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16. Abstract

This study is a detailed comparative analysis of liquefied natural gas (LNG) and compressed natural gas (CNG). The study provides data on two alternative fuels used by transit agencies in Texas. First, we examine the "state-of-the-art" in alternative fuels to establish a framework for the study. Efforts were made to examine selected characteristics of two types of natural gas demonstrations in terms of the following properties: energy source characteristics, vehicle performance and emissions, operations, maintenance, reliability, safety costs, and fuel availability. Where feasible, two alternative fuels were compared with conventional gasoline and diesel fuel. Environmental considerations relative to fuel distribution and use are analyzed, with a focus on examining flammability an other safety-related issues.

The objectives of the study included: (1) assess the state-of-the-art and document relevant findings pertaining to alternative fuels; (2) analyze and synthesize existing databases on two natural gas alternatives: liquefied natural gas (LNG) and compressed natural gas (CNG); and (3) compare two alternative fuels used by transit properties in Texas, and address selected aspects of alternative fuels such as energy source characteristics, vehicle performance and emissions, safety, costs, maintenance and operations, environmental and related issues.

A profile of two alternative fuels used by Texas transit agencies is presented. The comparisons made about properties of LNG and CNG provide a context within which an assessment of other alternative fuels such as methanol, ethanol, electric vehicles can be made.

The findings of the study will contribute to existing evidence on alternative fuels. Data included in the study will be useful to transportation industry officials in the public and private sector. Comparative data on alternative fuels will contribute to a greater understanding of their use and enhance policy decisions about alternative fuels.

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A COMPARATIVE ANALYSIS OF LIQUEFIED NATURAL GAS (LNG) AND COMPRESSED NATURAL GAS (CNG) USED BY TRANSIT AGENCIES IN TEXAS

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This study is based on a series of reports and references published by previous researchers and consultants. The Metropolitan Transit Authority of Harris County (known as Houston METRO) began its demonstration project in 1990 in response to a state mandate (Section 114.11 of the Texas Regulation IV of the Texas Natural Resource Conservation Commission, Control of Air Pollution from Motor Vehicles). Findings reflected in the comparative data on LNG used in this study were collected during the course of the LNG fleet conversion project. I would also like to acknowledge the support and cooperation of Russell H. Pentz, former Assistant General Manager of Maintenance for Houston METRO. While in progress, he served as the Project Monitor for the earlier study on cost associated with alternative fuel conversion. George A. Herman, Deputy Assistant General Manager of Maintenance, provided assistance also.

I would like to extend personal thanks to Capital METRO General Manager, Justin T. Augustine III and his Chief Financial officer, Alan Pegg, for allowing us to review and use data on the CNG vehicles currently in use at Capital METRO in Austin, Texas. Summary data is included in the Appendices and similar data on LNG for Houston Metro were included in the study entitled: A Study of Costs Associated with Alternative Fuels Development: A Case Study (Ledé, 1995).

The efforts of DeLinda Marzette, Research Associate, must also be recognized. Marzette conducted an extensive "state-of-the-art" search on alternative fuels. She analyzed and synthesized documents pertaining to the two forms of natural gas: liquefied Natural Gas (LNG) and Compressed natural Gas (CNG). Her extensive analysis contributed greatly to the quality of this report. Raquelle R. Wooten, Director of Technology transfer, provided assistance in developing graphic illustrations for the study and edited all versions of the final report. Sally Harrell typed early versions of the manuscripts, developed tables and charts, and assisted in locating valuable resources needed to complete the study. Khosro Godazi gave his expertise and energy to this study's development. This report has been considerably strengthened by the input of these individuals. The value of this study must be shared with these contributors while all errors must be contributed solely to me.

ABSTRACT

This study is a detailed comparative analysis of liquefied natural gas (LNG) and compressed natural gas (CNG). The study provides data on two alternative fuels used by transit agencies in Texas. First, we examine the "state-of-the-art" in alternative fuels to establish a framework for the study. Efforts were made to examine selected characteristics of two types of natural gas demonstrations in terms of the following properties: Energy source characteristics, vehicle performance and emissions, operations, maintenance, reliability, safety costs, and fuel availability. Where feasible, two alternative fuels were compared with conventional gasoline and diesel fuel. Environmental considerations relative to fuel distribution and use are analyzed, with a focus on examining flammability and other safety-related issues.

The objectives of the study included: (1) Assess the state-of-the-art and document relevant findings pertaining to alternative fuels; (2) analyze and synthesize existing databases on two natural gas alternatives: Liquefied natural gas (LNG) and compressed natural gas (CNG); and (3) compare two alternative fuels used by transit properties in Texas, and address selected aspects of alternative fuels such as energy source characteristics, vehicle performance and emissions, safety, costs, maintenance and operations, environmental and related issues.

A profile of two alternative fuels used by Texas transit agencies is presented. The comparisons made about properties of LNG and CNG provide a context within which an assessment of other alternative fuels such as methanol, ethanol, electric vehicles can be made.

The findings of the study will contribute to existing evidence on alternative fuels. Data included in the study will be useful to transportation industry officials in the public and private sector. Comparative data on alternative fuels will contribute to a greater understanding of their use and enhance policy decisions about alternative fuels.

EXECUTIVE SUMMARY

This study is a comparative analysis of natural gas as an alternative fuel. It examines two forms of natural gas, namely, liquefied natural gas (LNG) and compressed natural gas (CNG) from the perspective of several areas of interest, including energy source characteristics, vehicle performance and emissions, operation and maintenance, safety, fuel costs and facilities, and related issues. References are made to other alternative fuels in an effort to broaden and differentiate fuel properties and characteristics.

The objectives of the study include the following:

- To assess the state-of-the-art and document relevant findings pertaining to alternative fuels;

- To analyze and synthesize the existing database on two natural gas alternatives: LNG and CNG; and

- Compare two alternative fuels used by transit agencies in Texas, and address selected aspects of alternative fuels such as energy resource characteristics, vehicle performance and emissions, maintenance and operations, fuel costs, facility costs, safety, environmental and related issues.

The approaches used in the study consisted of several phases, some of which were performed concurrently. The first phase of the study included a review of related studies pertaining to alternative fuels. Existing databases on alternative fuels were located and used in the analysis. Data from previous surveys of transit authorities in Texas were also used (Ledé, 1995). Findings from previous on-site surveys at facilities using CNG and LNG were central to delineating specific variables on alternative fuels for the comparative analysis. A compendium of issues were compiled and structured around specific alternative fuels. Once a conceptual framework was developed, data were compared and documented in the study.

The results of this study are not considered to be final because of evolving technological improvements to alternative-fueled vehicles (AFVs). High performance technology is in the process of being developed. As a result, the findings presented in this study should be perceived as contributing to an evolving body of knowledge on alternative fuels.

The Federal Clean Air Act Amendments of 1990 mandated the Federal Clean Air Fleet (FCFF) Program to reduce motor vehicle air pollution in the nation's serious, severe, and extreme ozone non-attainment areas. In response to this legislation, Texas adopted the Texas Alternative Fuel Fleet (TAFP) Program. The TAFF program was designed to improve air quality by using fuels that burn cleaner than the conventional transportation fuels. Mass transit fleets and all fleets with 15 or more vehicles were affected by the requirements of the TAFF program. Several transit systems in the largest metropolitan areas in Texas began phasing in alternative fueled vehicles in their bus fleets after the TAFP program was initiated by the Texas Legislature. The findings of this study indicate that CNG and LPG continue to be at the cutting edge of alternative fuels for transit systems and school districts. The basic rationale for using natural gas lies in the fact that it is a clean burning fuel.

Additional findings, however, indicate that for natural gas to be more effective in vehicular use, it must be used in either liquefied or compressed form if it is to achieve a useful operating range. More research data are available on the use of CNG than LNG. One of the most extensive LNG fuel conversion experiences took place at the Metropolitan Transit Authority of Harris County (Houston METRO). Findings relative to the efficacy of the LNG fuel conversion project are inconclusive. What is known, however, is the cost of LNG approximates that of diesel on an energy basis. According to a report by TRB (1993:20), "local fuel diesel pricing and delivered LNG cost are important variables in making cost comparisons for facility and operation."

This analysis further shows that Houston METRO was, at one time, a leading proponent of LNG. Houston METRO selected LNG over CNG. There are problems with storing natural gas. Data indicate that other alternative fuels are easier to store than natural gas. Also, infrastructure requirements for LNG are different from those for CNG. There is need to develop better cost data on both forms of natural gas – LNG and CNG –regarding infrastructure development and near-term transition from diesel to natural gas. More information is needed on the hazards of natural gas distribution and use. The final observation pertains to training personnel to ensure safety. Previous research studies reveal that training manuals are being prepared for the Clean Air Program administered by the Office of Technical Assistance and Safety, Federal Transit Administration, U.S. Department of Transportation.

More research is needed on alternative fuels. Vehicle-related issues such as transport hazards, health hazards, storage system integrity, and hazards associated with refueling for LNG and CNG should be explored in-depth. A survey of transit agencies included in this study revealed that some concerns associated with maintenance, fueling, and storage of alternative fuels have not been resolved. The management of alternative fueled programs must ensure the safe handling of alternative fuels. Managers of transit bus fleets in the public and private sector will continue to explore alternative fuel options in the interest of energy conservation and air quality. The findings of this study and previous research are designed to enhance decision-making relative to choosing appropriate alternative fuel options.

Texas approved several alternative fuels, including natural gas. When forms of natural gas as alternative fuels are considered for use, both advantages and disadvantages should be carefully compared and analyzed in terms of costs and benefits. Alternative fuels meet state mandates for cleaner burning fuels. Also, they reduce exhaust emissions. Cleaner-burning fuels contribute to a reduction in the emissions of pollutants that contribute to the formation of smog and other air pollution problems. This document has attempted to provide additional information on the evolving nature of alternative fuels and factors that could contribute to their optimal utilization.

The analysis indicates that natural gas is equivalent to methanol and other alternative fuels in terms of its capability for reducing air pollution.

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I. INTRODUCTION

Research concerning alternative fuels has been motivated by a growing concern about the environment and the nation's continued dependence on petroleum from unstable areas of the world. The present interest in alternative fuels has been manifested by increasing awareness and a sustaining interest in new domestic sources of power for vehicles and new vehicle technologies. A report published by the Argonne National Laboratory and funded by the U. S. Department of Energy (1994: 2-5) indicates that "our country continues to consume more than one-fourth of the world's oil production. The transportation sector currently accounts for approximately two-thirds of all U. S. petroleum use and roughly one-fourth of total U. S. energy consumption." It further notes that a "virtual one-to-one relationship exists between additional gasoline consumption and America's increased use of imported oil. Clearly, any effort to decrease our use of oil hinges on reducing its use in transportation."

The United States has long recognized the challenge of identifying, tackling, and over-coming transportation-related problems. In response to an impending crisis, including the nation's dependence on petroleum from unstable areas of the world, congestion, pollution, energy efficiency and dwindling natural resources, several federal laws were passed. The 1990 Clean Air Act (CAA) and the Energy Policy Act (EPACT) imposed some fundamental requirements for protecting the environment and conserving energy. Section 405 of the Energy Policy Act (EPACT) of 1992 outlined several goals one of which was "to promote the use of alternative fuels and alternative-fuel vehicles. As defined by the Energy Policy Act, several terms, including alternative fuel, nonpetroleum fuel, domestic fuel, and clean fuel are often used interchangeably, as are clean-fuel vehicle and alternative-fuel vehicle. As defined by the Clean Air Act, any fuel or power source that enables a vehicle to emit less pollution than would be the case with conventional gasoline or diesel fuel. These include alternative fuels and specially formulated gasoline and diesel fuel.

The passage of the CAA and EPACT legislation clearly indicates that the nation is pursuing a new course toward its dependence on petroleum fuels in the transportation sector. Following the initiation of these environmentally-sensitive Acts, urban areas designed as non-attainment sectors began testing the feasibility of the long-term utilization of alternative fuels. Transit systems, including large, medium, and small properties, began to explore the use of alternative fuels as a potential replacement for conventional diesel and gasoline fuel. Driven by considerations such as air quality and energy diversification, local, state, and federal agencies started programs to purchase or retrofit bus fleets and other vehicles for alternative fuel use. In Texas, the Metropolitan Transit Authority of Harris County (Houston METRO) initiated a relatively vigorous agency-wide conversion to liquefied natural gas (LNG) powered buses, while the Capital Metropolitan Transportation Authority (CAPITAL METRO) in Austin, Texas selected compressed natural gas (CNG) powered buses to implement its alternative fuel program. This study was designed to compare two alternative fuel initiatives in terms of selected variables. Fuel cost, fuel facility, energy source, operation and maintenance, vehicle performance and emissions characteristics for two alternative fuels, namely, CNG and LNG, were analyzed.

I. LITERATURE REVIEW

A substantial body of literature exists on alternative fuels. The focus of this section is on key studies completed or in progress on alternative fuels and related environmental and energy-related research and technology. The general outlook and forecasts for alternative fuels, as revealed by scholars in the transportation field, suggest an admixture of opinions relative to legislative mandates, initiatives and issues, particularly fuel conversion and usage. Costs associated with the conversion and demonstration of alternative fuel, environmental considerations, energy conservation and efficiency are other major issues of concern. A report from *Business Communications, Incorporated* (1991:1), for example, indicates that alternative fuels can replace between 7.3 and 15 percent of imported and refined petroleum products needed for transportation by the year 2000. Bloch (1984) provides additional insight into alternative fuels as contingency protection in an evaluation conducted on alternative fuel transit buses.

The federal government and some states developed major new policies to induce changes in transportation markets. The legislative mandates were designed as an attempt to force technological advancement and market adoption of vehicles powered by fuels other than gasoline or diesel. The policies adopted by the federal government and some states were in response to various goals, including cleaner air, reduced dependency on foreign oil, enhanced economic development, and reduced greenhouse gas emissions. In September of 1995, a diverse professional group of individuals met in a conference setting to consider fuels and vehicles for the future, their impact on the environment, and whether or not current policies should be sustained, changed, or replaced. Sharp and Tierney (1995: 4-13) presents the findings in the volume, *Fueling the Future*. Policies pertaining to the Clean Air Act Amendments and the Energy Policy Act were analyzed. In addition, attention was also directed to the principal elements of the federal framework for promoting alternative fuels vehicles.

A. Alternative Fuels: Legislative Mandates

Maze (1993:55-58) presented a paper on "Alternative Fuels – Legislative Mandates, Initiatives and Issues." The paper examined the motivation for requiring state fleets to operate alternatively fueled vehicles. The author contended that "this is a public policy that is increasing in popularity and state fleets are logical test bed for the promotion of social objectives." The status of state alternatively fueled fleet programs is also examined.

Anderson (1995: 17-25) examines cleaner alternative fuels for fleets in an article published by the Transportation Research Board (TRB) in its publication, *Transportation Research Record 1472*. The author provides an in-depth overview of CAAA of 1990 and the EPACT of 1992. Michael J. Murphy of Battelle (1992) explores properties of alternative fuels in a technical report prepared for the Federal Transit Administration's Office of Technical Assistance and Safety. Compressed natural gas (CNG) and other fuels were also examined as part of the Clean Air Program of the agency. The Office of Alternative Fuels, however, contains a comprehensive background on alternative fuel vehicles (AFV). For each of the major alternative fuel types, data are presented on energy source characteristics, vehicle performance and emissions, and operation and maintenance. The document provides a basic understanding of commonly considered alternative fuel vehicles (AFV). Information is provided on an introductory level for those who have a basic understanding of convention (gasoline and diesel) vehicles and are considering alternative fuel vehicles for their fleets. Data from this document and relevant studies pertaining to alternative fuel were used in the formulation of the research design and methodology for the study.

B. Environmental Benefits

Previous researchers have examined alternative fuel from the perspective of environmental benefits. Levine (1990: 27-31) indicates that "while lead-free gasoline and catalytic converters have contributed to reduced emissions from mobile sources, ozone level improvement has been slow. As a result, the attention of industry and government on air quality," says Levine, "has continued to focus on tighter emissions standards." Included in the article is a discussion of the preliminary data available on compressed natural gas (CNG) and methanol, CNG vehicles in use today, the safety of CNG vehicles, the potential for reformulated gasoline use, the public understanding of the costs and benefits of meeting emission standards, government/industry cooperation in developing policies to improve the nation's energy position. According to DeLuchi, Johnston, and Sperling (1988:33-44), continued emissions of CO_2 and other "greenhouse" gases are expected to cause substantial global warming and adverse consequences for agricultural and coastal cities, the emission of greenhouse gases has not been a criterion in evaluation of alternative transportation fuels. DeLuchi and others (1988) evaluate emissions of CO_2, CH_4, N_{2O}, and other greenhouse gases from the use of gasoline and diesel fuel, electricity, methanol, natural gas, and hydrogen in highway vehicles. Emissions from initial resource extraction to end use of greenhouse gases are estimated. The authors found that the use of coal to make highway fuel would substantially accelerate greenhouse warming relative to the base-case use of petroleum. The use of natural gas as a feedstock would result in a small reduction. Another important finding of the study indicates that significant reductions in emissions of greenhouse gases can be achieved only by greatly increasing vehicle efficiency or by using biofuels, electrolytic hydrogen, or nonfossil-fuel-based electricity as the fuel feedstock. Emissions of gases other than CO_2 are likely to contribute appreciably to the warming, but better data are needed (Sperling, et.al. 1988).

Possible emission regulations on gasoline suppliers to encourage the use of alternative transportation fuels, including compressed natural gas, methanol, and electricity are examined by Rubin (1994). A theoretical model based on the concept of marketable emission permits was built for gasoline suppliers. The model shows that a fleet average emission standard on gasoline suppliers will encourage the sale of clean fuels that would otherwise not be profitable because clean fuels will generate valuable emission permit. The author also developed a dynamic empirical model that determines the least-cost solution to meeting emission standards for new vehicles and fuels. Under the assumption that individuals view all types of alternative fuel and gasoline vehicles as perfect substitutes, the least cost combination of fuels and vehicles consists mainly of methanol and compressed natural gas vehicles, according to Rubin's study which was published in the *Transportation Research Record No. 1444.*

According to a recent study, there are two main reasons to use alternative fuels: to reduce dependence on petroleum fuels and to reduce air pollution caused by vehicles using petroleum fuels. While these are desirable objectives, alternative fuels and alternative fuel vehicles are not widely available. Bechtold (1993: 63-65) discusses alternative fuel vehicle technology in a general way and provides insight into the effect that various alternative fuel vehicles have on fleet operations and cost.

C. Natural Gas: Alternative Fuel of Choice

An assessment of earlier efforts by transit agencies in Texas to meet the requirements of the Clean Air Act Amendments (CAAA), natural gas emerged as the alternative fuel of choice. A substantial number of transit agencies began pilot programs to test the extent to which natural gas was the best alternative. While natural gas is clean burning, it is not considered to be the ideal fuel in its natural form. To expedite its vehicular use and to achieve a useful operating range, it is necessary to use it in either compressed form (CNG) or liquefied form (LNG). In the article, "Alternative Bus Fuels: The CNG/LNG Experience" *(Transit Connections, March, 1995: 27-32)*, the assertion is made that natural gas must be compressed to about 3,000 to 4,000 psi. CNG requires 4.5 times the on-board storage capacity of diesel for the same operating range. CNG tanks can add as much as 3,000 pounds to bus weight, although some progress has been made with composites. When comparing CNG with LNG, it is important to note these distinguishing characteristics.

D. General Outlook on Natural Gas Supply

Over the past two decades, natural gas has generally held a steady share of the nation's household and commercial energy use. It lost its market share to oil and coal in the industrial and utility sector. As a result, the gas share of total U. S. energy demand dropped from one-third in 1971 to one-quarter in 1992. In recent years, however, gas has stabilized its share of industrial and utility demands. In 1970, gas supplied almost one-half of the nation's industrial energy demand and one-fourth of utilities' energy demand. By the end of the decade, these shares slipped to about one-third and one-sixth, respectively. As gas prices escalated in 1980, according to *Fiscal Notes* (September, 1994), drilling heated up. By 1986, the market was over supplied with production, creating a supply "bubble." Fierce competition for sales caused gas prices in Texas to plummet. In the past few years, gas demand has become revived. The 1993 marketed production was the highest since 1988, according to a report by the Texas Railroad Commission.

Some forecasters believe that the utilities demand for gas could double within 10 to 15 years. Others foresee slower growth in gas-fired generated capacity after 2000 because of rising gas prices and technological advances that will make it possible to burn coal more cleaner. Several factors have led analysts to forecast increased demand for natural gas. Mexico offers another potential significant market for Texas gas. According to Kimbrough and Martin (*Fiscal Notes*, 1994:9), "the natural gas marketplace is now driven by competition rather than by complex federal regulations. In 1989, Mexico began importing gas from Texas and California, mainly to meet industrial needs in northern Mexico. *Fiscal Notes* (1994) advises that "the natural gas industry will play a key role in Texas" and America's energy future. Texas is the nation's largest natural gas producer. It also consumes more natural gas than other states. In Texas, the value of gas production exceeded that of oil production for the first time in 1993. As shown in Table 1, out of a total production of 18.7 trillion cubic feet, Texas' share of U. S. marketed natural gas production was 33 percent in 1992.

Table 1
Shares of U. S. Marketed Natural Gas Production*
[Total production = 18.7 Trillion Cubic Feet]

State	Total Production – 18.7 Trillion C.Ft.
New Mexico	7.0
Oklahoma	11.0
Louisiana	26.0
Texas	23.0
All Others	23.0

** Includes state shares of production from the federal Outer Continental Shelf*
Source: John Sharp, Texas Comptroller of Public Accounts, and U. S. Department of Energy

E. Availability of Alternative Fuel

The availability of natural gas is a factor that influences alternative fuel choice in cities, particularly in Texas. Texas leads the United States in the use of natural gas for power generation. In 1977, natural gas accounted for 86 percent of the fuel used to generate electric power in Texas. Natural gas provides reduced emissions and, as such, is an acceptable fuel for meeting the requirements of the CAAA. It also has the advantage of an abundant domestic supply, lessening dependence on foreign oil.

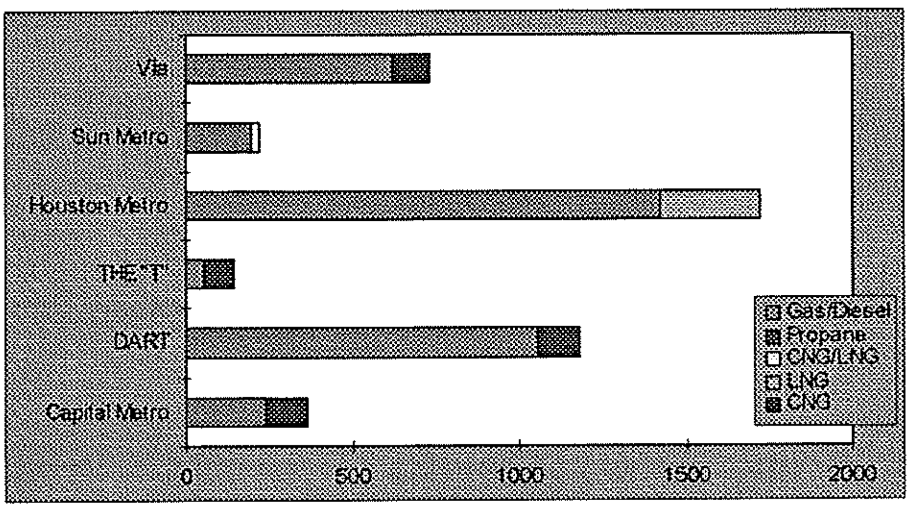
Texas, a major producer, mandated that only natural gas could be used in transit buses. Low emissions from natural gas were a factor in Canada's decision to scale-back zero-emissions for the electric trolley bus service in Toronto and Hamilton (*Transit Connections*, September 1994).

F. Natural Gas (LPG, CNG, AND LNG)

During the fiscal year 1991-1992, almost 50 percent of the school districts in Texas indicated that liquefied petroleum gas (LPG) was the preferred alternative fuel. Propane appears to be the most popular alternative fuel for school buses because it is cheaper than gasoline, costing about 8 cents per mile versus 17 cents for gasoline (*Alternative Fuels Transportation Brief*, July, 1993). A market study issued by the Texas Railroad Commission also noted the lack of a propane engine that was specifically designed for school buses in 1991-92. The report concludes that propane provides significant advantages over the use of compressed natural gas (CNG) because of propane's longer driving range and the wider availability of fueling stations.

Transit systems in Texas' six largest metropolitan areas began operating alternative fueled vehicles (AFVs), including both dedicated and dual-fueled vehicles after the passage of the Texas alternative fuels legislation (S. B. 740 and S.B. 769). A survey by the Texas Comptroller's Office in June 1994 revealed that transit systems in Houston, Fort Worth, Dallas, San Antonio, Austin and El Paso began operating alternative fueled vehicles. At that time, nearly one-fifth of the combined fleets in these cities were AFVs. Figure 1 reveals a comparison of alternative fuels by fleet vehicle fuel use as of June 1994. Transit authorities responded to both state and federal mandates by planning and implementing activities related to clean fuels and air quality.

Figure 1
Transit Authorities Phase in New Fuels



Source: Fiscal Notes, 1994

Alternative fuels are currently being used by transit agencies, private companies, and a variety of agencies and organizations throughout the United States and North America. Driven by considerations such as air quality and energy diversification, various mandates and incentives have been created to maximize the use of alternative fuels for transit applications. Lewis (1993), for example, outlined the aggressive alternative fuels program that grew out of the passage of Texas Clean Air Legislation. The passage of Texas Senate Bill 740 requires the use of Compressed Natural Gas (CNG) or alternative fuels in 90% of the State Agencies' fleets by 1998. To implement requirements in Texas Senate Bill 740, the State established the Alternative Fuels Group within the Division of Equipment and Procurement to assist in the development and implementation of an alternative fuel strategy for the Texas Department of Transportation (TxDOT). The Texas Alternative Fuel Fleet Program (TAFP) was designed to address the Federal Clean Air Act Amendments of 1990. The fleets affected by TAFP included state agencies, school districts, metropolitan rapid transit authorities, regional transportation authorities, and city transportation departments. Emergency and law enforcement vehicles were exempt from TAFP requirements (See: **Texas Natural Resource Conservation Commission**, Newsletter, April, 1994).

The newly adopted Texas Alternative Fuel Fleet (TAFF) Program was applicable in Houston, Galveston, Beaumont/Port Arthur, and El Paso non-attainment areas. Transit authorities in Texas began alternative fuels programs. The alternative fuels approved for Texas include Propane (LPG), Natural Gas (CNG and LNG), Methanol, Ethanol, and Electricity. Ledé (1995) conducted a study on costs associated with alternative fuels development. Using the Metropolitan Transit Authority of Harris County (Houston METRO) as a case study, an attempt was made to document the methodological and logistical problems associated with fuel conversion and alternative fuel use. Data were compared with a control sample using diesel fuel. Monthly status reports on the alternative fuels projects were compiled for use in the study. Data on accumulated mileage, road calls/unscheduled maintenance, fuel consumption, fuel cost per mile, alternative fuel purchases, and the schedule of activities, personnel, safety, and diesel emission test results. The data collected indicate several conclusions and future implications about technical and safety issues associated with the testing and use of Liquefied Natural Gas (LNG).

Booz, Allen and Hamilton (1991) were commissioned by the Capital Metropolitan Transportation Authority (Capital METRO) of Austin to recommend an alternative fuels conversion strategy. Whereas, HOUSTON METRO elected to use Liquefied Natural Gas (LNG) to test the feasibility of its use and potential for fleet conversion, Capital METRO chose Compressed Natural Gas (CNG) upon the recommendation of Booz, Allen and Hamilton (1991).

Good Company Associates, Incorporated (1993) conducted a study to assess the technical and market potential for converting school buses in Texas to use propane fuel on behalf of the Alternative Fuels Research and Education Division of the Railroad Commission of Texas. The study recommended the use of propane in school buses in Texas. The study cited economic advantages and lower maintenance costs as the central rationale for selecting propane as the alternative fuel. According to the study, the Northside Independent School District in San Antonio illustrated several advantages. Reports indicated that the District operated 300 buses on propane for more than 13 years. Some of the buses used propane-only; others used dual-fuel, while a small number of them used gasoline only buses. A comparative analysis of propane versus compressed natural gas (CNG) was made. The findings indicated that propane had at least three important advantages over compressed natural gas (CNG), which was the only other alternative fuel used in Texas school buses. First, propane is a much more compact fuel. With present tank technology, according to the study, it is difficult to design a CNG system that gives the bus a range of much more than 100 miles without significantly affecting the weight limit, whereas a propane system can readily provide a range of 300-400 miles. Second, the cost to convert a bus to propane is only about half that of converting one to CNG. Propane conversion costs are typically in the vicinity of $1500 to $1700 per vehicle, whereas CNG conversions cost around $3000 to $4000 per vehicle. A third advantage of propane over CNG is the much wider current availability of existing refueling stations at present and the lower cost of establishing new refueling stations. According to figures provided by Phillips 66 Company, propane refueling facilities cost only about one to two percent as much as CNG refueling facilities to refuel the same number of vehicles per hour *(Good Company Associates, 1993)*.

The advantages outlined in the study by Good Company Associates, Incorporated for the Railroad Commission of Texas did not appear to influence one transit system. In 1991, the El Metro transit service in the City of Laredo performed an assessment of available alternative fuel technologies. The city concluded that the local bus service would be best served by operating a CNG fleet of buses, vans, and service vehicles. Consultants were hired to design an expansion of the city's existing operations and maintenance facility to include on-site fueling of their future acquisitions of CNG vehicles (Jacques, 1993: 396-397).

In response to surfacing reports of engine damage due to inferior quality natural gas fuel, the use of Liquefied Natural Gas (LNG) was being reported as a feedstock for one-site storage to be later vaporized into high quality CNG for fueling of CNG vehicles. According to Jacques of Wilbur Smith Associates, Incorporated (1993), the technology is the same as used by most hospitals, which store oxygen on site in liquid form for later vaporization upon demand. LNG to CNG fueling, or LCNG, provides for many of the benefits of both technologies. The vehicles receive a cleaner and more consistent fuel supply, free of water and oils. The LCNG fueling system also possesses one other important feature: should the range of vehicles become an important obstacle to overcome, direct fueling of the longer-ranged LNG vehicles can be easily accommodated. Advantages cited in this study are similar to previous findings. The economics of LCNG systems appears to be the central theme. Jacques (1993) asserts that the "utilization of LCNG technology can save almost $100,000 on the installation costs of the natural gas fueling facility. He also cites savings on annual maintenance costs."

A review of the literature on alternative fuels suggests that the findings are both complimentary in some cases and contradictory in others. Several transit authorities have chosen Compressed Natural Gas (CNG) and Liquefied Natural

Gas (LNG) as alternative fuels. Transit authorities in the Texas cities of Houston and Austin have selected natural gas as their clean burning fuel. Natural gas, by virtue of its abundance and availability, meets the requirements for clean fuel use in Texas. Other transit agencies began introducing alternative fueled vehicles into their operations to meet requirements of the Clean Air Act Amendments of 1990 (CAAA) and the Energy Policy Act.

Some properties such as Washington METRO and the Boston MBTA chose clean diesel as their alternative fuel. Clean diesel has similar environmental effects, as do the other clean fuels. However, its unit cost is currently more expensive than natural gas options such as LNG and CNG. Houston METRO chose the liquefied form of natural gas (LNG) because of "its anticipated longer operating span due to higher energy density than CNG." Houston METRO chose LNG because of the "quicker fueling capabilities allowed by a liquid." In a study by Booz and Hamilton, Incorporated (1991), Capital METRO was advised about the advantages and disadvantages of CNG when compared to LNG. One advantage in using CNG was the fact that it is a "proven technology," according to findings from the study. Disadvantages of LNG noted in the study included the extensive refrigeration equipment and the lack of availability of already liquefied gas. For CNG, the disadvantages included its requirement for larger storage tanks on buses and slower bus fueling. Houston METRO pioneered the use of LNG in transit buses. As noted by Ledé (1995), Houston METRO launched an extensive fuel conversion demonstration project to determine the feasibility of using LNG as an alternative fuel. To examine specific aspects of alternative fuels in two transit properties, this study is a comparative analysis of CNG and LNG, with particular emphases on properties and practices of alternative fuel. The description of LNG and CNG must be considered when examining such variables as storage, facility costs, safety (fire hazards, cryogenic and other hazards), supply, estimated costs for facilities and operations, environmental considerations, and vehicle related issues are central when comparing alternative fuels.

Comparative data are available in several definitive studies on LNG and CNG as alternative fuels. A report by the Transportation Research Board on "Safe Operating Procedures for Alternative Fuel Buses," (Hemsley, 1993) provides a synthesis of various practices in the operation of bus fleets using alternative fuels. Argonne National Laboratory (1994) prepared a brochure for fleet owners and managers to provide useful information about alternative fuels. Other alternative fuel data summaries have also been used to complete this study, including the *Energy Data Book* and technical reports by the U.S. Department of Transportation's Federal Transit Administration (FTA). Battelle, Pine and Associates (1992) published several Fuel Use Training Manuals for FTA to provide technical assistance to transit properties involved in alternative fuel projects.

II. STUDY OBJECTIVES AND METHODOLOGY

This section of the study describes the objectives, methodology and approaches, a general framework for the study and key definitions. It should be noted that terms like alternative fuel, nonpetroleum fuel, domestic fuel, and clean fuel are often used interchangeably, as are clean-fuel vehicle and alternative-fuel vehicle. This section provides a conceptual description of selected terms.

Objectives

This comparative analysis of alternative fuels was initiated in 1996 following the publication of the study, *"A Survey of Costs Associated With Alternative Fuels Development: A Case Study,"* (Lede, 1995). This study had several research objectives:

- To assess the state-of-the art and document relevant findings pertaining to alternative fuels;

- To analyze and synthesize the existing database on two natural gas alternatives: LNG and CNG; and

- To compare two alternative fuels used by transit properties in Texas, and address specific aspects of alternative fuels such as energy source, safety, costs and operational differences, environmental, emissions, and related issues.

Methodology/Approaches

Several descriptions of the tasks performed in the study provide a framework for conducting the research. These tasks were included in strategic phases of the study. The research effort involved several phases, some of which were performed concurrently. The first phase of the study involved conducting a review of the literature, including locating and analyzing various existing databases on alternative fuels development. The second phase involved an examination of findings from previous surveys of transit authorities in which alternative fuel demonstration projects had taken place (Lede', 1995). Data from earlier on-site surveys conducted at facilities using CNG and LNG were central to delineating specific variables on alternative fuels for comparative analysis. A compendium of issues were compiled and structured around specific alternative fuels. The next phase involved the identification of the capabilities and deficiencies of the two alternative fuels, and an overview of the experiences of transit agencies. The third phase included the task of developing the conceptual framework for the comparative analysis from existing case studies. The last phase involved an analysis of the data and a documentation of the results of the study.

Framework for the Study

To establish a framework for the study, efforts were made to examine selected characteristics on two types of natural gas demonstrations in terms of the following properties: Energy source characteristics, vehicle performance and emissions, operation, maintenance, reliability, safety costs, and fuel availability. Where feasible, the alternative fuels will be compared with conventional gasoline and diesel fuel.

Fuel Description *– Natural gas is extracted from underground reserves, composed primarily of methane. For gaseous vehicle fuel, mainly Compressed Natural Gas (CNG), gas is compressed to 2,400 –3,600 pounds per square inch in specially designed and constructed cylinders. For Liquefied Vehicle Fuel (LVG), gas is cooled to minus (-) 259°F and stored in insulated tanks. Liquefied Petroleum Gas or LPG (commonly called propane) is a liquid mixture (at least 90% propane, 2.5% butane and higher hydrocarbons, and the balance ethane and propylene). It is a by-product of natural gas processing or petroleum refining (Argonne Laboratory, 1994: 22-24).*

Key Definitions

Certain terms used in this study have the meanings commonly ascribed to them in the areas of alternative fuel and air pollution control. In addition to terms defined by the Texas Natural Resource Conservation Commission (TNRCC), key definitions are included to have the following meanings, unless the context clearly indicates otherwise:

Alternative Fuel - Fuels used to power vehicular engines, including natural gas; liquefied petroleum gas; methanol; electricity; and any other fuel as approved by the TNRCC as an alternative fuel. As defined by the Energy Policy Act, methanol, denatured ethanol, and other alcohols; mixtures containing 85% or more by volume of methanol, denatured ethanol and other alcohols; with gasoline or other fuels, natural gas, liquefied petroleum gas; hydrogen; coal-derived liquid fuels; fuels (other than alcohol) derived from biological materials; and electricity – are alternative fuels.

Alternative Fuel System – Modification of the engine and fuel system of a vehicle to allow the use of an alternative fuel.

Bi-Fuel Vehicle – A vehicle capable of simultaneous operation on a mixture of a conventional fuel and an alternative fuel.

Fuels/Vehicles – Gasoline and diesel fuels. Vehicles that use either of these fuels.

Dual-Fuel – A vehicle capable of operating either on a conventional fuel or an alternative fuel, but not both simultaneously.

Emissions – Means emission (tailpipe, or other) of oxides of nitrogen, volatile organic compounds (VOCs), CO, particulate matter, smoke, or any combination of those substances.

Flexible-Fuel Vehicle – A vehicle capable of operating on varying mixtures of gasoline and an alcohol fuel (methanol or ethanol), up to a mixture of 85% and 15% gasoline (M85 or E85).

Clean Fuel – As defined by the Clean Air Act, any fuel or power source gasoline or diesel fuel and has been converted to run on an alternative fuel. Because of the limited availability and selection of original-equipment-manufactured vehicles, conversions are providing a transition to the time when automakers produce more alternative-fuel vehicles for public sale that enables a vehicle to emit less pollution than would be the case with conventional gasoline or diesel fuel. These include alternative fuels and specially formulated gasoline and diesel fuel.

Converted Vehicle – Any vehicle that originally was designed to operate on gasoline or diesel fuel and has been converted to run on an alternative fuel.

Flexible-Fuel Vehicles – Vehicle with a single tank, powered by any mixture of gasoline and alcohol fuel.

The next section of this study provides a comparative analysis of alternative fuels used by transit agencies in Texas. Selected aspects of natural gas, including compressed natural (CNG) and liquefied natural gas (LNG) are examined. In some instances, references are made to other alternative fuels in an effort to broaden a differentiation between fuel options. The analysis begins with a focus on selected characteristics of natural gas demonstrations in terms of the following: Energy source characteristics, vehicle performance and emissions, operation and maintenance, reliability costs and fuel availability. Data used in the analysis were compiled from a variety of research studies and demonstration projects. An overview of the general findings is provided in a previous section, "Review of Related Literature."

III. STUDY RESULTS

Selected characteristics were used to conduct an assessment of two alternative fuels used by transit systems in Texas. Existing data from previous studies were used to compare central features of two alternative fuels: Liquefied Natural Gas (LNG) and Compressed Natural Gas (CNG). A comparative analysis of each of these fuels has been included in this section of the report along with periodic references to other fuels when certain inferences are made. The scope of the assessment of natural gas demonstrations included a comparison of several indices, including an overview of published information on LNG/CNG as alternative fuels, energy source characteristics, vehicle performance and emissions, operation and maintenance, costs, supply, and vehicle - related issues.

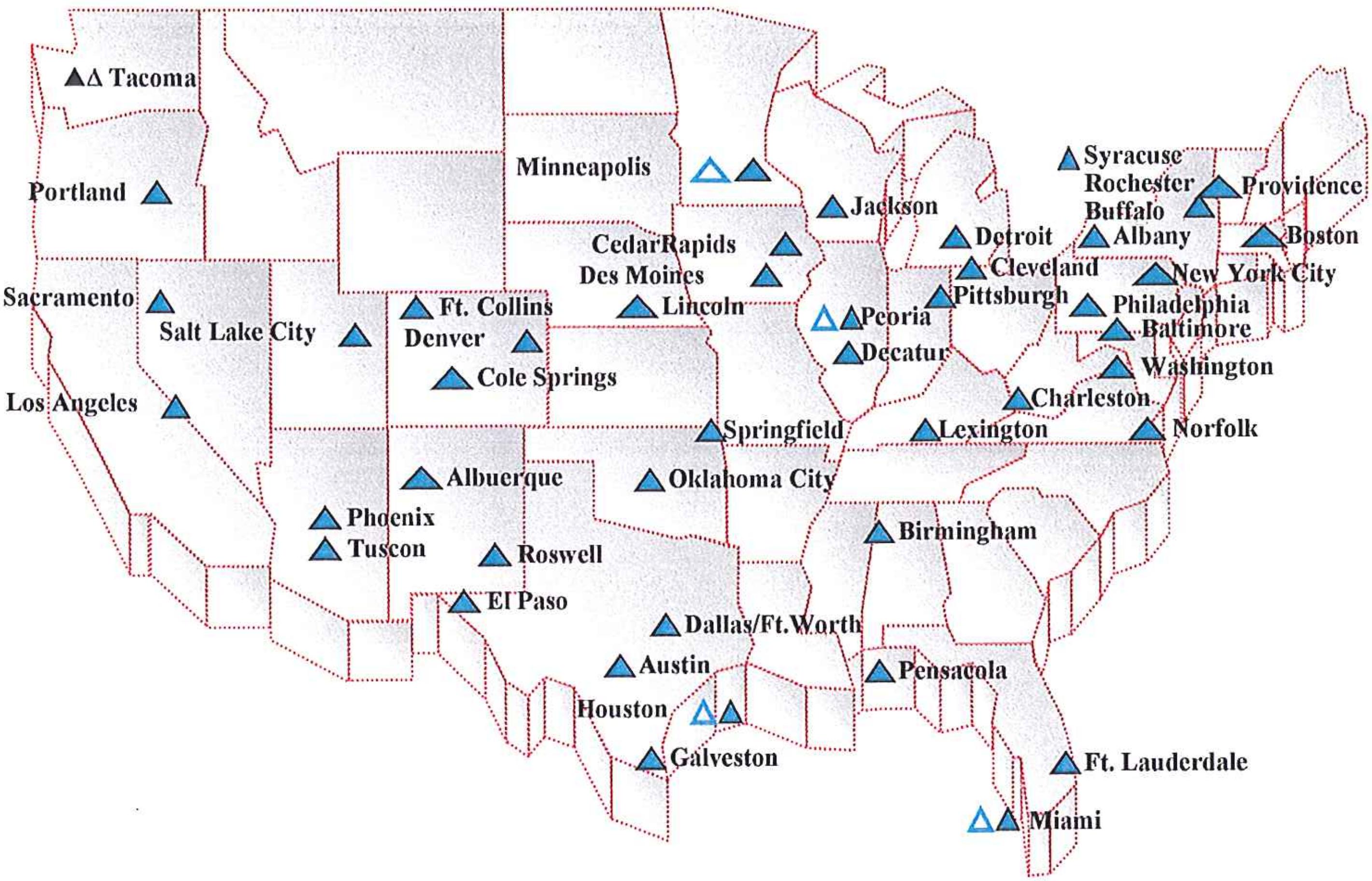
Published findings of previous studies suggest that natural gas continues to be a viable alternative fuel. It has been tested in transit systems applications in Texas and throughout the United States. In Texas, transit systems in the largest metropolitan areas have converted and incorporated alternative fuel vehicles into bus operations. For the most part, transit systems in Texas have relied heavily on natural gas as the alternative fuel option. Map 1 shows the location throughout the United States of transit bus fleets that use alternative fuels. Several transit systems in Texas are listed, including Houston, Austin, and El Paso. Galveston, and Dallas/Fort Worth. The alternative fuels bus program includes transit buses and school bus demonstration projects as well.

It should be noted that this analysis of technical characteristics of Liquefied Natural Gas (LNG) and Compressed Natural Gas (CNG) is from two selected representative projects in Austin and Houston, Texas. These transit agencies operated buses on compressed natural gas and liquefied natural gas. The data used in this analysis are primarily related to light duty, gasoline vehicles converted to dual-fuel capability. Specific findings are outlined in the section that follows.

♦ Energy Source Characteristics

Fuel Supply - Pipelines supply natural gas to most regions of the United States. Fuel supply is not generally viewed as a limiting factor in the development of natural gas vehicles. In 1988 there were approximately 1.7 million new purchases of centrally refueled vehicles. According to report prepared from the *Office of Alternative Fuels, U. S. Department of Energy (January 1993*), natural gas has been promoted as a means of increasing energy security.

Map 1
Location of Alternative Fuel Transit Bus Fleets

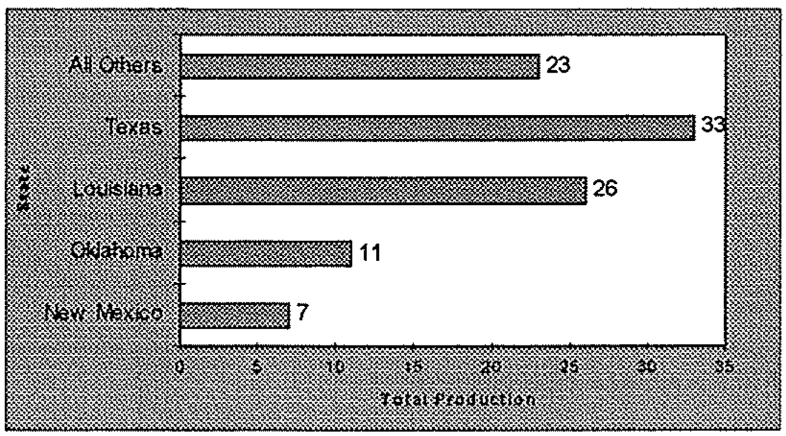


▲ *Federal Transit Authority Urban Transit Bus Project*

△ *DOE Urban Transit Bus*

The existing natural gas delivery system in the United States is comprised of the long-distance pipeline transmission system. The major producing states include Texas, Louisiana, Oklahoma, and New Mexico. Together, Texas and Louisiana produced over 65 percent of the Nation's natural gas production volume in 1985, according to a report by *Booz, Allen and Hamilton* (1991). As indicated in Table 1 and graphically illustrated in Figure 2, the total share of natural gas production in the United States for Louisiana and Texas was 59 percent in 1992.

Figure 2
Shares of U. S. Marketed Natural Gas Production



Source: Fiscal Notes, 1994

Gas supply trends indicate that the industry can meet future demands. Data obtained from reports by the U. S. Department of Energy tend to support this forecast. The Department of Energy (DOE) has estimated that the lower 48 states have 800 trillion cubic feet of recoverable natural gas from conventional onshore and offshore sources. The lower 48 states have an additional 259 trillion cubic feet in unconventional technically recoverable natural gas. (*Booz, Allen, and Hamilton*, 1991).

Supplies of LNG are generally located at major ocean terminals because much of the gas is produced overseas. However, the Texas users rely heavily on domestic sources and storage areas that are in closer proximity to the transit facilities. On-road use of LNG has not yet generated its own infrastructure. Natural gas vehicle fuel is stored on the vehicle in compressed form or liquid form. As a matter of comparison, Liquefied Natural Gas (LNG) has the advantage of greater range per volume fuel, but the disadvantage of less experience.

Fuel Composition – Natural gas composition varies throughout the nation, depending on original gas composition and processing. Pipeline quality natural gas is composed of several different gases, of which methane typically accounts for 85% to 99%. Nitrogen, helium, carbon dioxide, and trace amounts of hydrogen sulfide, water, and odorants are also present. Gas liquefaction requires the removal of these components. To this end, LNG does not contain any of them.

The importance of gas composition is a central issue for users of natural gas as an alternative fuel. Lyle (January 1989) evaluated the effects of natural gas contaminants on corrosion in CNG storage systems. The study addressed important considerations for users. Large amount of non-methane hydrocarbons will enrich the fuel mixture, reduce the octane number, lead to increased hydrocarbon emissions, and increase the potential for engine knock. Also, engine parameters such as air/fuel mixture and ignition timing should be adjusted on the basis of the composition of the supply of local natural gas. The Office of Technical Assistance and Safety (September 1992) prepared fuel use training manuals for the U. S. Department of Transportation, Federal Transit Administration. These training manuals were designed for users of alternative fuels, including CNG. The manual describes the advantages of CNG as a fuel, its physical properties, vehicle operations and maintenance, safety precautions and procedures *(Battelle, et. al*, September 1992).

♦ Vehicle Performance and Emissions

Natural gas vehicle performance, fuel economy, and emissions can be significantly altered with fine tuning (e.g., ignition timing, air/fuel ratio). Appropriate tuning adjustments can optimize either performance, fuel economy, or emissions. Alternatively, a compromise tuning may be effected. Tuning optimization for power generally increases emissions. Again, natural gas conversion kits that are specifically designed for a given vehicle make and model. Findings of previous studies indicate that the "best solution for fleet operation is to, at a minimum, re-tune each vehicle annually with the use of an exhaust gas analyzer to assure that good performance of emission control devices continues." Exhaust gas analyzers can provide additional information regarding vehicle performance when inserted before the catalytic conversion system (USDOE, January 1993).

With a catalytic converter or trap, the engine represents a complex combination of a gas engine, a diesel engine, and an exhaust treatment device. An analysis of a methanol demonstration project for Seattle METRO, Battelle (1991) reported on LNG and CNG. According to the report, the best role of the catalytic converter seems to lie in its function as a near term engine for development of CNG and LNG systems, as well as a near term solution for bus operators in Texas faced with strict alternative fuel mandates.

The development of an emissions database for bus engines utilizing alternative fuels is extremely complex for light duty vehicles. When considering CNG transit bus engine emissions, Sperling (1989: 134-135) indicates that " the low cetane number of CNG, like methanol, makes CNG use in diesel engines problematic. Its use is especially unattractive in the two-stroke diesel engine manufactured by Detroit Diesel Corporation (DDC), and DDC had done very little work – at the time of this study –with CNG. Since the 1989 study of alternative transportation fuels edited by Sperling was published, several transit systems instituted natural gas demonstrations of LNG and CNG, including those in Texas.

The use of Compressed Natural Gas (CNG) in a bus requires unavoidable bulky and heavy fuel storage cylinders. The weight increase for fuel tanks exceeds a ton in the Flexible bus, for example. In addition, some building modifications may be required to enhance parking inside a maintenance building for natural gas buses. When this happens, increased ventilation is essential to ensure safety and acceptable air quality (Battelle, 1991).

When compared to CNG, Liquefied Natural Gas (LNG) appears to offer distinct advantages over CNG. One important advantage is that the energy density of LNG is much better than CNG, and is not much different than diesel fuel on a per gallon basis. However, it should be noted that LNG is a cryogenic liquid with a boiling point of -258°F. This characteristic poses some difficulties relative to the fuel. It requires an elaborate refrigeration plant for LNG production, and the cost of refrigeration is about 15 percent higher in the best case representation. For example, 100BTUs of fuel delivered to the bus require an additional 15 BTUs for refrigeration.

Vehicle Related Issues - Vehicle related issues that affect Compressed Natural Gas (CNG) and Liquefied Natural Gas (LNG) transit bus operations include operating and safety training for personnel operating and maintaining CNG and LNG transit buses.

- **Training Requirements**

CNG – Because of the gaseous nature of CNG and the fact that it is stored under high pressure, handling characteristics are significantly different from more familiar liquid fuels. CNG bus operators must be aware of the reduced range of their vehicles and the location of fueling sites in the general areas served by the transit buses. Procedures for fueling CNG vehicles must be formalized and transmitted to operators to ensure the safe dispensing of fuel from CNG stations.

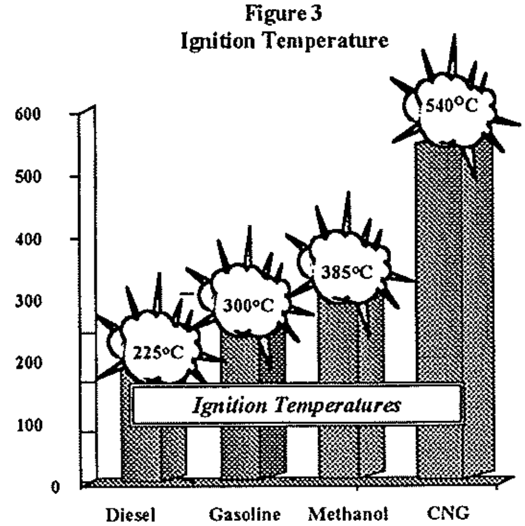
LNG – The unique characteristics of LNG mandate specialized training for bus operators. According to a report published by the *Transportation Research Board* (1993: 15, 19), Liquefied Natural Gas (LNG) is a cryogenic fluid and, as such, it presents special problems not found in other fuels. In contrast to some of the other alternative fuels, the cryogenic state of LNG does not lend itself to odorization, and having no odor of its own, users may not readily detect minor leaks. Natural gas is odorless, colorless, and tasteless. An odorant (trace amounts of an organic sulfur compound) is added to aid in the detection of leaks. It is important to point out that persons exposed to natural gas odor for a long period of time can find that the smell is no longer noticeable. LNG spills are especially hazardous because of the risk of personnel receiving cryogenics burns, and because the energy-dense fluid quickly vaporizes and becomes amenable to combustion. For both natural gas fuels, the training of all personnel is extremely important.

♦ Safety

This part of the report focuses primarily on concerns related to the fuel-systems hazards of LNG and CNG vehicles in normal operations. A discussion of issues pertaining to safety is drawn from a state-of-the-art assessment of LNG and CNG vehicles from numerous sources.

CNG – The issue of safety is critical to the utilization of alternative fuel in transit vehicles. As it is with any fuel, the use of natural gas requires a keen awareness and sensitivity to potentially hazardous situations. CNG fuel is flammable and fire is dangerous. In confined areas under certain conditions, natural gas can cause an explosion. CNG is always a vapor and susceptible to ignition. Ignition sources for natural gas are sparks, hot surfaces, and open flames. Ignition temperature is the temperature at which the fuel, when mixed in the proper proportion with air, can ignite. When compared with diesel, gasoline, and methanol, CNG, as shown in Figure 3, has the highest ignition temperature of these fuel counterparts (*Battelle*, September 1992: 10-11). CNG differs from liquid fuels in its hazards. In addition to fire hazards, physical hazards exist because of the high pressures at which CNG is stored.

Figure 3
Ignition Temperature



Source: CNG Fuel Use Manual - Page 10

LNG - Liquefied Natural Gas (LNG) has a safety concern pertaining to being a cold (-260°F) liquid under pressure. Severe frostbite may occur from contact with LNG or associated cold components. Leaks of LNG are very cold, will sink to the lowest available surface, and may disperse close to the ground for a significant distance. The hazards relating to LNG are fire, cryogenic burns, and changes in properties of materials, asphyxiation. Ignition of LNG can be brought about by contact with hot surfaces, open flames, and sparks, including static electricity. There is the added concern when common materials change their strength characteristics when exposed to LNG temperatures, thus presenting additional hazards. LNG tanks have the potential for explosions. The use of LNG and safety considerations is discussed in a report prepared by Battelle (1995) for FTA on the *Clean Air Program: Liquefied Natural Gas Safety in Transit Operations* (1995). According to the report, LNG is not any more dangerous than conventional fuels. It is different, however, and the differences can create hazardous situations for personnel unfamiliar with LNG's properties (*Newsline*, June, 1997: 3).

When LNG and CNG are compared, there is evidence to suggest that LNG appears to have certain advantages over Compressed Natural Gas (CNG). In the case of LNG, a transit agency does not have to be connected to the gas distribution network. LNG can be brought to the agency by truck. LNG has an advantage over CNG in that it is a liquid and is stored at a lower pressure than CNG (the pressure in CNG tanks can be up to 33,500 to 4,000 lb/in.^{2} compared to 150 lb/in.^{2} for LNG).

Gammer and Raj (1996) of Technology and Management Systems, Incorporated examined the dispersive behavior of natural gas. The research sought to evaluate the adequacy of safeguards against CNG-related fires in transit building where CNG-powered buses are fueled, stored, or maintained. The study examined the behavior of CNG when released through an orifice not greater than 6.25 mm in diameter. The premise that precautions need to be taken only at or near the ceilings of transit buildings is challenged. The authors contend that "precautions need to be taken because natural gas released from a high pressure source will remain in various locations, not just the ceilings, of CNG bus facilities long enough to pose a potential fire hazard." There appears to be a consensus among researchers on alternative fuel that natural gas poses three potential dangers, including fire, high pressures, and health hazards. CNG fire risks may emanate from vehicle system failures and from traffic accidents. Because CNG fuel is stored in high-pressure tanks, the threat of casual leaks is greatly reduced. On the other hand, because of the high pressure, leak rates could be high if a leak does occur.

The connecting lines required to store CNG fuel increase the vulnerability of the system to damage from severe collision. It should be noted here, however, that the risk of an exposure to an ignition source is no greater for CNG than for diesel fuel. But, due to the high pressure of the system, a fire that results from a collision could be severe.

♦ Operation and Maintenance

With the expansion of interest in alternative fuel vehicles a substantial demand is placed on transit systems to provide the proper infrastructure support to enhance vehicular operations and maintenance.

LNG - According to a report by the *Transportation Research Board* (TRB) (1993: 19-20), the characteristic properties of LNG introduce new hazards into bus maintenance operations. Any indoor maintenance must be done with the assurance that leaks are not present. The vehicle fuel system pressure is well below the set-pressure for venting so that the system will not need to vent while indoors. Two issues must be addressed for the indoor handling of LNG. According to the TRB synthesis of alternative fuels, the first issue pertains to the ventilation and elimination of likely ignition sources. LNG vehicles require insulated, pressurized (10 to 35 psi) fuel tanks. LNG is vaporized in the fuel line and warmed in the heat exchanger generally located under the hood. The pressure regulator reduces pressure before the vapors are transported to the mixer or carburetor.

CNG - A review of several videos on the safety of LNG and CNG indicates that natural gas is mostly methane, with traces of several other hydrocarbons and gases. *"Safety First With CNG,"* presented by the U. S. Department of Energy, the National Renewable Energy Laboratory (NREL) and the Southern California Rapid Transit District (SCRTD) focuses on environmental and safety issues. In terms of vehicle operations, CNG as an engine fuel exhibits the following characteristics: high octane, no cold start problems, reduced exhaust emissions, and no hot start problems. In the unlikely event of excessive pressure in the CNG tanks due to extreme heat, a thermal/pressure relief valve will vent the contents of the tanks through the upper portion of the coach and release it into the atmosphere. During cold start-ups of the vehicle, some condensation and water dripping from the exhaust pipe may occur. This is considered normal.

The same precautions and procedures regarding engine overheating should be taken for CNG fueled vehicles as for any conventionally fueled vehicle. The vehicle should be pulled to the side of the road, shut down, and the Dispatcher contacted. It should be noted that CNG engine exhaust is hotter than diesel exhaust. Nearby components are hot. Every effort should be made to ensure that the manufacturer's heat shielding is in place.

When compared with other alternative fuels, CNG vehicles require many of the same routine maintenance operations as conventionally fueled vehicles. However, the pressurized nature of the fuel and its different density and ignition properties require special maintenance procedures for CNG vehicles. To safely maintain and operate CNG vehicles, mechanics must be trained and made aware of the dangers of both CNG and LNG. The training for the maintenance and operation of LNG and CNG vehicles must be of sufficient intensity and depth to enable them to identify, locate, and repair leaks, using only approved replacement components in servicing LNG and CNG systems. In the event of a major leak within a maintenance facility, a predetermined evacuation plan will help to ensure safety.

Methane boils at a much lower temperature than most of the trace constituents of natural gas. The characteristic creates a problem of impurities building in the bus fuel tanks over time. Although the natural gas might be 98 percent methane, the two- percent impurities are never allowed to become warm enough to boil off or dissipate. If this happens, the engine receives a dramatically different fuel from the one for which it was designed. This has occurred in some of the LNG buses of Texas transit agencies. The problem can be easily eliminated by periodically purging the fuel tanks. This procedure increases the cost for maintenance.

♦ Environmental Considerations

"The alternative fuel policies in the Clean Air Act and the Energy Policy Act were driven by certain fundamental goals," according to a final report issued by the Eighty-eighth American Assembly on *"Fueling the Future: America's Automotive Alternatives, (September 1995:3)*. Environmental improvement in the form of reduced air pollution, reduced dependence on foreign oil, and enhanced economic development are goals that underlie alternative fuels policy. This phase of the study discusses the environmental issues related to the use of natural gas vehicles. The focus is on issues associated with the operation of vehicles in which LNG and CNG vehicles are used. Several research studies provide data on evaluating the comparative emissions from vehicle fuel by CNG versus LNG vehicle technology.

LNG – As a result of the Clean Air Act Amendments (CAAA) requirements for the Federal Clean Fuel Fleet (FCFF) program, Texas created the Texas Alternative Fuel Fleet (TAFF) program. The Texas Natural Resource Conservation Commission (TNRCC) approved CNG, LNG, LPG, methanol, ethanol, and electricity. An alternative fuel had to meet major requirements adopted by TAFF, including: It must demonstrate a quantitative emissions reduction plan equivalent to the FCFF program and affected non-attainment areas with serious and severe ozone and or CO areas had to comply with provisions of the CAAA. Fleet conversion goals were outlined for existing vehicles or by the purchase of new alternative fuel vehicles (*State Alternative Fuel Laws and Incentives,* U. S. Department of Energy, 1995, 23-24). The Eighty-eighth American Assembly on automotive alternative fuels assembled to discuss specific adopted by TAFF, including: It must demonstrate a quantitative emissions reduction plan equivalent to the FCFF program and affected non-attainment areas with serious and severe ozone and or CO areas had to comply with provisions of the CAAA. Fleet conversion goals were outlined for existing vehicles or by the purchase of new alternative fuel vehicles (*State Alternative Fuel Laws and Incentives,* U. S. Department of Energy, 1995, 23-24). The Eighty-eighth American Assembly on automotive alternative fuels assembled to discuss specific issues and goals in 1995. The Assembly noted that improving air quality and reducing the emissions from the motor vehicle sector remain critical national goals.

The Alternative Fuel Fleet (TAFF) Program conducted a technical evaluation "for equivalency determination through emission reduction calculations." The purpose of this action was to demonstrate the equivalency of the Texas Alternative Fuel Fleet (TAFF) Program to the Federal Clean Fuel Fleet (FCFF) Program. The evaluation of the program was based on the opt-out provisions mentioned in the State Implementation Plan (SIP) revision proposal. The TAFF SIP revision was required to demonstrate equal or greater emission reductions in the three non-attainment areas: El Paso, Beaumont/Port Arthur, and Houston/Galveston. Fleet parameters and emission factors as well as assumptions used for the equivalency determination are found in the Texas Alternative Fuels Program's *"State Implementation Plan Revision for the Substitution of the Federal Clean Fuel Fleet Program," (1994).*

Several types of data were needed in order to perform the calculations, including emission factor data, fleet turnover rates, mileage accrual rates, fleet growth rates. Data obtained from various studies on emission reductions from using alternative transportation fuels were used to compare the number of light duty low emissions vehicles (LEVs) acquired under TAFF and FCFF programs. Table 2 contains data for three non-attainment areas in Texas.

Natural gas has the potential to significantly reduce Nox emissions when compared to gasoline or diesel fuel. Natural gas produces very low levels of particulate matter when compared to diesel fuel. Reactive hydrocarbons are lower than gasoline and diesel vehicles (*TRB*, 1993, 20-21). A report by TRB reveals that carbon dioxide emissions are typically lower in LNG vehicles than those of gasoline vehicles and are comparable to diesel emission levels. The Annual Report of the Department of Energy (1993) determined particulate emissions and fuel economy during emissions testing. As indicated in Figure 4 and Figure 4A the particulate emissions for the pilot-injection natural gas engines are nearly the same as those for the diesel control vehicles. This appears to be the results even though a majority of the fuel consumed during the driving cycle is natural gas.

These particulate emissions are accounted for, in part, by lubricating oil consumption. Several of the Liquefied Natural Gas buses used in the Houston Metropolitan Transit Authority demonstration project were Pilot-Injection Natural Gas (PING) engines that were acquired from Detroit Diesel Corporation. Several of the Pilot–Injection Natural Gas engine were tested in the West Virginia Transportation Emissions Laboratory. METRO of Houston was one of the leading proponents of LNG. The Metropolitan Transit Authority of Harris County (Houston METRO) launched an aggressive program of fuel conversion and duel fuel (LMH/diesel) transit-operated buses. Although the current status of the program is not known at this juncture, previous reports indicated that LNG was judged to be superior to CNG for several reasons: A 400-mile operating range was required, but METRO was reluctant to add the full 3,000 pounds of required CNG onboard storage. (*Transit Connections, March 1995:31).*

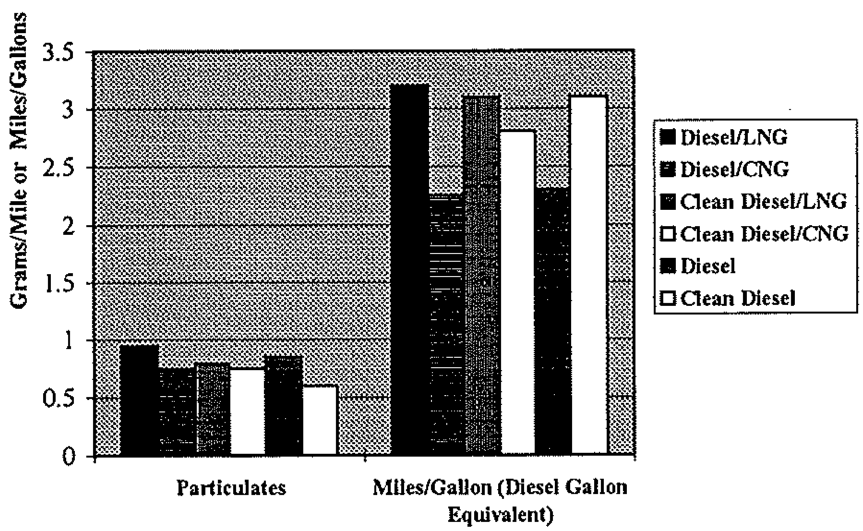
Table 2
Comparison of LEVs Required in the Three Covered
Non-attainment Areas under FCFF and TAFF
Light Duty Vehicles and Trucks

	BEAUMONT		EL PASO		HOUSTON	
YEAR	FCFF	TAFF	FCFF	TAFF	FCFF	TAFF
1998	531	617	641	748	10,157	12,447
1999	1,437	1,592	1,734	2,024	27,459	32,128
2000	2,732	2,591	3,297	3,293	52,213	52,274
2001	3,524	3,707	4,254	4,712	67,355	74,793
2002	3,791	4,871	4,794	6,191	75,910	98,278
2003	4,059	4,978	4,899	6,327	77,580	100,440
2004	4,148	5,088	5,007	6,466	79,287	102,650
2005	4,239	5,200	5,117	6,609	81,031	104,908
2006	4,333	5,314	5,230	6,754	82,814	107,216
2007	4,428	5,431	5,345	6,903	84,635	109,575
2008	4,525	5,550	5,463	7,054	86,497	111,986
2009	4,625	5,673	5,583	7,210	88,400	114,450
2010	4,727	5,797	5,706	7,368	90,345	116,967

Source: "State Implementation Plann Revision for the Substitution of the Federal Clean Fuel Fleet Program," (1994)

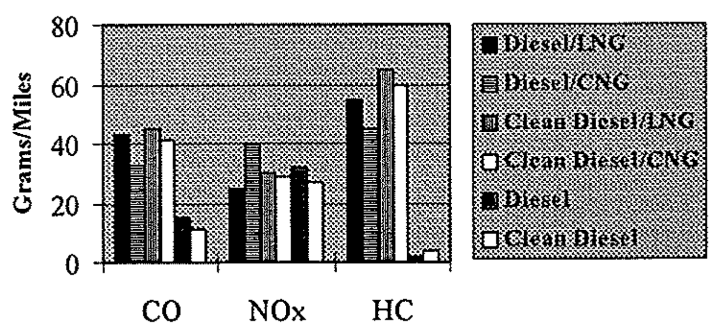
Liquefied Natural Gas (LNG) and Compressed Natural Gas (CNG) buses differ only in their fuel storage or dispensing systems. There are a number of different engine systems that can be used with both Compressed Natural Gas and Liquefied Natural Gas. With respect to environmental consideration, LNG is an attractive fuel.

Figure 4
Particulate Emission and Fuel Economy for Pilot Injection Compressed Natural Gas and Liquefied Natural Gas Buses Compared to Diesel Control Buses



Source: U.S. Department of Energy, 1993

Figure 4A
Carbon Monoxide (CO), Oxides of Nitrogen (NOx), and Hydrocarbon Emission for Pilot Injection CNG and LNG Buses Compared to Diesel Control Buses



Source: U.S. Department of Energy, 1993

Data on emissions from CNG vehicles are very limited, according to a technical report on environment, health, and safety concerns issued by the Office of Policy, Planning and Analysis of the U. S. Department of Energy in October 1991. However, available information suggests that CNG is more "environmentally benign" than gasoline. The report also advises that the efficiency and performance of CNG vehicles are possible concerns, particularly with dual retrofits – though there is evidence that dedicated, optimized CNG vehicles may have efficiency and performance levels equivalent to those of gasoline vehicles.

From an environmental perspective, there is evidence to suggest that total hydrocarbon emissions from spark-ignition CNG vehicles are generally higher than from their gasoline-fueled counter parts *(DOE Report*, 1991:x). These emissions are predominately methane, which is non-reactive, and therefore will contribute less to low-level ozone formation. Additional analysis and research will be needed to assess CNG's overall potential fin reducing low-level ozone. When used in spark-ignition engines will reduce carbon monoxide emissions, largely as a result of better air-fuel mixing and lean combustion.

Data indicate that relative to diesel-fueled vehicles, diesel vehicles converted to dual-fuel CNG-diesel operation, with fumigation, increase both hydrocarbon emissions (again, mostly non-reactive methane) and carbon monoxide emissions (See: USDOE, October 1991). Findings from previous research also indicate some general conclusions on the potential effect of natural gas emissions on urban air quality. One such finding suggests that spark-ignition (SI) engines using CNG will contribute to reduced carbon monoxide (CO) levels. The 1991 USDOE Report indicates that although some tests have shown higher levels of reactive HC emissions with CNG vehicles, natural gas vehicles with SI engines probably will reduce the reactive HC's that are precursors to ozone formation." It is further implied that the overall ozone-reduction potential of these vehicles is unclear. NO_x emissions, which also are ozone precursors, are expected to increase while CO emissions will be much lower with CNG.

The discussion on environmental considerations is somewhat limited in this study. Other air quality concerns need to be addressed, including global warming, stratospheric ozone depletion, and acidic deposition.

♦ Alternative Fuel Costs

One of the challenges to advocates of alternative fuel utilization is how to control fuel costs. The fuel economy of a transit bus is dependent on a variety of factors including engine efficiency, the weight of the bus, and typical routes that the bus travels. For transit buses, fuel economy is expressed in miles per gallon of diesel fuel. Natural gas is measured in units of standard cubic feet (SCF) of therms (100,000 Btus). In order to compare the fuel economy of the Compressed Natural Gas buses, for example, to diesel buses, it is necessary to calculate fuel economy in miles per diesel gallon equivalent, using the heating content of both the natural gas and the diesel fuel.

As indicated in the previous section, Compressed Natural Gas and Liquefied Natural Gas buses differ only in their fuel storage/dispensing systems. For natural gas vehicles, fuel cost is approximately three-fourths that of gasoline. Local utility rates vary. Conversion costs fall within the range of $2,700 to $5,000 per vehicle. The manufacturer's extra price premium can range from $3,500 to $7,500. Booz, Allen, and Hamilton (1991) conducted a life cycle cost analysis for comparing LNG, CNG, and other alternative fuels. Using both the capital and operating cost estimates, Booz and others (1991) developed a life cycle cost model to determine

the total allocated cost per mile. These data are more suitable for comparing alternative fuel cost. In this study, alternative fuel costs will be confined to facility, capital cost inputs, vehicle and operating cost inputs and total allocated cost per mile. In the case of LNG, projected fuel consumption data are presented because fuel economy data on LNG bus demonstrations were unavailable. The data presented for LNG are based on energy content – 84,000 BYTU/gallon for LNG versus 129,400 BTU/gallon for diesel fuel #2 – LNG consumption is expected to be a minimum of 1.54 times that for diesel fuel. A ratio, according to Booz, Allen and Hamilton (1991), LNG-to-diesel consumption was assumed (1.54 x 10 percent efficiency penalty).

LNG Facility and Operation - Estimated cost of a fuel storage and dispensing facility with 20,000 gallons (73000 liters) LNG storage is about $800,000 (1993 US$). Substantial proportions of the current costs relate to development and should decrease over time, according to a report by TRB (1993:20). The report also reveals that costs for upgrading existing buildings to accommodate LNG vehicles will depend on the building design and local factors. Costs for these improvements should be somewhat comparable to those for methanol and CNG.

CNG Facility and Operation – CNG is typically less expensive than gasoline or diesel fuel on an energy equivalent basis. Findings in *Natural Gas Fuels (October 1993)* reveal that CNG sells for about 60 percent of the diesel price. CNG fueling facilities are expensive. Costs for installing the facility are tied to compressor size, and can run from $10,000 to $400,000 (1993 US$). In some instances, CNG facility costs are underwritten by utilities in the interest of value capture of costs through increased natural gas sales. Table 3 shows the cost breakdown for a typical CNG storage and dispensing system. The fuel cost for this option is estimated at $0.32 per equivalent gallon.

Table 3
CNG Storage and Dispensing System Cost Summary

Component	Unit Price	System Price
CNG Storage Bottles (9ASME Bottles)	$12,000	$108,000
Cascade System Controls & Plumbing	$50,000	$50,000
250 HP Compressor (Slow Speed, Cooled)	$350,000	$700,000
Dispensers (4)	$25,000	$100,000
Electrical Leads and Equipment	$5,000	$5,000
Storage Facility (60 Sq. Ft.)	$30,000	$30,000
Fire Suppression Equipment	$6,000	$6,000
TOTAL		$999,00

Source: Booz, Allen, & Hamilton (1991: 5-8).

LNG – Facility and Operation – In 1991, costs for LNG storage and dispensing were calculated (Booz, Allen, and Hamilton, 1991) in a study prepared for the Capital Metropolitan Transportation Authority in Austin. The Metropolitan Transit Authority of Harris County (Houston METRO) conducted a preliminary analysis of costs associated with its fuel conversion demonstration program. The data indicated that the costs to convert its fleet to LNG were estimated to be $0.51 per diesel equivalent gallon including delivery charges for a LNG unit cost of $0.33/gallon. To calculate cost, Booz, Allen, and Hamilton used a price of $0.35/gallon. The total capital costs for LNG storage and dispensing exceeded $1.0 million which is comparable to that for CNG storage and dispensing of $999,000.

A life cycle cost analysis by Booz, Allen, and Hamilton (1991: 5-20) used several assumptions to project fuel consumption for LNG and CNG and compared these two alternative fuels to diesel and methanol. Table 4 shows projected fuel consumption based on an assumed average of five fills per week. Data for diesel fuel were calculated from a weighted average of fixed route service (diesel) and STS (diesel) miles accumulated. Table 4 contains data on LNG storage and dispensing. The summary includes capital costs for a 50,000-gallon tank, piping and dispensers, flow meter, and construction.

Table 4
LNG Storage and Dispensing Summary*

Component	*Unit Price*	*System Price*
50,000 gallon tank	$335,000	$1,005,000
Piping and Dispensers	$150 /linear ft	$18,000
Flow Meter	$5,000	$20,000
Construction	$50,000	$50,000
TOTAL		$1,093,000

* *Source: Capital METRO, Austin, Texas and Houston METRO, 1991.*

Table 5
Projected Alternative Fuel Consumption

	DIESEL	CNG	LNG	METHANOL
Miles Per Bus/Year	33.674	33,674	33,674	33,674
Miles Per Unit of Fuel	3.64 mpg	3.64 mil. Per equiv.	2.25 mpg	1.46 mpg
Units of Fuel/Year/Bus	9,251 gal	,251 equi. gal.	14,987 gal.	23,065 gal.
Units of Fuel/Day/Bus	36 gal.	36 equi.gal.	58 gal.	89 gal.

Source: Booz, Allen, and Hamilton, Development of Alternative Fuel Strategy. Prepared for Capital Metropolitan Transportation Authority, Austin, Texas, April, 30, 1991.

To analyze capital costs over the useful life of the asset, Booz, Allen, and Hamilton (1991), Battelle (1994) and TRB (1993) were reviewed. Capital costs included in this study were amortized. Total fleet miles to determine total allocated cost per mile were divided by the sum of amortized and operating costs. Using these data inputs, several fuel options were developed. In Table 6, the data show facility capital costs inputs for CNG and LNG options. These options are based on several assumptions. One assumption is that fuel facilities are amortized over a period of 20 years at a discount rate of 10 percent. Another assumption is that differential vehicle capital costs are amortized over the vehicle life in a straight-line fashion. The rationale for this assumption lies in the fact that transit buses are purchased over a number of years as opposed to all at once.

Table 6
Life Cycle Cost Model Facility Capital Cost Inputs
For CNG and LNG

Option	Fueling Facility	Maintenance Facility	Total
CNG Option 1 *(Mobile Delivery)*	$ 30,000*	$335,800	$365,800
CNG Option 2a *(Ground-based Gasmaster 2000)*	$185,000**	$335,800	$520,800
CNG Option 2b *(Conventional CNG compressor station/ cascade storage)*	$1,000,000	$335,800	$1,335,800
LNG Option 1 *(On-site liquefaction)*	$1,093,000	$335,800	$1,428,000

Source: Booz, Allen, and Hamilton, 1991, p. 5-21.

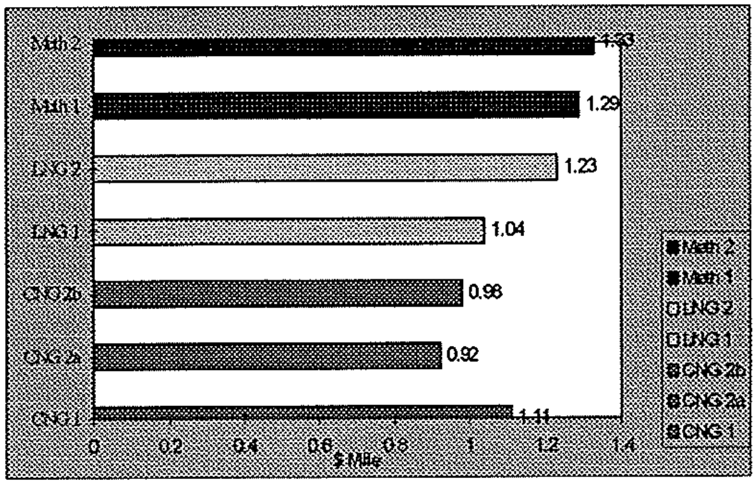
Vehicle and operating cost inputs have also been calculated for LNG and CNG and compared with other alternative fuels. The results of the cost analysis for vehicle and operating costs are shown in Table 7 while data on total allocated cost per mile are demonstrated in Figure 5. Annual costs for CNG and LNG fuels were calculated and compared with methanol. These data are revealed in Figure 6. The data illustrate cost differentials for vehicle and operating expenses as well as cost per mile and annual fuel cost.

Table 7
Life Cycle Cost Model Vehicle and Operating Cost Inputs for CNG and LNG Fuels

	Number of Vehicles/ Amoritization Period			Fuel Unit	Fuel Price $/Unit
	Full-Size Buses	STS Vans	Small Buses		
CNG Option 1	33/12 yrs.	17/4 yrs.	4/7 yrs.	Diesel equiv-gal	1.02
CNG Option 2a	33/12	17/4	4/7	Diesel equiv. gal	0.32
CNG Option 2b	33/12	17/4	4/7	Diesel equiv. gal	0.32
LNG Option 1	33/12	17/4	4/7	Gallon	0.35
LNG Option 2	33/12	17/4	4/7	Gallon	0.45
Methanol Option 1	33/12	17/4	4/7	Gallon	0.73
Methanol Option 2	33/12	17/4	4/7	Gallon	0.73

Source: U. S. Department of Energy, Office of Technical Assistance and Booz, Allen and Hamilton, 1993.

Figure 5
Total Allocated Cost Per Mile



Source: Battelle, p 10

As indicated in Table 7, CNG fuel, as expressed in diesel equivalent gallons, is calculated to be $1.02 for Option 1. When Option 2a and Option 2b are amortized, the cost equivalent is about $0.32. When these data are compared with LNG Option 1 and LNG Option 2, the cost for CNG is lowest. When LNG options are compared with methanol options relative to gallons, wider cost differentials are noted. Both options for LNG are lower than that for methanol.

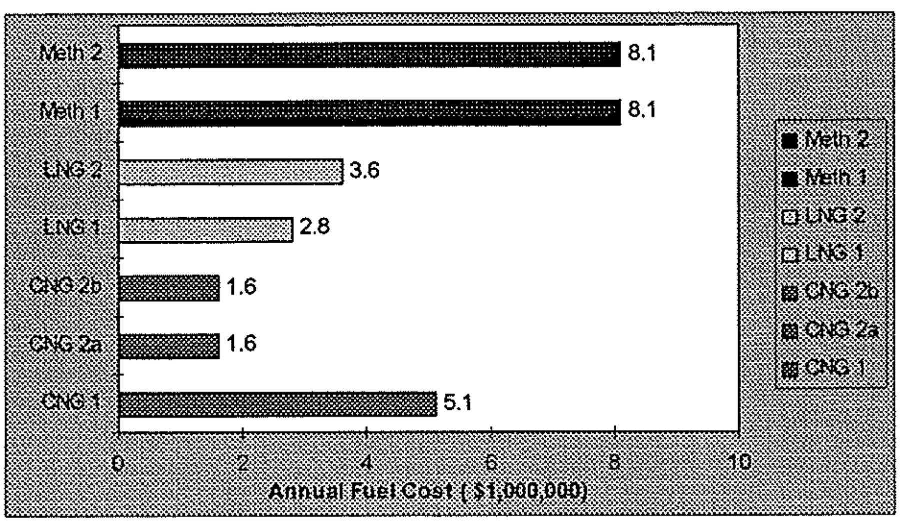
The aggressive program to convert buses from diesel to LNG clean-burning fuel at Houston METRO was discontinued in March 1995. At the time Houston METRO had an estimated 293 buses and vans running on LNG, or 21 percent of its 1,391 vehicle fleet. This percentage differs from data contained in *Fiscal Notes* (September 1994) which reported 1,423 buses using gasoline or diesel. Of this total, 301 were using LNG (Ledé, 1995: 57-58). The fuel economies of the LNG bus fleet and annual costs at Houston METRO are noted in Table 8.

Table 8
Fuel Economies of Proposed LNG Fleet
Annual Costs as of March 1, 1995 Prices

Transit – 50 Units	
Annual Average Mileage	40,000
If Diesel	$411,216
If LNG/Diesel	$452,556
Variance	**$41,340**
Commuter – 113 Units	
Annual Average Mileage	25,000
If Diesel	$514,489
If LNG/Diesel	$576,526
Variance	**$62,037**
Additional Annual Cost Above Diesel = $103,377	

Source: Naomi W. Ledé, A Study of Costs Associated with Alternative Fuels Development: A Case Study. A Report supported by a Grant from the U. S. Department of Transportation, University Transportation Centers Program, to the Southwest Region University Transportation Center, Texas A&M University, 1995, and The Metropolitan Transit Authority of Harris County (Houston METRO).

Figure 6
Annual Fuel Costs



Source: Battelle, p 10

IV. SUMMARY IMPLICATIONS AND GUIDELINES FOR POLICY

There is evidence to suggest that rapid gains have been made in alternative-fuel technologies. Extensive research and development is being conducted on alternative fuel and on both emerging and existing alternative-vehicle technologies. This study attempted to compare two forms of natural gas, liquefied natural gas (LNG) and compressed natural gas (CNG) to conventional and diesel fuel. Based on the findings of this research and data from previous studies, the analysis suggests advantages and disadvantages associated with alternative-fueled vehicles (AFVs). References are also made to the feasibility and implications of transitions to natural gas and introducing alternative-fueled vehicles into transit bus fleets.

Natural gas can be used in either compressed (CNG) or liquefied (LNG) form. Transit systems in Texas have concentrated their attention on CNG and LNG technologies. Previous findings indicate that CNG technology has been more fully developed and more widely adopted. LNG has had limited use in transit buses in Texas. More research is needed on natural gas and its potential for meeting Clean Air Act standards.

- **Advantages**

There are several advantages and environmental considerations associated with the use of natural gas as an alternative fuel. In transit use LNG has certain advantages over Compressed Natural Gas (CNG). If a transit agency selects LNG as an alternative fuel, it does not have to be connected to the gas distribution network. LNG is delivered to the agency in a truck. Natural gas is stored on-board a vehicle as either compressed (CNG) or a liquid (LNG). A major advantage to using natural gas as a motor fuel is its potential for reducing dependence on foreign oil. According to *Fiscal Notes* (September 1994), "the continental United States has an estimated 60-year supply of natural gas, with 28 percent located in Texas. In terms of supply and demand, natural gas is abundant worldwide. It has excellent emissions characteristics except for potential of somewhat higher nitrogen oxide emissions. It has the potential to significantly reduce No_x emissions, however, when compared to gasoline or diesel fuel.

Natural gas produces lower hydrocarbon and carbon dioxide emissions than gasoline. Both CNG and LNG have a high octane rating of 120. Driving range per tank is limited to about 100 to 120 miles. Researchers, currently in progress, are examining ways to enhance fuel efficiency. LNG has an advantage over CNG because it is a liquid and can be stored at a lower pressure than CNG. Also, LNG is not inherently more dangerous than conventional fuels.

Other major advantages of natural gas as a vehicle fuel include the following:

- **Natural gas is...**
  - Cheaper per gallon equivalent than gasoline or diesel;
  - Produces fewer pollutants than most fuels;
  - Supplies are abundant and available domestically; and based on
  - Physical properties, natural gas vehicles are safer than gasoline-powered vehicles.

Within each form of natural gas, there are some characteristics that are of primary importance relative to the appropriate selection of alternative fuels. The information that follows will highlight some of the important considerations and issues pertaining to LNG and CNG.

LNG – One advantage of LNG is that purity can be specified when it is purchased from the supplier. High purity (i.e., high methane content) minimizes or avoids problems of heavier hydrocarbons settling out in storage and results in decreased engine problems. Another consideration pertains to cost. The cost of LNG, although higher than CNG, is close to that of diesel on an energy basis (*TRB*, 1993:20-21).

CNG – Compressed Natural Gas has several advantages as a vehicle fuel. As previously indicated, natural gas is readily abundant, domestically and globally. A distribution network for CNG is already in place. Its use as a vehicle fuel is proven, as evidenced by the increasing number of transit systems selecting it as an alternative fuel option. Findings from previous studies reveal that natural gas engines emit less soot than diesel and that CNG promises to meet long-term mandated standards of emission. When compared with LNG, CNG is typically less expensive than gasoline or diesel fuel. With proper maintenance and the exercise of safety precautions, users will experience no hot or cold problems. Other advantages of CNG include the following characteristics: relatively high octane, no sludge or carbon deposits in engines, and low fuel toxicity.

Alternative fuels have the distinct advantage of meeting state mandates for cleaner burning fuels. The use of CNG and LNG has the potential for reducing exhaust emissions. This will reduce motor vehicle air pollution in several of the nation's serious, severe, and extreme ozone non-attainment areas. Two of the transit systems – Houston-Galveston and El Paso -- included in this study are ozone or carbon monoxide non-attainment areas in Texas. The Texas Alternative Fuel Fleet Program (TAFF) meets all the Federal requirements for the Federal Clean Fuel Fleet (FCFF) Program. The benefits to be accrued from alternative fuels such as CNG and LNG are enormous. In addition to ensuring compliance with new government standards, there is the added advantage of improving air quality by using fuels that burn cleaner than the conventional transportation fuels. Also, the cleaner exhaust helps to improve public transit's image to the public.

♦ **Disadvantages**

Several recent reports serve as guides to issues relating to disadvantages associated with the use of Liquefied Natural Gas (LNG) and Compressed Natural Gas (CNG).

Findings from previous studies indicate that some vehicle related issues contribute to disadvantages when LNG is considered. Some concerns have been articulated about the lack of availability of LNG vehicle maintenance facilities and equipment availability. Supplies of LNG are generally located at major ocean terminals because much of the gas is produced overseas. Texas users, however, rely on domestic sources and storage areas near transit facilities where LNG is in use. When compared to other alternative fuels such as CNG, Liquefied Natural Gas (LNG) poses some different and unusual hazards. To deal with this problem, proper training, suitable equipment, and good work practices can eliminate these hazards and enable users to obtain safety records equal to that for conventional fuels. Other disadvantages include cryogenic liquid handling problems, and the potential composition drift (weathering) due to the settling of hydrocarbons when LNG is stored.

CNG transit vehicles are at a disadvantage with respect to range and payload. According to TRB (1993:35-36), "as yet uncertified all-composite CNG on-board tank technology can reduce the payload disadvantage by about one-half." When compared to methanol, gasoline, and diesel fuel, CNG has less energy per volume. Another disadvantage, if not properly maintained, is flammability. As with any fuel, natural gas is flammable and fire is a danger. In a confined area, under certain conditions, natural gas could cause an explosion. Again, high level training in operating and maintaining CNG vehicles is critical to safety.

CNG may contain corrosive agents such as carbon dioxide or hydrogen sulfide in combination with water, all of which occur naturally in some natural gas "base stocks". Carbon steel is susceptible to stress corrosion cracking, if used in high-pressure applications. Also, CNG fueling facilities are expensive. However, utility companies often serve as underwriters for CNG fueling facilities. In addition, size and placement of CNG tanks can be an issue for virtually all CNG vehicles. Because the tanks are necessarily round, they cannot be custom fit into tight areas. New technology is in the process of being developed to enhance the performance and driveability of a CNG vehicle so that it becomes equal to that of a conventionally fueled vehicle. In terms of safety, CNG differs from liquid fuels in its hazards. In addition to fire hazards, physical hazards exist because of the high pressures at which CNG is stored. The training of personnel is critical to the safe utilization of CNG vehicles. The pressurized nature of the fuel and its different density and ignition properties require special maintenance procedures for CNG vehicles.

♦ **Policy Implications**

The scope of this study is limited to several alternative fuels currently in use by transit agencies in Texas. An effort has been made to conduct a comparative analysis of Liquefied Natural Gas (LNG) and Compressed Natural Gas (CNG). The background of this study is based upon a literature search of existing journal articles, books, reports, and other materials reviewed with the objective of delineating specific characteristics of the alternative fuels. Included in this analysis are issues such as energy source characteristics, including references to fuel supply and composition and safety, vehicle performance and emissions, training requirements, operation and maintenance, safety, environmental considerations, and costs for alternative fuels. Comparative data in the study will be useful for transit agencies, infrastructure developers, fleet operators – automotive, commercial and municipal operators, and alternative fuel providers. Policy decisions about alternative fuels until a critical comparison of the aforementioned issues is made. The "state-of-the-art" information included in this study will provide greater insight into the alternative fuel initiatives of policy makers, fleet managers, infrastructure developers, fuel suppliers, and auto manufacturers, particularly those interested in integrating alternative fueled vehicles into existing fleets.

Additional research will be needed to determine the most cost-effective alternative fueled vehicle strategy for transit systems. Attention should be directed to issues pertaining to the economics of alternative fueled vehicles. Refueling stations as well as refueling equipment needs are areas in need of evaluation and assessment. Air quality in urban areas, particularly ozone non-attainment areas such as Houston, El Paso and other cities in Texas, remains a continuing and significant problem. Motor vehicles of all sorts play a major role in air pollution in urban areas. Improving air quality and reducing emissions from motor vehicles will be central to meeting Federal and State air quality standards.

To guarantee the long-term sustainability of alternative fuels such as LNG and CNG, infrastructure development to supply the increasing number of alternative fueled vehicles will be needed in the years ahead. *The American Assembly* (Sharp and Tierney, 1995: 8-9) on "Fueling the Future" indicated that policies to stimulate cost-effective investments in domestically-produced advance vehicle and alternative fuel technologies could benefit the nation's economy. Also, public and private partnerships between fuel suppliers, policy makers, and fleet managers must be formed to enhance the continued development of alternative fuels. To achieve compliance with current and future environmental legislation, efforts must be directed toward the development of partnerships with the customers and the general public.

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APPENDIX A
TABLES

Four fuels are projected as capable of meeting the requirements for the transitional low-emission vehicles, low-emission vehicles, ultra-low emissions vehicles, and zero-emission vehicles. Gasoline, alcohol, compressed natural gas, and liquefied petroleum gas, with fuel and vehicle improvements, are projected as capable of meeting the first three levels. Electric vehicles are phased in as ultra-low emission vehicles and are the only vehicle type expected to be zero-emission vehicles.

Table 9
Possible Fuel/Vehicles for Clean Fuel Vehicles

TRANSITIONAL LOW-EMISSION VEHICLES (TLEVs)
- Gasoline - small/medium displacement engines, heated fuel preparation system, close-coupled catalyst
- Alcohol - improved close-coupled catalyst
- Compressed natural gas - close-coupled catalyst
- Liquified petroleum gas - close-coupled catalyst

LOW-EMISSION VEHICLES (LEVs)
- Gasoline - electrically heated catalyst, phase 2 gasoline
- Alcohol - heated fuel preparation system, close-coupled catalyst
- Compressed natural gas - electronic fuel injection, close-coupled catalyst
- Liquefied petroleum gas - electronic fuel injection, close-coupled catalyst

ULTRA-LOW EMISSION VEHICLES (ULEVs)
- Gasoline - heated fuel preparation system, electrically heated catalyst, phase 2 gasoline
- Alcohol - heated fuel preparation system, electrically heated catalyst
- Compressed natural gas - electronic fuel injection, electrically heated catalyst
- Electricity - range-extended hybrid vehicles, battery powered vehicles with auxiliary combustion heaters

ZERO-EMISSION VEHICLES (ZEVs)
- Electricity - battery-powered vehicles

Source:
U.S. Department of Energy, Office of Transportation Technologies, "Electric Vehicle Progress," Washington, DC, January 1991, p.3.

Table 10
Estimated U S. Emissions of Greenhouse Gases, 1992

Greenhouse gas	Unit of measure[a]	
Carbon dioxide	million metric tons of gas	5,1069.3
	million metric tons of carbon	1,383.0
Methane	million metric tons of gas	27.2
	million metric tons of carbon (gwp)[b]	163.0
Nitrous oxide	million metric tons of gas	0.4
	million metric tons of carbon (gwp)[b]	32.0
Carbon oxide	million metric tons of gas	79.0
Nitrogen oxide	million metric tons of gas	21.0
Nonmethane VOCS	million metric tons of gas	20.6
CFC-11,12,113[c]	million metric tons of gas	0.2
HCFC-22[c]	million metric tons of gas	0.1
HCFC-23 and PFCs[c]	million metric tons of gas	0.007
	million metric tons of carbon (gwp)[b]	19.0
Methyl Choloroform	million metric tons of gas	0.2

Source: *U. S. Department of Energy, Energy Information Administration, Emissions of Greenhouse Gases in the United States. 1987-1992 Washington, DC, November, 1994, pp. ix,xi.*

Table 11
U. S. Carbon Dioxide Emissions from Fossil Energy Consumption
by End-Use Sector, 1985-93[d]
(million metric tons of carbon)

Ends use	1987	1988	1989	1990	1991	1992	1993
Energy consumption sectors							
Residential	251.0	264.9	267.5	253.1	257.2	255.9	270.1
Commercial	197.2	207.6	210.0	206.7	206.4	205.5	212.1
Industrial	422.8	444.2	445.7	452.5	436.8	454.1	456.2
Transportation	412.4	428.7	433.7	433.2	425.5	432.3	437.1
Total energy	**1,283.4**	**1,354.4**	**1,356.9**	**1,345.5**	**1,325.9**	**1,347.8**	**1,375.5**
Electric utility sector							
	452.6	475.9	483.5	476.9	473.5	472.9	489.1

Source: U. S. Department of Energy, Energy Information Administration, Emissions of Greenhouse Gases in the United States. 1987-1992 Washington, DC, November, 1994, p 12

[a] Gases that contain carbon can e measured either in terms of the full molecular weight of the gas or just in terms of their carbon content. See Appendix B for details.
[b] Based on global warming potential.
[c] VOC = volatile organic compounds. CFC = chlorofluorocarbons. HCFC = hydrochlorofluorocarbons.
[d] Includes energy from petroleum, coal, and natural gas. Electric utility emissions are distributed across consumption sectors
[e] Preliminary.

Table 12
Estimates of Non-Federal Alternative Fuel Vehicles by Ownership and Vehicle Size, 1992 and 1994

	Private		State and local government		Total	
Fuel type	**1992**	**1994**	**1992**	**1994**	**1992**	**1994**
			Light-duty vehicles			
LPG	>167,600	>176,000	9,400	>10,000	>177,000	>186,000
CNG	16,500	29,900	3,700	12,700	20,200	42,600
M-85	24	54	2,390	8,378	2,414	8,432
E-85	28	59	117	338	145	397
Electricity	1,588	2,572	92	207	1,680	2,779
M-100	0	0	37	37	37	37
E-95	9	10	1	1	10	11
LNG	3	3	2	2	5	5
Total	**>185,752**	**208,598**	**15,739**	**31,663**	**201,491**	**240,261**
			Heavy-duty vehicles			
LPG	>44,000	>41,900	1,600	1,500	>43,500	45,500
CNG	2,500	1,300	1,000	2,800	2,300	5,300
M-85	0	3	131	252	134	252
E-85	1	1	1	1	2	2
Electricity	1	1	9	44	10	45
M-100	6	6	361	669	367	675
E-95	4	4	24	42	28	46
LNG	22	16	69	498	85	520
Total	**>46,534**	**>43,231**	**>3,195**	**>5,806**	**>46,426**	**>52,340**

Source: U. S. Department of Energy, Energy Information Administration, Alternatives to Traditional Transportation Fuels: An Overview, Washington, DC, June 1994, p. 14.

Table 13
Summary Statistics on Buses by Type, 1970-93

Year	Transit motor bus	Intercity bus	School bus
	Number in Operation		
1970	49,700	22,000	288,700
1975	50,811	20,500	368,300
1980	59,411	21,400	418,255
1985	64,258	20,200	480,400
1990	58,714	20,680	508,261
1991	60,377	21,158	513,227
1992	63,080	19,904	525,838
1993	64,648	19,119	534,872
	Vehicle-miles (millions)		
1970	1,409	1,209	2,100
1975	1,526	1,126	2,500
1980	1,677	1,162	2,900
1985	1,863	933	3,448
1990	2,123	331	3,800
1991	2,167	1,013	4,300
1992	2,178	1,022	4,400
1993	2,206	1,000	4,300
	Passenger-miles(millions)		
1970	18,210	25,300	[b]
1975	18,300	25,400	[b]
1980	21,790	27,400	[b]
1985	21,161	23,800	[b]
1990	20,981	23,000	74,200
1991	21,090	23,500	83,300
1992	20,336	23,700	90,000
1993	20,075	23,200	94,200
	Energy Users (Trillion BTU)		
1970	44.8	26.6	37.5
1975	51.5	24.8	42.6
1980	61.3	29.3	47.5
1985	72.4	31.5	57.0
1990	78.9	21.7	62.2
1991	80.6	22.6	70.6
1992	81.0	22.1	72.1
1993	87.8 [c]	[b]	[b]

Source: See Appendix A for Table 3.27.

[1] Data for Transit buses after 1983 is not comparable with prior data. Data for prior years were provided voluntarily and statistically expanded, but in 1984 reporting became mandatory.

[b] Data are not available.

[c] In 1993 data became available on alternative fuel use by transit buses.

Table 14
Location and Description of Transit Buses in the DOE Program

		Engine/Fuel Technology						
Agency Location	**Engine**	**M100**	**E95**	**LNG PING**[1]	**CNG SI2**[2]	**Diesel w/Trap**	**Diesel Control**	**Bus**
Houston	DDC 6V-92						5	40 ft Mercedes
Miami	DDC 6V-92 Cummins L10	5			5	5	5 10	40 ft Flxible
Minneapolis	DDC 6V-92		5			5	5	40ft Gillig
Peoria	DDC 6V-92		5			3		35 ft TMC
Tacoma	Cummins L10				5		5	40 ft Orion
Total		**5**	**10**	**10**	**10**	**13**	**30**	

[1] **Pilot-Injection Natural Gas**
[2] **Spark - Ignition**

Table 15
Chevorlet C2500 Pickup

Federal Fleet Sites	Vehicle Type	Fuel	Cumulative Fuel Economy miles/gallon --- gasoline equivalent (range)	No. of Vehicles That Contribued to this Sample
Denver, CO	CNG	CNG	9.0 (1.3 - 22.2)	28
Houston, TX	CNG	CNG	11.2 (1.2 - 29.3)	24
El Paso, TX	CNG	CNG	12.5 (1.2 - 29.9)	48

[a] Gasoline gallon equivalent miles per gallon is the M85 fuel economy adjusted for the difference in fuel-energy content between gasoline and M85 (e.g, M85 has 56 percent of the energy of unleaded gasoline).
[b] Based on limited information or not yet available.
[c] Gasoline gallon miles per gallinis the CNG fuel economy adjusted for the difference in fuel-energy between gasoline and CNG.

Table 16
Vehicle Location

	TOTAL VEHICLES
LOCATION	Gasoline
Washington, D. C.	10
Denver, CO	10
Houston, TX	10
Detroit, MI	30
New York/NJ	36
El Paso, TX	2
Bakersfield, CA	5
Los Angeles, CA	4
San Diego, CA	4
Argonne, IL	2
TOTALS	

[1] *Vehicles added in fiscal year 1994.*

APPENDIX B
Capital METRO Comparative Analysis

Comparative Analysis of CNG and Diesel Fuel
Capital Metropolitan Transit Authority, Austin, Texas

The data included in this section represent a comparative analysis of compress natural gas and diesel fuel used in vehicle operated by the Capital Metropolitan Transit Authority in Austin, Texas. The areas chosen for comparison included the following:

Capital Costs

- Vehicle Reliability
- Maintenance Costs (limited data)
- Fleet Mileage
- Fuel Costs
- Emissions Levels

Also included is a summary of each performance indicator. Specific analyses are supported with back-up documentation in the form of an attachment or series of attachments and are referenced for clarification.

Capital Costs
(referenced attachments A, B, C, D)

	GAS	DIESEL
Capital Costs *(referenced attachments A, B, C, D)*		
Unit Cost	$312,800	$240,000
Life Years	12	12
Allocated Costs/Year	$26,700	$20,100
Miles/Year	33,200	1,900
Costs/Mile	$0.80	$0.39
Vehicle Reliabilty *(referenced attachments E)*		
Miles between roadcalls	3.038	7.270
Towing Costs	150	150
Costs/Mile	0.05	0.02
Maintenance Costs *(referenced attachments F,G)*		
Parts $/Mile	0.43	0.36
Tune-Up Labor $/Year	437	106

Fuel Costs
(referenced attachments H,I)

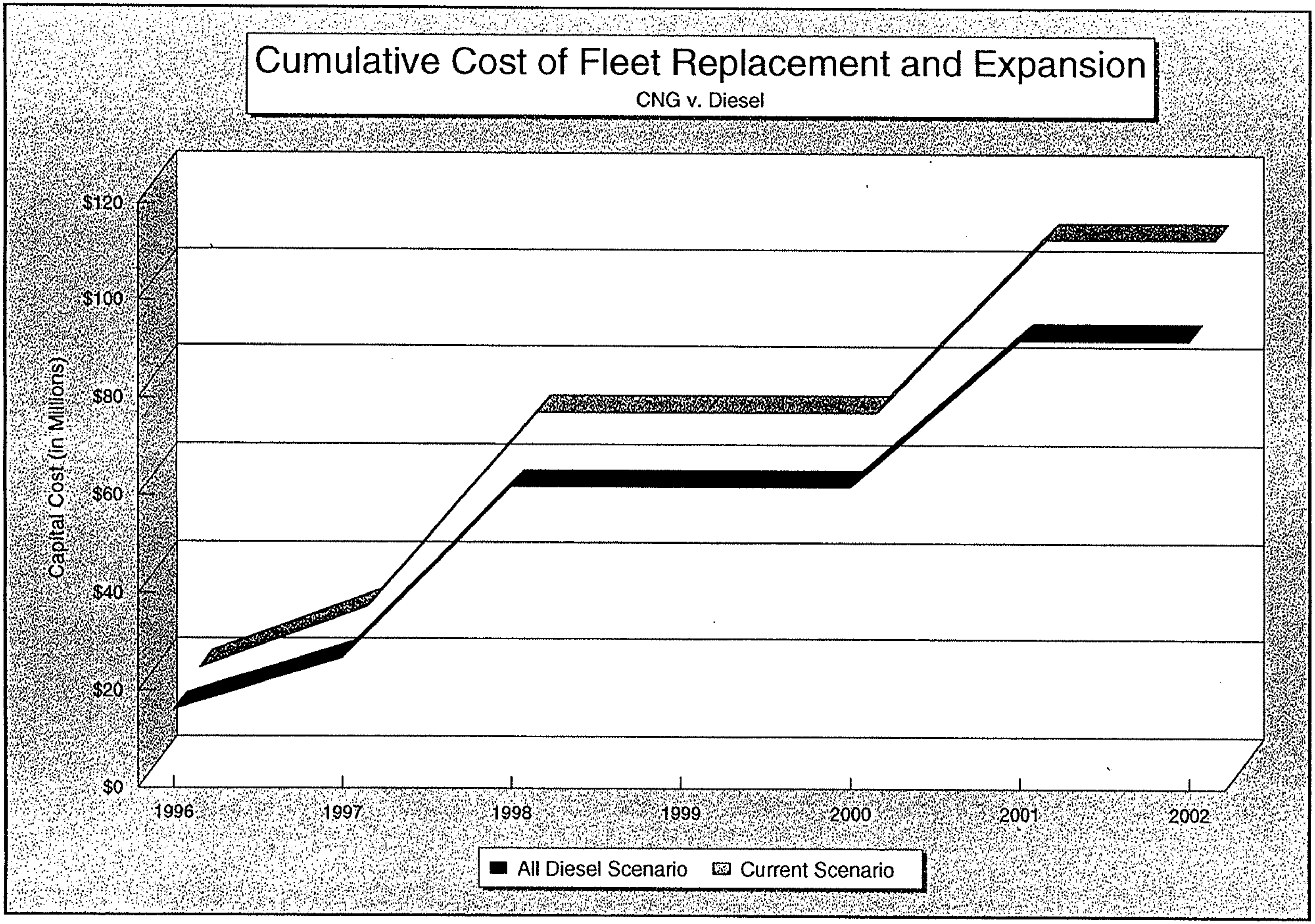
Fuel $/Mile	0.186	0.200

Emissions Levels Comparison
(please reference the full table in attachment J)

Conclusion
With the exception CNG fuel, the costs, both capital and operating are higher for CNG vehicles. Due to the lack of a comprehensive set of costs for both CNG and the diesel control group, we cannot come to a definite conclusion about the total cost difference per mile.

Companies with other users of CNG are less than satisfying due to the low average of CNG equipment and the high level of vendor support for the equipment warranty which distorts costs comparisons.

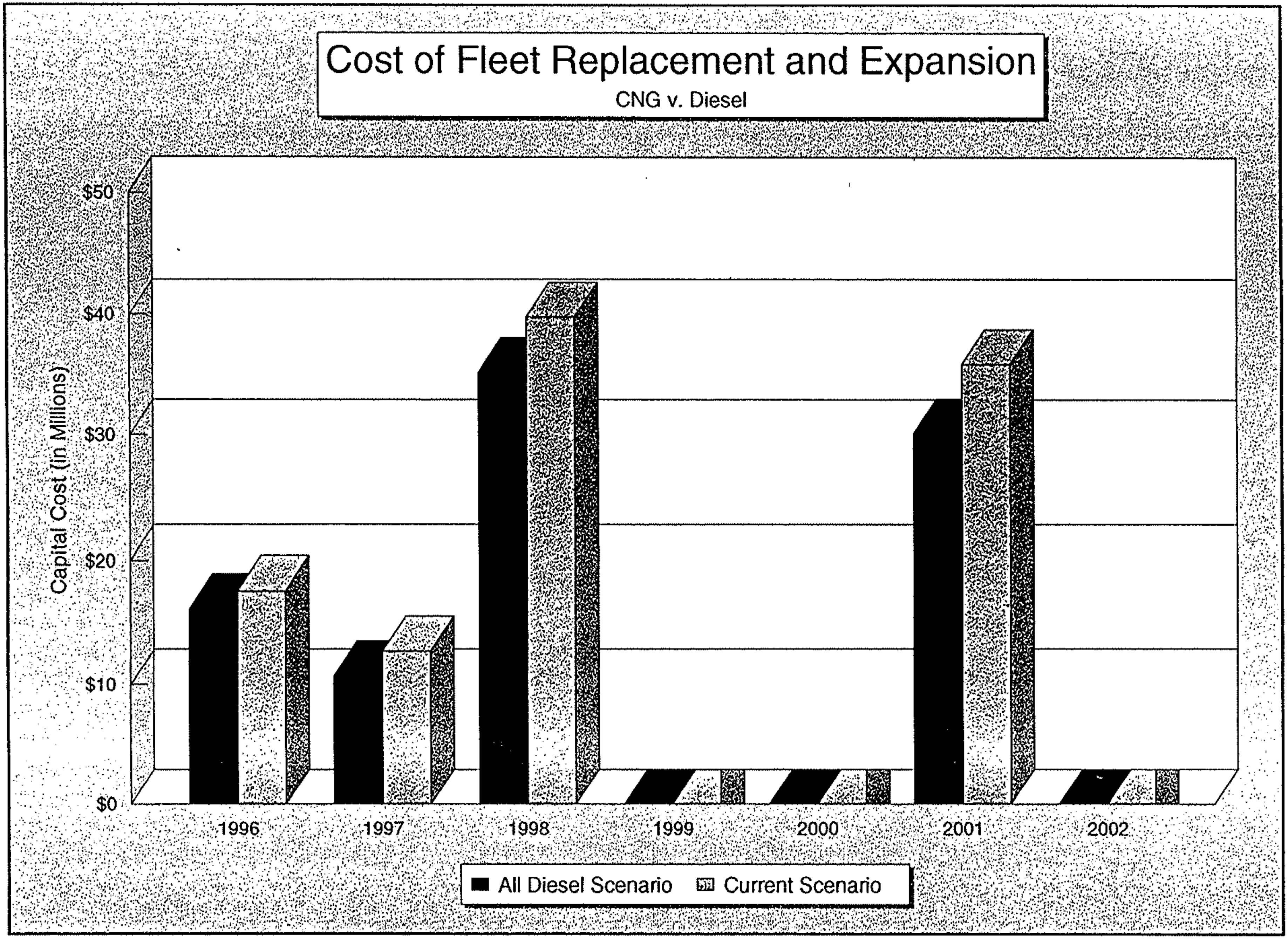
ATTACHMENT A



COMPARE.WK4

07/23/97

ATTACHMENT B



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ATTACHMENT C

Capital Metropolitan Transportation Authority
Cost of Fleet Replacement and Expansion
CNG vs. Diesel

Scenario	Unit Cost in 1997	1996		1997		1998		1999		2000		2001		2002	
		Qty	Cost	Qty	Cost	Qty	Cost	Qty	Cost	Qty	Cost	Qty	Cost	Qty	Cost
Current (CNG/Diesel)															
30 Foot - Diesel	240,693	34	8,183,562			41	10,673,676								
35 Foot - CNG	312,778	30	9,383,340	19	6,180,493	21	7,104,314								
40 Foot - CNG	312,500			20	6,500,000	65	21,970,000					94	35,770,973		
YEAR TOTAL		64	17,566,902	39	12,680,493	127	39,747,990					94	35,770,973		
Cumulative Total		64	17,566,902	103	30,247,395	230	69,995,385	230	69,995,385	230	69,995,385	324	105,766,358	324	105,766,358
Diesel															
30 Foot - Diesel	240,693	34	8,183,562			41	10,673,676								
35 Foot - Diesel	262,778	30	7,883,340	19	5,192,493	21	5,968,634								
40 Foot - Diesel	262,500			20	5,460,000	65	18,454,800					94	30,052,704		
TOTAL		64	16,066,902	39	10,652,493	127	35,097,110					94	30,052,704		
Cumulative Total		64	16,066,902	103	26,719,395	230	61,816,505	230	61,816,505	230	61,816,505	324	91,869,209	324	91,869,209

Year	Annual Cost: Current	Annual Cost: Diesel	Annual Cost: Variance	Cumulative Cost: Current	Cumulative Cost: Diesel	Cumulative Cost: Variance
1996	17,566,902	16,066,902	1,500,000	17,566,902	16,066,902	1,500,000
1997	12,680,493	10,652,493	2,028,000	30,247,395	26,719,395	3,528,000
1998	39,747,990	35,097,110	4,650,880	69,995,385	61,816,505	8,178,880
1999				69,995,385	61,816,505	8,178,880
2000				69,995,385	61,816,505	8,178,880
2001	35,770,973	30,052,704	5,718,269	105,766,358	91,869,209	13,897,149
2002				105,766,358	91,869,209	13,897,149
TOTAL	105,766,358	91,869,209	13,897,149			

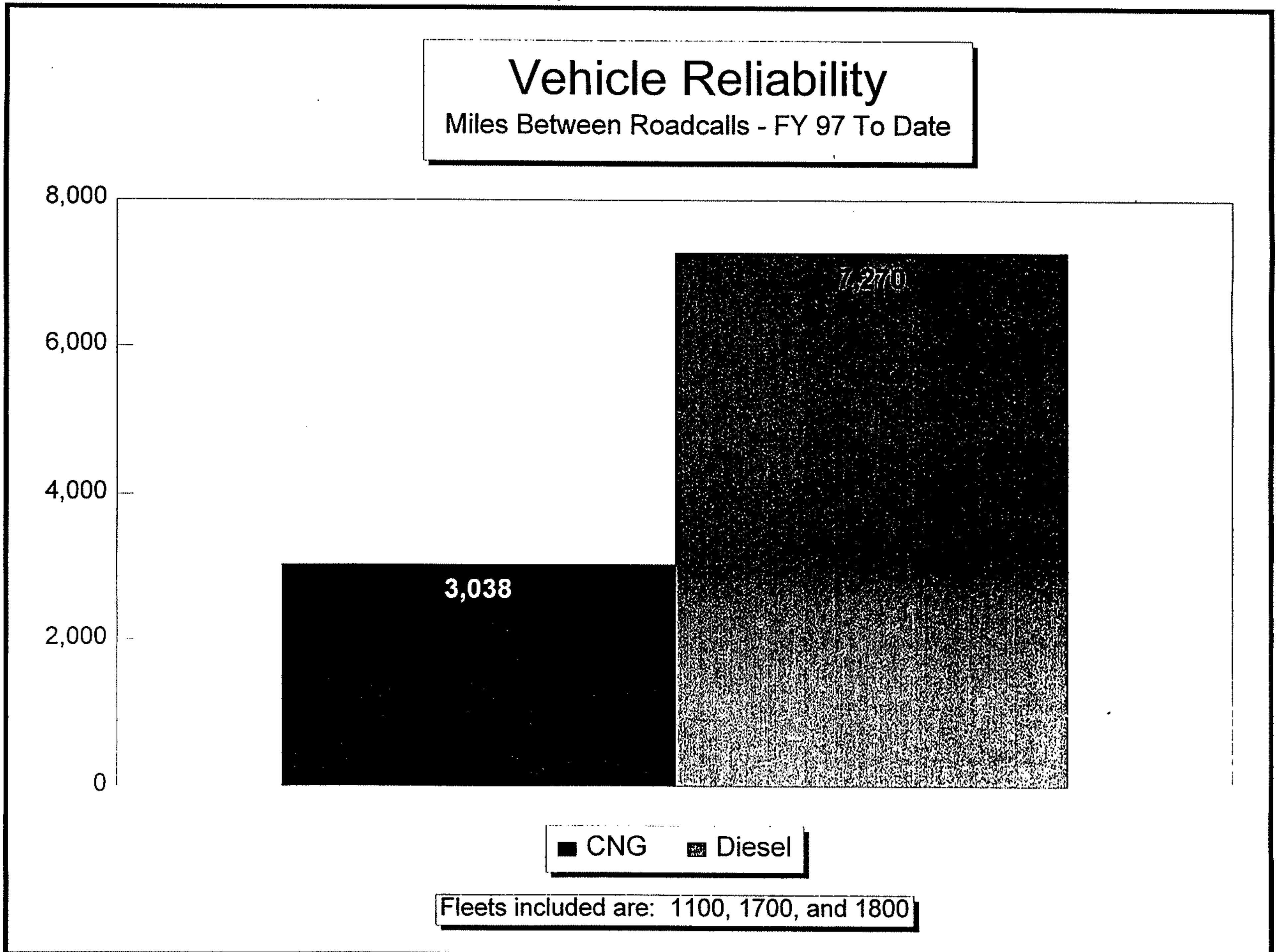
COMPARE.WK4

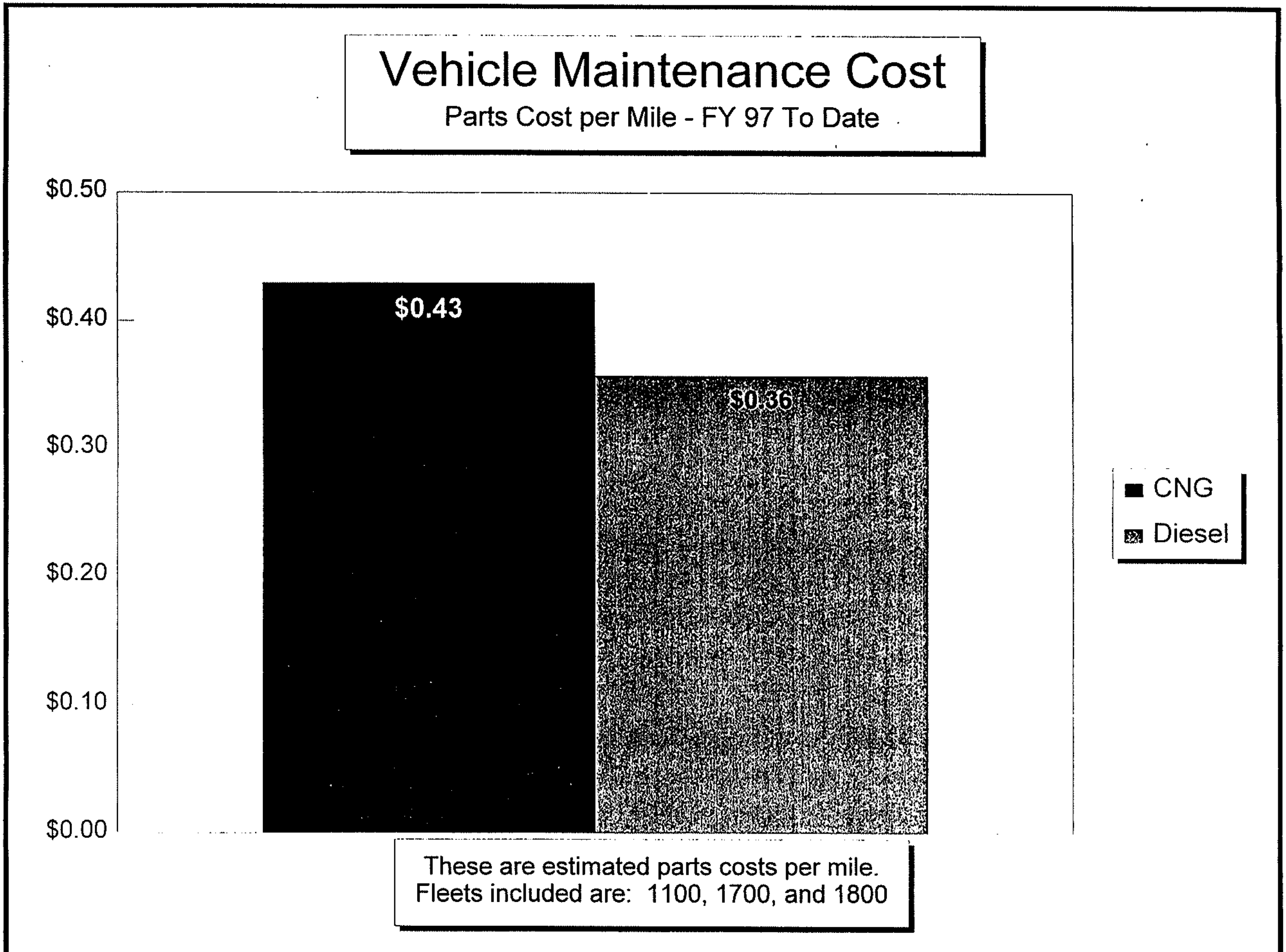
07/23/97

Capital Metropolitan Transportation Authority
Fleet Mileage Comparison by Fuel Type
Fiscal Year 1996

Fleet	Gillig (1101)	Gillig (1700)	TMC (1800)	TOTAL
Fuel Type	Diesel	Diesel	CNG	
# of Veh in Fleet	48	57	30	135
Oct '95	200,351	227,401	87,083	514,835
Nov	194,217	222,479	96,233	512,929
Dec	203,816	240,543	79,276	523,635
Jan '96	196,167	256,272	79,976	532,415
Feb	188,798	244,552	66,694	500,044
Mar	211,907	298,797	91,659	602,363
Apr	219,304	278,629	94,257	592,190
May	190,534	274,882	82,911	548,327
Jun	190,610	257,678	73,412	521,700
Jul	183,508	265,521	67,037	516,066
Aug	212,066	297,732	92,543	602,341
Sep	184,392	234,685	85,144	504,221
TOTAL	2,375,670	3,099,171	996,225	6,471,066
Avg .Miles/Vehicle	49,493	54,371	33,208	47,934

ATTACHMENT E

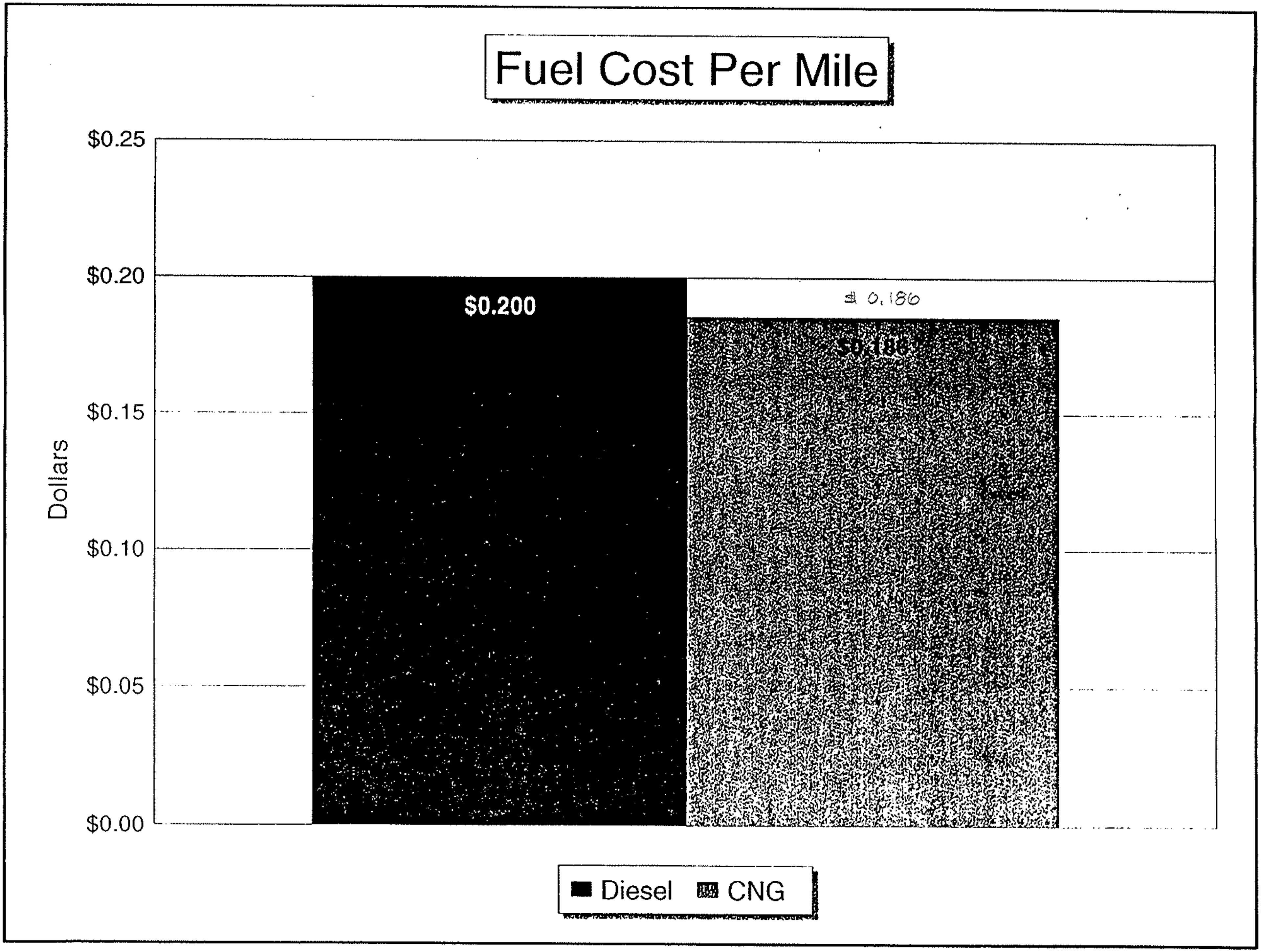



Vehicle Maintenance Cost
Parts Cost per Mile - FY 97 To Date
$0.50
$0.40
$0.30
$0.20
$0.10
$0.00
$0.43
$0.36
CNG
Diesel
These are estimated parts costs per mile.
Fleets included are: 1100, 1700, and 1800

ATTACHMENT G

Tune-Up Labor Information

	Labor Cost per hour	Time Req.	Fringe Costs	TuneUp Freq. per Yr.	TuneUps per Yr.	Cost per Yr.
CNG	$16.90	10	40%	18,000 Mi.	2	$436.50
Diesel	$16.90	4.5	40%	48,000 Mi.	1	$106.47


Fuel Cost Per Mile
$0.25
$0.20
$0.15
$0.10
$0.05
$0.00
Dollars
$0.200
$ 0.186
Diesel
CNG

ATTACHMENT I

Capital Metropolitan Transportation Authority
Fuel Cost Per Mile - Diesel vs. CNG

Month	1100 (Diesel)	1700 (Diesel)	1800 (CNG)
10/96	$0.203	$0.176	$0.171
11/96	$0.222	$0.207	$0.200
12/96	$0.204	$0.202	$0.132
1/97	$0.211	$0.218	$0.154
2/97	$0.198	$0.185	$0.133
3/97	$0.201	$0.192	$0.148
4/97	$0.186	$0.185	$0.186
5/97	$0.200	$0.194	$0.225
6/97	$0.209	$0.205	$0.323
Average	$0.204	$0.196	$0.186

Diesel Average: $0.200
CNG Average: $0.186

ATTACHMENT J

Emission Level Comparison

Detroit Diesel Series 50

	Oxides of Nitrogen	Hydrocarbons	Carbon Monoxide	Particulate Matter
Federal Standards	**5.0**	**1.3**	**15.5**	**0.1**
Diesel	4.7	0.1	1.1	0.04
Natural Gas - CNG	2.6	0.5	2.5	0.02

*NMHC only