local fire inspector, a fail-safe backup plan is needed in the event of a power outage. This might be accomplished by simply opening all the garage doors.

3.5 SAFETY

Handling characteristics of CNG are significantly different from those of more familiar liquid fuels because of its gaseous state and because it is stored under high pressure. Accordingly, operating and safety training is required for personnel operating and maintaining CNG buses. Fueling procedures must be formalized and transmitted to operators to safely dispense fuel from CNG fuel stations. The fueling procedure may vary depending on the location of the fueling facility.

The major safety hazards of CNG are briefly reviewed below. A thorough review of the safety and health impacts of alternative fuels recently has been published by the FTA, entitled, *Summary Assessment of the Safety, Health, Environmental and System Risks of Alternative Fuel.*[10]

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[9] Technology and Management Systems, Inc., *Design Guidelines for Bus Transit Systems Using Compressed Natural Gas as an Alternative Fuel.* Final Report No. DOT-FTA-MA-26-7021-96-1. U.S. Department of Transportation, Federal Transit Administration, Office of Research, Demonstration and Innovation (June 1996).

[10] Battelle Memorial Institute, *Summary Assessment of the Safety, Health, Environmental and System Risks of Alternative Fuels.* Final Report No. DOT-FTA-MA-90-7007-95-1. U.S. Department of Transportation, Research and Special Programs Administration, Columbus, Ohio (Aug. 1995).

3.5.1 Fire Hazards

At ambient temperatures, natural gas is lighter than air and will rise from the location of a leak. However, observations of actual leaks from CNG cylinders, as well as theoretical predictions, as discussed above, indicate that these leaks may hover at ground level for some time. The cold vapor produced by expansion cooling of a CNG leak can be 1.5 times as dense as the surrounding air, causing it to remain at ground level until it is warmed sufficiently to rise.[11] Trained personnel must be aware of the ways to detect a CNG leak. A small natural gas leak may be detectable only by the smell of the odorant or with a methane detector, which can detect small concentrations of methane in the air. People frequently exposed to natural gas often lose their capacity to notice small concentrations after some time. Larger leaks may also be detected by their sound.

People are prohibited from smoking when they are fueling CNG vehicles or working on the fuel systems. Work practices and facility design must eliminate potential ignition sources where natural gas is handled or where leaked natural gas may accumulate (e.g., near the ceiling). Natural gas is flammable in air at concentrations between 5 and 15 percent volume. Any natural gas leak is considered a fire hazard, because a flammable concentration exists at the interface between a gas plume and the surrounding air.

Specific fire-fighting practices apply to natural gas. Properly used fire extinguishers can effectively starve a small natural gas fire of oxygen and thus extinguish it. Most buses fueled with natural gas are equipped with automatic fire suppression systems.

3.5.2 Pressure Relief Device (PRD) Failures

All CNG fuel tanks are protected by pressure relief valves, which open and vent the tank's contents outside the vehicle in the event that tank pressures become dangerously high. This might occur, for example, if a compressor overfilled the tank or if the tank were heated in a fire. PRDs installed in buses at several transit agencies have opened improperly on several occasions. All these events have occurred while the buses were parked. Depending on the fuel system design, typically when a CNG bus is shut down, individual cylinders or banks of cylinders in the bus's fuel system are shut in by a solenoid valve located in the tank's outlet (the valve closes automatically when it is unpowered). When each cylinder is isolated by a solenoid valve, fuel release caused by a PRD failure is limited to the contents of the tank to which the activated PRD is connected. However, in most designs, each solenoid valve controls a bank of cylinders, usually three or four. In such designs, fuel leaks can empty the contents of the entire bank of cylinders. As such, a substantial quantity of gas may be released. PRDs in early bus models at one transit system failed repeatedly while buses were fueled or parked, but without the gas igniting. At another system, a PRD failed in a bus that was parked in the maintenance garage. The resulting plume of gas rose and was ignited by an open-flame heater located near the ceiling. The gas fire and explosion caused some damage to the garage.

PRDs are equipped with fusible metal plugs made with an alloy that melts at low temperatures (216°F or 102.2°C). The plug melts when exposed to fire or some other source of high heat, allowing the contents to vent and thereby preventing excessive gas pressure due to heating. The fusible plugs of early PRD models apparently failed because of the heat of compression developed during fueling. The fusible plug failure temperature has been increased to 259°F (126.1°C) in newer PRD models. As a result, the failure rate has reportedly decreased with replacement to the most recent PRD models.[12]

3.5.3 Defueling

Defueling CNG buses represents a positive means of preventing fuel leaks from buses parked indoors. Recent CNG bus models incorporate design provisions that make defueling convenient, in case a bus needs fuel system servicing or if it is to be parked indoors for an extended period of time. The CNG fueling station can be designed to receive defueled gas at the compressor inlet or to allow it to flow back into the local gas distribution system.

3.5.4 Hazards Related to High Pressure

The high storage pressure of CNG poses certain hazards, which are minimized by proper equipment and training. A high-pressure fitting, if loosened while under pressure, can become a missile. Skin contact with a high-pressure gas jet could result in a gas embolism in the bloodstream. Training that emphasizes these hazards enables personnel to avoid them. CNG tanks are highly loaded pressure vessels, which are designed, manufactured, and tested to rigorous standards. Tanks constructed with metal could corrode in service and therefore must be retested periodically to verify their good condition. All-composite tanks are exempt from this requirement. Composite-reinforced CNG tanks can sustain undetectable damage if they are affected by other objects. Recently, an all-composite tank installed in a new CNG bus at a transit system explosively ruptured without warning while the bus was parked in an outdoor servicing area. Although the gas

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[11] U.S. Department of Transportation, Federal Transit Administration, Office of Research, Demonstration and Innovation, based on work performed by Battelle, *Dispersion of CNG Following a High-Pressure Release.* Final Report No. FTA-MA-26-7021-96-2 (May 1996).

[12] Cooke, M., Maintenance Manager, Sacramento Regional Transit. Interview with R. Remillard, Acurex Environmental (Oct. 1994).

did not ignite, the force of the tank explosion caused significant damage to the bus. An investigation of the incident has been completed. Although the exact cause of the failure was not identified, it is believed that the cause of the explosion is related to internal tank damage.

3.5.5 Other Hazards

There is no danger of ingestion of CNG because of its gaseous state. Although natural gas is nontoxic, asphyxiation is possible in a closed environment because of displacement of oxygen. Absorption through the skin is not considered to be a hazard.

3.6 FUEL AVAILABILITY AND COST

Natural gas is a fuel widely used in the United States for home heating, electricity generation, and industrial processes; it has an extensive distribution network and there are large domestic reserves. It is expected that fuel supply will not constrain the development of natural gas as a vehicle fuel.

CNG fuel supply infrastructure generally consists of a gas pipeline provided by a local distribution company (LDC) to a refueling station owned by the LDC, a transit agency, a private fleet, or a commercial refueling company. The LDC receives the gas from a producer company through a pipeline company. LDCs are often eager to cooperate with transit agencies implementing CNG and sometimes cost-share fueling facility expenses.

As reviewed in Section 3.2, natural gas engines are prone to combustion knock if they are supplied with fuel that does not meet the engine manufacturer's specifications. In some regions of the United States, the quality of the local gas may not meet these specifications.

In particular, gas utilities in some areas meet peaks in wintertime gas demand by injecting a mixture of propane and air into the pipeline distribution system. Although this practice does not degrade the performance of the gas as a burner fuel, it does reduce the gas octane rating, which has caused instances of knock-related engine damage in transit bus fleets.

Therefore, transit agencies contemplating CNG as a motor bus fuel should check with their gas utility to establish whether the local pipeline gas consistently and reliably meets engine manufacturer's fuel-quality specifications.

Depending on local conditions and arrangements with LDCs, the price of CNG can be less than that of diesel fuel (on an energy-equivalent basis), even when amortization of the CNG compressor station costs is included. For example, LACMTA paid $0.26 per therm in November 1995 from Southern California Gas Company, which translates to $0.16 per mi after accounting for a fuel efficiency penalty and compression energy costs. This is lower than the $0.22 per mi ($0.67 per gallon) cost paid by LACMTA for diesel fuel at that time.[13] Large customers, such as a CNG transit bus division, often have the option of contracting directly with gas wholesalers for fuel. The gas transmission company and local distribution company will then add transportation and handling charges. Such arrangements can yield substantial cost savings compared with purchasing gas directly from the local utility.

3.7 CURRENT CAPITAL AND OPERATING COSTS

3.7.1 Vehicle Purchase Costs

The prices of heavy-duty natural gas engines are variable, depending on the manufacturer, engine model, and size of the order. Manufacturers are currently charging a substantial premium to cover some of their costs for development, certification, and warranty service. As a rule of thumb, manufacturers price heavy-duty natural gas engines at nearly twice that of counterpart diesels. This works out to approximately $25,000 for a CNG transit bus engine.

Conversion of buses to CNG operation is usually performed by the bus manufacturers. They design and install the fuel system (CNG tanks, plumbing, and valves) in addition to installing the natural gas engine. Onboard CNG fuel tank systems cost approximately $10,000 to $40,000 per bus, depending on the number and type of cylinders specified. CNG buses are usually specified with an onboard fire-suppression system, with an installed cost between $5,000 and $6,000. Total incremental costs relative to diesel buses are somewhat situation specific. The current incremental price of a 40-ft CNG bus ranges from $65,000 to $75,000 per vehicle based on recent procurements and price quotes from several bus manufacturers.

3.7.2 CNG Facility Costs

CNG fueling facilities and modifications to maintenance facilities entail additional capital costs. Although these costs vary substantially depending on the specific circumstances and equipment, a typical estimate for a 200-bus transit fleet is $600,000 for modifications to one maintenance garage and $1,700,000 for one CNG fueling facility.[14] If buses are parked indoors (which is common in cold climates), ventilation upgrades and methane detection systems will likely have to be installed in the parking area, which can significantly increase costs.

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[13] Review of MTA staff memorandum entitled *New Bus Procurement/Conversion of Methanol Buses,* and audit of MTA alternative fuels analysis, Acurex Environmental, for Los Angeles County Metropolitan Transportation Authority (Nov. 1995).

[14] The CNG fueling facility and maintenance facility cost estimates are based on ARCADIS Geraghty & Miller analyses of costs experienced at Pierce Transit, Los Angeles County MTA, Sacramento Regional Transit, Toronto Transit Commission, and Cleveland, as well as National Renewable Energy Laboratory (NREL) and Southern California Gas Company estimates, and previous analyses by ARCADIS Geraghty & Miller and Booz, Allen & Hamilton.

3.7.3 Bus Operating Costs

Operating costs for CNG buses, relative to diesel buses, depend primarily on fuel and maintenance costs. Fuel costs, as discussed in Section 3.6, can be lower for CNG buses than for diesel buses, even considering the fuel economy penalty experienced by CNG buses, as illustrated by the LACMTA example in Section 3.6 of $0.16 per mi for CNG and $0.22 per mi for diesel.

Reliable data on maintenance cost impacts of CNG operation are limited. Reported cost comparisons are sometimes poorly controlled. For example, comparisons may be made between new CNG buses operating under the manufacturer's warranty and old high-mileage diesel buses. The U.S. Department of Energy's (DOE's) National Renewable Energy Laboratory (NREL) recently concluded a program to evaluate alternative-fuel transit buses, which included fairly rigorous monitoring of maintenance costs. In this program, maintenance costs for CNG buses at Pierce Transit (Tacoma, Washington) were compared with costs of similar diesel controls in similar service.[15] Engine-related maintenance costs were found to be no more than 16 percent higher than those of the diesel controls. Incremental CNG maintenance costs were attributed to higher tune-up costs: spark plugs, spark plug wires,[16] and possibly more frequent adjustment of the fuel system. Note that engine-related maintenance typically accounts for about one-third of total maintenance costs, so a 16 percent incremental engine maintenance cost would likely result in a 5 percent increase in total maintenance costs. This will likely decline in the future, as fuel systems and ignition systems for CNG engines are becoming more robust.

3.7.4 CNG Engine Durability

Pierce Transit has been a pioneer of transit fleet conversion to CNG and has some of the highest-mileage CNG buses in the United States. They report that their Cummins L-10 240G-powered buses have now accumulated as much as 260,000 mi without engine rebuilding. Pierce Transit rebuilds diesel engines at between 300,000 and 350,000 mi; they expect the durability of their CNG engines to equal or exceed that of their diesel engines.[17] Sacramento Regional Transit District has accumulated mileage on their CNG buses similar to that of Pierce Transit and also believes that the engines can accumulate as much as 300,000 mi between overhauls.[18]

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[15] At Pierce Transit, engine-related maintenance costs were compared for five buses powered by 1994 Cummins L-10 260Gs with five powered by 1991 Cummins L10-280Es, respectively. All engines were installed in BIA Orion Vs. Motta, R., and Norton, P., NREL; Chandler, K., Battelle; Shumacher, L., University of Missouri; and Clark, N., West Virginia University, *Alternative Fuel Transit Buses: Final Results from the National Renewable Energy Laboratory (NREL) Vehicle Evaluation Program*. NREL Alternative Fuel Data Center World Wide Web site: http://www.afdc.doe.gov.

[16] Op. cit., p. 16

[17] Shipley, R., Director of Maintenance, Pierce Transit, interview with S. Barsony (July 1996).

[18] Lonnergan, M., personal communication with R. Remillard, ARCADIS Geraghty & Miller.

CHAPTER **4**

LIQUEFIED NATURAL GAS

4.1 OVERVIEW

Natural gas liquefies at very low temperatures. A number of gas utility companies store large volumes of LNG in peak-shaving plants. These facilities can rapidly evaporate the product and inject it into the pipeline system at times of very high customer demand. LNG can also be produced at gas processing plants, because these plants employ refrigeration to condense and separate heavier HCs and other undesirable constituents of the wellhead gas before it is injected into the pipeline system. In addition, imported LNG is distributed to some markets through import terminals in Louisiana and Massachusetts. LNG offers a substantially higher storage density than CNG, which gives it some advantages as a transportation fuel. In areas where LNG is widely available (such as the Gulf Coast), it can be purchased at prices that are competitive with, or below, those of diesel fuel.

From the comparative listing of chemical and physical properties of LNG and other fuels in Table 2, several key properties deserve to be highlighted. Table 11 summarizes several key properties of LNG that affect its use as a transportation fuel.

Section 4.2 presents the current state of technology including the effects of LNG fuel use on engine and vehicle performance and transit buses currently in operation using the technologies identified. Sections 4.3 and 4.4 discuss potential issues related to LNG use in fueling and maintenance facilities. Section 4.5 describes safety considerations. Section 4.6 identifies fuel availability and price issues. Section 4.7 evaluates potential cost implications including general capital and operating costs.

4.2 ENGINE AND VEHICLE TECHNOLOGY

4.2.1 Engine Technology

Any engine designed for CNG may also be used with LNG by simply vaporizing and heating the LNG before it is fed to the engine. All commercially available LNG buses use engines that were originally designed for CNG. Because LNG is usually formulated to consist of almost pure (>98 percent) methane, engines for LNG vehicles do not have the optimization difficulties associated with the more variable composition of CNG fuel. Also, fuel filtering to prevent contamination of the fuel system by water or compressor oil (which is normally used in CNG engines) is not needed with LNG.

4.2.2 Fuel System Design Considerations

The fuel metering systems of commercially available heavy-duty natural gas engines require that the fuel be supplied at pressures of not less than 90 to 100 psi. With its inherently high storage pressures, this requirement is easily met with CNG. In onboard LNG fuel systems, two approaches are in use for supplying the necessary fuel pressure: mechanical cryogenic fuel pumps and pumpless fuel systems using conditioned (heated) fuel.

Houston Metro, which pioneered the use of LNG in transit buses, has utilized onboard mechanical cryogenic pumps extensively. The agency has generally been disappointed by their performance, because of short operating lives and high replacement costs. Pumpless LNG tank systems are now most commonly specified. These systems require that the fuel be heated approximately 50°F (10°C) above its natural boiling point before it is supplied to the vehicle. This heating increases the saturation vapor pressure of the fuel to approximately 100 psi. Heat absorption in the onboard tank then tends to keep the tank pressure at or above 100 psi, even as vapor or liquid is withdrawn to supply the engine. Pumpless LNG fuel systems are inherently reliable and durable but require that the fueling station be capable of supplying properly conditioned fuel at all times.

4.2.3 Vehicle Performance

The performance and drivability of an LNG bus can be made equal to those of a diesel bus, as can fueling time and range.

4.2.3.1 LNG Tank Weight

Vehicular LNG fuel tanks are double-walled and vacuum-insulated pressure vessels, which are designed to support working pressures of up to 250 psi. The inner wall is normally fabricated with stainless steel, and the outer wall may be fabricated with stainless or carbon steel. The evacuated

TABLE 11 Summary of key properties of LNG versus diesel fuel

Property	Diesel	LNG	Implications for LNG Vehicle Use
Relative storage volume	100%	190%	Requires about twice as much fuel volume for equivalent range
Cetane number Octane number	40 to 51 (<0)	-10 116	Difficult to compression ignite, LNG is much more suitable for spark-ignition. Spark ignition entails a 20-40% fuel efficiency penalty
Phase at storage conditions	Liquid	Cryogenic liquid	Specialized materials, designs and operating practices are needed for LNG equipment
Relative vapor density (air = 1)	4 to 6	0.6	Natural gas vapors are lighter than air at room temperature and will pool near ceilings of enclosed structures
Boiling point at 1 atm (°F)	370 to 644	-260 (methane)	LNG must be stored in highly insulated containers to prevent rapid evaporation. However, fuel storage time even in the best available tank designs is limited by fuel evaporation and weathering

region between the inner and outer walls is filled with a very high performance insulating material consisting of 15 to 20 layers of Kevlar fabric and aluminum foil. This construction increases fuel tank weight compared with a diesel tank of similar capacity. Usable tank volume for LNG must be approximately double that of a diesel tank giving similar range, primarily because of LNG's lower density and, secondarily, to compensate for the comparatively poor fuel efficiency of spark-ignited natural gas engines. The greater strength, volume, and insulation of LNG tanks result in LNG buses normally being about 800 lb heavier than equivalent diesel buses. This increased weight may reduce legal passenger capacities in bus models with high curb weights in diesel form.

Current LNG buses are experiencing a fuel efficiency penalty of as much as 30 percent compared with diesel buses. LNG should offer somewhat higher in-service fuel economy than CNG buses because of its lower fuel storage weight. If compression ignition natural gas engines are successfully developed, the fuel efficiency of LNG buses could closely approach that of diesel buses.

Because the engine technology is the same, emissions from LNG vehicles are essentially identical to emissions from CNG vehicles, which are discussed in Section 3.2.2.

4.2.3.2 Venting

LNG buses should not be left fueled and unattended for more than 1 week. Even the most highly insulated LNG tanks continually absorb heat, which warms the fuel and increases its vapor pressure. When an LNG vehicle is operated, excessive tank pressures are prevented by a circuit that feeds vapor from the tank's ullage (vapor) space into the engine. In addition, all LNG tanks must be equipped with pressure relief valves, which automatically vent vapor from the tank to outside the vehicle, to prevent the occurrence of excessively high pressures. LNG pressure relief valves are commonly set at 250 psi. If an LNG vehicle is left parked for approximately 1 week, its tanks will absorb enough heat that the vapor pressure will increase to 250 psi and cause the tank to vent. This is normally not hazardous if the vehicle is parked outdoors. Indoors, the vented vapor could accumulate to form a combustible mixture.

4.2.4 Vehicles Currently in Use

Several transit agencies currently use LNG buses in their fleets. Table 12 lists these agencies and the vehicles they operate. Seven agencies currently operate LNG buses, two of which have additional LNG buses on order. In addition, three agencies are purchasing new LNG buses. Figure 7 shows an LNG bus at Tri-Met in Portland, Oregon.

4.3 FUELING FACILITY IMPACTS

4.3.1 LNG Fueling Facility Design Considerations

The primary components of an LNG fueling facility are diagrammed in Figure 8. Figure 9 is a photograph of an LNG fueling facility at Houston Metro in Houston. The LNG facility consists of one or more cryogenic fuel storage tanks, fuel dispensing pump, dispenser(s), refueling lines, and a refueling nozzle. LNG is delivered to the fueling facility by truck tanker. The tanker off-loads the LNG product as a cryogenic liquid at pressures of less than 15 psi gauge. The bulk storage tanks for LNG fuel are sealed containers designed to contain moderate pressures (<250 psi gauge). Prefabricated LNG sto-rage tanks are available in sizes between 6,000 and 60,000 gallons and in both vertical and horizontal configurations.

TABLE 12 LNG-fueled full-size transit buses in use and on order

Transit Agency	Location	In Service	On Order	Chassis Manufacturer	Chassis Model	Length (ft)	Engine
Mass Transit Admin., Maryland Dept. of Trans.	Baltimore, MD	4	0	Flxible	Metro 40102-6T	40	Cummins L-10G
Dallas Area Rapid Transit	Dallas, TX	25		Flxible	Metro 30102-6T	30	DDC Series 50G
Gary Public Trans. Corporation	Gary, IN	2	3	Flxible	35096-6-1	35	Cummins L-10G
El Paso Mass Transit Dept. (Sun Metro)	El Paso, TX	35	0	New Flyer	D40	40	DDC Series 50G
Los Angeles Dept. of Airports	Los Angeles, CA	21	6	Gillig	Phantom	35	Cummins L10-260G
			10	(RFP Pending)			
Metropolitan Transit Auth. of Harris County	Houston, TX	62	0	Ikarus USA	Suburban 416.04	40	DDC 6V-92PING
		54	0	Neoplan	Atriculated	60	DDC 6V-92PING
		61	0	Neoplan	Suburban	45	DDC 6V-92PING
		20	0	Stewart & Stevenson	Mercedes	40	DDC 6V-92PING
		3	0	General Motors	RTS-04	40	DDC 6V-92PING
Tri-County Metropolitan Trans. District	Portland, OR	8	0	Flxible	Metro 40102-6C-0	40	Cummins L-10G
		2	0	Gillig	Phantom 40TB102	40	Cummins L-10G
City of Phoenix Public Transit Auth.	Phoenix, AZ	0	29	New Flyer Industries	D40LF	40	DDC Series 50G
	TOTALS	**297**	**48**				

Compiled from American Public Transit Association 1995 Transit Passenger Vehicle Fleet Inventory and other sources.

LNG storage tanks are also superbly insulated. To provide the lowest possible rate of heat leakage, the double-walled vessel utilizes a combination of vacuum insulation with multiple wraps of a highly reflective fabric. As LNG in a sealed container absorbs heat, its temperature and vapor pressure increase simultaneously. The tank is equipped with redundant pressure relief valves, which vent LNG vapor if a pressure of 250 psi is reached. Even with the best insulation, after prolonged (>2 weeks) storage, the LNG product will eventually warm sufficiently to initiate venting. Although this does not present a safety hazard in well-designed facilities, it imposes a cost in wasted product. In fleet operations with predictable fuel consumption rates, the LNG facility is sized so that stored product is replaced rapidly (over a few days). This limits heat absorption and prevents venting.

Figure 7. Tri-Met's (Portland, Oregon) 40-ft Gillig Phantoms were the first OEM-warranted dedicated LNG transit buses. Photo courtesy of Gillig Corporation.

A submerged centrifugal pump, specially designed for cryogenic liquids, is used to dispense the LNG product. The pump can easily dispense at rates of 30 to 40 gallons per minute, while driven by a 10- to 20-hp motor. **This is 35 to 40 times less power than is required to operate a CNG compressor station with comparable capacity.** Pressures in the LNG storage tank are usually in the range of 20 to 40 psi gauge. The centrifugal pump increases the pressure by approximately 120 psi, giving a total pressure of 150 psi at the pump's outlet. The LNG is a compressed or subcooled liquid in this state.

Onboard LNG fuel systems do not use fuel pumps but rather develop fuel pressure from the fuel's own vapor pressure. A vapor pressure of 120 to 150 psi is needed to guarantee adequate fuel delivery rates in the Cummins L10-280G or the DDC Series 50G. To generate this much vapor pressure, the fuel must be warmed from its natural boiling point of –259°F (–161.7°C) to a temperature of approximately –190°F (–123.3°C). This warming process is referred to as "conditioning." Conditioning is accomplished continuously

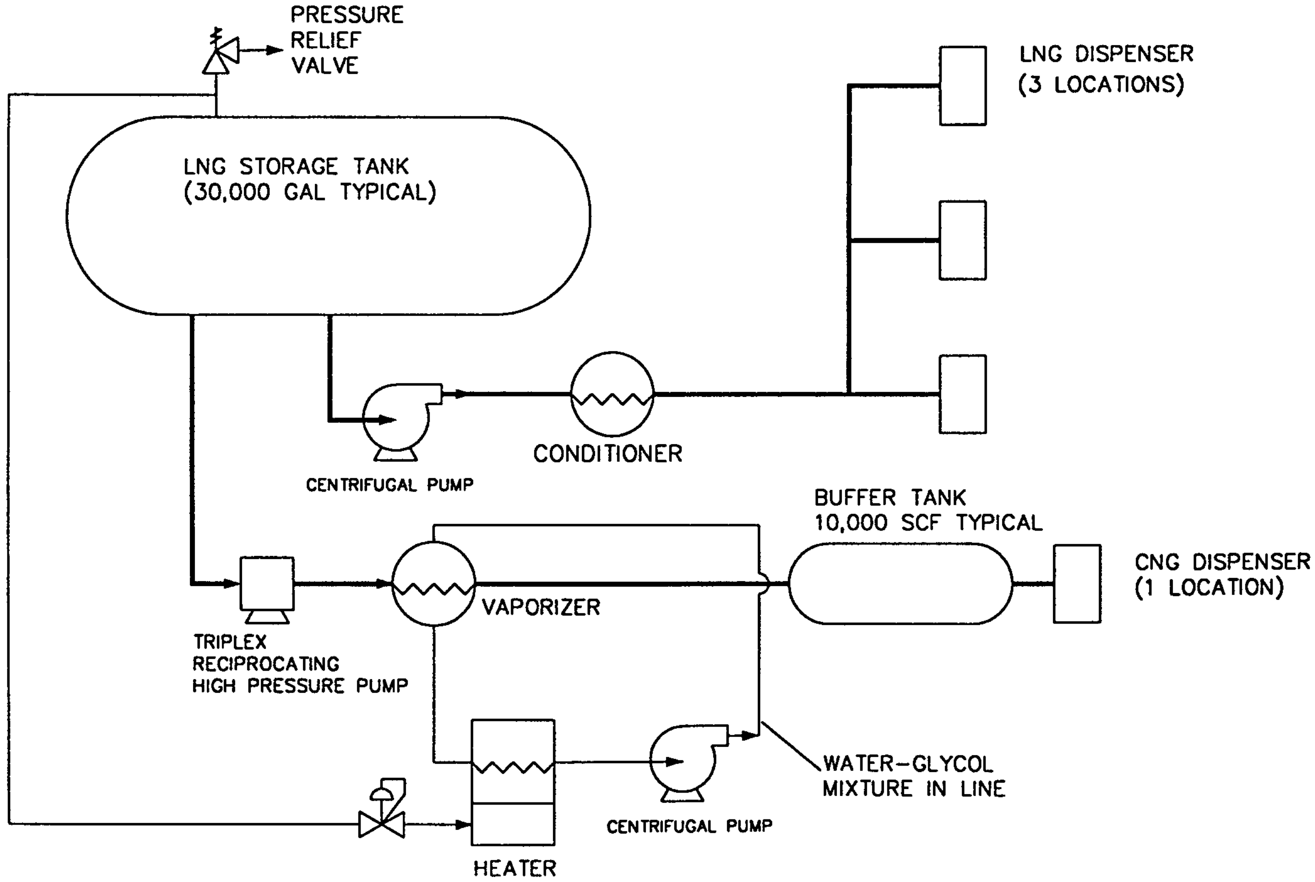

Figure 8. Elements of an LNG fueling facility.

with a heat exchanger or by warming a volume of fuel in a conditioning tank. The conditioned fuel is then piped to the dispensers. The dispenser is equipped with a transaction control system, which authorizes fueling and meters the fuel delivery. As it is a saturated or nearly saturated liquid in the dispenser, LNG easily forms vapor bubbles in flow meters, which makes it difficult to accurately meter flow. As with CNG dispensing, good flow-metering accuracy is achieved with vibrating-tube mass flow meters.

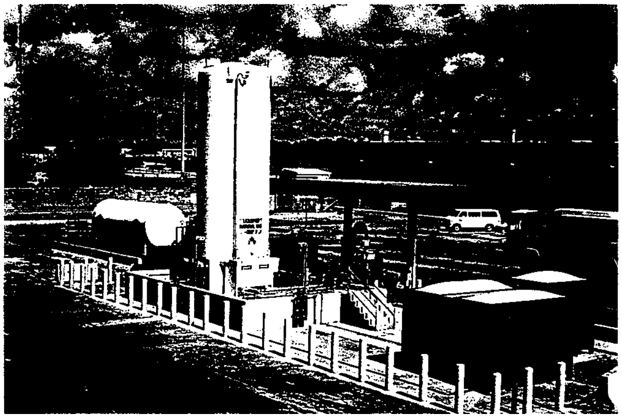

Figure 9. LNG fueling facility at Houston Metro (Houston, Texas).

4.3.2 Operating Considerations for LNG Fueling Facilities

LNG storage and dispensing systems are subject to requirements for minimum separation from other land uses under provisions of the NFPA and Uniform Fire Code (UFC). Distances vary depending on the code cited, adjoining land use, and LNG container volume. Containment of potential LNG spills is required, with provisions to prevent LNG from entering water drains, sewers, or any closed-top channel. Two containment options are available: containment at the location of the storage tank or remote impoundment. The containment system for a non-fire-protected system must accommodate the combined volume of containers it serves; if fire protected, the system must contain 110 percent of the volume of the largest container.

All containers or lines in which LNG could potentially be confined must be protected by pressure relief devices. Warmed to room temperature, confined LNG will vaporize and can develop pressures as high as 5,000 psi and could cause the container to rupture violently. This is prevented by the pressure relief device. LNG systems should be serviced only by properly qualified personnel.

Refueling operations require operator awareness of, and protection from, cryogenic hazards. Skin contact with leaking fuel can cause frostbite. Wearing leather gloves, face shield, and an apron provides good protection in the event of a leak. Worn LNG fueling nozzles begin to leak fuel, and LNG nozzles have shown poor durability in transit service in the past. The latest nozzle designs are much more durable, and improvements continue to be developed to improve durability to a satisfactory level. LNG is easily dispensed at flow rates high enough for LNG fill times to equal those of diesel buses. However, with many existing LNG fueling facilities, a cool-down cycle must be performed before vehicle fueling can begin. This is necessary to cool the piping and transfer lines to LNG temperature to prevent the liquid from boiling and flashing to a vapor during fueling. Once cool-down has been performed, successive buses can be fueled without interruption.

4.3.3 CNG from LNG Stored On-Site (L/CNG)

A possible variant of fueling with LNG is to dispense CNG from LNG stored on-site. This is accomplished by using high-pressure cryogenic pumps to compress the LNG to 4,000 to 4,500 psi and then vaporizing the highly compressed liquid. Pumps with outlet pressures as high as 5,000 psi are available with flow rates of 3, 6, and 12 gallons per minute (gpm) (these rates correspond to 250, 500, and 1,000 scf of CNG per minute, respectively). Three 12-gpm pumps would be needed, with a total CNG capacity of 3,000 scf per minute to meet typical dispensing rate requirements for a fleet of 160 CNG buses. A 50-hp electric motor is needed to drive each 12-gpm triplex pump. Total electric motor power for the L/CNG facility is 150 hp. This is considerably less than the 670 hp needed to drive the comparable CNG compressor station (refer to Chapter 3, Section 3.1). The energy savings results from the fact that the LNG is already highly condensed and incompressible, compared with pipeline gas, so comparatively little work is needed to elevate its pressure.

After the LNG is compressed by the triplex pump, it is vaporized to CNG in a heat exchanger. The CNG is stored in a buffer tank, which supplies the CNG dispenser(s). The heating medium is a water-glycol mixture, which is warmed by a gas burner. The gas burner may be fueled with boil-off vapor from the LNG storage tanks (Figure 8). This arrangement reduces the accumulation of heat and vapor pressure in the LNG storage tank and thereby tends to prevent venting of vapor from it. The LNG vaporizer may be adjusted to generate CNG at a temperature of approximately 40°F (4.4°C). With the moderate heat gain that the gas encounters through the dispenser piping and onboard tank manifold, the compressed gas is delivered to the onboard tank at ambient temperature. **That is to say, it is delivered at its settled pressure, so no overfilling to compensate for compression heating is needed.** This is a significant advantage compared with compressing pipeline gas.

As LNG may be procured as essentially pure methane, L/CNG provides a sure means of preventing contaminants such as water, compressor oil, and heavier HC from affecting the onboard fuel system. The elaborate drying and filtering systems needed with pipeline gas compression are thereby avoided. The variable quality of pipeline gas has, in a number of instances, led to engine malfunctions and engine damage in CNG buses. Using L/CNG enables the CNG fleet to fuel with gas having consistently high quality.

Also, although gas curtailments in most parts of the United States are now rare, they are a continuing possibility. In the event of a curtailment, a fleet relying on pipeline gas and a compressor station would be shut down. With either LNG or L/CNG, as much as a week's worth of fuel may be stored at the bus garage, providing a substantial buffer against possible interruptions in fuel delivery.

L/CNG fueling is currently utilized at Sun Metro in El Paso, Texas, for their mixed fleet of LNG and CNG buses. It is an attractive option for operations having a large fleet of LNG vehicles along with a smaller fleet of CNG buses or service vehicles. LNG fleet operators tend to get the most favorable prices for product when their consumption is on the order of thousands of gallons per day. Even with the most favorable LNG pricing, the cost of LNG will likely be higher than that available for pipeline gas. Therefore, the best economic case for L/CNG exists where a large fleet is being fueled with LNG, because of the operational advantages of LNG versus CNG (greater range, lighter weight, and reduced pressure hazard), but where a smaller fleet of CNG vehicles also exists.

4.4 MAINTENANCE FACILITY IMPACTS

LNG leaks from vehicles differ from those of CNG in that the vapor is always initially cold and heavier than air. Given the recent test data showing that high-rate CNG leaks can also produce cold, dense vapor, prudent maintenance garage modification practices for both CNG and LNG appear to be very similar. A well-designed LNG maintenance garage will have classified (explosion-proof) electrical wiring and devices in pits and should incorporate features to prevent liquid LNG leaks from flowing into drains. It may also be prudent to specify classified wiring in all work areas at elevations less than 18 in. above the floor. The latter practice is consistent with that specified by codes for other volatile fuels having vapors heavier than air, such as gasoline and LPG. Once it warms to ambient temperature, LNG is buoyant like warm CNG, so all garage modifications recommended for CNG apply with LNG. To avoid making modifications to indoor facilities for temporary vehicle demonstrations, LNG vehicle maintenance can be done outside.

The FTA recently published *Design Guidelines for Bus Transit Systems Using Liquefied Natural Gas (LNG) as an Alternative Fuel*,[19] which provides transit agencies with a comprehensive review of facility and vehicle design practices used to ensure safe operation with LNG. Transit agencies interested in converting to LNG, or who are operating LNG vehicles, should utilize this document to guide their planning process or operating procedures.

4.5 SAFETY

Because of LNG's cryogenic characteristics, safety training is very important. LNG poses some different hazards relative to other fuels—notably, the possibility of frostbite if it contacts skin. However, awareness of these hazards, proper training, suitable equipment, and good work practices can result in a level of safety and a safety record that equal that of conventional fuels. More detailed reviews of LNG vehicle safety and appropriate operating practices may be found in *Introduction to LNG Vehicle Safety*, published by the Gas Research Institute,[20] and in *Liquefied Natural Gas Safety in Transit Operations*, recently published by the FTA.[21] NFPA 57, *LNG Vehicular Fuel Systems*, is the only code or standard written specifically for LNG vehicles, and it covers engine fuel systems; LNG fueling facilities; and fire protection, security, and safety.

4.5.1 Fire Hazards

When LNG is inadvertently released from a cryogenic storage tank (e.g., as in a leak), it will appear as a cold fog. The fog results from the condensation of water vapor in the air. Upon contact with warmer surfaces, LNG will vaporize into a gas that is heavier than air. Contact with air quickly warms the LNG vapors. When the vapors reach a temperature of approximately –170°F (–112.2°C), they become lighter than air. The natural gas will then rise toward the ceiling and it must be vented into the atmosphere to avoid buildup of potentially flammable mixtures of natural gas and air (similar to CNG).

Conventional natural gas odorants solidify and become ineffective at LNG's low temperatures, and odorants suitable for LNG have not yet been developed. Methane has no odor of its own, so minor leaks may not be perceptible to personnel. LNG spills are especially hazardous because the energy-dense liquid quickly vaporizes and becomes combustible.

Natural gas is flammable in air at concentrations between 5 and 15 percent volume. Any natural gas leak is considered a fire hazard because a flammable concentration exists at the interface between a gas plume and the surrounding air.

Specific firefighting practices apply to natural gas. Properly used fire extinguishers can effectively starve a small natural gas fire for oxygen and thus extinguish it. Most natural gas buses are equipped with automatic fire suppression systems. These systems are desirable because natural gas is more flammable than diesel.

4.5.2 Frostbite

Methane boils at –260°F (–162.2°C) at atmospheric pressure, so LNG is at cryogenic temperatures. Skin contact with leaked LNG or with hardware that is cooled by LNG can freeze tissue and inflict cryogenic burns. Training that covers cryogenic hazards enables personnel to avoid them.

4.5.3 Other Hazards

If LNG is confined in a closed container or a shut-in section of piping, pressures as high as 5,000 psi can be generated as it evaporates and warms to ambient temperature and can cause the container to fail violently. Therefore, all containers or piping in which LNG could be confined must be protected by a PRD.

Structural steel tends to become brittle at cryogenic temperatures. Exposing structural steel to LNG leaks could cause them to fracture and fail if they are subjected to heavy loads at the same time. Structural members located in areas where contact with LNG leaks is possible (such as in an LNG containment vessel) should be suitably protected from LNG contact.

Ingestion of LNG is unlikely because of the fuel's tendency to vaporize at ambient conditions. Asphyxiation is possible in a closed environment as a result of displacement of oxygen. Absorption through the skin is not considered a problem.

4.6 FUEL AVAILABILITY AND COST

There are a wider variety of fuel supply scenarios for LNG than for CNG, as illustrated in Figure 10. These include on-site liquefaction, central liquefaction facilities, LNG from gas processing plants, use of peakshaving LNG, and imported LNG. Each of these has supplied fuel for LNG vehicles in the United States. Because natural gas is widely used in the United States for home heating, generation of electricity, and industrial processes, fuel supply is not expected to constrain the development of natural gas as a vehicular fuel. However, the costs of supplying LNG through various supply scenarios will vary regionally, and not all fuel supply scenarios will be economically viable at all locations.

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[19] Raj, P. K., Hathaway, W. T., and Kangas, R., *Design Guidelines for Bus Transit Systems Using Liquefied Natural Gas (LNG) as an Alternative Fuel.* DOT-FTA-MA-26-7021-97-1. Technology & Management Systems, Inc., Burlington, Mass. (March 1997). Available from the National Technical Information Service, Springfield, Va. 22161.

[20] *Introduction to LNG Vehicle Safety,* GRI 992/0465. Gas Research Institute, Chicago, Ill.

[21] U.S. Department of Transportation, Federal Transit Administration, Research and Special Programs Administration, *Liquefied Natural Gas Safety in Transit Operations.* Final Report DOT-FTA-MA-90-7007-95-3 (March 1996).

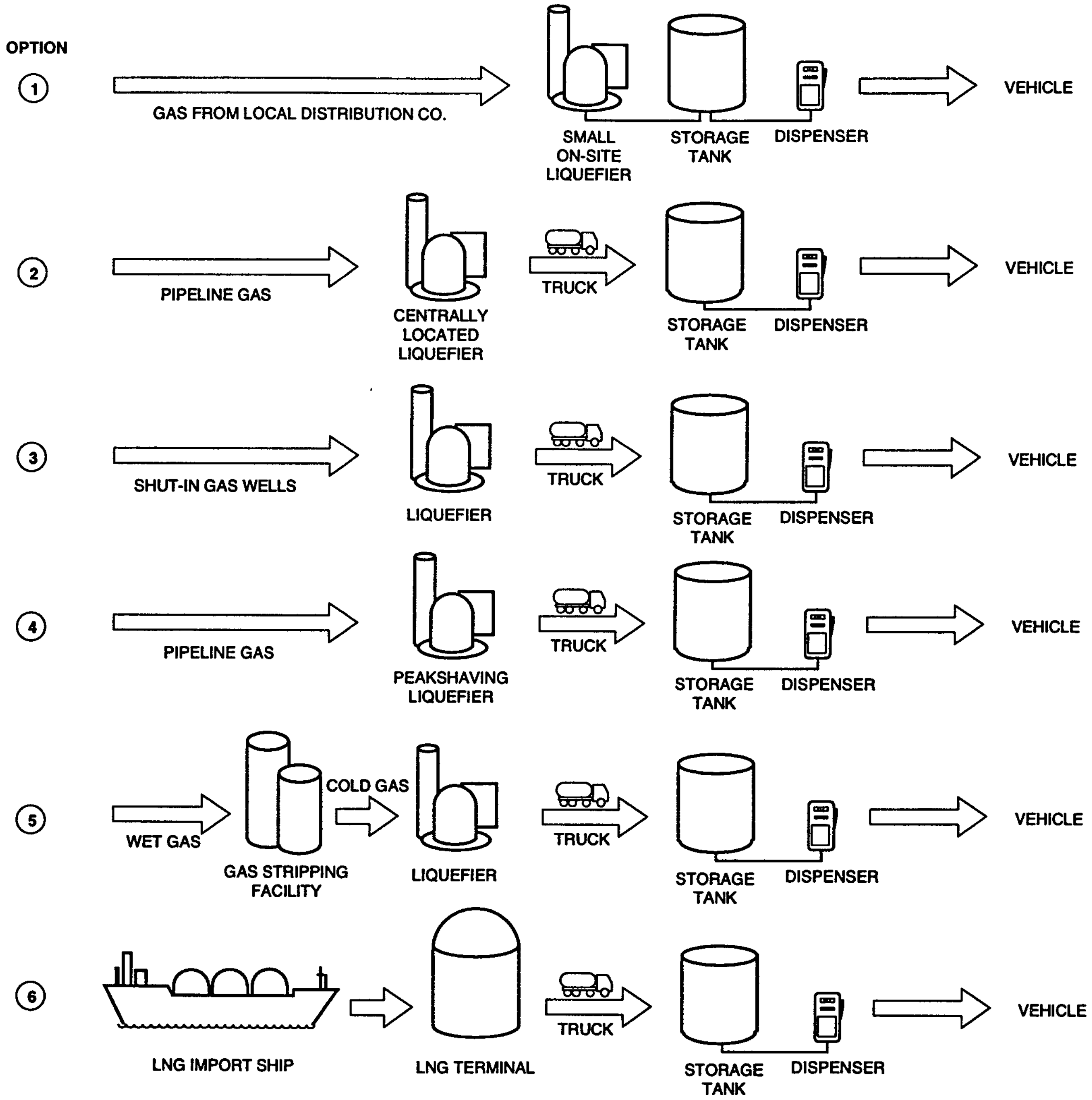

Figure 10. Candidate LNG fuel supply scenarios.

On-site liquefaction is analogous to a CNG station, except the liquefier replaces the compressor. This is the only LNG supply infrastructure that does not require LNG trucking, but it is not generally believed to be the most economical. Large, centrally located liquefaction plants (with LNG trucked to nearby users) benefit from economies of scale. In addition, transit agencies normally are not interested in making the large investments in capital and specialized skills needed to operate and maintain the plant.

Some existing gas-processing plants can easily produce LNG, but these are not always located near LNG vehicle fleets. For example, a gas plant near Evanston, Wyoming, can supply low-cost LNG. Approximately 56 gas utilities in North America liquefy gas and store it for reevaporation during periods of peak demand (i.e., peakshaving). Obviously, some of this LNG can be used to fuel vehicles. Baltimore Gas and Electric, Northern Indiana Public Service, and Northwest Natural Gas are examples of utilities that provide peakshaving LNG for vehicle fleets. There are two active LNG import terminals in the United States—in Everett, Massachusetts, and in Lake Charles, Louisiana. Both of these have supplied LNG for vehicle projects, but it is uneconomical to truck LNG from these terminals to distant locations, such as the western United States.

Currently, LNG production capability substantially exceeds demand (although significant transportation distances may be applicable for some locations), but there are not many LNG refueling stations. Note that the broad availability of fuel and the limitation due to expensive refueling stations is analogous to the situation with CNG.

LNG tends to be available at a price less than diesel fuel (on an energy-equivalent basis). For most fuel sources, the price of LNG is highly dependent on the buyer's willingness to contract to purchase a given quantity over a given time period as well as on the transportation costs involved.

For example, one company plans to charge customers at its public LNG fueling station in Ontario, California, $0.50 per gallon, before taxes.[22] Sun Metro in El Paso, Texas, currently pays $0.38 per gallon for LNG, with the price fixed over a 3-year contract. LNG is available for as little as $0.30 per gallon (approximately $0.51 per diesel-equivalent gallon) from peakshaving utilities, gas processing plants, and large liquefaction plants—although each source carries significant restrictions at this price (e.g., geographic location, quantity purchased, transportation, and purity).

As with all the alternative fuels (with the possible exception of LPG), LNG prices are projected to fall if a substantial market for the fuel develops. This would enable economical utilization of large, highly economical liquefaction plants, for example. It would also generate cost savings through higher utilization of the fuel transportation infrastructure. LNG is unique among alternative fuels in that a variety of private companies aspire to sell LNG for transportation applications, and they are making significant investments to develop this market.

As with CNG, even though under certain conditions LNG costs less than petroleum fuels on an energy-equivalent basis, the fuel cost savings is inadequate to compensate for the additional capital equipment costs at current prices.

4.7 CURRENT CAPITAL AND OPERATING COSTS

As discussed in Section 3.7, the prices of heavy-duty natural gas engines are variable, depending on the manufacturer, engine, and project. Manufacturers charge a substantial premium to cover some of their costs for development, certification, warranty service, etc. As a rule of thumb, manufacturers price heavy-duty natural gas engines at nearly twice the price of counterpart diesels. This works out to approximately $25,000 for an LNG transit bus engine.

LNG buses are usually assembled by the bus manufacturer, including installing the natural gas engine and the LNG fuel system. Various transit bus manufacturers are willing to sell factory-assembled and warrantied LNG buses. Incremental costs relative to diesel buses depend on the quantity of vehicles purchased, their equipment, and other factors. On the basis of recent procurements and price quotes from several bus manufacturers, the incremental price of LNG transit buses can range from $45,000 to $65,000 per vehicle. These prices are anticipated to decrease if and when the market develops and more sales are made.

In addition to incremental bus replacement costs, other capital costs incurred when bus operations are being converted to LNG include those for maintenance garage modifications and construction of fueling facilities. Estimating maintenance garage modification costs for LNG is complicated by the small number of garages actually modified. Given the emerging view that CNG leaks and LNG leaks generally behave similarly, we expect that maintenance garage design requirements will be very similar in the future as well. Based largely on garage modification costs reported for CNG operations, we assume that median costs for LNG modifications will be $600,000 for a 150- to 200-bus garage. Actual costs vary greatly depending on the condition of existing facilities and the conservatism of code officials.

Installation costs are arguably more variable for LNG than for CNG fueling stations, as far fewer LNG stations have been installed. The comparative immaturity of the LNG facility technology is reflected in widely varying design and safety requirements across code official's jurisdictions. The adoption of NFPA 57, *Standard for Liquefied Natural Gas Vehicular Fuel Systems* will likely ameliorate problems related to various code interpretations by code officials.

In August 1997, Phoenix Transit awarded a contract to build a permanent LNG fueling station at one of their two bus garages. The design specification included the following features:

- Two 30,000-gallon vertical LNG storage tanks;
- Dispensers supplied by submerged centrifugal pump, located in a housing below the storage tanks;
- Vacuum-jacketed lines to the pump and dispensers;
- Three dispensers, each rated at 50 gpm, equipped with Micro-Motion mass flow meters; and
- L/CNG capability for shuttle buses and service vehicles at 1,000 scf/min from a 10,000-scf/min CNG buffer tank, with 250 scf/min generated by a high-pressure LNG pump and vaporizer.

The winning bid was $2.7 million for detailed design and construction. Except for the L/CNG capability, the station is suitable for fueling bus fleets of 130 to 160 vehicles. The L/CNG dispenser is suitable for only a small fleet of CNG

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[22] Bartlett, S., LNG equipment manager, ALT-USA. Personal communication with R. Remillard, ARCADIS Geraghty & Miller.

buses or trucks (approximately 20 or fewer). It is estimated that the L/CNG capability adds $200,000 to the cost of the station, giving a cost of $2.5 million for the LNG fueling capability.

In 1994, Sun Metro in El Paso constructed an LNG facility, similar in size to the Phoenix facility, for $2.2 million (refer to the case study in Chapter 13 for details). Sun Metro's station also has a more extensive L/CNG capability; a pure LNG facility there would likely cost about $1.9 million.

As with the CNG facility, operating costs consist of energy costs and maintenance costs. The energy requirements for pumping LNG are small enough to be negligible. Maintenance costs for LNG fueling stations include periodic tightening or replacement of valves, packings, and fill connectors as well as servicing of cryogenic pumps, flow measurement systems, methane detectors, and electronic transaction control systems. Based on discussions with industry experts, the following relation for LNG fueling facility maintenance costs was developed from the available data:

Annual LNG facility maintenance cost = $11,500 + (number of gallons dispensed per weekday) × ($2.60 per gallon).

Operating costs for LNG buses, relative to those for diesel buses, depend mainly on fuel pricing, relative fuel economy, and maintenance costs. As discussed in Section 4.6, in regions with favorable LNG fuel pricing, fuel costs with LNG can be lower than with diesel, even with the 30 percent lower fuel efficiency of spark-ignited gaseous fuel engines.

Reliable data on maintenance costs for LNG buses are limited. High maintenance items reported include frequent replacement of spark plugs, adjustment of fuel-metering systems, and recalibration of onboard methane leak detection systems. Sun Metro, which has comparatively extensive experience with spark-ignited LNG bus engines, reports that maintenance costs of its LNG fleet are approximately equal to those of its diesel fleet. Mileage accumulation at Sun Metro has not been great enough to establish LNG engine durability. However, maintenance staff performed teardowns on two engines at 100,000 mi; both engines were in excellent condition and did not exhibit any premature wear.[23] We believe that long-term LNG bus maintenance costs will be moderately (15 percent) higher than diesel baseline.

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[23] Chavez, G., Superintendent of Maintenance, Sun Metro. Interview with S. Barsony (May 1997).

CHAPTER 5

METHANOL

5.1 OVERVIEW

Methanol, or methyl alcohol, is a clear, colorless liquid that can be made from a variety of feedstocks including coal, natural gas, and various grains. Today, methanol is made mainly from natural gas because that is the most economical method. In the transportation sector, methanol typically has been sold either blended with gasoline (M85) or unblended (M100). The following discussion focuses on the use of M100, because it is the predominant fuel formulation in heavy-duty methanol engines.

From the comparative listing of chemical and physical agencies of methanol and other fuels in Table 2, several key properties deserve notice. These are summarized in Table 13.

Section 5.2 presents the current state of technology including the impacts of methanol fuel use on engine and vehicle performance and transit buses currently in operation that use the technologies identified. Sections 5.3 and 5.4 discuss potential issues related to methanol use in fueling and maintenance facilities. Section 5.5 describes safety considerations. Section 5.6 identifies fuel availability and price issues. Section 5.7 evaluates potential cost implications including general capital and operating costs.

5.2 ENGINE AND VEHICLE TECHNOLOGY

5.2.1 Engine Technology

Unlike diesel fuel, methanol has a very low cetane number, which makes it difficult to compression-ignite. A number of approaches have been pursued for converting diesel engines to methanol operation, including conversion to spark ignition, using cetane improvers, using a dual-fuel system, and direct injection of methanol with ignition assisted by glow plugs. Methanol is corrosive to a variety of metals and plastics. Therefore, to prevent premature failure, engine and fuel system materials must be carefully selected. Methanol fuel also has much lower "lubricity" than diesel fuel. Lubricity refers to the ability of a fluid to protect bearing surfaces from mechanical wear. Because of low lubricity, it has been difficult to achieve good durability in highly loaded methanol-wetted components, such as fuel injectors.

Although methanol presents difficult material selection and component design problems for heavy-duty engines, it has demonstrated an ability to produce reliably low NO_x emissions in combination with low PM emissions. This is probably because methanol has the largest evaporative cooling effect of any of the motor vehicle fuels (Table 2), which results in lower combustion temperatures, and, hence, lower NO_x rates. For example, in Model Year 1992, the methanol Detroit Diesel 6V-92TA was certified at 1.7 g/bhp-hour NO_x and 0.03 g/bhp-hour particulate, and the diesel version of the engine was federally certified at 4.8 g/bhp-hour NO_x and 0.23 g/bhp-hour particulate.

Although several manufacturers have developed experimental and prototype heavy-duty methanol engines (including Caterpillar, Cummins, Deere, and Detroit Diesel), the Detroit Diesel 6V-92TA engine was the only fully commercialized and emission-certified methanol bus engine made available in the United States. In this engine, the compression-ignition combustion cycle was retained, which results in fuel efficiency approximately equal to that of the diesel version. Compression ignition with methanol is achieved by increasing the compression ratio to 23:1 (compared with 19:1 in the diesel version) and by incorporating a blower bypass valve. This valve reduces the exhaust scavenging by the roots blower, causing the combustion chamber to retain more of the hot exhaust gases at the time of fuel injection, which then promote autoignition. In addition to these modifications, glow plugs were used to initiate ignition during start-up and at low loads. A good review of the design and development of the methanol 6V-92 has been provided by Karbowski and Pellegrin.[24] Five hundred methanol engines have been sold, mostly to transit fleets. More than 300 of these were operated by the LACMTA until their conversion to ethanol. During its development, the methanol engine had problems with glowplug failures, fuel injector plugging, and leaking cylinder head seals, but much progress has been made in solving these issues. The future availability of these methanol engines, however, is uncertain because the diesel version of the 6V-92TA is no longer commercially sold as a new bus engine in the United States.

In its methanol bus operations, the LACMTA experienced high rates of engine failures and poor engine durability. The

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[24] Karbowski, G., and Pellegrin, V., *The Methanol Transit Bus, Research and Development to Operational Reality.* SAE Technical Paper Series 911632 (1991).

TABLE 13 Summary of key properties of methanol versus diesel fuel

Property	Diesel	Methanol	Implications for Methanol Vehicle Use
Relative storage volume	100%	228%	Requires about twice the storage volume of diesel for equivalent range
Cetane number	40 to 51	0 to 4	Difficult to compression ignite
Heat of vaporization/lower heating value	0.49%	5.40%	Evaporation of methanol liquid gives a strong charge cooling effect, which promotes low NO_x emissions.
Reid vapor pressure (PSIa at 100 °F)	0.02 to 0.2	4.6	Diesel's vapor pressure at ambient temperatures is too low to form ignitable vapors above a fuel spill, or in a tank's vapor space. Methanol's vapor pressure and flammability limits result in ignitable vapors normally being present in these locations.
Flammability limits (volume %)	0.6 to 5.5	5.5 to 44	Facilities for methanol fuel must be designed with adequate ventilation to prevent accumulation of flammable concentrations of vapors. Ignition sources must be avoided near methanol dispensing, storage, and maintenance areas. Spark arresters should be used with methanol fuel storage tanks.

agency reported that it had to rebuild methanol engines every 45,000 mi (approximately annually), whereas diesel engines normally required rebuilds at intervals of 135,000 mi (approximately 3 years).[25] The poor durability appears to be mainly attributable to leaking fuel injectors as a result of mechanical wear and accumulation of combustion deposits in the injector tips. Leaking methanol fuel mixes with the lubricating oil and degrades it, leading to failure of the crank bearings.[26] Currently, there is little effort to develop new heavy-duty methanol engines, although Caterpillar has been working with DOE support to develop a modern four-stroke truck engine that could use methanol or diesel fuel or any combination of the two. Such a "fuel-flexible" engine could make a transition to increased use of methanol fuels in the heavy-duty sector much simpler than relying on dedicated methanol engines that could be used only in areas where methanol is available.

5.2.2 Vehicle Performance

The performance of methanol bus engines is similar to that of comparable diesel engines. Differences in acceleration performance between methanol and diesel engines depend on the engine configuration and horsepower rating.

The range of methanol buses depends on the fuel economy and fuel storage capacity. A methanol bus requires about 2.3 to 2.6 times as much fuel to go the same distance as a similar diesel bus, so larger fuel tanks and a corresponding weight penalty must be weighed against reduced range. The range of most current methanol buses is between 250 and 300 mi, which allows them to operate on most transit routes.

The additional fuel needed to achieve diesel-equivalent range adds approximately 1,100 lb to a full-sized methanol transit bus. This increased weight may reduce legal passenger capacities in bus models, which are already heavy in diesel form.

On an energy-equivalent basis, current methanol buses experience slightly lower fuel economy than diesel buses. Energy consumption for the methanol engine is about 5 to 10 percent more than that of the diesel operating over the same load cycle. However, the methanol buses at the LACMTA have experienced a 20 percent fuel economy penalty (on the basis of heating value) compared with diesel buses on similar routes.[14] The larger fuel economy penalty experienced in service is likely due to the additional fuel storage weight carried by the methanol buses.

5.2.3 Vehicles Currently in Use

Several transit agencies currently operate methanol buses in their fleets. Table 14 lists these agencies and the vehicles they operate. The largest methanol bus fleet consisted of 333 buses at LACMTA. However, LACMTA converted these buses to ethanol during 1995 and 1996 in the belief that this will improve engine durability. No transit agencies currently have any plans to purchase methanol buses.

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[25] Davis, L. R., et al., Davis and Associates, *The Los Angeles Methanol Bus Experience.* Draft report to the South Coast Air Quality Management District (April 1996).

[26] Davis, L. R., Davis and Associates, personal communication with R. Remillard, ARCADIS Geraghty & Miller (Oct. 1996).

TABLE 14 Methanol-fueled full-size transit buses in use and on order

Transit System	City	Units in Use	Units on Order	Chassis Manufacturer	Chassis Model	Length (ft)	Engine Manufacturer
Metro-Dade Transit Agency	Miami, FL	5	0	Flxible	Metro 40102-6C-1	40	Cummins
Metropolitan Bus Authority	San Juan, PR	36	0	TMC	T80 206	40	Detroit Diesel
MTA New York City Transit	Brooklyn, NY	1	0	TMC	T80 206	40	Detroit Diesel
New York City Dept. of Transportation	New York, NY	18	0	TMC	T80 206	40	Detroit Diesel
City of Phoenix Public Transit Department	Phoenix, AZ	2	0	TMC	T80 206	40	Detroit Diesel
Riverside Transit Agency	Riverside, CA	3	0	General Motors	T80 204	40	Detroit Diesel
	TOTALS	66	0				

Compiled from American Public Transit Association, 1995 Transit Passenger Vehicle Fleet Inventory and other sources.

5.3 FUELING FACILITY IMPACTS

Like a diesel fueling facility, a methanol fueling facility consists of one or more underground fuel storage tanks, leak detection devices, dispensing piping, dispenser, and environmental and safety systems.

Methanol is more corrosive than diesel fuel. Materials wetted by the fuel must be carefully selected to be compatible with the chemical characteristics of methanol. Metal components fabricated from black iron or stainless steel or having nickel-plated wetted surfaces have been found to work well with methanol fuel. Aluminum, copper, zinc, some brass alloys, plastics, and elastomers are not methanol compatible. Incompatible gasket and O-ring materials can quickly soften, dissolve, and leak. Dissolved materials become suspended in the fuel as particles or gel and can quickly clog fuel filters after the fuel is dispensed into the vehicle. Because of the proliferation of light-duty methanol fueling stations, a number of methanol-compatible fueling station components are now offered by equipment suppliers.

Underground storage tanks in existing installations designed for diesel or gasoline may not be methanol compatible. Tanks are constructed of either fiberglass or steel. Fiberglass-reinforced plastic (FRP) tanks are not methanol compatible unless they were manufactured with a special resin that does not dissolve in methanol. A number of companies currently manufacture FRP methanol-compatible tanks. Steel storage tanks are methanol compatible. To inhibit corrosion, steel tanks must be provided with cathodic protection when they are installed underground. Because methanol has a lower energy density than diesel fuel, methanol storage tanks must be proportionately larger and dispenser flow rates must be higher to provide diesel-equivalent capabilities.

Methanol dispensing equipment is similar to diesel equipment, except that some components have been replaced with methanol-compatible parts. Fluorocarbon (e.g., Viton) gasket materials are used in the dispenser and meter. Dispensing hoses designed for methanol or chemical transfer service should be used. High-capacity submerged turbine pumps must be specified to ensure that sufficiently high dispensing rates are achieved. High-rate dispensers delivering nearly 34 gpm have been installed at LACMTA. At this rate, it takes approximately 6 minutes to fill a typical methanol transit bus. To prevent fuel spills at the nozzle, dispensers at LACMTA were equipped with the positive-locking nozzles.

In many parts of the United States, all gasoline or methanol dispensing systems must be equipped with vapor recovery systems for the purpose of minimizing evaporative emissions. Vapor recovery is not required for diesel dispensers, because of the fuel's low vapor pressure. It is critical that vapor recovery piping in neat (pure) methanol dispensing equipment be equipped with flame arresters. This follows from the fact that flammable vapor/air mixtures will usually be present in the ullage space in a methanol storage tank. This is unlike the case with gasoline and diesel, where the ullage-space vapor concentrations are, respectively, too high and too low to be flammable.

5.4 MAINTENANCE FACILITY IMPACTS

Maintenance facility requirements for methanol-fueled vehicles are functionally similar to those for diesel fuel. Methanol buses require the same basic tools and equipment for maintenance as diesel buses. Because methanol is more volatile than diesel fuel, special attention must be paid to the design of maintenance facilities to eliminate possible ignition sources. This is easiest for new facilities because they can be built according to appropriate codes. Maintenance garage design requirements for methanol vehicles are very similar to those for gasoline. When spilled, both fuels rapidly evaporate and produce vapor that is heavier than air. Older facilities can be made methanol compatible by modifying ventilation systems to provide enough air flow to prevent buildup of vapors in the main maintenance area as well as in adjacent office and closet areas and underground maintenance pits. To avoid the potentially costly facility modifications required for methanol, maintenance can also be done outside where natural convection will dissipate fuel vapors.

As with gasoline and other flammable liquids, flow to sewers and drains must be prevented. Unlike diesel fuel, methanol cannot be separated from water with an oil/water separator, so methanol runoff must be disposed of separately.

NFPA design codes applicable to facilities for gasoline vehicles may also be applied to methanol. Specifically, NFPA 88B, Standard for Repair Garages, details the ventilation and heating requirements. NFPA 70, the National Electric Code, describes the electrical system requirements. Finally, NFPA 30, the Flammable Liquid Code, describes the precautions that must be taken when handling flammable liquids.

As it has with CNG and LNG, the FTA has published a comprehensive reference on transit facility design requirements for alcohol-fueled vehicles entitled *Clean Air Program: Design Guidelines for Bus Transit Systems Using Alcohol Fuel (Methanol and Ethanol) as an Alternative Fuel.*[27] Transit agencies that are interested in converting to methanol or that are operating methanol vehicles should use this document to guide their planning process or operating procedures.

5.5 SAFETY

Because the properties of methanol make it different from gasoline and diesel in terms of fire safety, operating and safety training is required for personnel who operate and maintain methanol-fueled vehicles. Transit agencies that use methanol fuel provide training to address the safety requirements for methanol and often use a training manual developed by the FTA.[28] The FTA manual and training programs such as the TSI program cover the safety topics discussed in this section. Operators are also trained in the special aspects of methanol bus operations, including engine starting and warm-up and emergency procedures.

5.5.1 Fire Hazards

The flammability limits of methanol differ from those of gasoline and diesel fuel (see Table 2). These properties dictate the conditions under which methanol vapors will ignite. In spills on the ground or in the open, methanol does not ignite as readily as gasoline and it burns with a less intense flame. Smoking should be prohibited when methanol vehicles are being fueled as well as during maintenance activities. Pure methanol also burns with a nearly invisible flame in daylight.

The flammability hazard in vehicle fuel tanks is also different. In a gasoline fuel tank, the vapor concentration is high enough that the vapors are too rich to burn at temperatures above -20°F (-28.9°C). In a diesel fuel tank there is not enough vapor to support combustion under most conditions. The vapor space in a tank of 100 percent methanol forms an ignitable mixture in the temperature range of 50° to 110°F (10° to 43.3°C). The risk of accidentally igniting these vapors is reduced by installing flame arresters in the fuel tank filler neck and vent. Flame arresters are required by law on all methanol-fueled vehicles. Flame arresters are usually made of stainless steel mesh.

Firefighting requirements need to be considered for methanol. Alcohol-resistant foams are required to fight large methanol fires; small fires of this type can be extinguished with water.

5.5.2 Fuel Toxicity

The toxic effects of methanol are the same regardless of the mode of exposure (inhalation, ingestion, dermal contact). Methanol can cause acute toxic effects, including severe gastrointestinal irritation, blindness, and death from ingesting quantities as small as a few milliliters.[29] Toxic effects can also result from extensive skin exposure or inhalation of high concentrations of vapor. With immediate medical attention, the severe toxic symptoms can be treated. Safety training covers precautions that protect personnel from methanol exposure. The use of eye protection and gloves is recommended during fueling and vehicle fuel system maintenance.

5.5.2.1 Hazardous Materials

All personnel who handle hazardous materials are required to undergo safety training. Hazardous materials encountered in maintenance facilities include fuels, lubricants, and coolant. Methanol is a hazardous material. Training for hazardous materials covers spill cleanup and disposal of waste materials, such as used fuel filters and oil filters.

5.6 FUEL AVAILABILITY AND COST

Methanol is used primarily as a feedstock for conversion into other commodity chemicals, such as formaldehyde and

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[27] Raj, P. K., DeMarco, V. R., Hathaway, W. T., and Kangas, R., *Clean Air Program: Design Guidelines for Bus Transit Systems Using Alcohol Fuel (Methanol and Ethanol) as an Alternative Fuel.* DOT-FTA-MA-26-7021-96-3. Technology & Management Systems, Inc., Burlington, Mass. (Aug. 1996). Available from the National Technical Information Service, Springfield, Va. 22161.

[28] *Training Manual for Methanol Use in Transit Operations*, U.S. Department of Transportation, Office of Technical Assistance and Safety (July 1988).

[29] Litovitz, T., *Acute Exposure to Methanol in Fuels: A Prediction of Ingestion Incidence and Toxicity.* National Capital Poison Center (Oct. 1988).

acetic acid. Conversion to methyl tertiary butyl ether (MTBE) has recently emerged as a major new use for methanol. MTBE is used mainly as a gasoline additive. It contains oxygen and also increases the gasoline's octane rating. The federal oxygenated fuels program, which took effect in November 1992, requires that gasoline contain at least 2.7 percent oxygen by weight, or approximately 11 percent MTBE by volume, during the winter months in many regions of the United States. This is done to reduce automotive emissions of CO. Oxygenation of gasoline has also been found to reduce exhaust emissions of reactive organic gases, which promote the formation of ozone. In January 1995, the federal reformulated gasoline program took effect, which requires that gasoline sold in ozone nonattainment areas contain at least 2.0 percent oxygen by weight, or approximately 11 percent MTBE by volume, year-round. As a result of these programs, MTBE use in the United States has increased from 4.9 million tons in 1992 to 10 million tons in 1995.[30]

Before 1994, wholesale methanol prices remained fairly stable at between $0.40 and $0.60 per gallon. During 1994 and 1995, methanol prices increased to unprecedented levels of $1.60 to $1.75 per gallon in late 1994, only to plummet to $0.35 to $0.38 per gallon by September 1995. Strong demand for MTBE by gasoline refiners planning for the oxygenated gasoline program, combined with methanol plant outages and start-up delays, were principal causes of the price increase. Several areas of the country then opted out of the reformulated gasoline program, which led to a collapse in methanol prices. In addition to poor engine durability, high operating costs resulting from this escalation in methanol fuel prices was a principal reason cited by the LACMTA for converting its methanol fleet to ethanol operation.

Methanol as a motor fuel would be stored and shipped much like gasoline and diesel fuel are today, with the exception that shipping methanol by pipeline is technically easy but would require upgrading current petroleum-product pipelines. The lower energy density of methanol, compared with gasoline and diesel fuel, means that in commercial practice more volume needs to be stored and trucked, which would increase distribution costs over that of the petroleum fuels. Before transporting neat (100 percent) methanol fuel, tank trailers must be thoroughly cleaned of any residual petroleum products. Given that the primary markets for methanol are in higher value products such as chemical feedstock and gasoline additive, combined with the difficulties in transporting neat methanol fuel, it appears unlikely that methanol will soon become cost competitive with other fuels.

5.7 CURRENT CAPITAL AND OPERATING COSTS

Several diesel engine manufacturers have engaged in methanol engine development work, and there have been a number of on-road demonstrations of methanol-fueled heavy-duty vehicles, but only one manufacturer has commercialized an engine, as previously discussed.

The methanol engine was priced at roughly twice as much as the counterpart diesel engine—i.e., on the order of $10,000 more for a bus manufacturer purchasing a number of engines. In addition, to use this engine in a transit bus, a somewhat different fuel system is required (i.e., a larger capacity tank fabricated from methanol-compatible materials and usually a heat exchanger in the fuel recirculation system). Actual incremental costs for methanol buses when they were available for purchase were approximately $25,000 to $35,000.

Methanol fueling facilities and modifications to maintenance facilities entail additional capital costs. Although these costs vary substantially depending on the specific circumstances and equipment, a typical estimate for a 200-bus transit fleet is $300,000 for modifications to one maintenance garage and $400,000 for one methanol fueling facility.[15]

Operating costs for methanol buses, relative to diesel buses, depend primarily on fuel costs and maintenance costs. Fuel costs are substantially higher for methanol buses because of current methanol fuel prices and a fuel economy penalty. For example, methanol buses at LACMTA have experienced fuel costs of $0.53 per mi for methanol buses (based on methanol costs of $0.58 per gallon and fuel economy of 1.1 mi per gallon) and $0.22 per mi for diesel buses (based on diesel fuel costs of $0.67 per gallon and fuel economy of 3.1 mi per gallon).[14]

Current data on relative maintenance costs for methanol buses are based largely on experiences at the LACMTA. The LACMTA has experienced high maintenance costs because of the need for frequent engine rebuilds. It is likely that additional development work would lead to more robust fuel injector designs that could greatly improve their durability. However, the industry's experience to date indicates that two-stroke diesel engines are much more suited to methanol operation than four-stroke engines. With the transit industry's transition to four-stroke engines and methanol's high cost compared with diesel or natural gas, there is little likelihood that a methanol engine meeting modern standards of durability will be developed for some time.

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[30] Methanex's 1995 annual report on methanol markets, Methanex's World Wide Web page: http://www.methanex.com (Nov. 1996).

CHAPTER **6**

ETHANOL

6.1 OVERVIEW

Ethanol, or ethyl alcohol, is also known as grain alcohol because it is usually fermented from grains, such as corn or other agricultural products. Ethanol proponents point out that ethanol is the only truly "renewable resource" alternative fuel because it is made from agricultural products and not from hydrocarbon-based fossil fuel feedstocks. Ethanol has emerged as an alternative fuel in regions where corn and other agricultural resources are abundant, such as the midwestern United States. Ethanol, like conventional fuels, is a liquid. The form of ethanol primarily used in transportation is 95 percent ethanol and 5 percent gasoline. This small amount of gasoline provides a taste deterrent to reduce the possibility of the ethanol being abused for its inebriating effects; it also provides greater flame luminosity. E85 and E100 are other fuel formulations that have been used.

Ethanol has a higher energy density than methanol, and therefore a bus fueled with ethanol will have a longer range than a methanol-fueled bus with the same size fuel tank. However, ethanol generally costs more than methanol and large quantities are needed for transit usage.

From the comparative listing of chemical and physical properties of ethanol and other fuels in Table 2, several key properties deserve special notice. Table 15 summarizes three key properties of ethanol that affect its use as a transportation fuel.

Section 6.2 presents the current state of technology, including the effects of ethanol fuel use on engine and vehicle performance, and lists the transit buses currently in operation using the technologies identified. Sections 6.3 and 6.4 discuss potential issues related to ethanol use in fueling and maintenance facilities. Section 6.5 describes safety considerations. Section 6.6 identifies fuel availability and price issues. Section 6.7 evaluates potential cost implications, including general capital and operating costs.

6.2 ENGINE AND VEHICLE TECHNOLOGY

6.2.1 Engine Technology

Ethanol has a low cetane number, and therefore it is difficult to compression ignite. A number of approaches have been pursued for converting diesel engines to ethanol operation, including conversion to spark ignition, use of cetane improvers, use of a dual-fuel system, and direct injection with ignition assisted by glow plugs. The methanol DDC 6V-92 is easily modified for ethanol with minor changes in calibration. The Detroit Diesel 6V-92TA is the only ethanol bus engine commercially available in the United States.

6.2.2 Vehicle Performance

The range of ethanol buses depends on the fuel economy and fuel storage capacity. Because of ethanol's lower energy content, about 1.7 times more fuel per mi is required to operate an ethanol-fueled bus than a similar diesel. With standardsized tanks, ethanol buses have enough range to operate on most transit routes.

The performance of ethanol engines is equivalent to that of similar diesel engines. Differences in acceleration performance between ethanol and diesel engines depend on the engine configuration and horsepower rating.

Like methanol buses, ethanol buses suffer a fuel economy penalty compared with diesel buses. Ethanol buses at LACMTA have experienced 17 percent lower fuel economy, on an energy-equivalent basis, than diesel buses on similar routes, although this is based on limited operating experience.[26]

Transit buses powered by ethanol achieve low particulate emissions but do not achieve NO_x rates as low as the methanol version. For example, the ethanol (E95) engine has certification emission rates of 4.1 g/bhp-hour NO_x and 0.04 g/bhp-hour particulate, whereas the methanol version was certified at 1.7 g/bhp-hour NO_x. Some of this difference is attributable to the fact that engine calibrations were not extensively optimized for ethanol during conversion of the methanol engine. However, evaporation of ethanol liquid produces a much weaker charge cooling effect than that of methanol (Table 2). Combustion temperatures and NO_x rates with ethanol therefore may also be inherently higher. The certification emission rates for NO_x and PM for the ethanol engine are very similar to those of 1996 California-certified diesel transit bus engines (Table 6). (More information on comparative emission rates from buses in transit service is included in Chapter 12.)

TABLE 15 Summary of key properties of ethanol versus diesel fuel

Property	Diesel	Ethanol	Implications for Ethanol Vehicle Use
Fuel energy value, LHV (Btu/gal)	128,000	76,400	Requires somewhat more fuel storage for equivalent range
Cetane number	40 to 51	5 to 15	Difficult to compression ignite
Flammability limits (volume %)	0.6 to 5.5	3.3 to 19	Ignition sources must be avoided near ethanol dispensing, storage, and maintenance areas

6.2.3 Vehicles Currently in Use

Few transit agencies currently operate ethanol buses in their fleets. Table 16 lists these agencies and the vehicles they operate. The only large ethanol bus fleet consists of 333 buses at LACMTA. These buses were converted from methanol operation during 1995 and 1996. (Note: These buses have been recently converted back to methanol.) No transit agencies currently have any ethanol buses on order.

6.3 FUELING FACILITY IMPACTS

Storage and handling requirements for ethanol are similar to those for methanol. Most of the fueling facility design considerations reviewed above for methanol also apply for ethanol. Existing steel storage tanks can be retrofitted for ethanol use. Newer alcohol-compatible fiberglass tanks can also be used for ethanol storage. Ethanol is somewhat less corrosive than methanol, so fuel pumps, tank-top equipment, and dispensing equipment designed for methanol service are also quite suitable for ethanol. Ethanol dispensers can be equipped with mechanically locking nozzles that deliver fuel at about 40 gpm. Conventional automotive nozzles can also be used.

6.4 MAINTENANCE FACILITY IMPACTS

Maintenance garage design requirements for ethanolfueled vehicles are functionally similar to those for methanol fuel. Both methanol and ethanol are volatile liquids that generate vapors that are heavier than air. Ethanol buses and methanol buses require basically the same tools and equipment for maintenance. Classified wiring should be installed at low points (less than 18 in. above floor level), and ventilation should be adequate to disperse accumulations of vapor. This is easiest to achieve in new garages because they can be built according to current codes. Older garages can be made ethanol compatible by modifying ventilation systems to provide enough airflow to prevent buildup of vapors in the main maintenance air as well as in adjacent office and closet areas and underground maintenance pits. To avoid the potentially costly facility modifications required for ethanol, maintenance can also be done outside where natural convection is enough to dissipate vapors from fuel leaks.

As with gasoline and other flammable liquids, the flow to sewers and drains must be managed. Because ethanol is miscible with water, oil/water separators used for diesel and gasoline are not effective, and ethanol runoff must be disposed of separately.

Codes governing the design and construction of facilities for gasoline vehicles are also generally applicable to ethanol. Specifically, NFPA 88B, Standard for Repair Garages, details the ventilation and heating requirements. NFPA 70, the National Electric Code, describes the electrical system requirements. Finally, NFPA 30, the Flammable Liquid Code, describes the precautions that must be taken when handling flammable liquids.

TABLE 16 Ethanol-fueled full-size transit buses in use and on order

Transit System	City	Units In Use	Units on Order	Chassis Manufacturer	Chassis Model	Length (ft)	Engine Manufacturer
Los Angeles County Metropolitan Trans. Auth.	Los Angeles, CA	333*	0	TMC	T80 206	40	Detroit Diesel
Metropolitan Council Transit Operations	Minneapolis, MN	5	0	Gillig	Phantom 40TB102	40	Detroit Diesel
Greater Peoria Mass Transit District	Peoria, IL	14	0	TMC	T70 606	35	Detroit Diesel
	TOTALS	352	0				

Compiled from American Public Transit Association Transit Passenger Vehicle Fleet Inventory (1995) and other sources.
*Recently converted back to methanol.

6.5 SAFETY

Because ethanol's properties make it different from gasoline and diesel in terms of fire safety, operating and safety training is required for personnel who operate and maintain ethanol-fueled vehicles. Ethanol is perhaps the safest of the alternative fuels. Relative to methanol, ethanol is less toxic and it has a more visible flame. Relative to CNG, it does not have to be stored at high pressures, and it "leaks down" like gasoline. Relative to LNG and hydrogen, ethanol is not stored at cryogenic temperatures and there is no venting issue. Relative to LPG, it does not have to be stored under pressure, and leaks are not as hazardous.

6.5.1 Fire Hazards

Ethanol's flammability limits differ from those of gasoline and diesel fuel (see Table 2). These properties dictate under what conditions ethanol vapors will ignite. In spills on the ground or in the open, ethanol does not ignite as readily as gasoline and it burns with a less intense flame. Smoking should be prohibited when ethanol vehicles are being fueled as well as during maintenance activities. Pure ethanol also burns with a nearly invisible flame in daylight.

Firefighting requirements need to be considered for ethanol. Alcohol-resistant foams are required for fighting large ethanol fires; small fires of this type can be extinguished with water.

6.5.2 Fuel Toxicity

Unlike methanol, which can cause severe toxic health effects if ingested or inhaled in large amounts, the most significant health effect related to ethanol is inebriation. Ethanol is the alcohol present in alcoholic beverages. To discourage intentional ingestion of ethanol, small concentrations of taste deterrent are added to ethanol fuel. Small amounts of gasoline, around 5 volume percent, are enough to give ethanol fuel a sufficiently bad taste to deter people from drinking it. Addition of gasoline does not adversely affect the characteristics of ethanol fuel. Besides slightly improving the ease of combustion of ethanol, addition of gasoline also improves flame visibility.

6.5.3 Hazardous Materials

All personnel who handle hazardous materials are required to undergo safety training. Hazardous materials that are encountered in maintenance facilities include fuels, lubricants, and coolant. Ethanol is also a hazardous material. Training for hazardous materials covers spill cleanup and the disposal of waste materials, such as used fuel filters and oil filters.

6.6 FUEL AVAILABILITY AND COST

Most fuel ethanol in the United States is currently made from corn through fermentation and distillation. Ethanol can also be made from other grains or any starch-yielding agricultural product or even from cellulose (although this process is not commercialized). Ethanol produced from biomass such as agricultural wastes or municipal wastes is of particular interest because these feedstocks are not also food sources. For this reason, DOE (through NREL) conducts research to reduce the cost of producing ethanol from biomass.

Ethanol is produced and used mainly in the Midwest—i.e., the corn-growing states—where it is sold as an additive to gasoline to form gasohol. In addition, nearly neat ethanol (85 percent or 95 percent ethanol blended with 15 percent or 5 percent gasoline) is sold in limited quantities as a vehicle fuel. The ethanol is trucked from production or intermediate storage/distribution facilities to refueling stations. The United States has a relatively small ethanol fuel infrastructure, consisting of roughly 40 refueling stations (all of which are private), which support a few hundred ethanol-fueled vehicles.

The ethanol production capacity in the United States is approximately 1.4 billion gallons per year. Only a small fraction of this production capacity is used directly as a vehicle fuel. A much larger fraction is used for gasohol. There is some question about whether an adequate ethanol supply can be made available at a reasonable price if the ethanol fuel market grows to a significant fraction of the current gasoline or diesel fuel market.

Among the fuels being reviewed here, on the basis of energy content only hydrogen is more expensive than ethanol. Because ethanol is basically an agricultural product, agricultural economics and institutions dominate its production. For example, the price of ethanol is related to crop prices—when the weather is bad and crop yields are poor, the price of ethanol goes up. Researchers are attempting to develop processes for efficiently fermenting ethanol from agricultural waste products (biomass feedstock) that are rich in cellulose. If this research is successful, it could fundamentally improve the economics of ethanol production.

Another effect on ethanol prices is the fact that there are three competing fuel uses of ethanol: direct use as a vehicle fuel (as E100 or E85), gasohol, and ETBE (ethyl tertiary butyl ether, an oxygenated additive used in reformulated gasoline).

6.7 CURRENT CAPITAL AND OPERATING COSTS

The ethanol engine costs roughly twice as much as the counterpart diesel engine—i.e., on the order of $10,000 more for a bus manufacturer purchasing a number of engines. Actual incremental costs for alcohol buses when they were available for purchase were approximately $25,000 to $35,000.

Ethanol fueling facilities and modifications to maintenance facilities entail additional capital costs. Although these costs vary substantially depending on the specific circumstances and equipment, a typical estimate for a 200-bus transit fleet is $300,000 for modifications to one maintenance garage and $400,000 for one ethanol fueling facility.[14]

Operating costs for ethanol buses, relative to diesel buses, depend primarily on fuel costs and maintenance costs. Fuel costs are substantially higher for ethanol buses, as discussed in Section 6.6. For example, LACMTA has experienced fuel costs of $0.68 per mi for ethanol buses (based on $1.04 per gallon ethanol costs and 1.53 mi per gallon fuel economy) and $0.22 per mi for diesel buses (based on $0.67 per gallon diesel fuel costs and 3.1 mi per gallon fuel economy).[13]

Because of the limited use of ethanol transit buses, no definitive estimate of the incremental maintenance costs of ethanol buses exists.