Guidebook for Evaluating Fuel Choices for Post-2010 Transit Bus Procurements

DETAILS

243 pages | | PAPERBACK
ISBN 978-0-309-21325-7 | DOI 10.17226/22882

AUTHORS

TRANSIT COOPERATIVE RESEARCH PROGRAM

TCRP REPORT 146

Guidebook for Evaluating Fuel Choices for Post-2010 Transit Bus Procurements

SCIENCE APPLICATIONS INTERNATIONAL CORPORATION
McLean, VA

Subscriber Categories
Public Transportation • Energy • Vehicles and Equipment

Research sponsored by the Federal Transit Administration in cooperation with the Transit Development Corporation

TRANSPORTATION RESEARCH BOARD

WASHINGTON, D.C.
2011
www.TRB.org

TRANSIT COOPERATIVE RESEARCH PROGRAM

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

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

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

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

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

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

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

TCRP REPORT 146

Project C-19
ISSN 1073-4872
ISBN 978-0-309-21325-7
Library of Congress Control Number 2011929842

NOTICE

The project that is the subject of this report was a part of the Transit Cooperative Research Program, conducted by the Transportation Research Board with the approval of the Governing Board of the National Research Council.

The members of the technical panel selected to monitor this project and to review this report were chosen for their special competencies and with regard for appropriate balance. The report was reviewed by the technical panel and accepted for publication according to procedures established and overseen by the Transportation Research Board and approved by the Governing Board of the National Research Council.

The opinions and conclusions expressed or implied in this report are those of the researchers who performed the research and are not necessarily those of the Transportation Research Board, the National Research Council, or the program sponsors.

The Transportation Research Board of the National Academies, the National Research Council, and the sponsors of the Transit Cooperative Research Program do not endorse products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to the object of the report.

Published reports of the

TRANSIT COOPERATIVE RESEARCH PROGRAM

are available from:

Transportation Research Board
Business Office
500 Fifth Street, NW
Washington, DC 20001

and can be ordered through the Internet at

http://www.national-academies.org/trb/bookstore

Printed in the United States of America

THE NATIONAL ACADEMIES

Advisers to the Nation on Science, Engineering, and Medicine

The **National Academy of Sciences** is a private, nonprofit, self-perpetuating society of distinguished scholars engaged in scientific and engineering research, dedicated to the furtherance of science and technology and to their use for the general welfare. On the authority of the charter granted to it by the Congress in 1863, the Academy has a mandate that requires it to advise the federal government on scientific and technical matters. Dr. Ralph J. Cicerone is president of the National Academy of Sciences.

The **National Academy of Engineering** was established in 1964, under the charter of the National Academy of Sciences, as a parallel organization of outstanding engineers. It is autonomous in its administration and in the selection of its members, sharing with the National Academy of Sciences the responsibility for advising the federal government. The National Academy of Engineering also sponsors engineering programs aimed at meeting national needs, encourages education and research, and recognizes the superior achievements of engineers. Dr. Charles M. Vest is president of the National Academy of Engineering.

The **Institute of Medicine** was established in 1970 by the National Academy of Sciences to secure the services of eminent members of appropriate professions in the examination of policy matters pertaining to the health of the public. The Institute acts under the responsibility given to the National Academy of Sciences by its congressional charter to be an adviser to the federal government and, on its own initiative, to identify issues of medical care, research, and education. Dr. Harvey V. Fineberg is president of the Institute of Medicine.

The **National Research Council** was organized by the National Academy of Sciences in 1916 to associate the broad community of science and technology with the Academy's purposes of furthering knowledge and advising the federal government. Functioning in accordance with general policies determined by the Academy, the Council has become the principal operating agency of both the National Academy of Sciences and the National Academy of Engineering in providing services to the government, the public, and the scientific and engineering communities. The Council is administered jointly by both Academies and the Institute of Medicine. Dr. Ralph J. Cicerone and Dr. Charles M. Vest are chair and vice chair, respectively, of the National Research Council.

The **Transportation Research Board** is one of six major divisions of the National Research Council. The mission of the Transportation Research Board is to provide leadership in transportation innovation and progress through research and information exchange, conducted within a setting that is objective, interdisciplinary, and multimodal. The Board's varied activities annually engage about 7,000 engineers, scientists, and other transportation researchers and practitioners from the public and private sectors and academia, all of whom contribute their expertise in the public interest. The program is supported by state transportation departments, federal agencies including the component administrations of the U.S. Department of Transportation, and other organizations and individuals interested in the development of transportation. **www.TRB.org**

www.national-academies.org

COOPERATIVE RESEARCH PROGRAMS

CRP STAFF FOR TCRP REPORT 146

Christopher W. Jenks, *Director, Cooperative Research Programs*
Crawford F. Jencks, *Deputy Director, Cooperative Research Programs*
S. A. Parker, *Senior Program Officer*
Tiana Barnes, *Senior Program Assistant*
Eileen P. Delaney, *Director of Publications*
Maria Sabin Crawford, *Assistant Editor*

TCRP PROJECT C-19 PANEL
Field of Engineering of Vehicles and Equipment

James D. Pachan, *Los Angeles County Metropolitan Transportation Authority, Los Angeles, CA* (Chair)
John Bradley, *Automotive Manufacturers Equipment Compliance Agency, Ovid, NY*
Van Chesnut, *Advance Transit, Inc., Wilder, VT*
Woodrow W. "Woody" Clark, II, *Clark Strategic Partners, Beverly Hills, CA*
Gordon M. Exel, *Cummins Westport, Vancouver, BC*
John H. Overman, *Texas A&M University, Arlington, TX*
Jack Requa, *Washington Metropolitan Area Transit Authority, Washington, DC*
Darryl Spencer, *Dallas Area Rapid Transit, Dallas, TX*
Ted Williams, *American Gas Association, Washington, DC*
Christina Gikakis, *FTA Liaison*
Jeff Hiott, *APTA Liaison*
Quon Kwan, *Federal Motor Carrier Safety Administration Liaison*
Dennis A. Smith, *US Department of Energy Liaison*
Kimberly Fisher, *TRB Liaison*
Jennifer A. Rosales, *TRB Liaison*

AUTHOR ACKNOWLEDGEMENTS

This project represents a collective effort. SAIC would like to thank the TCRP Project C-19 panel for their diligence and contributions to the content of this project. Delma Bratvold was the SAIC project manager. New West Technologies, LLC, provided initial content for many of the fuel-specific chapters in this report, which were built upon, updated, and edited by SAIC staff including Kateri Young and Maxwell Cohen with contributions by David Friedman. Layout design is by Margaret Scott. The accompanying lifecycle cost model (FuelCost2) includes programming contributions from Robert Laramey and Connor Hackett of SAIC.

FOREWORD

By S. A. Parker
Staff Officer
Transportation Research Board

TCRP Report 146: Guidebook for Evaluating Fuel Choices for Post-2010 Transit Bus Procurements and its accompanying life-cycle costs and life-cycle emissions model spreadsheet (*FuelCost2*) will be of interest to transit managers, policymakers, operations and maintenance professionals, and others considering the deployment of, or conversion to, alternative fuel buses. The guidebook and *FuelCost2* are intended for individuals who, while being quite knowledgeable about the transit industry, may not be familiar with alternative fuels and implementation issues. The guidebook and *FuelCost2* provide tools to simplify the process of developing an alternative fuel strategy by clearly identifying the issues, and the costs and benefits associated with the conversion to various available alternative fuel technologies. This report updates, expands on, and replaces *TCRP Report 38: Guidebook for Evaluating, Selecting, and Implementing Fuel Choices for Transit Bus Operations*.

There are many factors that may affect fuel choice decisions. Particularly for public transit agencies that receive essential funding from the local government, local policies can over-ride all life-cycle economic or emissions analyses. Life-cycle cost analyses can provide easy-to-understand comparisons to help decision makers see the overall costs of different policies.

This guidebook begins with an overview of how to choose a transit bus fuel, followed by 13 chapters, each addressing one particular fuel or powertrain type. In each fuel or powertrain chapter, readers will find a fuel description; fuel usage; safety and training; technology and performance; maintenance, reliability, and storage; emissions; and cost and availability. A summary table of pros and cons concludes each chapter. Each chapter can be read on its own as a stand-alone document, allowing users to concentrate on chapters that focus on their primary interests. The data provided in each fuel-specific chapter provides the basis for default values used in the *FuelCost2* lifecycle spreadsheet.

FuelCost2 has been developed to assist transit operators in assessing their bus fuel choices. A number of workshops were held in conjunction with CTAA and APTA to field test draft versions of *FuelCost2,* which provides life-cycle costs and life-cycle emissions of various bus fuel and powertrain options.

The components of this report available at http://www.trb.org/Main/Blurbs/165390.aspx include the following:

- The *FuelCost2* life-cycle costs and life-cycle emissions spreadsheet;
- The guidebook, which provides introductory information on the fuel and powertrain choices in *FuelCost2;*
- A user's guide in the form of slides that provide more detailed instructions on *FuelCost2* use and tips for adapting *FuelCost2* for other applications (e.g., small buses and vans); and
- A 2-page set of instructions for using *FuelCost2*.

CONTENTS

Note: Many of the photographs, figures, and tables in this report have been converted from color to grayscale for printing. The electronic version of the report (posted on the Web at www.trb.org) retains the color versions.

Guidebook for Evaluating Fuel Choices for Post-2010 Transit Bus Procurements **1-1**

1.0 Introduction

Photo courtesy of Pearson Fuels

As an increasing number of transportation fuels are developed and commercialized, selecting the best fuel for a particular transit bus application is no small undertaking. For any given fuel, an agency must consider short- and long-term costs, safety, storage, maintenance, reliability, training requirements, and emissions, in addition to the availability of the fuel and parts over a bus life. The purpose of this guide is to help transit agencies compare the many fuel options for transit buses, with emphasis on full-size buses (i.e., 35- to 40-ft lengths).

This guide and its companion lifecycle cost spreadsheet, FuelCost2, are updates to the Transportation Research Board's *TCRP Report 38* and the original FuelCost model published in 1998. For each fuel and powertrain technology discussed, information is provided about its state of development, emissions, capital and operating costs, and more. The guide allows users to compare different, sometimes unfamiliar fuels, and come up with a short list of fuels to further consider. The guide and FuelCost2 do not provide definitive fuel selections, rather, they are a starting point for researching transit bus fuel options.

1.1 Drivers of Fuel Change

For many years, selecting a fuel for transit buses was relatively simple for most transit agencies since diesel was regarded as the only feasible option. But over the last few decades, there has been increasing consideration of other market forces including the following:

- Environmental concerns, both about regulated pollutants and greenhouse gases,
- Historically high prices for fuels derived from petroleum, and
- A desire to increase national security by decreasing the U.S.'s reliance on imported fuels.

These factors have led policy makers and the public to support alternatively fueled vehicles. Often, subsidies are available for alternative fuels, making them more competitive with baseline diesel. As a result, over the last few decades, non-diesel propulsion systems have entered the transit bus market, particularly in the form of compressed natural gas (CNG), liquefied natural gas (LNG), liquefied petroleum gas (LPG, or propane), all-electric battery, and alcohol fuels due to their promises of reduced emissions and costs. These, in addition to the older overhead catenary electric buses (i.e., trolley buses) each gained a small market share, but failed to ignite broad interest. Underlying reasons for these fuels' limited success to-date include performance issues, costs, and a lack of supplies and infrastructure support.

More recently, additional fuels and powertrain technologies have been developed, providing still more options (i.e., dimethyl ether (DME), hydrogen, hybrid-electric, and fuel cells). The ultimate selection of these and the older options depends on the purchaser's valuation of each option's strengths and weaknesses. These include both direct costs over the life of a bus, and the more subjective valuation of indirect costs. These valuations vary with specific applications, suggesting a future in which many different options may have a role to play.

1.2 Lifecycle Analyses and Policy Decisions

There are, of course, many factors that may affect fuel choice decisions. Particularly for public transit agencies that receive essential funding from the local government, local policies (and politics) can override all lifecycle economic or emissions analyses. Lifecycle cost analyses can provide easy-to-understand comparisons to help decision-makers see the overall costs of different policies. Some examples of policy considerations that may be worth higher lifecycle costs for a transit fleet include the following:

- **Enabling Technology Development**—Use of new technologies in transit bus fleets can provide a public means for encouraging technology development.
- **Stimulating the Regional Economy**—Use of regionally produced fuels can support the regional economy from both direct fuel purchases, and from helping to maintain a constant regional market that may encourage other types of fleets to use regional fuels.
- **Labor Factors**—Labor union concerns can significantly affect purchasing policies. In some locations, union acceptance of fuel changes is an important consideration.
- **Public Perception**—Customers may or may not respond positively to buses powered with new fuels. Ridership may increase if passengers believe that the new vehicles are good for the environment.

1.3 Guide Use

Within this guide is a chapter addressing an overview of how to choose a transit bus fuel, followed by 13 chapters, each addressing one particular fuel or powertrain type. Each fuel or powertrain chapter includes the following sections: fuel description; fuel usage; safety, training, and disposal; technology and performance; maintenance, reliability, and storage; emissions; and cost and availability. A summary table of pros and cons concludes each chapter. Each chapter can be read on its own as a stand-alone document, allowing users to concentrate on chapters that focus on their primary interests.

Topics in Each Chapter

- Fuel description
- Fuel usage
- Safety, training, and disposal
- Technology and performance
- Maintenance, reliability, and storage
- Emissions
- Costs and availability
- Summary

The data provided in each fuel-specific chapter provide the basis for default values used in the FuelCost2 lifecycle spreadsheet. The fuel properties and costs tables in these chapters are combined to create a summary table showing all the addressed fuels in Appendix A.

It must be recognized that actual on-the-ground experience with any fuel varies significantly depending on how an agency uses its buses, so none of the data in the guide or in FuelCost2 should be assumed to be a good estimate for a specific fleet. As such, this guide provides a starting point for assessing fuel options, and should by no means be the only source consulted.

Users will also note that, as a group, the chapters cover liquid fuels, gaseous fuels, and electric powertrains. Though electric buses all use electricity for propulsion, there are several different powertrain types. For this reason, rather than one chapter on electric vehicles, there are separate chapters addressing hybrid-electric, battery-electric, fuel cell, and trolley buses. For the purposes of this guide, various types of electric powertrains are considered to be "fuels."

Most of the sources used to create this guide are available on the internet. Every chapter contains a list of endnotes with web links (when available) to the original sources. In addition, this project conducted a survey of selected transit agencies to collect technical and cost data to fill data gaps. These surveys are cited when appropriate in chapter endnotes, but they are not available to the public.

2.0 Choosing a Fuel

Choosing a fuel is a decision that will impact an organization's long-term costs, performance, and public perception. Many of the factors important for making a prudent fuel choice decision are considered in this guide. It provides a starting point for assessing fuel choices.

This chapter addresses the fuel choice process in the following four steps:

1. Developing a short list of fuel choices to further explore (Section 2.1).
2. Basic use of FuelCost2 for initial fuel comparisons (Section 2.2).
3. Site-specific use of FuelCost2 with detailed data additions (Section 2.3).
4. Means for accounting for risk in lifecycle analyses (Section 2.4).

Photos courtesy of National Renewable Energy Laboratory

2.1 Developing a Short List

Transit agency fuel choice decisions are based on a variety of factors, including the following:

- Capital and operating costs,
- Environmental concerns,
- Reliability of fuel and technology suppliers,
- Popularity, including political support,
- Transit agency experiences, and
- Risks associated with fuel change.

A detailed analysis of each fuel option takes significant time and effort. Many agencies reduce their detailed analyses by first establishing a short list of two to three fuels. To aid in developing this short list, overall fuel comparisons are shown in the following tables and graphs. The subsequent fuel-specific chapters provide more comprehensive information, and can further aid in developing a short list for a more careful assessment.

Fuel-Specific Chapters

Liquid Fuels (4)
Diesel
Biodiesel
Gasoline
Ethanol

Gaseous Fuels (5)
Compressed Natural Gas
Liquefied Natural Gas
Hydrogen
Propane
Dimethyl Ether

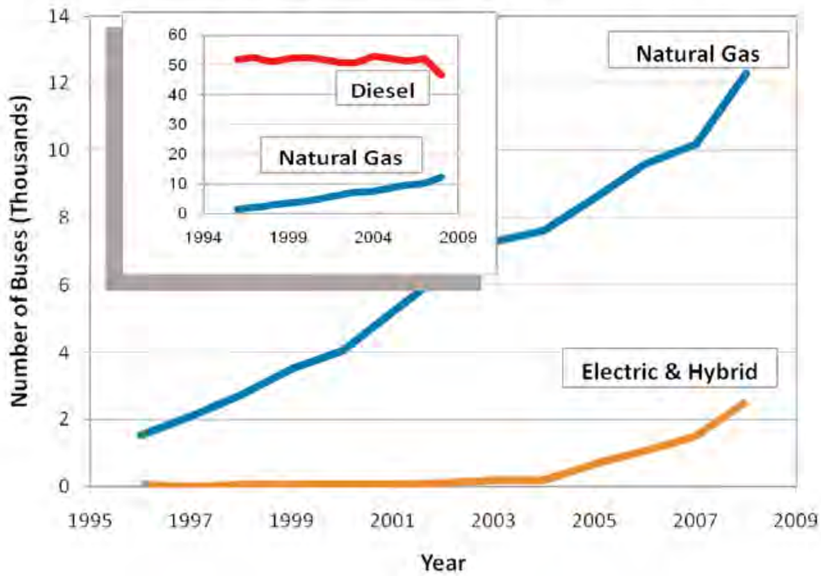
Electric Power (4)
Trolleybus
Battery Electric
Hybrid Electric
Fuel Cell

Infrastructure and Availability

Infrastructure risks are one of the types of risks associated with changing fuels. These risks include unavailability or interruption in the fuel supply, fuel-specific equipment, spare parts, and maintenance and warranty services. Infrastructure risks are generally for less broadly used fuels. Over time, relative usage of different fuels has varied. The level in recent years is often a direct indicator of the availability of the fuel and its associated technology.

Figure 2.1 shows the total number of natural gas buses in the U.S. compared to the total number of electric and hybrid buses between 1996 and 2008 based on data collected by APTA for transit buses (fixed-route service). While the number of natural gas buses steadily increased during this period, electric buses were initially very slow to increase in numbers. However, beginning around 2004, a technology improvement in the hybrid powertrain led to subsequent increases in hybrid buses.

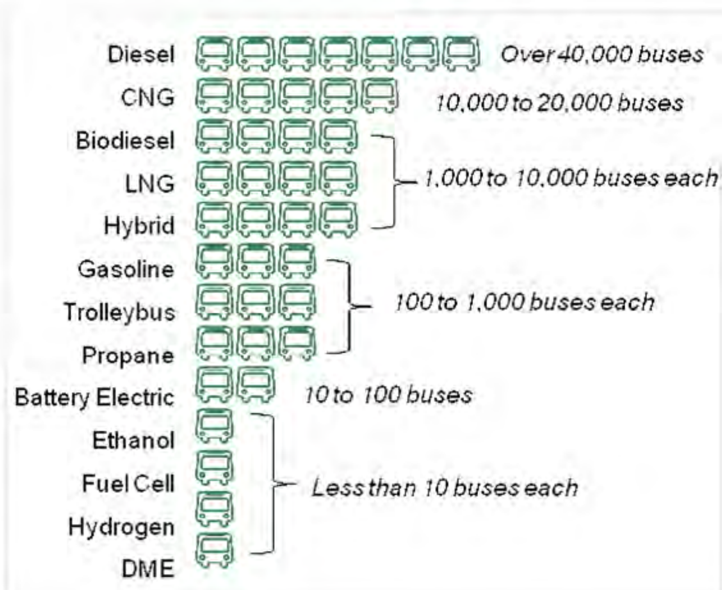
Figure 2.1 Number of Transit Buses by Fuel Type over Time



The inset box in Figure 2.1 shows on a different scale the same data for natural gas and diesel buses. From the inset, it can be seen that while natural gas usage has been steadily increasing, most transit buses are still powered by diesel.

All other alternatives have lower usage than natural gas. Figure 2.2 shows the relative number of transit buses currently running in the United States for each fuel discussed in this guide. These number ranges are based on a variety of recent estimates with differing precision, and imply general differences in availability and confidence in generalizing the available data. The fuel-specific chapters that follow provide more detailed information on the number of transit buses estimated to be operating with each fuel. Note that 5 of the 13 fuel types have less than 100 operating buses nationwide in 2010.

Figure 2.2 Number of Transit Buses by Fuel Type



Guidebook for Evaluating Fuel Choices for Post-2010 Transit Bus Procurements 2-3

Diesel Gallon Equivalents (DGE)

DGE is a unit used when comparing different fuels. One DGE always has the same energy content as one gallon of diesel. Since diesel has around 128,450 Btu per gallon, one DGE is defined as being whatever the quantity of another fuel that contains 128,450 Btu. A DGE is more than one gallon of the common alternative fuels because they contain less energy per gallon.

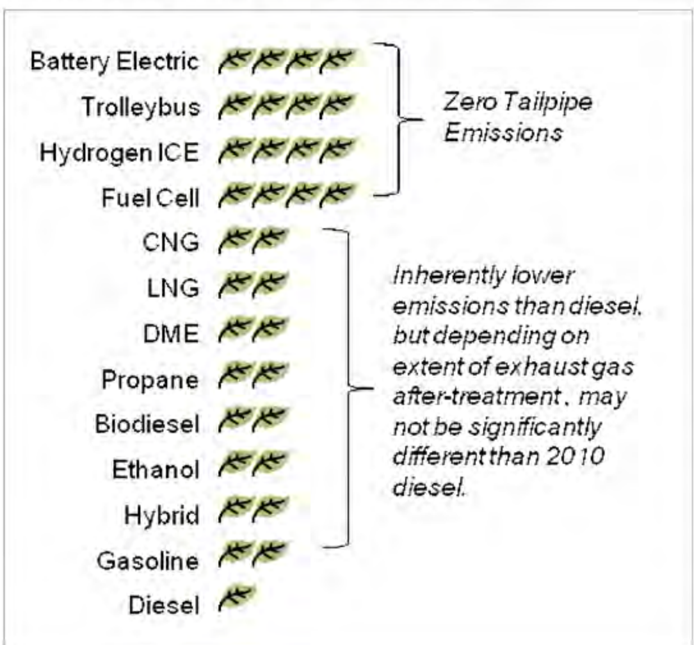
Emissions Comparisons

Emissions have been an important factor in the fuel selections at many transit agencies. The more stringent EPA 2010 emissions standards apply to all heavy-duty engines no matter which fuel they burn. As such, the difference in tailpipe emissions between the various fuel choices has been greatly reduced. Most bus engines require emission control technologies to bring emissions down to the level mandated in the 2010 standard, regardless of the fuel.

Figure 2.3 shows a basic comparison of emissions from the various fuels discussed in this guide. Figure 2.3 only shows tailpipe emissions of regulated pollutants—these pollutants are released locally as the bus operates. While some 2010 emissions data is provided in the fuel-specific chapters, the availability of this data is quite limited at the time of this writing. As a result, rankings in Figure 2.3 are very general to prevent undue focus on limited data.

A recent NETL analysis of Greenhouse Gas (GHG) emissions from conventional transportation fuels found that "Opportunities for lowering the life cycle GHG emissions from transportation-related fuels will best be achieved through improved vehicle efficiency or alternative sources of transportation fuels."[1]

Figure 2.3 Regulated Tailpipe Emissions



GHG emissions are not currently regulated. A fuel's lifecycle GHG emissions can vary greatly depending on how it is produced and transported. Fuels such as ethanol could potentially reduce or increase lifecycle GHG emissions compared to diesel depending on factors such as feedstock and land use. Fuels such as hydrogen and electricity only produce zero GHG emission on a tailpipe level; on a lifecycle basis, these fuels may be responsible for significant levels of GHG emissions depending on how they are produced. Each fuel-specific chapter provides a "default value" for GHG as a relative comparison of lifecycle GHG emissions compared to diesel. These values are dependent on assumptions that should often be adjusted on a regional, if not local, level.

Cost Comparisons

There are many costs that come with purchasing a new type of bus, ranging from retrofitting garages to training employees to handle the fuel. The two most obvious costs, however, are the buses themselves and the fuel required to power them. Figure 2.4 and Figure 2.5 show comparisons of these costs. Appendix A provides a summary table with additional costs as presented in each of the fuel-specific chapters.

Figure 2.4 New Bus Purchase Prices by Fuel Type

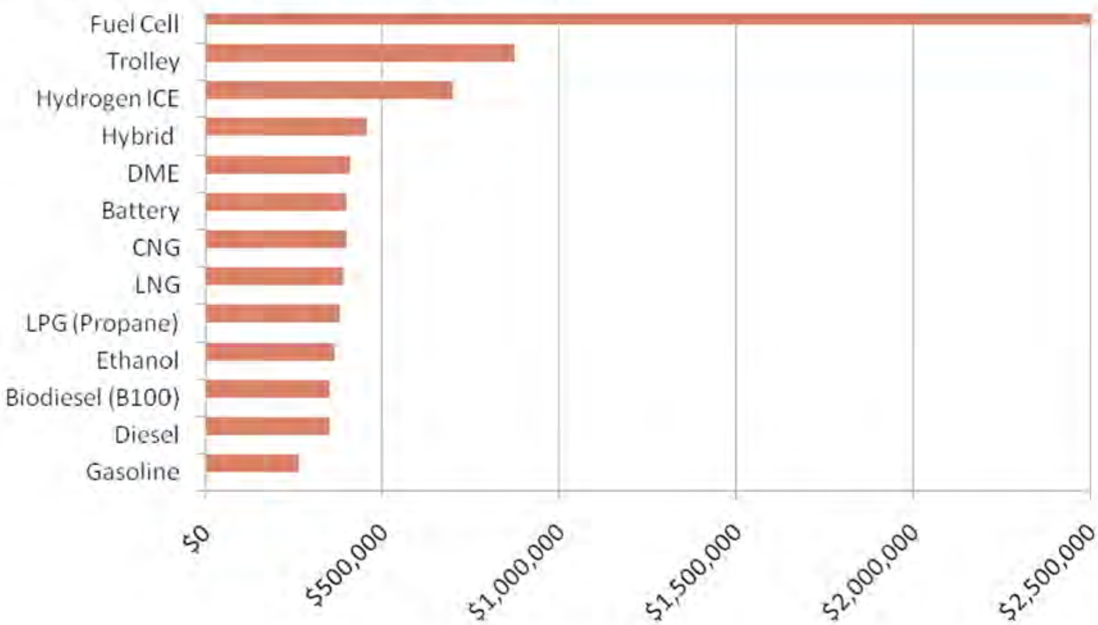
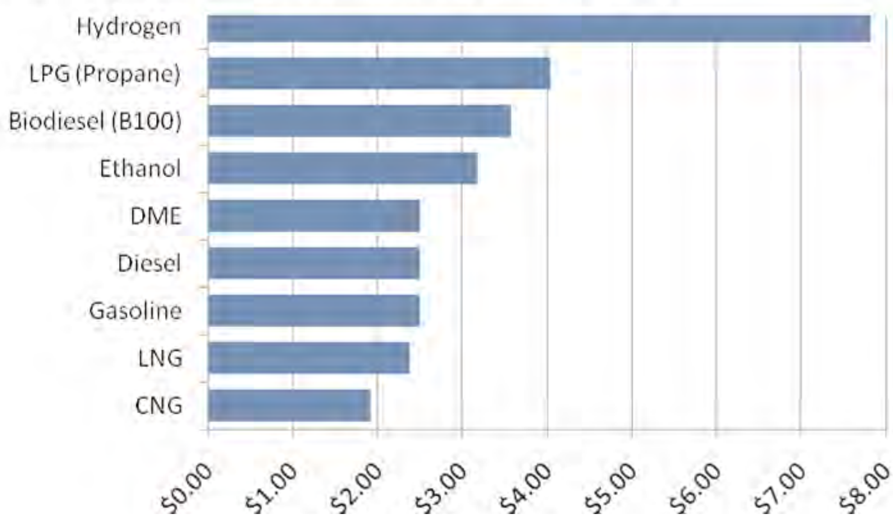


Figure 2.5 Fuel Prices per Diesel Gallon Equivalent (DGE)



Guidebook for Evaluating Fuel Choices for Post-2010 Transit Bus Procurements 2-5

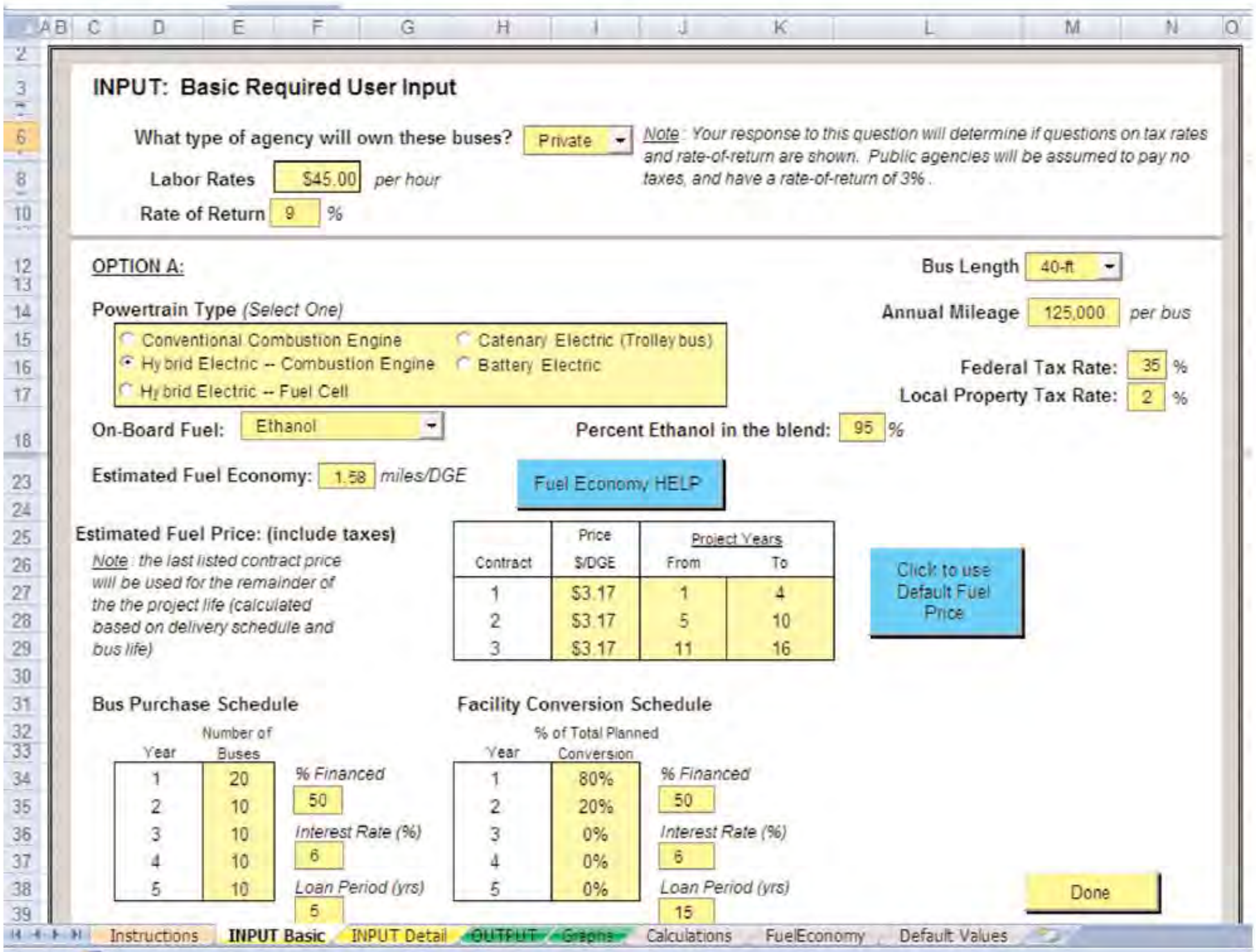
2.2 FuelCost2: Basic Input and Output

FuelCost2 has been designed to be user-friendly, and basic functions require little instruction if the user is already generally familiar with spreadsheet applications such as Microsoft Excel™. Even so, users are highly encouraged to save a backup copy of FuelCost2 as a precautionary first step. Appendix C provides more detailed instructions for the use of FuelCost2, including instructions on adjusting Excel security levels to permit proper functioning of the spreadsheet's features.

After opening FuelCost2 with macros enabled, the first sheet provides basic instructions and explains the organization of its workbook sheets. For cursory comparisons of fuel/powertrain options, the user needs to only input data on the "INPUT Basic" sheet. Lifecycle costs and emissions will then be calculated based on both these basic user inputs and the default data built into FuelCost2. For more reliable comparisons of fuel/powertrain options, the user can provide more detailed information in the "INPUT Detail" sheet, but this is not required for a quick, cursory comparison.

The top rows of the INPUT Basic sheet are for entering basic information about a user's transit agency. This information will remain unchanged. Users then select which fuel/powertrain options they would like to compare. A maximum of three fuel/powertrain options can be compared in one run. Figure 2.6 shows the entry areas for the top rows and the first selected fuel/powertrain option (Option A).

Figure 2.6 FuelCost2 "INPUT Basic": Required User Input



FuelCost2 results are shown on the "OUTPUT" and "Graphs" sheets. FuelCost2 employs lifecycle cost (LCC) methods of evaluating project economics including total capital and operating costs, with results displayed in both tables and graphs. Regulated pollutants are also evaluated in terms of total project-life tailpipe emissions, displayed in both a table and a graph. A table of relative rankings of the selected options is also provided for general evaluations of technological maturity; effects of fuel use on the regional economy; and lifecycle emissions of greenhouse gases (GHG), nitrogen oxides (NOx), and particulate material (PM). Figure 2.7 displays a sample "OUTPUT" sheet.

Figure 2.7 FuelCost2 "OUTPUT" Sheet

Project Life-Cycle Results
SUMMARY TABLE

		A	B	C
		Hybrid Electric -- Fuel Cell, Hydrogen	Hybrid Electric -- Combustion Engine, Gasoline	Hybrid Electric -- Combustion Engine, Biodiesel 20%
Costs	**Total Cash Outflow**			
	Cash Outflow (Current $)	$ 427,327,592	$ 90,661,934	$ 475,813,736
	Present Value ([illegible] Rate of Return)	$ 229,648,417	$ 45,106,970	$ 221,366,108
	Capital Costs			
	Year 1	$51,812,800	$4,173,050	$3,931,000
	Year 2	$25,503,200	$4,167,050	$3,923,500
	Year 3	$25,100,000	$4,165,050	$3,921,000
	Year 4	$25,100,000	$4,165,050	$3,921,000
	Year 5	$25,100,000	$4,165,050	$3,921,000
	Total (Current $)	$ 152,616,000	$ 20,835,250	$ 19,617,500
	Other Costs & Offsets *(Total project life)*			
	Interest Payments	$ 12,568,691	$ 1,668,048	$ 1,571,331
	Fuel	$ 225,712,031	$ 33,851,237	$ 365,482,239
	Other O&M	$ 84,245,512	$ 42,183,552	$ 96,558,757
	Tax Deductions ($ value)	$ (67,814,642)	$ (7,876,155)	$ (7,416,091)
	Subsidies/ Rebates	$ -	$ -	$ -
	Total (Current $)	$ 274,711,592	$ 69,826,684	$ 456,196,236

Emissions (Metric tons)	Carbon Monoxide	0.000	274.219	397.880
	Nitrogen Oxides	[illegible]	18.291	436.861
	Particulate Matter	0.000	1.828	6.543
	Hydrocarbons	0.000	18.098	98.719

KEY ASSUMPTIONS	A	B	C
Default Data:	*Very Limited*	*Moderate*	*Moderate*
NOTE: "Project Life" is based on bus life and the last year of bus deliveries.			
Project Life (yrs)	19	19	19
Ownership	Private		
Bus Length	40-ft	40-ft	40-ft
Annual miles/bus	125,000	125,000	300,000
Buses purchased	80	50	50
% Financed			
Facility	50%	50%	50%
Buses	50%	50%	50%
Interest rate			
Facility	6.0%	6.0%	6.0%
Buses	6.0%	6.0%	6.0%
Loan Period (yrs)			
Facility	15	15	15
Buses	5	5	5

O&M Year 6	A	B	C
Fuel	$ 15,047,469	$ 2,256,749	$ 24,365,483
Other	$ 5,979,084	$ 2,732,100	$ 7,037,100

NOTE: "Other" includes bus and facility maintenance, safety training, and bus overhauls.

Instructions | INPUT Basic | INPUT Detail | OUTPUT | Graphs | Calculations | FuelEconomy | Default Values

Default Data Limitations

The FuelCost2 default values are estimates for model year (MY) 2010 buses. To meet the 2010 EPA emissions standards, most MY2010 buses include significant changes in emissions control technologies, which sometimes cause changes in maintenance requirements. Currently, there has been little opportunity for data collection from MY2010 buses of any fuel type. More problematic is that some fuels discussed in this guide (ethanol and DME, for example) are not being used in any full-size MY2010 transit buses in the United States. Further, while diesel hybrid-electric buses are becoming sufficiently widespread for collection of generally applicable statistics, the number of hybrid buses using other fuels is still far too low for much more than site-specific data.

Due to this lack of data, many of the estimates used as default values in FuelCost2 are based on the authors' judgment after consideration of the body of literature reviewed for this project, as described in each fuel-specific chapter. Comparisons of fuel/powertrain options based on FuelCost2 default values should be considered as very preliminary. Users should seek out and enter up-to-date information prior to using FuelCost2 to assist with significant decision-making.

Default data used in FuelCost2 lifecycle cost calculations can be viewed in the INPUT Detail sheet. This sheet shows only the default data for the selected fuel and powertrain options. Default values can be edited on this sheet. As default values are changed, the data cells turn white for easy identification of default versus edited values. All default data can be returned by clicking the reset buttons at the top of each column, as shown in Figure 2.8. This sheet allows the user to enter values for subsidies as either the percent of each cost carried by the agency, or as lump sum.

Figure 2.8 FuelCost2 INPUT Detail Sheet

NOTE: No entry is required on this page when the default values are acceptable.
User-entered data will be lost when the option's "Reset" button or "Done" button (on INPUT Basic) is clicked.

DETAILED INPUT
Data cells turn WHITE when edited by the user.

Reset Option A | Reset Option B | Reset Option C

			A		B		C	
		Powertrain:	**Hybrid Electric -- Fuel Cell**		**Hybrid Electric -- Combustion Engine**		**Hybrid Electric -- Combustion Engine**	
		Fuel:	**Hydrogen**		**Gasoline**		**Biodiesel 20%**	
		Default Data:	**Very Limited**		**Moderate**		**Moderate**	
	New Bus Life	years	15		15		15	
CAPITAL Costs			**Cost**	**by purchaser**	**Cost**	**by purchaser**	**Cost**	**by purchaser**
Bus	New Vehicle	**$/bus**	$ 2,500,000	100%	$ 408,000	100%	$ 384,000	100%
	Extended Warranty	**$/bus**	$ 10,000	100%	$ 8,505	100%	$ 8,100	100%
Facility	Depot & Fueling Conversion	**$**	$ 2,010,000	100%	$ 5,000	100%	$ 7,500	100%
	Equipment	$	$ 6,000	100%	$ 5,000	100%	$ 5,000	100%
Subsidies, Rebates and Other Incentives NOT accounted for above.								
	Annual *(Combined Value)*	$/yr						
	Lump Sum #1 *(Project year received and $-value)*	1						
	Lump Sum #2 *(Project year received and $-value)*	2						
O&M Costs								
Annual	Bus Maintenance	$/mile	$0.53		$0.18		$0.18	
	Facility Maintenance	$/mile	$0.20		$0.22		$0.22	
	Safety Training	hr/yr/bus	13.92		7.60		7.60	
	Learning Curve Cost Multiplier: Year 1		1.87		1.20		1.26	
	Learning Curve Cost Multiplier: Year 2		1.66		1.20		1.20	
Bus (Overha	Overhaul Interval	miles	400,000		400,000		500,000	
	Overhaul Cost per bus	$	$50,400		$24,000		$36,000	
Emissions *(when 100% of the fuel type)*								
	Carbon Monoxide	g/mile	0.00		2.93		1.77	
	Nitrogen Oxides	g/mile	0.00		0.20		0.61	

Instructions | INPUT Basic | INPUT Detail | OUTPUT | Graphs | Calculations | FuelEconomy | Defau

2.3 FuelCost2: Detailed Input and Data Considerations

Once users understand how to operate FuelCost2 and have selected which fuels/powertrain options they wish to compare, it is recommended that they update the data in the model themselves in order to obtain better comparisons than those provided by the default values. New data should reflect actual market or field data. High-quality data may be provided by vehicle supplier bids and fuel contracts, among other sources.

The "Input Detail" sheet displays specific data that may need updating, including site-specific costs associated with bus purchases, possible facility modifications, fuel availability and costs, operational characteristics, and more.

Assessing Data Quality and Relevance

The best estimates for a fuel/powertrain system's lifecycle costs, emissions, and reliability are from the assessment of multiple sources that track this data over a long period of time. Unfortunately, that means it is difficult to impossible to find good estimates for relatively new and evolving fuel/powertrain technologies that are used by a relatively small number of buses.

When reviewing data from other sources to enter into FuelCost2, users should consider the following to insure that their data are of the highest possible quality:

- **Number of Tests**—Clearly, the more tests done to collect data, the better. However, when "more" means that tests were conducted in many varied conditions, then it should be recognized that the summary data will only reflect the general average of these conditions, which may not be appropriate for the user's needs. For example, if there are two transit agencies—one agency's bus routes have slow speeds with starts and stops nearly every block, while the other agency's routes have high speeds along a highway with very few stops. In this case, a study that provides summary data as an average of both of these drive cycles would not be a good estimate for an agency that has routes similar to just one of the agencies from which the data were collected.
- **Time Span of Tests**—Many tests conducted within a short period of time provide an accurate snap-shot of that short period. However, conditions change over time with general wear and tear, expiration of warranties, etc. More confidence can therefore be placed in the general applicability of conclusions that come from studies conducted over a longer period of time.
- **Drive Cycle**—Some studies are highly controlled, such as those conducted over specific drive cycles using a dynamometer. A study like this might be very good at providing information related to one specific drive cycle, but not necessarily other drive cycles. Unless a user's agency runs its buses on a drive cycle similar to the one in the study, it is very likely that the agency's actual results will vary from those reported in the study.
- **Local Climate**—If a user's agency is located in a region with extreme temperatures, its experience may be quite different than the results that come from controlled tests in temperate environments. The importance of temperature effects varies from fuel to fuel. The fuel-specific chapters in this guide address the effects of temperature on fuels when relevant.
- **Make, Model, Year, and Aftermarket Changes**—Studies that cover many makes and models generally give results that are indicative of a general average. While this can be helpful early in the decision-making process, users will ultimately need to decide on specific makes and models. At

that time, users should refer to studies that focus more narrowly on buses similar to the makes and models under consideration. When reviewing studies, be sure to note any aftermarket changes that have been made to the buses—emission control additions are among the most common.

Engine versus Tailpipe Emissions: Standards and Data

U.S. Environmental Protection Agency (EPA) emission standards for light-duty vehicles are tailpipe standards expressed as grams per mile (g/mi). In contrast, EPA standards for heavy-duty vehicles are expressed as grams per brake-horsepower-hour (g/bhp-hr). This difference in units for light- and heavy-duty vehicle standards is due to the EPA's recognition that the wide variety of body styles and associated applications for heavy-duty engines has a significant effect on tailpipe emissions. Engine emission standards (versus vehicle emission standards) for heavy-duty vehicles prevent the need to conduct EPA emissions certification tests on every body style, many of which are highly customized to serve niche markets. However, after a vehicle has been assembled and is put into use, emissions are most commonly measured from the tailpipe in units of grams per mile (g/mi) regardless of engine size.

From a data use perspective, this means that when engine emissions data are the best (or only) data available for assessing expected emissions from a new vehicle, their units must be converted to g/mi to estimate vehicle lifecycle emissions. EPA has calculated conversion factors for gasoline and diesel engines for this purpose. The conversion factors are generally considered to be acceptable for all newer engines within a particular class (e.g., transit bus engines using the same fuel).[2] Appendix B provides more details on the conversion of engine emissions in g/bhp-hr to tailpipe emissions in g/mi.

2.4 Accounting for Risks

When changing fuels or adding a new fuel to a fleet, there are risks, just as there are risks with the currently-used fuel(s). For example, even if fuels are always available in the quantities needed, their prices may vary significantly over time, presenting a price risk. Many risks can be accounted for in a lifecycle analysis. Comparisons of lifecycle costs with and without accounting for risk reduction measures allow estimation of the economic value of a risk. It is then up to the decision-maker to decide if the reduction in risk is worth the cost. Some risk factors and means for incorporating them into lifecycle analyses are summarized herein.

- **New Technology Risks**—New technologies are more likely to have relatively poor estimates of reliability, maintenance labor needs, training needs, fuel-specific parts costs, and sometimes fuel availability and infrastructure costs. Risk factors associated with technology may be accounted for with performance-based service contracts in which the amount a contractor is paid depends on specified levels of performance.

- **Performance Risk**—Changing to another fuel inevitably has some risks in performance changes. The simplest way to take performance risk into account is to price in the cost of a performance warranty, either from the fuel/technology suppliers or an independent insurer.

- **Safety Risk**—Safety risks are a well understood concept at the first level of impact (death, injury, damage to property). But safety risks can have severe secondary impacts too. In the case of transit buses, the mere perception of a safety problem can ground a fleet and impose severe redesign and insurance costs. The simplest way to take safety risk into account is to compare full coverage insurance rates for the fuel or technology options.

- **Fuel Availability Risk**—This cost component may be determined by adding one or more of the following: cost of storage to address short-term interruptions, probability-adjusted cost of loss of service, cost of alternative stand-by sources of fuel and cost of fuel unavailability insurance.

Chapter 2 References

[1] Skone, T.J., and Gerdes, K. (November 2008). *Development of Baseline Data and Analysis of Life Cycle Greenhouse Gas Emissions of Petroleum-Based Fuels, Appendix J*. National Energy Technology Laboratory (DOE/NETL-2009/1346).

[2] U.S. Environmental Protection Agency, Air and Radiation (May 1998). *Update Heavy-Duty Engine Emission Conversion Factors for MOBILE6: Analysis of BSFCs and Calculation of Heavy-Duty Engine Emission Conversion Factors*. Retrieved from: http://www.epa.gov/otaq//models/mobile6/m6hde004.pdf

3.0 Diesel

Diesel fuel is the primary transit bus fuel, and it has an extensive national distribution network. The diesel-fuelled engine and aftertreatment system have recently undergone a significant amount of research and development to meet evolving emissions requirements. Diesel remains viable as a powertrain option for 2010 and beyond.

3.1 Fuel Description

Petroleum diesel is a "distillate" fuel that is refined from crude oil. There are various grades or types of distillates, but as of October 2006, the U.S. Environmental Protection Agency (EPA) required that 80% of on-highway diesel must meet ultra low sulfur diesel (ULSD) standards of no more than 15 parts per million (ppm) (or 0.0015%).

Diesel {**dee**-*zuh*l} noun –
A combustible petroleum distillate commonly used as fuel in both stationary and mobile compression-ignition engines.

By June 1, 2010, all on-road diesel fuel was required to meet ULSD standards. Table 3.1 presents some important diesel fuel characteristics.

Almost all diesel fuel sold today is produced by petroleum refining of crude oil. However, due to both environmental concerns and the expected eventual depletion of limited petroleum reserves, there has been growing interest in diesel fuels that are not from petroleum. Because different groups use different terms to describe these "alternative" diesels, particularly in older references, confusion and misunderstanding can occur.

Table 3.1 Diesel Fuel Properties

Property	Diesel
Boiling Temperature (°F)	356 to 644
Autoignition Temperature (°F)	600
Cloud Point (°F)	5 to 30
Cetane Number	40 to 55
Flash point (°F)	140 to 176
Flammability Limits (vapor in air by volume %)	1.0 to 6.0
Lower Heating Value (Btu/gal)	128,450
Relative Weight (by volume) Compared to air = 1 Compared to water = 1	 >3 *(as vapor)* 0.85
Soluble in water	No

In order to understand the distinctions between the various alternative diesels, it should first be understood that traditional, petroleum-based diesel is a mixture of chemicals. Most of the chemical compounds in petroleum diesel are straight chains of 10 to 15 carbons and associated hydrogen, but there are also some cyclic carbon compounds (referred to as "aromatics"), and some sulfur. Petroleum contains the chemical components of diesel fuel, in addition to many other groups of chemical compounds.

> **Key Point**
>
> Because diesel engine technology is mature, a significant amount of research and development has already gone into making it a viable and economical choice for transit applications.

As part of the refining process, distillation is used to separate diesel components from the many other groups of chemical compounds in petroleum. In order to meet today's emissions standards, additional processes are used to remove sulfur, and additives are used to replace the fuel lubricity that is lost when sulfur is reduced.

Alternative diesel forms are described herein and shown in Figure 3.1, but it is important to note that other sources may use these same terms differently:

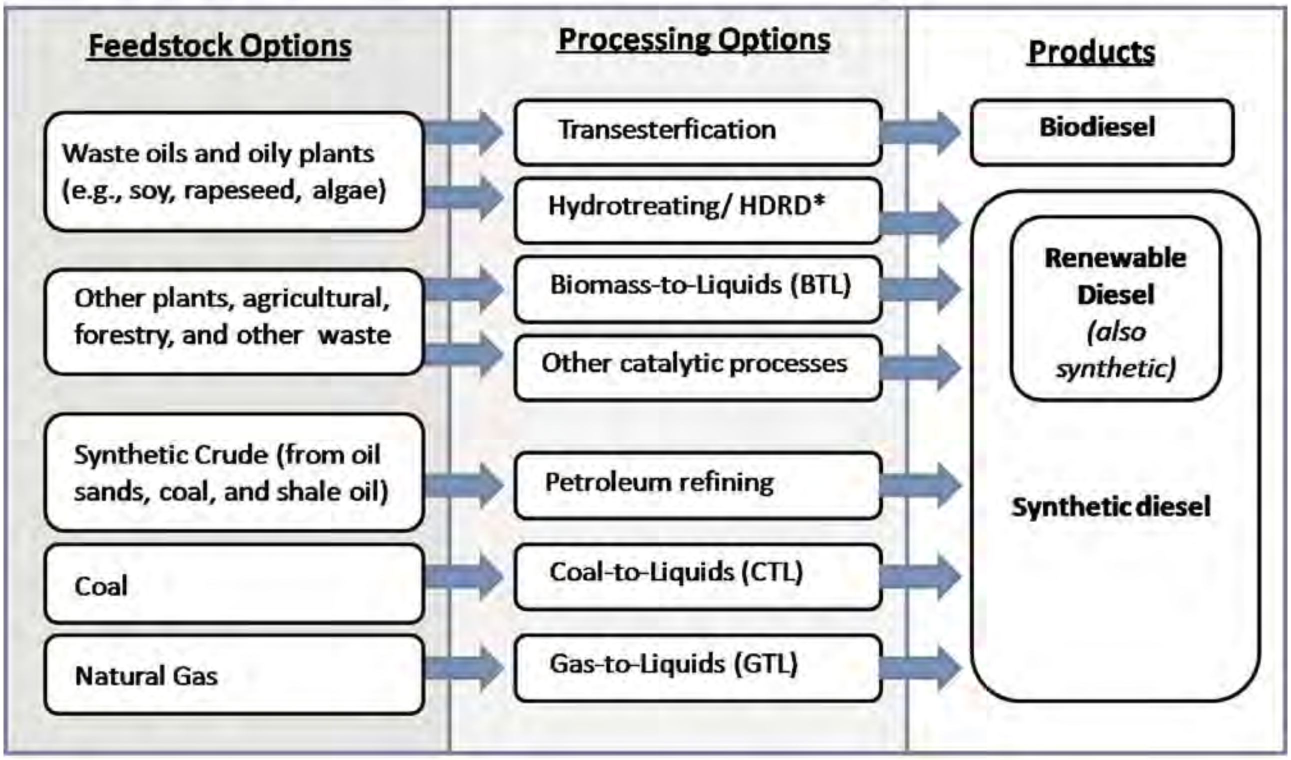
- **Synthetic Diesel**—These fuels are composed of chemical mixtures that are very similar to the chemical mixtures of petroleum diesel, but are not produced from petroleum feedstock. Synthetic diesel may be produced from either synthetic crude (which may be produced from coal, oil sands, or shale oil), or from coal, natural gas, or biomass through processes referred to as coal-to-liquids (CTL), gas-to-liquids (GTL), and biomass-to-liquids (BTL). These "xTL" processes break down the feedstock to simpler compounds (i.e., syngas—a mixture of carbon monoxide and hydrogen) in a step referred to as gasification. The gaseous products undergo the Fischer-Tropsch (FT) process, or a similar metal-catalyst process, to build paraffin waxes that contain much longer carbon chains than diesel. These long chains are then broken up through the process of hydrocracking to produce the final fuel. The FT fuels have fewer aromatics and sulfur than petroleum-based diesel. Synthetic diesels, whether FT fuels or fuels refined from synthetic crude, are designed to meet the American Society for Testing and Materials (ASTM) standard for Diesel Fuel No. 2 (ASTM D975). These fuels are generally in the research and demonstration phases of development. GTL may be considered to be in the early commercialization phase, somewhat beyond the demonstration phase, but not yet a mature technology.

> **The Fischer-Tropsch Process** is a catalyzed chemical reaction in which synthesis gas (syngas) is converted into liquid hydrocarbons of various forms.

- **Renewable Diesel**—These fuels are composed of chemical mixtures that are very similar to the chemical mixtures of petroleum diesel, but they are produced from renewable feedstocks, which include plants, animal products, and waste. Renewable diesel may be produced by a variety of methods, including BTL, hydrotreating (in a process distinct from the BTL process), or other catalyst-based processes that use renewable feedstock. Renewable diesels are able to meet ASTM standard for Diesel Fuel No. 2 (ASTM D975), and are in the research and demonstration phases of development.

- **Biodiesel**—The feedstocks used for biodiesel are from renewable sources (e.g., soybeans and other plants with high oil content), but the chemical mixtures that compose biodiesel are esters that are distinct from petroleum diesel. There is a separate ASTM standard (ASTM 6751) for biodiesel that is used for blending with petroleum diesel. The diesel fuels of today often include up to 5% biodiesel as an additive to increase lubricity. With this low level of biodiesel, these fuels meet the ASTM diesel standard, but fuel blends with more biodiesel do not. Another ASTM standard, ASTM 7467, is for fuel blends containing 6 to 20% biodiesel. Biodiesel is typically formed using the process of transesterification, which employs a relatively mature technology. Biodiesel is addressed in a separate chapter of this guidebook.

Figure 3.1 The Many Paths to Alternative Diesel Fuels



*HDRD = hydrogenation-derived renewable diesel

Synthetic fuels can be viewed as "designer" fuels that have ideal properties for diesel engines, including high cetane ratings, low aromatics, and negligible sulfur content, all of which may reduce diesel engine emissions. Despite the attractive characteristics of these fuels, the higher capital costs and the market risks due to crude oil price fluctuations present substantial barriers for their wider commercialization.

3.2 Fuel Usage

Diesel is the most common transit bus fuel, and therefore is the baseline for comparisons of alternative fuels and alternative powertrains (e.g. hybrid-electric). The FTA estimates that in 2007 there were 46,271 diesel buses in the United States that are 30 ft or longer (Table 3.2).[1] Diesel buses remain the most popular choice among transit agencies, as shown in Table 3.3, which lists new buses built between 2005 and 2007.[2]

Table 3.2 Diesel Transit Bus Inventory Summary

Bus Length (ft)	Number	Percentage
30 to 35	4,286	9.3
36 to 39	5,497	11.9
40 to 44	30,734	66.4
45	2,886	6.2
60	2,868	6.2
Total	46,271	100.0

Table 3.3 New Bus Builds by Year[2]

	Numbers Built by Year		
Bus Fuel Type	2005	2006	2007
Diesel	1,819	1,701	1,257
CNG	638	255	366
Other	538	582	895
Total	2,995	2,538	2,518

Diesel engine technology used in transit buses has been evolving rapidly since the mid-1990s. This has occurred in response to the following three driving influences:

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

Transit bus weight has increased since the early 1990s as features such as wheelchair lifts and air conditioning have become standard equipment. Chassis and suspension components were required to be more robust in design to retain the same levels of durability while supporting the weight of this equipment. Air conditioning also represents a large accessory power load on the engine. To maintain adequate performance of heavier vehicles equipped with air conditioning, engine ratings increased from 180 bhp (typical of 1980s-era two-stroke engines) to ratings between 230 bhp and 250 bhp in the mid-1980s. The combined effects of increased vehicle weight, air-conditioning, and higher engine ratings led to increased fuel consumption compared to the early 1980s at most transit agencies. Subsequent technology developments of turbocharged, intercooled, and high-pressure electronically controlled fuel injection engines have worked to reverse this trend.

Fuel cost is a major contributor to the expense of operating a transit bus fleet. Diesel baseline fuel consumption can vary widely depending on several factors:

- Presence, or absence, of air-conditioning;
- Engine horsepower rating;
- Duty cycle, e.g., urban (stop-start, low average speed), express service (infrequent stops, high average speed), and suburban (in between urban and express) cycles;
- Curb weight and representative passenger loadings; and
- Engine aftertreatment systems used to meet emissions regulations (discussed below).

These factors should be considered when fuel economy data from other agencies are used to predict fuel needs and costs.

Is It Imported?

In 2008, two-thirds of the crude oil used by U.S. refineries to make petroleum diesel came from other countries. In addition to this, 4% of the petroleum diesel used in the U.S. was imported as a finished fuel, mostly from Canada and the Virgin Islands.

3.3 Safety, Training, and Disposal

Since diesel-fueled buses are the most commonly used transit buses, their safety, training, and disposal requirements are well known to most fleet operators. Safety, training, and disposal needs are briefly summarized below.

Safety

As the predominant transit bus fuel, diesel fuel is generally well understood by most transit fleet operators. Diesel fuel's high flash point (between 145°F and 176°F) and correspondingly low volatility make it a very safe fuel, so fires resulting from fuel spills are generally of low concern.

Diesel must be stored and handled in proper containers, as it can be corrosive to some materials. It should also be stored and handled in well-ventilated areas because the vapors are harmful to humans. Contact with the eyes and skin should also be avoided, as irritation can occur.

Some of the relevant fire codes, guidelines, and standards that are available from the National Fire Protection Association (NFPA) and other organizations related to diesel storage, fueling, and vehicle safety are listed in Table 3.4.

Training

Maintenance and fueling staff should be trained to understand diesel fuel properties to ensure that safe handling practices are followed, and proper clean-up methods are used in the event of a release.

Table 3.4 Selected Codes, Standards, and Guidelines for Diesel Vehicles and Infrastructure

Standard	Description
NFPA 88A – Standard for Parking Structures, 1998	Covers open, enclosed, basement, and underground parking structures.
NFPA 30A – Code for Motor Fuel Dispensing Facilities and Repair Garages, 2003	Covers facilities dispensing both gaseous and liquid fuels at the same facility.
NFPA 1 – Uniform Fire Code, 2009	This provides a primary basis for local fire codes.

Disposal

Diesel fuel is toxic to soil, water, and plant/animal life, and degrades slowly when released to the environment. Leakage from underground diesel and gasoline storage tanks is considered by the U.S. EPA to be a major source of soil and groundwater pollution.[3] The minimum volume of spilled diesel that requires reporting and clean-up is determined at the state level, and may depend on how the land or water is used (e.g., in an industrial area or residential area).[4] An example of standard operating procedures for diesel spills at municipal operations in Boulder, Colorado, is available online at http://www.bouldercolorado.gov/www/pace/government/documents/FuelingandFuelSpillCleanupSOP.pdf. In the Colorado example, spills of more than 25 gallons or spills that cause a sheen on nearby surface water are to be reported to state authorities. In general, when in doubt, it is better to report a spill than to risk sizable fines for not reporting.

When diesel is disposed, it can be characterized as a hazardous waste due to both its ignitability and benzene content.[5] Diesel-saturated sorbents used in spill clean-up are often exempt from state Hazardous Waste Rules under certain conditions (e.g., spill size, timely reporting, immediate clean-up). The appropriate state authorities should be contacted for guidance. For disposal of fuel containers, the container contents should be completely emptied prior to discard, and large empty containers should be returned to the distributor.

3.4 Technology and Performance

Diesel fuel is combusted in compression-ignition engines, which are common in the transit industry. Diesel engines are known for their fuel economy, power, torque, and reliability. Major technological changes have been made recently in heavy-duty diesel vehicles, due to the 2007 and 2010 emissions standards, which required new emissions control technologies. These technologies are briefly described herein, followed by a summary of fuel economy.

Diesel Particulate Filters

Diesel particulate filters (DPFs) physically filter engine exhaust to capture part of the particulate matter (PM), essentially removing the visible portion of diesel exhaust (i.e., soot). DPFs are used along with oxidation catalysts, which react with PM portions that pass through the DPF. DPFs have been commercialized for the light-, medium-, and heavy-duty vehicle markets, and typically reduce PM emissions by over 90%.

There are several DPF technologies that offer different types of filter materials and different means of removing soot accumulations from the filter. As the amount of soot captured by the filter increases, backpressure increases, and this in turn reduces engine performance and efficiency. For this reason, DPFs must be periodically regenerated. When exhaust temperature is high enough, filter accumulations are burned off. A precious metal catalyst is used to reduce the temperatures needed for soot removal. Because sulfur degrades these catalysts, DPF life is significantly extended with the use of ULSD. Active DPF regeneration is used when the exhaust temperature is too low for passive regeneration. For heavy-duty vehicles, this usually involves raising the temperature through burning extra fuel as determined by the onboard computer.

Exhaust Gas Recirculation

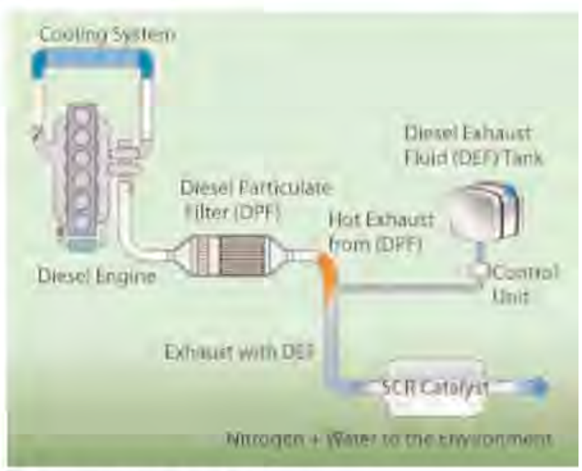
Exhaust gas recirculation (EGR) has been a standard method for reducing NOx formation in spark-ignition engines for over 25 years, and has been more recently applied to heavy-duty diesel engines. EGR involves the addition of exhaust gases (mainly inert nitrogen, CO_2, and water vapor) into the engine intake air. Most current diesel engines operate with "cooled" EGR systems, which reduce EGR temperatures before addition to the intake manifold. This lowers combustion temperatures, oxygen, and associated NOx formation, while allowing a higher density and amount of EGR to be added. Diesel engines operate at leaner fuel-air ratios than spark-ignition engines, and their exhaust contains more oxygen and less CO_2 and water vapor. As a result, diesel engines must circulate higher proportions of exhaust gases in the intake air. Advanced versions of cooled EGR systems employ a dual stage (high- and low-pressure) EGR loop to optimize engine and emissions performance.

Selective Catalytic Reduction

Selective catalytic reduction (SCR) has been used to reduce NOx from large stationary diesel engines for more than a decade, and has been used on trucks in Europe since 2004. SCR uses a mixture of urea and water. This mixture is known by the trade name AdBlue in Europe, and as Diesel Exhaust Fluid (DEF) in the U.S. In the SCR process, the DEF is injected into the exhaust stream where it forms ammonia (NH_3) and CO_2. The ammonia then reacts with NOx to form nitrogen gas and water vapor.

An SCR system includes a DEF storage tank, injection nozzles, a catalyst chamber for reaction with NOx, and a downstream catalyst to oxidize any remaining ammonia. The storage tank and lines to the catalyst chamber are

Figure 3.2 Diagram of an Emissions Control System with SCR



Source: www.truckscr.com

heated because the water-diluted urea freezes at 12 °F. SCR systems can reduce NOx by 75 to 90%. [6] An emissions control system with SCR is shown in Figure 3.2.

SCR has become the preferred method for lowering NOx emissions by heavy-duty engine manufacturers, and an infrastructure for distributing and supplying DEF is rapidly developing. The Department of Energy's Alternative Fuels and Advanced Vehicles Data Center provides a DEF retail locator online tool as part of its Alternative Fuel Station Locator (http://www.afdc.energy.gov/afdc/locator/def/).

Fuel Economy

Regardless of the fuel or powertrain, fuel economy depends on many factors, such as the number of stops per mile, the average route speed, the route topography (hills vs. flat), etc. For this reason, the best studies of fuel economy are based on comparisons within a particular fleet. Full-size transit bus fuel economy reported in the literature in recent years (2000 and later) has generally been around 3 mpg,[7] and this is the diesel bus fuel economy used as a reference throughout this guide.

Both Cummins and Detroit Diesel have MY2010 diesel engines that use SCR, in addition to DPF and high-pressure, common rail fuel delivery systems. While slight reductions in fuel economy are expected due to the additional weight and other demands of these systems, early testing of MY2010 vehicles suggests that at least some MY2010 buses may have fuel economy improvements of 2% to 5%.[8]

3.5 Maintenance, Reliability, and Storage

Because diesel-fueled buses are the most common type in use by the transit industry, their maintenance, reliability, and storage requirements are well known to most fleet operators. Additional requirements have been brought about by the second, and final, stage of the 2007/2010 EPA emissions regulations. It is important for fleet operators to understand the impact of these new requirements.

Maintenance

The required maintenance of 2010-compliant diesel buses is expected to be only slightly more involved than the current maintenance of diesel buses. The additional maintenance is due to the need to periodically refill the urea tank of the SCR system. Technicians must be trained to understand the maintenance changes required by the new systems on 2010-compliant diesel buses. They must also be trained on the procedures for safely working on these engines.

Reliability

The reliability of the heavy-duty diesel engine is one of its key attributes. 2010-compliant engines overall should be as reliable as current engines, even though there are additional systems with added complexity.

Storage

Because diesel is the most common transit bus fuel, most transit agencies are familiar with the storage requirements. There are many codes and regulations that govern the design of diesel bus storage, maintenance facilities, fuel storage, and fuel dispensing. Some are listed above in Section 3.3, but a review of local regulations is recommended, as they can differ by state and city.

3.6 Emissions

Emissions are addressed in the following two sub-sections. The first discusses local and regional pollutants that are currently regulated under the Clean Air Act (i.e., hydrocarbons (HC), nitrogen oxides (NOx), particulate matter (PM), non-methane hydrocarbons (NMHC), and carbon monoxide (CO)). The second section discusses pollutants that contribute to global warming (i.e., greenhouse gases (GHG)).

Regulated Pollutants

In 2007, federal emissions standards for heavy-duty, on-road engines became more stringent for PM, NOx, and NMHC. In the prior year, ULSD, with maximum sulfur levels of 15 ppm, was phased in to enable long lifetimes of the DPF needed to meet the 2007 standards for PM.

The 2007 emission standards were planned to be implemented in two phases. The first phase went into effect in 2007 and required manufacturers to fully meet the new PM requirements. Between 2007 and 2010, manufacturers were allowed two choices on how the NOx standard would be phased in, but by 2010, the new NOx standard of 0.2 g/bhp-hr had to be fully met. Table 3.5 presents a summary of the recent progression of heavy-duty diesel engine emission standards.

Table 3.5 Recent Federal Emission Standards for Heavy-Duty Diesel Engines

	Pollutant (g/bhp-hr)					
Model Years	HC	NMHC	CO	NOx	HC+NOx	PM
1996-2003	1.3	---	15.5	4.0	---	0.05
2004-2006	1.3	n/a	15.5	---	2.4 (Option 1)	0.05
	1.3	0.5	15.5	---	2.5 (Option 2)	0.05
2007 (Phase I Implementation 2007-2009)	1.3	0.14	15.5	0.2 (50% of vehicles)/ 2.5 (50% of vehicles) (Option 1)	---	0.01
	1.3	0.14	15.5	1.2 - 1.5 (Option 2*)	---	0.01
2010-on (Phase II Implementation)	1.3	0.14	15.5	0.20	---	0.01

*Most engine manufacturers elected for Option 2, which required that engines meet the Family Emission Limit (FEL) averages.

There is only a small amount of available literature that includes emissions measurements from MY2010 buses at the time that this report was written. This is a significant consideration for comparisons of emissions differences between new diesel buses and other fuel types since engines were required to meet more stringent emissions regulations beginning in 2010. For preliminary analysis purposes, U.S. EPA certification data for MY2010 on-road engines with power ratings of 300 to 350 horsepower are shown in Table 3.6. The values shown are the average certification test emissions as converted to grams/mile based on EPA conversion factors and are the values used as default emissions values for diesel engine emission in the accompanying FuelCost2 model. These estimates should be updated as more emission measurements are reported for 2010 buses.

Table 3.6 Diesel Engine Emissions: EPA MY2010 Certification Tests *

	g/bhp-h	g/mile
Carbon Monoxide	0.0	0.0
Nitrogen Oxides	0.14	0.65
Particulate Matter	0.0	0.0
Non-Methane Hydrocarbons	<0.01	0.01

*Emissions estimates based on EPA certification test data for MY2010 highway engines between 300 and 350 horsepower available at http://www.epa.gov/oms/crttst.htm. Units of g/bhp-h are converted to g/mile using the EPA conversion factor of 4.679 bhp-h/mi for diesel.[9]

Greenhouse Gases

Conventional diesel buses are the comparison benchmark for most transit agencies. For this reason, the lifecycle GHG emissions associated with all other transit bus fuel options are compared to diesel buses. GHG is primarily a function of the amount of fuel that is consumed. Therefore, the GHG performance will depend on the fuel economy performance of 2010-compliant engines. As mentioned earlier, testing data from production-state 2010 compliant engines are very limited at this time, but anecdotal reports suggest that any changes in fuel economy amount to no more than a small percentage.[10] For the purposes of the FuelCost2 model that accompanies this guidebook, the GHG emissions associated with MY2010 diesel buses will be assumed to be the same as for previous model years, thus retaining previous reports of the relative comparisons of GHG and other fuel types.

With respect to alternative diesel fuels, it should be noted that FT fuels produced from fossil fuels do not provide a clear GHG benefit relative to petroleum diesel unless the FT feedstock is natural gas that would have been flared anyway. In contrast, lifecycle assessments of BTL compared with conventional diesel fuel suggest that on a well-to-wheels basis, GHG emissions may be reduced by as much as 80% or 90%.[11]

3.7 Cost and Availability

Vehicle Capital Costs

Diesel-fueled buses are the primary transit buses in the United States, and have an extensive national sales, distribution, and service network. The cost of a diesel bus is the baseline cost for comparison of all other technologies. The price for a typical full-size diesel transit bus is roughly $350,000.[12]

Vehicle Operating Costs

A review of maintenance costs for diesel buses was included in the West Virginia University Assessment of Hybrid-Electric Transit Bus Technology for a lifecycle costing model. Costs for several fleets were determined. As shown in Table 3.7, the values were separated into scheduled and unscheduled maintenance; propulsion and braking system maintenance costs are also listed separately.

Guidebook for Evaluating Fuel Choices for Post-2010 Transit Bus Procurements 3-11

Table 3.7 Summary of Diesel Bus Maintenance Costs

Maintenance Category	Low ($/mile)	Mid ($/mile)	High ($/mile)
Scheduled	0.15	0.21	0.27
Unscheduled	0.32	0.38	0.45
Total	0.47	0.59	0.72
Propulsion Portion	0.13	0.16	0.19
Brake Portion	0.04	0.07	0.16

Table 3.8 presents a summary of the major diesel bus capital and operations costs that are used as default cost values in the FuelCost2 model that accompanies this guidebook.

Table 3.8 Diesel Cost Estimates

Item	Diesel
New Vehicle ($)	350,000
Facility Conversion ($/ 50 Buses)	N/A
Fuel ($/gal) [a]	2.51
Fuel Economy (mpg) [b]	3.2
Propulsion System Maintenance ($/mile) [b]	0.16
Facility Maintenance and Operation ($/mile) [c]	0.18

a. Based on Clean Cities Alternative Fuel Price Report, average retail price (including taxes) in 2009.[13]

b. Clark, N., Zhen, F. and Wayne, W. S., et al. (December 2009). *TCRP Report 132: Assessment of Hybrid-Electric Transit Bus Technology*. Transportation Research Board, Washington, D.C. Fuel economy assumes 40-ft bus with average speed of 13 mph and 3 months per year hotel load.

c. Fleet survey conducted for TCRP Project C-19, September 2009.

3.8 Summary

Diesel

Pros	Cons
Because diesel engine technology is mature, a significant amount of research and development has already gone into making it viable and economical for transit applications.	Diesel engines are affected by increasingly strict federal emissions standards for transit buses, which began implementation in heavy-duty, on-road engines in 2007.
Diesel fuel can be synthetically produced from various carbon-bearing feedstocks such as renewable fuel feedstocks and natural gas.	The most common diesel fuel is produced by refining crude oil, a resource that is associated with economic and environmental concerns.
As the predominant transit bus fuel, diesel fuel is generally well understood by most transit fleet operators.	Specific details regarding differences in the initial cost and operating cost (mainly fuel economy) between pre-2010 and 2010 compliant engines are not yet known.
Robust emissions reduction strategies will allow diesel engines to meet the 2010 EPA emissions standards.	Specific details regarding the emissions system cost and performance impacts of 2010 compliant engines are not yet known.

Diesel References

[1] U.S. Department of Transportation, Federal Transit Administration (2007). *2007 National Transit Database*. Retrieved from: http://www.ntdprogram.gov/ntdprogram/data.htm.

[2] American Public Transportation Association (May 2007). *Public Transportation Fact Book, 58th Edition*.

[3] U.S. Environmental Protection Agency (December 2008). Don't Let Those Tanks Leak: EPA Enforces Underground Storage Tank Requirements. *Enforcement Alert*, Volume 10, Number 1. Retrieved from http://www.epa.gov/compliance/resources/newsletters/civil/enfalert/ust.pdf

[4] Oklahoma Department of Environmental Quality (May 2010). *Land Diesel and Gasoline Spills Fact Sheet*. Retrieved from http://www.deq.state.ok.us/factsheets/land/Dieselspill.pdf.

[5] Phillips Petroleum Company, (2002). *MSDS Summary Sheet: No. 2 Diesel Fuel*. Retrieved from http://www.petrocard.com/Products/MSDS-ULS.pdf .

[6] Alternative Fuels and Advanced Vehicles Data Center (October 22, 2009). *Diesel Selective Catalytic Reduction*. Energy Efficiency and Renewable Energy, U.S. Department of Energy. Retrieved from: http://www.afdc.energy.gov/afdc/vehicles/diesels_catalytic.html

[7] Clark, N., Zhen, F. and Wayne, W. S. (December 2009). *TCRP Report 132: Assessment of Hybrid-Electric Transit Bus Technology*. Transportation Research Board of the National Academies, Washington, D.C.

[8] Birkland, C. (August 2009). 2010 Engine Test Fleets Weigh In: Fleet Managers Talk About Their Experiences Testing 2010 Diesel Engines. *Fleet Equipment Magazine*. Retrieved from http://www.fleetequipmentmag.com/Item/65899/2010_engine_test_fleets_weigh_in.aspx

[9] U.S. Environmental Protection Agency (May 1998). *Update Heavy-Duty Engine Emission Conversion Factors for MOBILE6: Analysis of BSFCs and Calculation of Heavy-Duty Engine Emission Conversion Factors*. EPA420-P-98-015. Retrieved from: http://www.epa.gov/oms/models/mobile6/m6hde004.pdf

[10] Birkland, C. (August 2009). 2010 engine test fleets weigh in: fleet managers talk about their experiences testing 2010 diesel engines. *Fleet Equipment Magazine*. Retrieved from http://www.fleetequipmentmag.com/Item/65899/2010_engine_test_fleets_weigh_in.aspx

[11] Nicholls, T. (July 2006). BTL: The Next Step on from GTL. *Petroleum Economist.*

[12] Fleet survey conducted for TCRP Project C-19, September 2009.

[13] U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy (2009). *Clean Cities Alternative Fuel Price Report*, 2009 quarterly reports. Retrieved from: http://www.afdc.energy.gov/afdc/price_report.html

4.0 Biodiesel

Biodiesel is a domestically produced, renewable fuel produced from a wide range of vegetable oils, animal fats, and recycled restaurant greases. Either in its pure state or blended with petroleum diesel, it can be used to fuel diesel vehicles.

Biodiesel can be blended with petroleum diesel at any percentage. In labeling abbreviations, the number after the "B" indicates the percentage of biodiesel in the blend; hence B100 is pure biodiesel, B20 is 20% biodiesel and 80% diesel, and so on. Under the Energy Policy Act (EPAct), blends with 20% or more biodiesel qualify for alternative fuel credits, and federal fleets receive one credit for every 450 gallons of biodiesel used in biodiesel blends. Thus, 2,250 gallons of B20 is eligible for one credit.

B20 (20% biodiesel and 80% petroleum diesel) is the most commonly used biodiesel blend in the United States. Using B20 provides some of the benefits of biodiesel but avoids many of the cold-weather performance and material compatibility concerns associated with B100. Blends between B20 and B100 can be ordered, but are less common.

In this discussion, biodiesel and diesel are defined based on the American Society for Testing and Materials (ASTM) definitions. Specifications for biodiesel fuel blends between B6 and B20 are defined by ASTM 7467, and B100 for use by blenders is defined by ASTM 6751. Diesel for compression-ignition engines, diesel fuel No. 2, is defined by ASTM Standard D975. Ultra Low Sulfur Diesel (ULSD) is a sub-category of diesel fuel No. 2 within ASTM D975. It contains 15 ppm sulfur or less, and has fuel additives to increase the lubricity lost with sulfur removal. As much as 5% biodiesel may be blended with diesel to increase lubricity and still meet ASTM D975 diesel fuel standards. In contrast, this discussion focuses on fuel blends with at least 20% biodiesel, which do not meet diesel standards (i.e., ASTM D975).

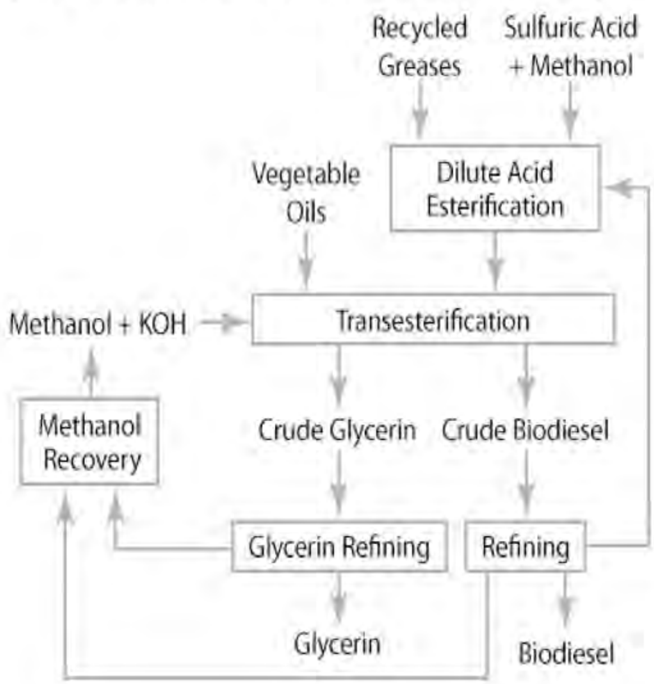
Renewable Diesel and Biodiesel Distinctions: Biodiesel meets different ASTM standards than renewable diesels. Renewable diesel refers to diesel-like fuels produced from biomass (i.e., plant material or animal waste). Renewable diesel commonly refers to fuels with chemical properties that are *closer to petroleum-based diesel than to biodiesel*. The Federal Trade Commission (FTC) requires **separate labels for ASTM-biodiesel blends and other biomass-based diesels** (i.e., renewable diesel). Limited market introduction of other biomass diesels began around 2008. These fuels have not been tested as extensively as biodiesel.

4.1 Fuel Description

Biodiesel is a renewable fuel that contains no sulfur or aromatics. As defined by ASTM, biodiesel is composed of mono-alkyl esters of long chain fatty acids derived from vegetable oils or animal fats (ASTM D6751). In some reports, this fuel is referred to as FAME (fatty acid methyl ester). Biodiesel may be used alone (i.e., B100), or blended with petroleum diesel. Fuels marketed for end-use as B100 may include a small portion of fuel additives; when additives comprise as much as 1% of the fuel by volume, the fuel is labeled B99.

Biodiesel,{ bī-ō-dē-zəl } noun—
a fuel composed of mono-alkyl esters of long chain fatty acids derived from vegetable oils or animal fats.

Figure 4.1 A Common Biodiesel Production Pathway



Currently, biodiesel is typically produced as a result of the process of transesterification, in which fats and oils are chemically reacted with alcohol (commonly methanol) in the presence of a catalyst that is a strong base (e.g., sodium or potassium hydroxide).[1, 2] The diagram in Figure 4.1 shows a typical pathway for biodiesel production. A variety of different vegetable oils may be used. Soybean oil is most common in the United States, while rapeseed oil is most commonly used in Europe. Alternatively, animal fats may be used, as well as waste cooking oils and trap grease from restaurants (i.e., yellow grease). There are subtle differences in the biodiesel end-product based on the type of fat or oil, as well as alcohol used in production. These production differences may result in subtle differences in engine performance and emissions.[3]

Pure biodiesel (i.e., with no additives) produced via transesterification contains 11% oxygen by weight, in contrast to 0% oxygen in diesel. As a practical matter, the presence of oxygen in the fuel facilitates a more complete burn, resulting in engine emissions reductions of hydrocarbons (HC), toxic compounds, carbon monoxide (CO), and particulate matter (PM). However, the oxygen content contributes to a lower energy content of biodiesel compared to diesel, which means fuel economy may be slightly reduced.

Table 4.1 shows some of the key properties of biodiesel and diesel without fuel additives. The greater temperature range shown for some diesel properties reflects the wider range of chemical compounds that are present in diesel.

Table 4.1 Biodiesel (B100) and Diesel Fuel Properties*

Property	B100	Diesel
Boiling Temperature ($^{\circ}$F)	599 to 662	356 to 644
Autoignition Temperature ($^{\circ}$F)	N/A	600
Cloud Point ($^{\circ}$F)	27 to 54	5 to 30
Cetane Number	48 to 65	40 to 55
Octane Number (R+M)/2	NA	N/A
Flash point ($^{\circ}$F)	≥ 212	≥ 140
Flammability Limits (vapor in air by volume %)	None known	1 to 6
Lower Heating Value (Btu/gal)	119,550	128,450
Relative Weight (same volume) Compared to water = 1	0.88	0.85
Soluble in water	No	No

* Based on corn feedstock with transesterification production process.

So-called second-generation renewable fuel production methods are in the early stages of introduction. One of these is hydrogenation-derived renewable diesel (HDRD), which is produced in a refinery from vegetable oils or animal fats. The oils and fats undergo a hydrotreating process in which they react with hydrogen in the presence of a catalyst.[4, 5] The resulting product has less oxygen and higher energy content than biodiesel produced by the transesterification process. Because it lacks the mono-alkyl esters found in biodiesel, it is not technically "biodiesel." Under FTC labeling requirements, HDRD should be labeled as "biomass diesel" rather than as "biodiesel." FTC biodiesel and biomass-based diesel pump labeling requirements became effective in December 2008. A summary of these requirements with further references is available in a National Biodiesel Board issue brief available at: http://www.biodiesel.org/resources/PR_supporting_docs/20080811_Final%20-%20Issue%20Brief-FTC%20Ruling%20_August11_.pdf.

Another second-generation production method, referred to as biomass-to-liquids (BTL), converts biological material from living or recently living plants and animals into hydrogen and carbon monoxide, and then applies the Fischer-Tropsch process to yield liquid fuels.

The Fischer-Tropsch Process is a catalyzed chemical reaction in which syngas (i.e., carbon monoxide and hydrogen) is converted to liquid hydrocarbons of various forms.

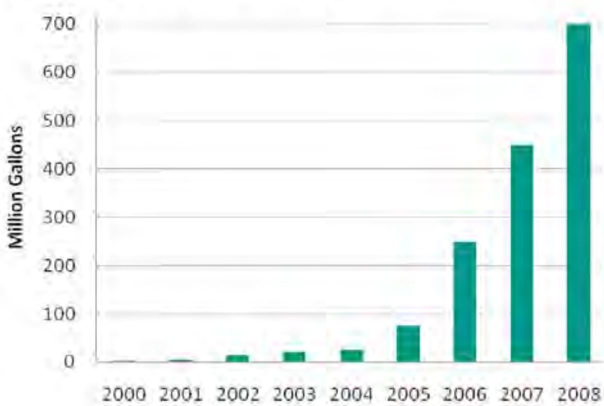
The BTL process yields a diesel-like fuel with no oxygen. Its energy content is higher than that of biodiesel or other biomass diesels, but still slightly lower than petroleum-based diesel.[6] Under FTC labeling requirements, BTL-produced diesel is a "biomass diesel" rather than biodiesel.

4.2 Fuel Usage

There is no explicit tracking of the number of fleets or vehicles that use biodiesel for either public or private transit. The National Biodiesel Board has estimated that there are over 500 fleets of various types using B20. B20, and to a lesser extent, B99 and B100, are offered at several hundred truck stops located throughout the country.[7] Fleets operating on B20 are primarily government motor fleets, urban bus fleets, and school buses. B100 use is substantially lower than B20 use—B100 has been more of a niche market fuel, with use in mining, power generation, garbage truck fleets,[8] and agricultural equipment.[9] Minneapolis Metro Transit runs on B20 from May to October, and has worked with Cummins to gain full warranty coverage with use of B20. During the cold Minnesota winters, Metro Transit has used B10 to reduce chances of cold-operation issues, and has installed fuel filter heaters. Other transit bus fleets that use biodiesel blends include those in Cincinnati, Ohio; St. Louis, Missouri; Cedar Rapids, Iowa; and Seattle, Washington.

Although the number of fleets and vehicles using biodiesel is not well tracked, the production volume of biodiesel is very carefully tracked for tax and incentive purposes. Like diesel, biodiesel is generally sold to end-users within a few months of production, so trends in production volume can indicate trends in biodiesel use.

Figure 4.2 U.S. Biodiesel Production



U.S. biodiesel production remained very small and flat until establishment of a USDA program that provided cash payments to biodiesel producers from 2000 through 2005. Largely as a result of the USDA program, biodiesel production jumped from 500,000 gallons in 1999 to 75 million gallons in 2005. High diesel prices and new tax incentives have enabled further increases in biodiesel production. In 2008, biodiesel production was around 700 million gallons, as shown in Figure 4.2.[10]

Increased demand for biodiesel has been as a result of being used as both an alternative fuel for use in B20, B99, and B100, and as a fuel additive. Biodiesel use as a fuel additive increased greatly in 2006 as a result of a new requirement for use of diesel with a low sulfur content (i.e., ultra low sulfur diesel, ULSD)—a biodiesel additive replaces the lubricity lost due to sulfur reductions. The requirement was necessary because sulfur harms tailpipe particle traps, which are installed on MY2007 and later diesel vehicles to help them meet more stringent emissions standards.

Is It Imported?

Biodiesel used for blending is 100% domestic. When petroleum diesel is blended with biodiesel, the final fuel has multiple origins. In 2008, two-thirds of the crude oil used by U.S. refineries to make petroleum diesel came from other countries. In addition to this, 4% of petroleum diesel used in the United States was imported as a finished fuel, mostly from Canada and the Virgin Islands.

4.3 Safety, Training, and Disposal

Handling

Biodiesel is non-toxic, more biodegradable, and much less irritating to the skin than petroleum diesel, but it is still recommended that the standard handling procedures used for petroleum diesel be applied to biodiesel. These procedures should include wearing eye protection and provision of adequate ventilation.

Flammability and Toxicity

The flash point of biodiesel is over 100 degrees higher (Fahrenheit) than common ambient temperatures (see Table 4.1). This means that the air-to-fuel ratio above a pool of biodiesel is too low to be ignited, and fuel flammability is not generally a concern. In fact, the flash point for diesel is lower than for biodiesel, which means that of the two, biodiesel is more difficult to ignite. Biodiesel is also less toxic than diesel, both as liquid fuel, and as exhaust from combustion. Biodiesel can also be more readily degraded than diesel when released into the environment.

Training

There are no unique training needs for drivers using B20, but drivers should be aware of possible changes in performance and fuel economy. Maintenance personnel should be knowledgeable on B20 fuel issues, including cold flow properties and associated solutions (e.g., block or fuel filter heater installations). When working with B100, further training should address differences in solvent properties, materials compatibility, and emissions.

U.S. Department of Transportation's Transportation Safety Institute (TSI) offers training courses specifically for transit agencies. Their 2011 course listings include "Safety Evaluations for Alternative Fuels Facilities and Equipment." This 3-day course provides "awareness and training in conducting safety evaluations for alternative-fueled vehicles, support equipment, and facilities using Compressed Natural Gas (CNG), Liquefied Natural Gas (LNG), hydrogen, fuel cells, propane, ethanol, electricity, bio-diesel, and hybrid electric." Classes are scheduled on an as-needed basis. Those interested should contact TSI.

Disposal

Biodiesel is usually blended with diesel, which generally poses greater disposal concerns than biodiesel. Thus, following conventional fuel disposal and spill clean-up procedures is a conservative approach. Waste disposal rules are set at the state level, and may vary from state to state. The appropriate state authorities should be contacted for further guidance.

4.4 Technology and Performance

As a result of the substantial similarities in the properties of biodiesel and diesel fuels, biodiesel can be used as a drop-in fuel in new diesel systems, with no modification needed in warmer climates. However, older diesel systems may require some materials replacements prior to using higher biodiesel blends.

The energy content of B100 is 6% to 8% less than diesel on a per volume basis, with plant-based biodiesel having slightly higher energy content than animal-based biodiesel. Reduced energy content causes lower fuel economy, power, and torque. The higher cetane number of B100 increases engine performance, however, which may partially offset fuel economy reductions. Based on B100 energy content, B20 should have 1% to 2% less power, torque, and fuel economy than diesel—this is within the range of variation that would be expected from diesel from different sources. In the field, most B20 users report little to no difference.[11]

Both vehicle and refueling system performance may be affected by the following differences between diesel and biodiesel fuels:

- **Materials Compatibility—**Materials compatibility is not likely to be an issue for B20 when used in current diesel systems. B100, however, is not compatible with some materials commonly used for hoses and gaskets made prior to 1993. Materials including nitrile rubber compounds, polypropylene, polyvinyl, and Tygon will soften and degrade with B100, ultimately causing fuel leaks.[11] Hose and gasket materials in newer diesel fuel systems are typically compatible with B100 (e.g., Vitron, Teflon, fluorinated plastics, and Nylon). Although not expected in diesel fuel systems, other materials that are not compatible with B100 include some metals such as copper or copper containing metals (i.e., brass, bronze), lead, tin, and zinc, including galvanized surfaces. B100 is also not compatible with some plastics, such as polyethylene and polypropylene. Thus, these materials should not be used for storage or regular transfer of B100 or high biodiesel blends.

Did You Know?

On August 31, 1937, G. Chavanne, a Belgian academic at the University of Brussels, obtained the patent, "Procedure for the transformation of vegetable oils for their uses as fuels." This patent describes the alcoholysis, commonly referred to as trans-esterification, of vegetable oils using alcohol to separate the fatty acids from the glycerol by replacing the glycerol with short linear alcohols. This appears to be the first account of the production of what is known today as "biodiesel."

- **Cold Flow Properties—**When temperatures fall to levels at which a fuel begins to freeze or gel, the viscosity increases, causing fuel filter clogging, stress on fuel pumps and fuel injection systems, and ultimately failure of these components. The temperature at which this is a concern for biodiesel is higher than for diesel. Cold weather properties are often a primary reason for using biodiesel blends rather than B100. Biodiesel cold flow issues are addressed in the same way they are typically addressed with diesel, i.e., blend the fuel with kerosene or an additive package, store vehicles indoors, and/or install block and filter heaters.[12] There are several different terms (and associated tests) used to characterize low temperature operability of both diesel and biodiesel fuels. These are:
  - Cloud point—the temperature at which solid crystals begin to form;
  - CFPP—cold filter plugging point; and
  - LTFT—low temperature filterability test.

  As for diesel, purchase contracts for biodiesel blends are written to include specifications of critical operational properties such as cold flow, although usually only one of the above low temperature operability measurements is used. Cold flow specifications for specific geographical regions are commonly defined monthly based on the ASTM Tenth Percentile Minimum Ambient Air Temperatures as listed in the ASTM Standard Specification for Diesel Fuel Oils D-975.

- **Solvent Properties and Removal of Fuel Deposits—**Biodiesel is a better solvent than diesel fuel. Thus, fuel sediment deposits that collect in diesel fuel systems may be loosened when changing to biodiesel blends that are higher than B20, causing fuel filter clogs.[11] As a result, fuel filters on vehicles that have previously operated on diesel are typically changed after the first tank of a higher biodiesel blend. Subsequent fuel filter changes can be at the same intervals as recommended for diesel fuel.

Can I Use Biodiesel in My Existing Diesel Engine?

Biodiesel blends of up to 20% (and oftentimes more) work in any diesel engine with no modifications to the engine or the fuel system. Biodiesel has a cleansing effect that may release deposits from previous diesel fuel use. These deposits may end up in fuel filters, so fuel filters should be replaced more frequently at first. In colder climates, block or filter heaters may be needed.

4.5 Maintenance, Reliability, and Storage

Maintenance, repair, and road calls for transit buses powered by B20 do not appear to be significantly different from diesel. Proving these changes with certainty is difficult because of the high variability in maintenance costs from vehicle to vehicle regardless of fuel type. It is thought that longer-term studies with more vehicles may ultimately show both maintenance advantages and disadvantages of biodiesel blends compared to diesel. Maintenance and reliability related issues for biodiesel include the following:

- **Fuel Quality Control—**Biodiesel quality control has been an issue, particularly with respect to cloud point. The fuel into which biodiesel is blended must meet ASTM D975, and may be either 15,500, or 5,000 ppm sulfur; thus 15 ppm sulfur must be specified when a product similar to ULSD is desired. There have been reports of suspected variation of biodiesel blends beyond the stated specifications, and resulting fuel filter plugging and road calls.[13] Some of these inconsistencies are thought to have resulted from inadequate blending due to inexperience. In 2008, ASTM released standards for B6 through B20 (ASTM D7467), which, along with blender experience, may help increase biodiesel consistency. To help prevent extra maintenance needs due to reduced fuel quality, the following may be incorporated into fuel purchasing contracts:
    - A warranty of fuel specifications;
    - Receiver testing of fuel deliveries; and
    - Use of suppliers that are part of the National Biodiesel Accreditation Program. This voluntary program, called BQ-9000, is for the accreditation of biodiesel producers and distributors. More information is available at http://www.bq-9000.org/.

> **How is it Stored?**
>
> Standard storage and handling procedures are the same for diesel and biodiesel.

- **Equipment Warranties—**Most major engine companies have specifically stated the acceptability of the use of biodiesel blends up to B5. Cummins, John Deere, and International have approved B20 or higher on some engine models, and B100 has been approved for some construction engines. For a complete list of OEM position statements on biodiesel, visit: http://www.biodiesel.org/pdf_files/OEM%20Statements/OEM_Statements_Summary.pdf. Original equipment manufacturers (OEMs) may approve higher biodiesel blends on a case-by-case basis, and should be contacted for discussion. A common OEM policy is to not deny warranty coverage solely for use of higher biodiesel blends than they recommend, but they will deny coverage if the failure is attributed to the fuel used.[12] This is essentially the same approach used for diesel—if it is determined that equipment problems are caused by the fuel, and are not related to materials or workmanship, repairs are the responsibility of the fuel supplier rather than the manufacturer.[14]

In general, the standard storage and handling procedures used for diesel can be used for biodiesel, as described in NFPA 30: Flammable and Combustible Liquids Code. Underground storage of biodiesel is regulated by the EPA and is the same as for petroleum diesel. These regulations can be found in the Code of Federal Regulations 40 CFR 280. Biodiesel users should check with the appropriate local agencies to determine if there are special state or local regulations that are applicable to biodiesel storage.

Site Visit!

SEATTLE, WASHINGTON—A citywide minimum goal of 7% reduction in GHG emissions by 2010 has been declared, and the local power company, Seattle City Light, has committed to a long-term goal of meeting all of Seattle's electricity needs with zero net GHG emissions. To help achieve these goals, King County Metro Transit has committed to the use of a 20% blend of biodiesel (B20) to help power its fleet of 640 buses. Beginning in 2006, B20 use reduced Metro Transit's fuel bill by more than $10,000 per week in the first year. In addition to GHG reduction, the biodiesel program is promoted to improve energy security and help the regional economy. The thinking is that as biodiesel demand builds, local production will increase and the price will go down, encouraging more widespread use. This will increase opportunities in rural communities where vegetable oil producing crops are grown.

It is recommended that fuel storage tanks be cleaned prior to storing blends with substantially higher biodiesel content. Biodiesel has a cleansing effect that may release deposits accumulated on tank walls and pipes from previous diesel fuel usage. Deposits released from vehicle fuel tanks can plug the fuel filter, so fuel filters should be replaced more frequently at first.

Biodiesel blended in any proportion with diesel stays blended even in cold temperatures. There have been concerns that biodiesel quality may degrade with several months of storage. A study completed over a 24-month period at the University of Idaho found that biodiesel stores about as well as diesel fuel, with small decreases in energy content, viscosity, density, peroxide, and acid value.[15] There is anecdotal evidence that during storage microbial contamination may be more likely for biodiesel than for diesel, which can plug dispensers and vehicle fuel filters and cause vehicles to stall. The best way to deal with this issue (for both diesel and biodiesel) is to minimize water contact with the fuel, remove any water bottoms in standing tanks, and periodically (e.g., monthly) sample and test for microbial contamination. As with diesel, it is usually recommended not to store biodiesel longer than 6 months.

4.6 Emissions

Emissions are addressed in the two sub-sections below. The first discusses local and regional pollutants that are currently regulated under the Clean Air Act (i.e. hydrocarbons (HC), nitrogen oxides (NOx), particulate matter (PM), non-methane hydrocarbons (NMHC), and carbon monoxide (CO)). The second section discusses pollutants that contribute to global warming (i.e., GHG).

Regulated Pollutants

Pure biodiesel contains 11% oxygen which facilitates a more complete burn of the fuel compared to diesel. A more complete burn results in reduced generation of HC, NMHC, PM, and CO.[16] However, actual tailpipe emissions are greatly affected by the emissions control system. Differences in tailpipe emissions from biodiesel and diesel are reduced with more extensive emissions aftertreatment systems.

Most of the published biodiesel emissions studies do not use vehicles with the most recent emissions aftertreatment technologies. These studies are most appropriate for assessing potential emissions reductions through fuel-switching older vehicles that do not have emissions aftertreatment retrofits. There is much variation in emissions results both among and within these studies due to differences in drive cycles, fuel sources, engine design, etc. Thus, caution should be used in extrapolating published results to a particular fleet, both with respect to the direction and magnitude of emissions changes.

How Do Biodiesel Emissions Compare to Diesel?

Prior to MY2007, biodiesel offered reductions in HC, NMHC, PM, and CO. More stringent emissions standards and related use of additional emissions control technologies have greatly reduced the magnitude of emissions benefits that can be achieved with biodiesel. Beginning with MY2010, emissions differences between biodiesel and diesel are expected to be insignificant.

Beginning with MY2007, more stringent PM standards required all diesel buses to have diesel particulate filters (DPF), although many transit buses began using DPF several years earlier. Because the particles in biodiesel and diesel exhaust are composed of slightly different chemical compounds, they react differently with the DPF, which may cause emissions differences. A review of emissions from vehicles with and without DPF suggests that emissions differences between B20 and diesel do not substantially change with DPF use—these results are summarized in Table 4.2.[17]

Table 4.2 B20 Emissions and Fuel Economy as a Percentage of Diesel With and Without Diesel Particulate Filter (DPF) for Cummins ISB 5.9L Engines (pre-2010 engines)

	Without DPF (Pre-2007 Equivalent)	With DPF (MY2007 Equivalent)
Carbon Monoxide	-22%	ND
Nitrogen Oxides	+4%	+4%
Particulate Matter	-24%	-27%
Hydrocarbons	-50%	-74%
Fuel Economy (mpg)	+3%	+3%

ND = not determined

Emissions standards for MY2010 heavy-duty engines call for further reductions in NOx. Both Cummins and Detroit Diesel have MY2010 diesel engines that use Selective Catalytic Reduction (SCR), in addition to DPF and high-pressure, common rail fuel delivery systems. SCR requires the addition of a urea tank and associated periodic refilling, but early fleet testing of these systems suggests these additional costs may be offset by fuel savings (i.e., fuel economy increases of 2% to 5%).[18] These systems are further described in the diesel chapter.

At the time of this research, reports on the testing of biodiesel emissions with SCR have not been released. It is thought that for MY2010 and beyond, slight differences in NOx between diesel and biodiesel-fueled buses will be lost as a result of SCR. In the FuelCost2 model, default emissions values for biodiesel are the same as for diesel. These values should be updated as more data become available.

Greenhouse Gases

Biodiesel is generally viewed as a means to reduce GHG emissions when considered on a lifecycle basis—from oil wells and crop fields to vehicle tailpipe emissions. However, the extent of overall emissions reductions varies substantially depending on factors such as the feedstock crop, farming methods, prior land use, etc. Under some scenarios, GHG emissions may increase, rather than decrease.

The actual tailpipe emissions of GHG from vehicles fueled with biodiesel are slightly greater than tailpipe GHG emissions from vehicles fueled with diesel. This is a general reflection of lower energy per carbon content of biodiesel, and related reductions in fuel economy. In calculating the lifecycle GHG emissions from biodiesel, the carbon that is captured from the air during crop growth must also be considered—this can cause a net reduction in GHG emissions with biodiesel compared to diesel.

The emissions from fossil fuels used for crop cultivation (including fertilizer and herbicide production) and biodiesel production are less than the carbon captured during crop growth. However, crop field soil releases carbon dioxide (CO_2), nitrous oxide (N_2O), and methane, all of which are GHG. The amount of GHG released from fields varies with crop type and cultivation method. In general, crops that require more fertilizer produce more N_2O during cultivation. Relatively small differences in N_2O production result in large differences in climate warming ability (i.e., expressed as CO_2 equivalents) because N_2O is a GHG 296 times more potent than CO_2. As a result, N_2O release from soybean crop fields is currently estimated to be the single largest GHG source in the biodiesel lifecycle. Shifts from soybeans grown with conventional tillage practices versus no-tillage may yield nearly 2-fold reductions in net GHG field releases, and feedstock shifts from soybeans to perennials such as switchgrass and hybrid poplar may yield nearly 5-fold reductions in net GHG field releases.[19]

The controversy over the extent of GHG savings associated with biodiesel stems primarily from two issues:

1. The amount of GHG produced by soil bacteria during the crop cycle, relative to what would have been produced from the soil prior to cultivation of biodiesel feedstock
2. The emissions savings associated with co-products of biofuel crops (i.e., livestock feed).

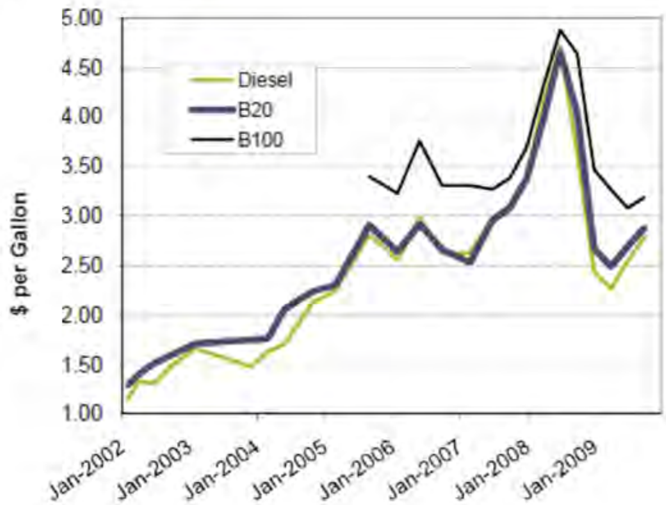
Estimations of overall GHG savings with biofuels use will likely become more explicitly qualified as further research improves understanding of these issues. Development of a biofuels rating system for GHG has been proposed, wherein a particular fuel will be rated with respect to the relative GHG savings associated with its use compared to conventional fossil fuels.[20]

For the purposes of providing initial GHG values in FuelCost2, the Excel tool that can be found on the web at http://www.trb.org/Main/Blurbs/165390.aspx, EPA estimates of GHG emissions associated with biodiesel use in 2012 (as published in 2007) are used.[21] These estimates, based on biodiesel from 80% soybean feedstock and 20% yellow grease feedstock, suggest that B100 reduces lifecycle GHG by about 70%, while B20 reduces GHG emissions by about 10% compared to diesel.

4.7 Cost and Availability

The primary component of biodiesel production costs is the feedstock. Feedstock prices (and hence biodiesel prices) vary from year to year based on short-term supply, which is determined by factors such as the weather, crop disease, and the price of other crop choices.[22] The most common biodiesel feedstocks, soybeans, and rapeseed (i.e., the source of canola oil), are traded globally. Thus, while around 80% of biodiesel currently used in the U.S. is from domestic soybeans, the effect of supply and demand on feedstock price occurs at a global level. As commodity fuels, B20 and B100 can be hedged for a year or two to protect the user from wild price spikes. The price risks of biodiesel can also be moderated by switching between B20 and diesel use.

Figure 4.3 Average U.S. Retail Prices for Biodiesel (B20 and B100) and Diesel



As shown in Figure 4.3, B20 pump prices have, at times, dipped below diesel prices. This has been the result of high diesel prices in combination with a fuel blenders excise tax credit of $1/gallon of blended biodiesel. In 2009, average pump prices for B20 were 7% higher than diesel, while B100 prices were 30% higher.[23]

Without federal tax credits, B20 prices would not be as competitive with diesel. For the last two decades, the federal government has consistently offered biofuel incentives to support the national policy of promoting the use of renewable fuels in transportation to meet energy security and environmental goals. Given its long history, the general thrust of the renewable fuels policy is likely to be continued. For this reason, some form of biodiesel incentive is likely to continue, although the magnitude and type of the incentive may change. Incentives that allow a drop-in fuel such as biodiesel to be sold at lower prices than conventional fuel are unlikely to be sustained for many years.

The price of biodiesel also varies with geographic area and supplier. While biodiesel can be found in every state, sources are greatest in the Midwest; hence biodiesel blends are most common in this region. Estimates of biodiesel adoption costs used as initial values in FuelCost2 are summarized in Table 4.3, along with estimates for diesel to allow relative comparisons. These estimates are based on an assessment of costs at only a few transit agencies, and thus should be considered with caution.

Guidebook for Evaluating Fuel Choices for Post-2010 Transit Bus Procurements

Table 4.3 Biodiesel and Diesel Cost Estimates

Item	B100	B20	Diesel
New Vehicle	$350,000	$350,000	$350,000
Facility Conversion	$400[a]	$400[a]	--
Fuel ($/gal)[b] ($/DGE)	$3.25 $3.57	$2.68 $2.74	$2.51 $2.51
Fuel economy (mpg) (miles/DGE)	3.1[c] 3.3	3.2 3.3	3.2 3.2
Propulsion System Maintenance ($/mile)	$0.16	$0.16	$0.16
Facility Maintenance ($/mile)	$0.18	$0.18	$0.18

a. Cost for cleaning the refuel system and diesel storage tanks: 8 hours labor, $50/hour.
b. Based on Clean Cities Alternative Fuel Price Report, average retail price (including taxes) in 2009.
c. Based on a fuel economy equivalent to diesel on an energy content basis with a 3% benefit due to a higher cetane number and associated efficiency improvements. Fuel economy assumes 40-ft bus with average speed of 13 mph and 3 months per year hotel load.

The default value for the price of B100 in FuelCost2 and in the table above is based on the average retail price of B100 in the 2009 Clean Cities Alternative Fuel Price Reports. The prices of vehicles and parts for vehicles powered by biodiesel are expected to be the same as for diesel vehicles, given that this alternative fuel is essentially interchangeable with diesel.

Future improvement in the biodiesel production process[24] and development of new crops for biodiesel feedstock[25] offer the greatest potential for longer-term decreases in biodiesel costs. Biodiesel feedstock crops that have no food value, broad growing conditions, and minimal fertilizer requirements are under development. Some examples of potential non-food crops with high plant oil content that may be used in the currently common transesterification process for biodiesel production include algae and jatropha.[26, 27] These crops will allow greater independence between biofuel and food costs. With continued biodiesel demand to promote crop research and development, non-food crops are likely to provide a significant future biodiesel source—this scenario is viewed as moderately likely to occur in the 2018 to 2028 timeframe.

4.8 Summary

Biodiesel

Pros	Cons
B20 is a drop-in fuel that is substantially interchangeable with diesel, thus reducing risks associated with its use.	Switching between diesel and B100 requires more care to prevent clogging due to diesel fuel deposits that may be loosened by B100.
Fuel economy with B20 is 1% to 2% lower than with diesel—within the range of variation expected from different diesel sources.	Fuel economy with B100 is around 5% to 10% less than with diesel.
Quality control concerns have been reduced in the last few years.	Quality control and consistency in biodiesel blends has been an issue.
Methods to improve diesel cold flow can be used for biodiesel.	Cold temperatures can cause reliability and maintenance problems for biodiesel.
In buses without emissions control (i.e., MY2006 and earlier), biodiesel blends may reduce PM, HC, CO, and HC.	Advanced emissions controls in MY2007 and later may make emissions benefits of biodiesel insignificant.
Earlier reports of slightly higher NOx from biodiesel than diesel are not relevant for buses with MY 2010 and later NOx controls.	The effect of biodiesel on NOx emissions compared to diesel is uncertain—a particular concern in ozone non-attainment areas.
Lifecycle GHG can be reduced with biodiesel—the percent reduction depends on the feedstock type, cultivation method, and use of co-products.	Further research is needed for general agreement on the magnitude of GHG reductions.
Competitive non-food feedstock crops are under development, and moderately likely in the 2018 to 2028 timeframe.	The current feedstock commonly used for biodiesel raises food-for-fuel concerns.

Biodiesel References

[1] National Biodiesel Board (n.d.). *Biodiesel Production*. Retrieved from http://www.biodiesel.org/pdf_files/fuelfactsheets/Production.PDF

[2] Methanol Institute and International Fuel Quality Center (April, 2006). *A Biodiesel Primer: Market & Public Policy Developments, Quality, Standards & Handling.* Retrieved from http://www.biodiesel.org/resources/reportsdatabase/reports/gen/20060401-GEN369.pdf

[3] McCormick, R.L., Williams, A., Ireland, J. and Hayes, R.R. (October 2006). *Effects of Biodiesel Blends on Vehicle Emissions.* National Renewable Energy Laboratory, NREL/MP-540-40554. Retrieved from http://www.osti.gov/bridge/product.biblio.jsp?query_id=0&page=0&osti_id=894987

[4] Alternative Fuels and Advances Vehicles Data Center (n.d.). *Hydrogenation-Derived Renewable Biodiesel.* Energy Efficiency and Renewable Energy, U.S. Department of Energy. Retrieved from http://www.afdc.energy.gov/afdc/fuels/emerging_green.html

[5] Sims, B. (December 2008). Workshop Defines Biomass-Based Diesel Options. *Biodiesel Magazine*. Retrieved from http://www.biodieselmagazine.com/article.jsp?article_id=2952

[6] VapOil (n.d.). *Production of BtL BioDiesel*. Retrieved from http://www.vapoil.fi/en/en/?id=2105

[7] BioTrucker.com (n.d.). *Biodiesel Fueling Sites*. Retrieved from http://www.biotrucker.com/sites/

[8] Nelson, R. (February 2006). *Biodiesel: Road to Renewables '06*. National Biodiesel Board. Retrieved from http://www.seco.cpa.state.tx.us/zzz_altfuels/alt_ethanol2006_nelson.ppt#256,1,Biodiesel

[9] Case IH expands biodiesel use for equipment (December 3, 2007). *The Business Journal of Milwaukee*. Retrieved from http://www.bizjournals.com/milwaukee/stories/2007/12/03/daily7.html

[10] National Biodiesel Board (n.d.). *FAQs, How Much Biodiesel has been produced in the U.S.?* Retrieved from http://www.biodiesel.org/resources/faqs/

[11] National Renewable Energy Laboratory (January 2009). *Biodiesel Handling and Use Guidelines* (4th ed.). NREL/TP-540-43672. Retrieved from http://www.nrel.gov/vehiclesandfuels/npbf/pdfs/43672.pdf

[12] Nelson, R. (February 2006). *Biodiesel: Road to Renewables '06*. National Biodiesel Board. Retrieved from http://www.seco.cpa.state.tx.us/zzz_altfuels/alt_ethanol2006_nelson.ppt#256,1,Biodiesel

[13] Proc, K., Barnitt, R., Hayes, R., Ratcliff, M., McCormick, R., Ha, L. and Fang, H. (October 2006). *100,000-Mile Evaluation of Transit Buses Operated on Biodiesel Blends (B20)*. National Renewable Energy Laboratory, NREL/CP-540-40128. Retrieved from http://www.biodiesel.org/resources/reportsdatabase/reports/tra/20061001_tra-55.pdf

[14] National Biodiesel Board (n.d.). *OEM Information/ Standards and Warranties*. Retrieved from http://www.biodiesel.org/resources/oems/default.shtm

[15] Thompson, J.C., Peterson, C.L., Reece, D.L. and Beck, S.M. (1998). Two-Year Storage Study with Methyl and Ethyl Esters of Rapeseed Oil. *Transactions of the ASAE*, 41(4):931-939. Retrieved from http://asae.frymulti.com/abstract.asp?aid=17250&t=1

[16] McCormick, R.L., Williams, A., Ireland, J. and Hayes, R.R. (October 2006). *Effects of Biodiesel Blends on Vehicle Emissions.* National Renewable Energy Laboratory, NREL/MP-540-40554. Retrieved from http://www.osti.gov/bridge/product.biblio.jsp?query_id=0&page=0&osti_id=894987

[17] Williams, A., McCormick, R.L., Hayes, R.R., Ireland, J. and Fang, H.L. (2006). *Effect of Biodiesel Blends on Diesel Particulate Filter Performance*. Presented at the Powertrain and Fluid Systems Conference and Exhibition, October 2006, Toronto, Canada. Retrieved from http://www.nrel.gov/vehiclesandfuels/npbf/pdfs/40015.pdf

[18] Birkland, C. (August 2009). 2010 Engine Test Fleets Weigh In: Fleet Managers Talk About Their Experiences Testing 2010 Diesel Engines. *Fleet Equipment Magazine*. Retrieved from http://www.fleetequipmentmag.com/Item/65899/2010_engine_test_fleets_weigh_in.aspx

[19] Adler, P.R., Del Grosso, S.J. and Parton, W.J. (2007). Net Greenhouse Gas Flux of Bioenergy Cropping Systems Using DAYCENT. *Ecological Applications*, 17(3):675-691.

[20] Schill, S.R. (August 2007). Biofuels GHG Rating System. *Ethanol Producer Magazine*. Retrieved from http://www.ethanolproducer.com/article.jsp?article_id=3169&q=&page=2

[21] Office of Transportation and Air Quality (April 2007). *Regulatory Impact Analysis: Renewable Fuel Standard Program*. U.S. Environmental Protection Agency, EPA420-R-07-004, p.250. Retrieved from http://www.epa.gov/otaq/renewablefuels/420r07004.pdf

[22] Economic Research Service (February 12, 2009). *Agricultural Baseline Projections: Global Agricultural Trade, 2009-2018*. U.S. Department of Agriculture. Retrieved from http://www.ers.usda.gov/briefing/Baseline/crops.htm

[23] Alternative Fuels and Advanced Vehicle Data Center (March 2005 through October 2009). *Clean Cities Alternative Fuel Price Reports*. U.S. Department of Energy. Retrieved from http://www.afdc.energy.gov/afdc/price_report.html

[24] Core, J. (April 12, 2005). *Biodiesel gets simplified new method*. Agricultural Research Service, U.S. Department of Agriculture. Retrieved from http://www.ars.usda.gov/is/pr/2005/050412.htm

[25] Kurki, A., Hill, A. and Morris, M. (2006). *Biodiesel: The Sustainability Dimensions*. ATTRA—National Sustainable Agriculture Information Service. Retrieved from http://attra.ncat.org/attra-pub/biodiesel_sustainable.html

[26] LaMonica, M. (May 2, 2008). Race to Algae-Based Biodiesel Heats Up. *Cnet News*. Retrieved from http://news.cnet.com/8301-11128_3-9933355-54.html

[27] Layden, L. (April 5, 2008). New Biodiesel Crop Jatropha Taking Off in S.W. Florida. *naplesnews.com*. Retrieved from http://www.naplesnews.com/news/2008/apr/05/new-biodiesel-crop-jatropha-taking-sw-florida/

5.0 Gasoline

Gasoline is the world's most commonly used motor fuel. In the United States alone, over 137 billion gallons are consumed annually.[1] Gasoline is produced by refining crude oil. About 42% of crude oil in the U.S. is refined into gasoline, while only 27% is refined into diesel fuel.[2]

Even so, gasoline is rarely used in full-size transit buses or heavy equipment primarily because diesel compression-ignition engines can deliver much more power on a continuous basis than gasoline spark-ignition engines. This is a function of the fuel properties and the related engine type—compression-ignition engines have inherently better efficiencies than spark-ignition engines.

In 2005, the High-Efficiency, Durable Gasoline Engine (HEDGE) consortium was launched by Southwest Research Institute (http://www.thefreelibrary.com/SwRI+Launches+Heavy-Duty+Gasoline+Engine+Consortium-a0111871009) to "hedge" bets on the direction of heavy-duty engines after the 2010 EPA emission standards take effect. To meet these standards, significant advances were needed in diesel engines and their exhaust gas treatment, and meeting these standards by the 2010 deadline was viewed as challenging. By early 2010, major heavy-duty diesel engine manufacturers were able to offer 2010-compliant engines. If these prove to be reliable and durable with minimal increased maintenance, the incentive for further heavy-duty gasoline engine development will be reduced, as the emissions benefit of gasoline compared to diesel will no longer be significant.

5.1 Fuel Description

Gasoline, { gas-uh-**leen** }
noun—a volatile, flammable liquid mixture of hydrocarbons, obtained from petroleum, and used as fuel for internal-combustion engines, as a solvent, etc.

Generally light yellow in color, gasoline is composed of a variety of hydrocarbons that are typically between 5 and 12 carbon atoms per molecule. The relatively high octane rating of gasoline makes it a good fuel for spark-ignition engines. Octane ratings are a relative measure of a fuel's resistance to autoignition, or "knock," in a spark-ignition engine. Engine knock is caused by the detonation of fuel when it is compressed in the engine cylinder—the higher an engine's compression ratio, the more important octane becomes. At commercial refueling stations in the United States, gasoline is available in a variety of octane levels, typically ranging from 86 to 94. Higher octane gasoline requires additional refining, so it is more expensive.

Fuel additives are used in gasoline to alter fuel performance or characteristics and to differentiate the fuel of each producer. Table 5.1 lists some commonly used gasoline additives and their purposes.

Table 5.1 Common Gasoline Additives

Name	Common Name	Timeline	Description
Tetra-ethyl lead	Lead	1920s–1970s	Added to gasoline in order to increase the octane rating to allow for higher power through higher compression ratios. It was removed when studies linked lead in gasoline to health problems.
Methylcyclopentadienyl manganese tricarbonyl	MMT	1970s–present	Replaced the use of lead to increase the octane rating. Controversy exists over its use due to suspected health risks.
Oxygenates: Methyl tertiary butyl ether, Ethyl tertiary butyl ether	MTBE, ETBE	MTBE: 1979–2006 ETBE: 1992 (first used in France)–present	Used to increase the oxygen content of gasoline to improve combustion efficiency and reduce carbon monoxide (CO) emissions. MTBE is banned in some states for ground water contamination and was voluntarily phased out of use by U.S. fuel producers in 2006.
Anhydrous ethanol	Ethanol	1800s–present	Commonly mixed with gasoline at 5% to 10% by volume to reduce petroleum content and emissions. It is also used as an oxygenate, as described below.
Custom-engineered additives	Varies by company	On-going	Created by petroleum companies to differentiate their products from that of competitors. Some additives are designed to prevent deposits from forming on fuel injectors and to prolong the life of the engine.

Ethanol is a common gasoline additive. Nationwide year-round use of low-level ethanol blends began in 2006 when gasoline blenders phased out the additive MTBE and replaced it with ethanol. These low-level blends are sometimes referred to as "gasohol" blends, although over time this terminology has been used with less frequency. The most common blend is E10 (10% ethanol/90% gasoline). Although gasohol sold under the E10 nameplate may contain up to 10% ethanol, many fuel suppliers use a 5% to 6% blend.

Guidebook for Evaluating Fuel Choices for Post-2010 Transit Bus Procurements 5-3

Is it Imported?

Gasoline used in the United States comes from both domestic and foreign refineries, which use crude oil for domestic and foreign sources. About two-thirds of the crude oil used by U.S. refineries is imported from other countries. Both the crude oil and gasoline infrastructure allows mixing of products from different suppliers in pipelines and in bulk storage, so there is no way to tell how much of an individual batch of gasoline originates from foreign or domestic crude oil.

Table 5.2 shows some of the key fuel properties of gasoline as it compares to diesel fuel. Some properties, such as cetane number and octane number, are not comparable because gasoline is used in spark-ignited engines while diesel is used in compression ignition engines.

Table 5.2 Gasoline and Diesel Fuel Properties

Property	Gasoline	Diesel
Boiling Temperature (°F)	80 to 437	356 to 644
Autoignition Temperature (°F)	495	600
Cetane Number	Not applicable	40 to 55
Octane Number ([R+M]/2)	84 to 93	Not applicable
Flash point (°F)	-45	140 to 176
Flammability Limits (Vapor in air by volume %)	1.4 to 7.6	1.0 to 6.0
Lower Heating Value (Btu/gal)	116,090	128,450
Relative Weight (same volume) Compared to air = 1 Compared to water = 1	 >2.5 *(as vapor)* 0.75	 >3.0 *(as vapor)* 0.85
Soluble in water (by volume)	Negligible	No

The flash point of gasoline is significantly lower than that of diesel, which means released gasoline vaporizes much more quickly than diesel. As a result, at room temperature, flammable air-vapor mixtures will occur over a pool of gasoline but not over a pool of diesel. The relative weight of gasoline vapors compared to air indicates that these vapors will stay low to the ground before gradually dispersing with air currents.

5.2 Fuel Usage

In the past, gasoline engines were used in heavy-duty applications but this use declined as the benefits of the greater power, low-speed torque, and durability possible with diesel compression ignition engines were more widely recognized. In general, gasoline engines only meet the power and torque requirements of cutaway and transit buses that are 34 ft or smaller.

Use of gasoline in transit buses in the United States has been remarkably steady over the past 15 years. Between 1996 and 2009, gasoline-powered transit buses consistently represented less than 1% of all transit buses. Diesel-powered buses on the other hand have seen their share fall from over 95% in 1996 to slightly less than 70% in 2009. Despite this clear movement away from diesel, gasoline has not become a popular alternative fuel for transit applications. However, gasoline has remained a popular fuel for smaller (i.e., 20 to 34-ft) paratransit buses. As of 2009, nearly 40% of paratransit vehicles were powered by gasoline.[3]

In 2005, Long Beach Transit became the first transit agency in the world to provide regular service with 40-ft hybrid gasoline-electric buses. Produced by New Flyer, Long Beach buses get 5.5 miles per gallon, an improvement of up to 50% over comparable diesel buses.[4] Other transit agencies now operate these buses as well—with over 100 in operation in 2007. For more information about this technology, see the Hybrid Electric section of this report.

Research institutions, such as the Southwest Research Institute (SwRI), have begun to investigate the potential advantages of developing a modern, high-efficiency, heavy-duty gasoline engine. Reasons for doing so include gasoline's lower fuel cost and the market-proven low-cost emissions control technologies of gasoline engines. The 2010 emissions regulations make such technologies all the more attractive.

5.3 Safety, Training, and Disposal

Safety

Gasoline contact with the eyes and skin should also be avoided as irritation can occur. Gasoline vapors contain benzene, which is a carcinogen and should not be inhaled. Compared to diesel fuel, gasoline has a lower flash point and thus a higher fuel volatility. These differences are important because additional safety measures and training are required to safely use the fuel. A higher volatility makes gasoline more susceptible to ignition from electric and open flame sources. That said, the fact that there are over 160,000 public gasoline stations in the United States and thousands of vehicle repair facilities, demonstrates that gasoline fueling can be performed safely.[5]

Wiring and electrical equipment in low areas (up to 18 in. above the ground) must be explosion-proof (classified) in all fueling and maintenance facilities for gasoline-powered buses. Building ventilation must be able to remove ground-level gasoline vapors, as they are harmful to your health and extremely flammable. Maintenance facilities should also be equipped with flammable gas detectors. These devices can detect a high concentration of vapors before they reach flammable levels.

Key Point

Gasoline has a much lower flash-point than diesel fuel. It creates ignitable air-fuel mixtures, even at low ambient temperatures. For this reason, it is far more flammable than diesel and far more dangerous to handle and transport. Procedures, safety equipment, and training related to gasoline use should reflect this difference.

Gasoline must be stored and handled in appropriate containers as it can be corrosive to some materials. Table 5.3 lists some of the relevant fire codes, guidelines, and standards that are available from the National Fire Protection Association (NFPA) and the EPA related to gasoline storage, fueling, and vehicle safety.

Table 5.3 Selected Codes, Standards, and Guidelines for Gasoline Vehicles and Infrastructure

Standard	Description
NFPA 88A—Standard for Parking Structures (1998)	Covers open, enclosed, basement and underground parking structures.
NFPA 30A – Code for Motor Fuel Dispensing Facilities and Repair Garages (2003)	Covers facilities dispensing both gaseous and liquid fuels at the same facility.
NFPA 1—Uniform Fire Code (2009)	The UFC is the most widely adopted model building code in the United States. Provides basis for local fire codes.
EPA 40 CFR Part 63 Subpart C—National Emission Standards for Hazardous Air Pollutants for Source Categories	Covers gasoline dispensing facilities.

Training

The transportation, handling, and dispensing of gasoline is very similar to that of diesel. Special precautions need to be taken to eliminate ignition sources during fueling and transferring. Ignition sources might include the following:

- a running vehicle,
- smoking, and
- electronic equipment.

Static electricity is another concern because static sparks can ignite gasoline and gasoline vapors. To prevent static charge ignition, training should cover the proper use of grounding techniques. Such techniques would include discharging static electricity from objects before fueling, and using ground straps where applicable.

Disposal

Gasoline is toxic to soil, water, and plant/animal life, and degrades slowly when released to the environment. Leakage from underground diesel and gasoline storage tanks is considered by the U.S. EPA to be a major source of soil and groundwater pollution.[6] The minimum volume of spilled gasoline that requires reporting and clean-up is determined at the state level, and may depend on how the land or water is used (e.g., in an industrial area or residential area).[7] An example of standard operating procedures for fuel spills at municipal operations in Boulder, Colorado, is available online at http://www.bouldercolorado.gov/www/pace/government/documents/FuelingandFuelSpillCleanupSOP.pdf. In the Colorado example, spills of more than 25 gallons or spills that cause a sheen on nearby surface water are to be reported to state authorities. In general, when in doubt, it is better to report even if it is not needed than to risk sizable fines for not reporting.

When gasoline is disposed, it can be characterized as a hazardous waste due to both its ignitability and benzene content.[8] Gasoline-saturated sorbents used in spill clean-up are often exempt from state Hazardous Waste Rules under certain conditions (e.g., spill size, timely reporting, immediate clean-up). The appropriate state authorities should be contacted for guidance. For disposal of fuel containers, the container contents should be completely emptied prior to discard, and large empty containers should be returned to the distributor.

5.4 Technology and Performance

Like other spark-ignited engine fuels, gasoline has a low cetane number, meaning it is unsuitable for use in compression-ignition (diesel) engines. In most commercially available gasoline engines, fuel is injected and mixed with air before it enters the combustion chamber (known as port fuel-injection).

Did You Know?

Gasoline consumption in the U.S. averages out to over a gallon a day for every man, woman, and child.

In order to achieve sufficient power levels, many gasoline engines suitable for cutaway buses feature larger displacements. In other gasoline powered vehicles, turbochargers or superchargers are used as a means to achieve engine power requirements. As an alternative to increased displacement, this approach gives the engine the required performance with significant fuel consumption benefits.

Newer gasoline engines use direct fuel injection, meaning gasoline is injected directly into the cylinder without first being mixed with air in the intake manifold. Direct injection provides a cooling effect as well as allows for better control of injected gasoline, including its amount, timing, and spray pattern.[9] Direct-injection engines can operate at stoichiometric conditions or in lean-burn (excess air) mode, which can improve fuel efficiency.

There are three gasoline engines currently available for small- to medium-size (less than 34 ft in length) transit bus applications. These engines can power buses in the 16,000 lb to 18,000 lb gross vehicle weight rating range. They are the following:

- The **Ford Triton** has a 6.8 liter V-10 with 352 hp and 467 ft-lb of torque. This is arguably the most popular gasoline engine used in small transit buses.
- The **General Motors Vortec** 8.1 liter V-8 engine has a power rating of 325 hp and 450 ft-lb of torque.
- The **Dodge 5.7L HEMI** V-8 engine offers 390 hp and 407 ft-lb of torque.

5.5 Maintenance, Reliability, and Storage

Maintenance

Scheduled maintenance operations for gasoline engines are more frequent than for diesel engines due to the needs of spark-ignition engines (i.e., spark plug and wire replacements). Gasoline engines typically have a shorter useful life than diesel engines. Technicians must be trained to understand the differences between diesel and gasoline and the procedures required to safely work on gasoline buses.

Reliability

The overall reliability of gasoline buses varies widely regardless of fuel type due to factors such as drive cycle and bus body up-fitter manufacturer. On the other hand, the chassis and powertrains of these buses are very reliable. They are built by major automotive vehicle manufacturers using proven technologies. The powertrain reliability is very similar to that of 1- and 2-ton trucks, recreational vehicles, and utility vehicles, as all of these vehicles share very similar chassis and powertrains.

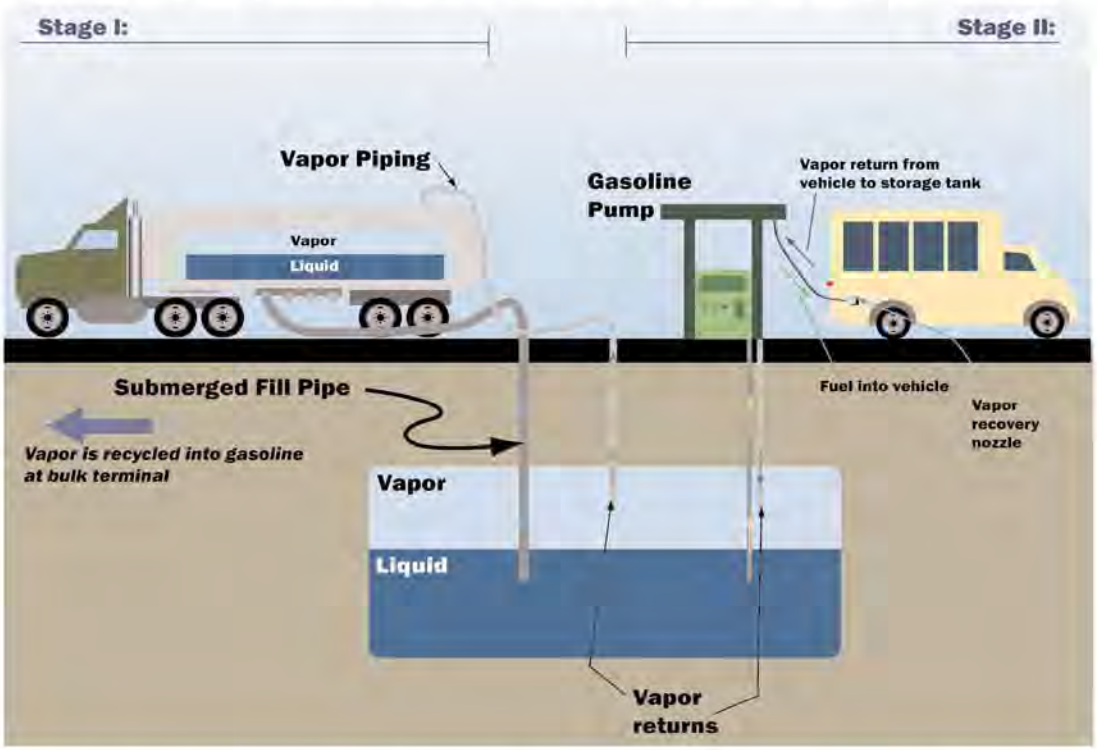
Storage

There are many codes and regulations that govern the design of gasoline storage, maintenance facilities, fuel storage, and fuel dispensing. Some of these codes and regulations are listed in the Training section under Table 5.3, but for a comprehensive overview, it is necessary to check local regulations as they can differ by state and city.

A particular concern with gasoline storage is preventing the release of fuel vapors from the storage containers and fueling processes. To that end, regulations have been established requiring vapor recovery systems. These systems can be classified into two stages as described below and illustrated in Figure 5.1:

- Stage 1 Vapor Recovery System: this system contains the vapors of fuel tankers when re-supplying fueling stations. The vapor in the underground storage tank is displaced into the tanker truck when the new fuel is delivered. The vapor is then transported back to the refinery where it can be recycled into more gasoline. The tanker truck also transports vapor from the Stage 2 recovery.
- Stage 2 Vapor Recovery System: this system contains the vapors displaced from vehicles' fuel tanks when refueling at stations. The operation is identical to the Stage 1 system. Many vehicle operators are unaware of the vapor recovery line contained in the nozzle of the dispensing unit.[10]

Figure 5.1 Diagram of Gasoline Station and Vehicle Vapor Recovery Design



Vapor emissions are reduced by 95% when both stages are implemented.[11] The regulation of vapor recovery systems varies by state and by city. Specific mandates often depend on the volume of gasoline dispensed at the fueling station.

5.6 Emissions

Emissions are addressed in two sub-sections below. The first section discusses local and regional pollutants that are currently regulated under the Clean Air Act (i.e., hydrocarbons (HC), nitrogen oxides (NOx), particulate matter (PM), CO, and vapors). The second section discusses pollutants that contribute to global warming (i.e., greenhouse gases (GHG)).

Regulated Pollutants

The emissions characteristics of gasoline engines are different from those of diesel engines. Gasoline engines have higher HC and CO emissions than diesel, but lower NOx and PM emissions. A diesel engine requires relatively advanced emission control technologies to reduce NOx and PM sufficiently to meet the same emission levels as a gasoline engine. Tailpipe emissions from both engine technologies are required to meet the same regulations, and gasoline engines tend to achieve this with less expensive and more-established emissions control technologies. Diesel engines, on the other hand, offer greater fuel efficiency.

At the time this report is being written, available emissions measurements from model year (MY) 2010 buses are quite limited. This is a significant consideration for comparisons of emissions differences between new gasoline and diesel buses because these engines were required to meet more stringent emissions regulations beginning in 2010. For a preliminary comparison of gasoline and diesel bus emissions, U.S. EPA certification data for MY2010 on-road engines with power ratings of 300 to 350 horsepower were compared. Table 5.4 shows the average certification test emissions as converted to grams/mile based on EPA conversion factors. These emissions estimates are used as default values in the FuelCost2 model. These estimates should be updated as more emission measurements are reported for 2010 buses.

Table 5.4 Gasoline Diesel Engine Emissions: EPA Model Year 2010 Certification Tests *

	Gasoline (g/mile)	Diesel (g/mile)
Carbon Monoxide	23.6	0.0
Nitrogen Oxides	0.2	0.65
Particulate Matter	0.0	0.0
Non-Methane Hydrocarbons	0.3	0.01

* Emissions estimates based on EPA certification test data for model year 2010 highway engines between 300 and 350 horsepower available at http://www.epa.gov/oms/crttst.htm. Units of g/bhp-h are converted to g/mile using EPA conversion factors of 3.354 bhp-h/mi for gasoline and 4.679 bhp-h/mi for diesel.[12]

Based on this early comparison, it appears that the historical differences in PM emissions from gasoline and diesel vehicles are entirely removed with diesel particulate filter (DPF) technology. With respect to NOx, gasoline engines may still offer reductions, but no longer the order-of-magnitude differences of years past. Finally, with respect to CO, gasoline engines continue to have higher CO emissions than diesel engines, but these levels are well within regulatory limits.

In addition to tailpipe emissions, the release of gasoline vapors is also regulated because:

- Gasoline vapors contain benzene, which is a carcinogen and should not be inhaled.
- Gasoline vapors contain volatile organic compounds that react with NOx to form ground-level ozone (smog). This reaction is made worse by sunlight and heat. Many states and cities have created "ozone action days" in an attempt to reduce harmful activities such as refueling gasoline-powered vehicles.

Today's vapor recovery systems address many concerns about these effects, but also add to the cost of storage and fueling facilities.

Greenhouse Gases

GHG emissions are typically expressed in terms of carbon dioxide equivalents (CO_2E) to take into account the different global warming potentials of various emissions. GHG emissions analysis of the transportation sector typically also distinguishes well-to-tank emissions and tank-to-wheels emissions. Well-to-tank emissions refers to emissions from crude oil production and transport, refinery operations, and product transport to refueling stations. Tank-to-wheels refers to emissions from the engine and vapors from the on-board fuel tank.

A recent analysis of lifecycle GHG emissions from conventional transportation fuels found that for both gasoline and diesel, the well-to-tank GHG emissions (CO_2E) represented about 20% of the lifecycle GHG emissions, with the remainder resulting from engine emissions. Gasoline well-to-tank CO_2E were found to be approximately 18% higher than for diesel, while tank-to-wheels CO_2E emissions from transit buses were estimated to be 17% higher for gasoline than for diesel buses. [13]

For the purposes of a default value in the FuelCost2 model that accompanies this guide, gasoline buses are assumed to have 17% higher lifecycle GHG emissions than comparable diesel buses.

5.7 Cost and Availability

Gasoline prices depend on many factors, including crude oil feedstock price, refinery source capacity, location within the United States, state and local taxes, and whether the purchase is at wholesale (e.g., fleet) or retail level. In 2009, the average cost of gasoline was $2.24 per gallon, or $2.50 per diesel gallon energy equivalent (DGE). For comparison, diesel averaged $2.51 during the same time period.[14] Though in recent years diesel has tended to be more expensive than gasoline, the price of gasoline does sometimes go above diesel's. Gasoline and diesel prices generally rise and fall together, but not necessarily at the same rate.

Because no gasoline engines currently meet the required torque levels for a full-size (40-ft) bus, no gasoline buses of that size are available for cost analysis. One manufacturer offers a 40-ft gasoline hybrid electric model, but this type of bus is covered in the Hybrid Electric section of this report because it is not solely powered by a gasoline engine. There are several OEM gasoline engines available for cutaway or shuttle bus applications (i.e., typical lengths around 25 ft).

Based on the American Public Transportation Association's *2007 Transit Vehicle Database*, the average cost of new cutaway gasoline buses was $50,711, while new diesel-powered cutaway buses had an average cost of $67,299. [15] This suggests that a gasoline bus costs about 25% less than a diesel bus. This cost reduction was applied to the 40-ft diesel bus cost to estimate the cost of a new 40-ft gasoline bus for the purposes of a default value in the FuelCost2 model.

Adding gasoline fueling facilities and modifications to existing maintenance facilities for transit bus properties would entail additional capital costs. These costs vary substantially depending on the specifics of the site and current facilities. There are over 160,000 gasoline fueling stations in the United States, so there are ample supplies and vendors available to install this equipment.[16] Table 5.5 shows bus and other costs for gasoline bus operations that are used as default values in FuelCost2.

Guidebook for Evaluating Fuel Choices for Post-2010 Transit Bus Procurements 5-11

Table 5.5 Gasoline and Diesel Bus Cost Estimates (40-ft buses)

Item	Gasoline	Diesel
New Cutaway Vehicle ($)	262,500[a]	350,000
Garage Facility Conversion ($)	100,000	N/A
Fuel[b]	$2.24/ gal $2.50/ DGE	2.51/ gal
Fuel Economy (mpg) (miles/DGE)	2.2[c] 2.4	3.2 3.2
Propulsion System Maintenance ($/mile)	0.18	0.16
Facility Maintenance ($/mile)	0.18	0.18

a. Estimated 40-ft gasoline bus cost based on the relative costs of gasoline and diesel cutaway buses.
b. U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy (2009). Clean Cities Alternative Fuel Price Report, 2009 quarterly reports. Retrieved from: http://www.afdc.energy.gov/afdc/price_report.html.
c. Fuel economy assumes 40-ft bus with average speed of 13 mph and 3 months per year hotel load,[17] adjusted for gasoline engine efficiencies.

Fuel efficiency estimates shown in Table 5.5 are based on three general assumptions. First, it is assumed that the average gasoline engine efficiency is 15% lower than diesel engines over the driving speed range in terms of energy for useful work. Second, it is assumed that at the slow speeds typical for most transit bus drive cycles there is an additional 10% reduction in efficiency compared to diesel engines due to throttle-associated efficiency losses that occur in spark-ignition (gasoline) engines, but not in compression-ignition (diesel) engines. Third, the ratio of the typical energy content of gasoline and diesel is applied to yield miles per gallon of gasoline.

The maintenance costs for spark-ignition gasoline engines are estimated to be slightly higher than for compression-ignition diesel engines due to additional needs such as spark-plug replacement. Propulsion system maintenance costs shown in Table 5.5 are assumed to be the same for CNG buses, which also have spark-ignition engines.

5.8 Summary

Gasoline

Pros	Cons
Based on its fuel price and operational characteristics, gasoline can be competitive with diesel in small transit bus applications.	Gasoline engines have lower torque than diesel engines and are less durable.
The lower PM and NOx emissions of gasoline engines can give them an advantage in regions with stringent regulations aimed at the elimination of diesel power.	The fuel economy for gasoline buses is lower than for diesel buses, due to the inherently lower fuel efficiencies of spark-ignited engines compared to compression-ignition engines.
Gasoline's long history in fleet applications and use as a fuel in the passenger car industry mean that associated equipment and technologies are well developed.	Gasoline is significantly more flammable than diesel and requires fuel vapor management.
There are many second stage manufacturers available for fitting a variety of transit bodies. Also available are gasoline hybrid electric 40-ft buses.	There are only a few OEM chassis manufacturers offering gasoline engine options. Available gasoline engine sizes limit transit bus applications to less than 34 ft.

Guidebook for Evaluating Fuel Choices for Post-2010 Transit Bus Procurements 5-13

Gasoline References

[1] U.S. Department of Energy, Energy Information Administration (n.d.). *Prime Supplier Sales Volumes*. Retrieved from: http://tonto.eia.doe.gov/dnav/pet/pet_cons_prim_dcu_nus_a.htm.

[2] U.S. Department of Energy, Energy Information Administration (n.d.). *Petroleum Refinery Yield*. Retrieved from: http://tonto.eia.doe.gov/dnav/pet/pet_pnp_pct_dc_nus_pct_m.htm.

[3] American Public Transportation Association (April, 2010). *2010 Public Transportation Fact Book, Appendix A: Historical Tables*. Retrieved from: http://www.apta.com/resources/statistics/Pages/transitstats.aspx

[4] Long Beach Transit (n.d.). *Hybrid E-Power Bus Fact Sheet*. Retrieved from: http://www.lbtransit.com/about/pdf/epower-fact-sheet.pdf

[5] U.S. Department of Energy, Energy Information Administration (n.d.). *Frequently Asked Questions—Gasoline*. Retrieved from: http://tonto.eia.doe.gov/ask/gasoline_faqs.asp#retail_gasoline_stations

[6] U.S. Environmental Protection Agency (December 2008). Don't Let Those Tanks Leak: EPA Enforces Underground Storage Tank Requirements. *Enforcement Alert*, Volume 10, Number 1. Retrieved from http://www.epa.gov/compliance/resources/newsletters/civil/enfalert/ust.pdf

[7] Oklahoma Department of Environmental Quality (May 2010). *Land Diesel and Gasoline Spills Fact Sheet*. Retrieved from http://www.deq.state.ok.us/factsheets/land/Dieselspill.pdf.

[8] Phillips Petroleum Company, 2002. *MSDS Summary Sheet: No. 2 Diesel Fuel*. Retrieved from http://www.petrocard.com/Products/MSDS-ULS.pdf .

[9] Gold, A. (n.d.). *Direct Fuel Injection: What It Is, How It Works*. About.com. Retrieved from: http://cars.about.com/od/thingsyouneedtoknow/a/directinjection.htm

[10] New Hampshire Department of Environmental Services (2008). *New Hampshire's Gasoline Vapor Recovery Program: Protecting the Air We Breathe*. Retrieved from: http://des.nh.gov/organization/commissioner/pip/factsheets/rem/documents/rem-25.pdf

[11] New Hampshire Department of Environmental Services (2008). *New Hampshire's Gasoline Vapor Recovery Program: Protecting the Air We Breathe*. Retrieved from: http://des.nh.gov/organization/commissioner/pip/factsheets/rem/documents/rem-25.pdf

[12] U.S. Environmental Protection Agency (May 1998). *Update Heavy-Duty Engine Emission Conversion Factors for MOBILE6: Analysis of BSFCs and Calculation of Heavy-Duty Engine Emission Conversion Factors*. EPA420-P-98-015. Retrieved from: http://www.epa.gov/oms/models/mobile6/m6hde004.pdf

[13] Skone, T.J., and Gerdes, K. (November 2008). *Development of Baseline Data and Analysis of Life Cycle Greenhouse Gas Emissions of Petroleum-Based Fuels, Appendix J*. National Energy Technology Laboratory (DOE/NETL-2009/1346).

[14] U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy (2009). *Clean Cities Alternative Fuel Price Report*, 2009 quarterly reports. Retrieved from: http://www.afdc.energy.gov/afdc/price_report.html

[15] Federal Transit Administration (December 21, 2007). *An Evaluation of the Market for Small-to-Medium-Sized Cutaway Buses*. Department of Transportation, MI-26-7280.07.1. Retrieved from: http://www.fta.dot.gov/documents/MI-26-7280.07.1_FINAL_REPORT.pdf (see especially 1.3 Vehicle Costs).

[16] U.S. Department of Energy, Energy Information Administration (n.d.). *Frequently Asked Questions—Gasoline*. Retrieved from: http://tonto.eia.doe.gov/ask/gasoline_faqs.asp#retail_gasoline_stations

[17] Clark, N., Zhen, F. and Wayne, W. S., et. al. (December 2009). *TCRP Report 132: Assessment of Hybrid-Electric Transit Bus Technology*. Transportation Research Board of the National Academies, Washington, D.C.

6.0 Ethanol

Ethanol is a renewable fuel that can be made from a variety of plant materials. Ethanol contains the same chemical compound found in alcoholic beverages. Nearly half of U.S. gasoline contains ethanol in a low-level blend to oxygenate the fuel and reduce air pollution. Ethanol is also increasingly available in E85, which is a gasoline and ethanol blend that contains 85% ethanol. E85 is an alternative fuel that can be used in flexible-fuel vehicles (FFVs). Studies have estimated that ethanol and other biofuels could replace 30% or more of U.S. gasoline demand by 2030.[1]

This discussion will focus on ethanol blends that are defined as alternative fuels under the Energy Policy Act (EPAct), i.e., gasoline blends of 85% or more alcohol by volume, with reductions to 70% when necessary to maintain cold-start capability.

This chapter does not address:

- **E-diesel or diesel blends of ethanol**. These are currently marketed under names such as O_2Diesel and OxyDiesel. They contain 7.7% and 15% ethanol by volume respectively, in addition to proprietary additives. The E-diesel blends do not meet the American Society of Testing and Materials (ASTM) standards for diesel fuel, nor are they considered alternative fuels under EPAct.
- **Methanol, or methyl alcohol**. This fuel, most commonly produced from natural gas, was promoted in California during the 1980s and 1990s, but has since fallen out of favor. Primary problems are: relatively low energy content, high corrosiveness, low lubricity, associated reduced engine reliability, and fuel availability difficulties.
- **Ethanol as a gasoline fuel additive**. These fuels meet ASTM standards for gasoline and may contain up to 10% ethanol.

Ethanol { ETH-uh-nol **}**
noun—a colorless, volatile, flammable liquid, C_2H_5OH, typically produced by fermentation of carbohydrates.

Key Point

In 2010, there are no transit fleets in the United States that operate heavy-duty, ethanol-fueled transit buses, and no manufacturers in the United States that have bus engines available for use with alcohol fuels.

Butanol—A Future Fuel?

In recent years there has been a growing interest in another alcohol, butanol. Biobutanol has been referred to as a "second-generation" biofuel. Though there is very little data currently available on butanol use as a transportation fuel, it is similar to ethanol but with some properties that make it a preferable choice. Specifically, butanol is generally more compatible with the materials used in conventional vehicles and the current fuel distribution system. Though butanol in the United States is currently produced primarily from petroleum, plans were recently announced for a pilot biobutanol plant (*New York Times,* January 13, 2010). Butanol may become a viable fuel choice sometime after 2010. Like ethanol, butanol used as a fuel would have a denaturant added, and to retain EPAct classification as an alternative fuel, it would likely have to be at least 85% butanol (with reductions to no lower than 70% in the winter, if necessary, to retain cold-start capabilities).

Several steps are required to make ethanol available as a vehicle fuel. First, feedstocks are grown, then various systems are used to collect and transport them to ethanol production facilities. After ethanol is produced at the facilities, a distribution network supplies ethanol-gasoline blends to fueling stations for drivers to use.

6.1 Fuel Description

Ethanol (CH_3CH_2OH), also known as ethyl alcohol, grain alcohol, and EtOH, is a clear, colorless liquid. Its molecules contain a hydroxyl group (-OH) bonded to a carbon atom. Ethanol is made of the same chemical compound, whether it is produced from starch- and sugar-based feedstocks such as corn (as it primarily is in the U.S.), from sugarcane (as it primarily is in Brazil), or from cellulosic feedstocks.

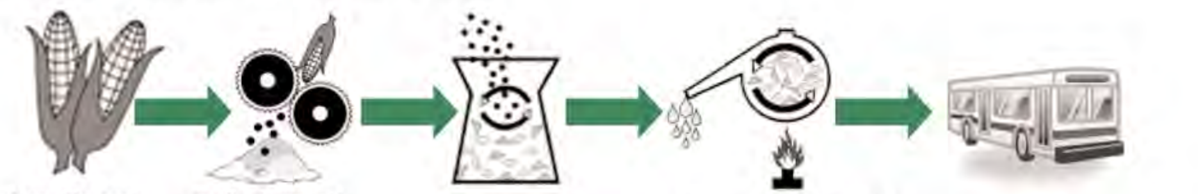
Is it Imported?

In 2008, only about 6% of ethanol used in the U.S. was imported, mostly from countries in Central and South America and the Caribbean. This figure could change dramatically, though, depending on future policy decisions and demand. For example, at present there is a tariff on imported ethanol, which tends to reduce imports to the U.S. market. But demand for ethanol is expected to increase. If the tariff is lowered or removed in order to help meet demand, import levels could increase.

The ASTM developed E85 fuel specifications to ensure proper vehicle starting, operation, and safety. E85, like gasoline and diesel fuels, is adjusted seasonally to ensure proper starting and performance in different geographic locations. Ethanol is a high-octane fuel. High octane helps prevent engine knocking in spark ignition engines.

U.S. fuel-grade ethanol has been exclusively bio-ethanol (produced from renewable crops) since passage of the 1978 Energy Tax Act, which defined gasohol as a blend of gasoline and ethanol produced from renewable biomass feedstocks. In the most common ethanol production process, sugars and starches in corn or sugarcane are fermented by yeast and bacteria to produce ethanol. Second-generation production methods seek to improve the breakdown of more complex plant compounds (i.e., hemicellulose and cellulose) into their component sugars, allowing the conversion of agricultural waste (e.g., corn stover and wheat stalks), switchgrass, and fast-growing trees into ethanol. The extent of government incentives is expected to substantially affect the timing of commercial adoption. The U.S. Department of Energy (DOE) has targeted the achievement of a cellulosic ethanol process that is cost-competitive with corn-based ethanol by 2012,[2] and several companies have announced plans to begin operating a commercial-scale demonstration facility within this timeframe.[3,4] It is reasonably likely that cellulose-based ethanol will begin to be commercially available between 2015 and 2020.

Figure 6.1 Ethanol Crop-to-Fuel Process



Making ethanol from cellulosic feedstocks—such as grass, wood, crop residues, or old newspapers—is more challenging than using starches or sugars. These materials must first be broken down into their component sugars for subsequent fermentation to ethanol in a process called biochemical conversion. Cellulosic feedstocks also can be converted into ethanol using heat and chemicals in a process called thermochemical conversion. Cellulosic ethanol conversion processes are a major focus of DOE research.

A full-size, E94 city bus made by Scania, first debuted in 2007.

Ethanol fuel typically includes a number of additives which serve the following purposes:

- Ignition improvement to compensate for ethanol's low cetane number (applicable for use in compression ignition engines);
- Corrosion inhibition to offset ethanol's corrosiveness; and
- Denaturant to reduce palatability and increase flame luminosity in the event of a fire.

Demonstrations of dedicated ethanol vehicles during the 1990s in the United States typically used either E95 or E100 (95% or 100% anhydrous ethanol, respectively). In contrast, the ethanol-dedicated buses currently produced by the Swedish manufacturer Scania use fuel that is 94% hydrous ethanol, which may include up to 5% water with the remainder being additives. These buses are not available in the United States.

The only vehicle fuel sold in the United States today that is substantially ethanol is E85, which is sold for the growing number of light-duty FFVs.[5] This fuel is blended for operation in gasoline spark-ignition engines, and contains 15% gasoline and 85% anhydrous ethanol (with less than 0.5% water). Winter blends may have an ethanol content that is as low as 70% ethanol to retain cold starting. E85 designed for today's FFVs cannot be used in compression-ignition ethanol engines.

Table 6.1 shows some of the key properties of alcohol fuels with no additives.

Table 6.1 Alcohol Fuel Properties [6,7]

Property	Ethanol (E100)	1-Butanol
Boiling Temperature (°F)	172	244
Autoignition Temperature (°F)	793	649
Cetane Number	0 – 54	NA
Octane Number (R+M)/2	115	87
Flash point (°F)	55	99
Flammability Limits (vapor in air by volume %)	4.3 to 19	1.4 to 11.2
Lower Heating Value (Btu/gal)	76,330	99,837
Relative Weight (same volume) Compared to air = 1 Compared to water = 1	 0.79 *(as vapor)* 1.6	 0.81 *(as vapor)* >1.6
Soluble in water (by volume)	Miscible in all proportions	Yes, up to 9%

6.2 Fuel Usage

The use of ethanol as a fuel has greatly increased in the last few years, though primarily as a gasoline additive. Additional near-future increases in ethanol demand are also projected from E85 sales for light-duty FFVs. Fuel uses such as these are discussed herein to provide a better understanding of the broader ethanol fuel market, since transit operations using ethanol fuel would have to compete with these other sources of ethanol demand.

A Brief History

- Since the phase-out of leaded gasoline from 1975 to 1986, many corn-producing states have promoted adding ethanol to gasoline because doing so boosts octane, increases energy security, and contributes to the regional economy. Containing around 10% ethanol by volume, this blended product was initially called gasohol.
- In the late 1980s, ethanol was also added to gasoline as an oxygenate in order to reduce winter carbon monoxide (CO) emissions.

Guidebook for Evaluating Fuel Choices for Post-2010 Transit Bus Procurements

- Throughout the 1990s, ethanol blends were only available on a regional and, in some places, seasonal basis. Methyl tertiary butyl ether (MTBE) was the most common additive in gasoline, primarily because it was cheaper than ethanol and other additives.

- In the late 1990s and into the next decade, some states began banning MTBE, which the U.S. EPA lists as a "potential" human carcinogen due to its leakage from fuel storage tanks into groundwater.

- Nationwide year-round use of ethanol blends began in 2006 when gasoline blenders implemented an industry-wide decision to replace MTBE with ethanol.

- The switch to ethanol was encouraged by the Renewable Fuels Standard (RFS), a provision of EPAct (2005). The 2005 RFS mandated that refiners, blenders, and importers implement a phased-in introduction of renewable fuels. The RFS 2012 target of 7.5 billion gallons of fuel ethanol use was nearly met in 2007 when 6.8 billion gallons were sold.[8]

- The Energy Act of 2007 increased and extended the phased-in goals of the RFS. It set an ultimate goal of using 36 billion gallons of biofuels (such as alcohols and/or biodiesel) by 2022. At least 21 billion gallons would come from "advanced" feedstocks (i.e., not corn starch), while 15 billion gallons may come from corn starch.[9] The availability and price of ethanol fuel for dedicated ethanol transit buses is likely to be substantially affected by the competing use of ethanol as a gasoline additive.

Did You Know?

One bushel of corn yields about 2.8 gallons of ethanol.

Demand for ethanol fuel is also expected to increase over the next several years due to demand for E85 from FFVs that are able to run on conventional gasoline, E85, or any combination of these. FFVs have been commercially available since the early 1990s, and since 1998 all U.S. auto manufacturers have sold FFVs designed for E85.[10] FFV production is promoted by incentives begun in the Alternative Motor Fuels Act (AMFA) of 1988 which allow alcohol-powered or dual energy vehicles to count towards auto companies' compliance requirements for the federal Corporate Average Fuel Economy (CAFE) Standards.[11,12] E85 use is currently limited by the number of stations where it is available, rather than by the number of FFVs. With nearly 7 million on the road, most are powered entirely by conventional gasoline by owners who do not even know that their vehicles are FFVs (the incremental purchase cost of an FFV versus a gasoline-only light-duty vehicle is around $200). Increases in the number of public service stations offering E85 is therefore likely to increase competition for the fuel needed by dedicated ethanol transit buses.

There were several demonstrations of dedicated alcohol transit buses in the 1990s. The Metropolitan Transit Commission of Minneapolis/St. Paul operated five buses powered by E95, Greater Peoria Transit in Illinois operated five ethanol buses powered by E93/95, and Miami-Dade operated five methanol buses.[13,14] The Los Angeles County Metropolitan Transportation Authority (LACMTA) also had a fleet of 330 buses powered by methanol in the 1990s. For the last year of the LACMTA demonstration, the buses were switched to ethanol to compare these alcohol fuels. The fleet was subsequently converted to diesel (as also occurred with alcohol-fueled buses in other cities) largely due to the higher costs associated with alcohol fuels and maintenance issues.

Internationally, the largest current ethanol transit bus fleet has operated since the early 1990s in Stockholm, Sweden. At this time, the Stockholm fleet has over 300 buses powered by E94, manufactured by the Swedish company Scania. Several Scania ethanol buses are also currently operated in Madrid, Spain; La Spezia, Italy; Slupsk, Poland; and several locations in Australia. After several years of field testing, the Brazilian transit agency, São Paulo Transporte (SPTrans), has announced the purchase of 50 Scania ethanol buses to be delivered in 2011. SPTrans has announced plans for further ethanol bus purchases, with manufacture of the buses in Brazil.[15] The Scania ethanol buses are not commercially available in North America.[16]

Site Visit!

June 30, 2009, STOCKHOLM, SWEDEN—Swedish bus manufacturer Scania has sold 85 ethanol-powered articulated buses to Busslink, operator of bus services for Storstockholms Lokaltrafik, the regional public transport company in the Swedish capital. Stockholm already boasts the world's largest fleet of ethanol buses providing service in the central areas of the city. The 85 buses for Busslink will go into service on routes supplied from depots in the northern and southern suburbs of the city; 40 of the buses are specifically designed for urban traffic while the others are adapted for regional service.

6.3 Safety, Training, and Disposal

Ethanol refueling station safety is addressed under the National Fire Protection Association (NFPA) codes 30 and 30-A, which are for the handling of motor fuels and other combustible liquids. E85 is poisonous and flammable, and, unlike gasoline, ethanol conducts electricity. While this does not necessarily result in additional safety issues, it does mean that some materials used in gasoline equipment need to be modified to dispense ethanol. In general, the same safety measures that apply to gasoline apply to E85.

All employees and fleet drivers using an E85 fueling system should do the following:

- Know basic safety practices.
- Understand the purpose and content of the fuel site's emergency action plan.
- Be familiar with signage and emergency equipment including the emergency shutdown button.
- Understand what emergency actions must be taken in the event of an accident.
- Possess an emergency action plan that includes the following:
    - Identification of what incidents might trigger the action plan.

- Actions to take for specific events.
- Notification procedures.
- Evacuation procedures.
- Safety systems.
- Emergency event action items.

Flammability and Toxicity

E85 has been determined to be a flammable liquid per the OSHA Hazard Communication Standard and should be handled accordingly. Ethanol vapors disperse more rapidly than gasoline vapors, lowering concentrations to safe levels more quickly after an accident. Water is not effective in extinguishing fires until the alcohol is diluted with water to be less than 20%. The flames from an ethanol fire are pale blue and may not be easily visible. Fire suppression systems would likely be recommended for ethanol buses with an appropriate fire suppressant.

Ethanol is less toxic than gasoline. The denaturant added to all fuel-grade ethanol may increase the ethanol's toxicity. Other alcohol fuels such as butanol, are more toxic than ethanol. Ingestion of as much as 3 to 7 ounces of butanol may cause death. Ethanol can be absorbed through the skin, with symptoms paralleling ingestion.

Training

There are no unique training needs for drivers who use ethanol fuels, although they should be aware of reductions in fuel economy. Maintenance personnel should also understand differences in the maintenance schedules, fuel flammability, solvent properties, materials compatibility, and emissions of alcohol fuels compared to diesel. The safety standards for handling E85 are the same as those for gasoline.

Did You Know?

Henry Ford designed the first mass-produced automobile, the Model T Ford, to run on pure anhydrous alcohol (ethanol).

U.S. Department of Transportation's Transportation Safety Institute (TSI) offers training courses specifically for transit agencies. Their 2011 course listings include "Safety Evaluations for Alternative Fuels Facilities and Equipment." This 3-day course provides "awareness and training in conducting safety evaluations for alternative-fueled vehicles, support equipment, and facilities using Compressed Natural Gas (CNG), Liquefied Natural Gas (LNG), hydrogen, fuel cells, propane, ethanol, electricity, bio-diesel, and hybrid electric." Classes are scheduled on an as-needed basis. Those interested should contact TSI.

Disposal

Ethanol fuel may be blended with gasoline, as in the E85 used in current light-duty vehicles in the United States. It may also be blended with diesel, as in the ethanol fuel used in the current Scania transit buses operating outside the United States. In either case, the conventional fuel (diesel or gasoline) generally poses greater disposal concerns than ethanol, thus following conventional fuel disposal and spill clean-up procedures is a conservative approach. Waste disposal rules are set at the state level, and may vary from state to state. The appropriate state authorities should be contacted for further guidance.

6.4 Technology and Performance

The technology of the ethanol buses demonstrated in the United States during the 1990s is significantly different from the ethanol buses that are currently available outside the United States. In the past, demonstrations in the United States used spark-ignition (gasoline) engines, while the continued ethanol bus operations outside the United States use modified compression-ignition (diesel) engines. The U.S. demonstrations were short-lived, due in large part to high costs of fuel and maintenance and reliability issues.

Outside the United States, transit buses using ethanol are manufactured by Scania, a Swedish company. Diesel engine modifications for ethanol use in the Scania buses include the following:

- Larger engine injector holes,
- Modified injection timing,
- Fuel pump with larger flow capacity, and
- Gaskets and filters in the fuel system changed to more alcohol-resistant materials.

Ethanol's energy content is about 40% less than diesel's on a per volume basis. The resulting larger fuel capacity gives ethanol buses a weight penalty that may cause slight reductions in acceleration compared to diesel buses. In the 1990s, U.S. field tests, performance of ethanol buses was reported to be similar to diesel buses.[17]

On an energy equivalent basis, the fuel economy for the 1990s ethanol buses was reported to be "about" the same as diesel transit buses, even though ethanol buses were 1,000 to 1,500 pounds heavier (depending on fuel capacity) and had higher frictional losses in the engine (due to the engine's higher compression ratio and greater piston side losses).[18]

The fuel economy of recent Scania ethanol buses that were field tested in Brazil was lower than expected on an energy equivalent basis. The lower fuel economy was attributed at least in part to a fuel system optimized for a colder climate. Adjustments for warmer climates have since been made.[19] The newest generation of Scania ethanol buses are projected to have fuel economy on par with diesel buses on an energy equivalent basis. These newest buses are being tested in Sao Paolo, where public transit is operated by private companies, which promotes inclusion of all direct costs in the assessment of these buses.

6.5 Maintenance, Reliability, and Storage

It has been over a decade since transit buses in the United States have operated with ethanol—the 1990s demonstrations were not continued because the overall results were not favorable. This discussion of maintenance and reliability mentions some of the issues of the 1990s and contrasts them to the information available on recent, more successful ethanol vehicles, particularly Scania ethanol buses.

Heavy-duty vehicles operating on E95 in the 1990s were reported to have maintenance costs that were two to three times greater per year than their diesel counterparts. Fuel filters were a significant cause

Guidebook for Evaluating Fuel Choices for Post-2010 Transit Bus Procurements

of these increased costs—the filters were costly and required frequent replacement compared to diesel buses.[20] This was due to the smaller pore size of the filter, which was required because the lower lubricity of E95 (even with a lubricity additive) causes lower tolerance for fuel impurities.[21] This issue appears to be reduced in the light-duty FFVs using E85 with spark-ignition engine. It has also not been reported as a significant issue for the recent Scania buses, although Scania does carefully specify fuel requirements.

The reliability of ethanol transit buses in the 1990s was generally lower than for diesel buses.[22] Reliability issues have not been noted for the Scania ethanol buses, which use a different engine technology.

Since the ethanol fuel specified for use in Scania ethanol buses is not used in the United States, there is no U.S. guidance specific for these fueling facilities. However, there has been significant address of E85 refueling as used by light-duty FFVs. Although an E85-certified fuel dispenser is not yet available, Underwriters Laboratories (UL) is currently evaluating E85 dispensing equipment.[23] Analysts of the

How is it Stored?

Because ethanol is corrosive, special attention must be given to the materials used for fuel storage. Zinc, brass, lead, and aluminum are generally sensitive to high-blend alcohol fuels, so fueling system components containing them should be avoided. Terne-plated steel (steel plated with a lead-tin alloy) and lead-based solder are not compatible with E85. Other materials that may degrade in the presence of high-blend alcohol fuels include natural rubber, cork, leather, polyurethane, polyvinyl chloride (PVC), polyamides, methyl-methacrylate plastics, and some types of thermo and thermoset plastics.

1990s transit experience with ethanol suggest that materials incompatibility in the fuel dispenser system may have been a significant cause of fuel filter plugging and associated increased road-calls.[24] A checklist for installing and converting dispensing equipment for E85 is available from DOE's Office of Energy Efficiency and Renewable Energy (EERE).[25] While these sources are directed towards refueling light-duty FFVs, their recommendations may also assist bus operators. Local petroleum equipment suppliers often have the recommended fueling components and any qualified equipment installer can perform the necessary changes.

Maintenance and storage facilities that are certified for gasoline do not require heating, ventilation, or electrical changes with the use of ethanol. However, a cistern is required for the drain to trap fuel leakage, and no ignition sources are to be placed within 18 inches of the floor.[26] The primary differences in fueling facilities are related to the materials composition of the storage tank and refueling system components. There may also be increases in fuel storage and transfer rate capabilities to make them similar to diesel on an energy basis.

Most states, DOTs, and other authorities having jurisdiction require specific E85-related signage at refueling stations. Contact the appropriate official in your area to determine the required signage for E85. Storage tanks containing E85 must be labeled on all fillboxes and fillbox covers with a bronze pentagon (left, above) with "E85" printed in black in the middle. In addition, the Federal Trade Commission requires that a small sticker (left, below) be placed on the face of the fuel dispenser as close as possible to the price per unit of fuel.

6.6 Emissions

Emissions are addressed in the following two sub-sections. The first section discusses local and regional pollutants that are currently regulated under the Clean Air Act [i.e., hydrocarbons (HC), nitrogen oxides (NOx), particulate matter (PM), and carbon monoxide (CO)]. The second section discusses pollutants that contribute to global warming [i.e., greenhouse gases (GHG)].

Regulated Pollutants

The oxygen content of ethanol allows a more complete burn of the fuel compared to diesel. This means fewer emissions of HC, PM, and CO. Transit buses powered by E95 have PM levels comparable to similar diesel buses equipped with particle traps.[27] Tests on light-duty FFVs have shown that, compared to reformulated gasoline, E85 reduces NOx as well as the toxics benzene and 1.3-butadiene, although it does increase formaldehyde and acetaldehyde emissions.

Emissions measurements from the ethanol bus demonstration programs of the 1990s can be used to suggest emissions changes in the event that pre-MY2007 buses are converted to E95. These data are shown in Table 6.2.

Guidebook for Evaluating Fuel Choices for Post-2010 Transit Bus Procurements

Table 6.2 Comparison of Emissions and Fuel Economy for 1990s Buses Powered by E95, and Diesel, With and Without a Diesel Particle Filter (DPF)

	Diesel (g/mile)	Diesel w/ DPF (g/mile)	E95 (g/mile)
Carbon Monoxide	7.9	-	23.9
Nitrogen Oxides	25.7	-	17.7
Particulate Matter	0.86	0.39	0.56
Hydrocarbons	2.73	-	9.7
Fuel Economy (mpg)	4.4	-	2.7

Average of Peoria and Minneapolis/St.Paul bus fleets (after repair of Peoria buses) as reported by Motta, Norton, Kelly, Chandler, Schumacher, and Clark, 1996.

The only currently manufactured ethanol bus (by Scania) meets Euro V standards, which are not as stringent as EPA MY2010 heavy-duty engine standards. Scania has not sold their ethanol engines or buses in the U.S. market, and thus has not applied for EPA certification. For the purposes of default values in the FuelCost2 model, it is assumed that if a dedicated ethanol bus becomes available in MY2010 or beyond, it will meet the applicable EPA standards, thus, an upper end default value for ethanol is simply the EPA standard converted to grams per mile, as shown in Table 6.3.

Table 6.3 Upper-End Emissions Permissible from Ethanol Buses in 2010

	g/ bhp-h	(g/mile) *
Carbon Monoxide	15.5	52.0
Nitrogen Oxides	0.20	0.67
Particulate Matter	0.01	0.03
Non-Methane Hydrocarbons	0.15	0.50

* Based on EPA Emission standards for heavy-duty engines in 2010. Units of g/bhp-h are converted to g/mile using the EPA conversion factor for gasoline (spark-ignition) engines. Note: these estimates are not appropriate for Scania's compression-ignition ethanol engines.

Greenhouse Gases

Because GHG emissions affect the whole globe no matter where they are produced, it is necessary to consider all the GHG emissions created by ethanol fuel over its entire lifecycle, from crop field to tailpipe. Producing ethanol from biomass is generally viewed as a way to reduce GHG emissions, although the extent of the reductions varies substantially depending on factors such as feedstock crop, farming methods, prior land use, etc. Under some scenarios, GHG emissions may increase rather than decrease.

As a result of the lower energy content of alcohol fuels, tailpipe emissions of GHGs from alcohol-fueled vehicles are greater than those from gasoline- and diesel-fueled vehicles. However, the GHG emissions from biomass-based alcohols represent carbon that was recently captured for crop growth. Using current corn-based production methods, the GHG emissions associated with ethanol fuel use are about 12% less than those associated with gasoline use (assuming no land use changes for cropland).[28]

A large portion of corn-based alcohol fuels' lifecycle GHG emissions comes from gaseous releases from crop fields. In particular, the fertilizer used in corn fields leads to significant emissions from the soil of nitrous oxide (N_2O), a GHG that is 296 times as potent as CO_2. In fact, N_2O released from crop fields is the single largest GHG source in the ethanol lifecycle. Partly because conventional corn cultivation uses a particularly high level of fertilizer, corn-based alcohol has fewer GHG benefits than soybean-based biodiesel.[29] Alcohol feedstock shifts to perennials such as switchgrass and hybrid poplar may substantially reduce net GHG field releases.[30]

There is some controversy over the extent of GHG savings associated with biomass-based alcohols. This stems from questions about both the amount of N_2O produced during the crop cycle (primarily by soil bacteria) and the assumptions used to account for the emissions savings from biofuel crop co-products, such as feed for livestock. Development of a biofuels rating system for GHGs has been proposed, in which a particular fuel source or supply would be rated with respect to the relative GHG savings associated with its use compared to the conventional fossil fuel.[31]

EPA estimates of GHG emissions associated with corn-based ethanol use in 2012 (as published in 2007) suggest that for every energy unit (Btu) of gasoline replaced by ethanol, there is approximately a 20% decrease in GHG production.[32] In contrast, other sources have estimated this decrease in GHG releases to be only 12%.[33] Ethanol produced from other feedstock can substantially improve GHG emissions relative to diesel, but for the purposes of providing initial GHG values in FuelCost2, corn-based ethanol GHG reductions of 12% will be used as the default value.

6.7 Cost and Availability

Vehicles

The major U.S. automakers produce light-duty FFVs capable of running on E85, including some vans that may be applicable for some paratransit applications. Current availability of FFVs can be searched through the DOE EERE website.[34] Availability of light-duty E85 vehicles is likely to continue at least until 2022, when the Energy Act of 2007 calls for an end to allowing dual energy vehicles to count towards a manufacturer's CAFE requirements for light-duty vehicles.

In contrast, there are currently no U.S. manufacturers producing heavy-duty vehicle engines designed for use with alcohol fuels. Detroit Diesel Corporation's 6V-92TA engine was designed to be fueled by methanol or ethanol, and was used in transit buses, school buses, and heavy-duty trucks. Production of this engine ceased in the mid-1990s due to low demand which has been largely attributed to high fuel costs.[35] As discussed previously, Scania is currently the only manufacturer that offers buses fueled by ethanol.[36]

The average incremental cost of an ethanol bus in the demonstration fleets of the 1990s was $20,000, or about 9% of then-current diesel bus costs.[37] The incremental cost of an ethanol bus was less in 2007, based on the Scania ethanol bus base price of $334,700, which is only $17,000 (5%) more than its diesel counterpart.[38] The FuelCost2 model uses the Scania 2007 proportionate incremental price of 5% as the default incremental cost of an ethanol bus over a diesel bus.

Vehicle maintenance costs of dedicated ethanol vehicles have been reported to be significantly higher than for comparable diesel vehicles. While the amount varies, it is estimated based on reports from the 1990s that dedicated heavy-duty ethanol vehicles have maintenance costs around three times greater than for similar diesel vehicles.[39, 40] In a year of operation of a Scania ethanol bus in Brazil, maintenance costs were similar for diesel and ethanol buses, although ethanol fuel costs were 20% to 40% higher for ethanol than diesel.[41] For the purposes of providing a default value for bus maintenance costs in the accompanying FuelCost2 spreadsheet, ethanol bus maintenance costs will be estimated to be the same as for diesel buses.

Fueling Facility

It has been more than a decade since a transit bus operation has added (or converted to) E85 refueling. Still, the results of a recent survey of the costs of adding E85 fueling to gasoline stations for light-duty vehicles may provide hints as to what the expense of conversion might be. These survey results showed a large variance in the cost of adding E85 fueling.[42] Some of the major variables were:

- The number of dispensers needed.
- Excavation and concrete work required for new tank installation (which largely depends on the type of ground being excavated).
- Sell backs: tanks and dispensers can be sold on the second-hand market for a considerable price.
- Canopy requirements: a large expense when needed.
- Fuel tank size requirements.
- Location: regions that already have many E85 stations tend to have lower costs due to competition between experienced installation technicians.

Based on the survey, the mean cost of adding E85 fueling to gasoline stations is estimated at $71,735 in cases with new tank/dispensers and $21,031 in cases with converted tank/dispensers.[43] For an "apples and oranges" comparison, the fueling facility conversion costs for new tank/dispensers for a 160-bus fueling facility in the mid-1990s was estimated to be $50,000 to $100,000 in 1994 dollars.[44]

The default value for refueling facility capital costs in the FuelCost2 model is $100,000, or the upper end of the 1990s value without any inflation adjustment. It is assumed that cost reductions related to light-duty vehicle E85 refueling experience is roughly equal to inflation.

Fuel

Ethanol feedstock prices (and hence fuel ethanol prices) vary from year to year based on short-term supply, which in turn is determined by factors such as the weather, crop disease, and the prices of other crops. The most common ethanol feedstock, corn, is traded globally. Thus, while around 80% of fuel ethanol currently used in the United States is from domestic corn, the effect of supply and demand on feedstock price occurs at a global level. As a commodity fuel, ethanol can be hedged for a year or two to protect the user from wild price spikes.

Currently, it is possible that any ethanol bus engines that may become available in the United States in future years may use Scania's compression ignition engine technology. These would have fuel specifications that are significantly different than the specifications for the light-duty FFVs currently in the United States. Nevertheless, for the purposes of discussing ethanol fuel costs in the United States, the FFV fuel, E85, is used.

E85 prices at the pump were less than diesel prices in 2007 due in part to a fuel blenders' tax credit (the Volumetric Ethanol Excise Tax Credit, or VEETC) of 51 cents per gallon of blended ethanol. Without VEETC E85 prices would have remained above diesel prices throughout 2007. VEETC was reduced to 45 cents per gallon in 2008 and it is currently set to expire on December 31, 2011.[45] While the U.S. government has consistently offered biofuel incentives over the past few decades, it is not likely that tax credits allowing E85 to be sold at prices lower than conventional fuels will play a major role in the future.

The price of fuel ethanol also varies with geographic area and supplier. Sources are greatest in the Midwest. Estimates of ethanol adoption costs used as initial values in FuelCost2 are summarized in the table below along with estimates for diesel.

Table 6.4 Dedicated Ethanol Bus and Diesel Cost Estimates

Item	E85	Diesel
New Vehicle	$367,500 [a]	$350,000
Facility Conversion	$100,000 [b]	--
Fuel[c]	$2.02/gal E85 $3.19/DGE E85	$2.51/gal
Fuel economy (mpg) (miles/DGE)	1.9 [d] 3.2	3.2 3.2
Propulsion System Maintenance ($/mile)	$0.18 [e]	$0.16
Facility Maintenance ($/mile)	$0.18 [e]	$0.18

a. E85 bus price is estimated to be 5% higher than a diesel bus based on the 2007 Scania ethanol bus price of $334,700, and comparable diesel bus price of $321,143.
b. Based on 1990s demonstration fleets[46]
c. Based on the 2009 Clean Cities Alternative Fuels Price Report annual average
d. Assumes 40-ft bus with average speed of 13 mph and 3 months per year hotel load. Calculated as a 25% reduction in fuel economy compared to diesel on an energy basis due to engine efficiencies that are similar to gasoline engines.
e. Projected to be the same as for CNG (spark-ignition engines)—this assumes improvements over the 1990s demonstration fleets with $0.45/mile propulsion system maintenance costs.[47]

Future E85 fuel prices in FuelCost2 are based on the assumption that over multiple years the average price of E85 will be 20% more than diesel on a per diesel gallon equivalent (DGE) basis. This was the average difference between the price of E85 and diesel throughout 2008 and 2009.[48]

Future improvement in alcohol production processes and development of new crops for feedstock offer the greatest potential for decreases in the relative costs of alcohol fuels. With continued alcohol demand to promote crop research and development, non-food crops are moderately likely to provide a growing future alcohol source through 2020.

6.8 Summary

Ethanol

Pros	Cons
Ethanol is fairly established as an alternative fuel for light-duty vehicles in the United States and for full-size buses in Sweden.	Currently, there are no buses in the United States that use E85 or other high ethanol percentage blends.
Ethanol is less toxic than gasoline. There is no special training necessary for bus drivers to operate ethanol-powered buses. Most safety requirements for gasoline are the same as for ethanol.	Ethanol is a flammable liquid. Unlike gasoline, ethanol conducts electricity, meaning some materials used to dispense gasoline must be redesigned for use with ethanol.
Using ethanol fuel produced from biomass such as corn can provide modest reductions in lifecycle GHG emissions compared to diesel. GHG reductions can be substantially increased with cellulosic ethanol.	Until cellulosic ethanol becomes common, the modest GHG reductions with corn-based ethanol may be of questionable benefit in light of food-for-fuel concerns.
Ethanol is often produced regionally, and use of ethanol for a transportation fuel can support the regional economy.	The chemical properties of ethanol make it more easily suited for spark-ignition gasoline engines than for heavy-duty diesel engines.
A combination of reductions in ethanol content and fuel additives can significantly improve cold-start issues with ethanol.	There can be cold-start issues with higher ethanol-content fuels.

Ethanol References

[1] U.S. Department of Energy (DOE), Office of Energy Efficiency and Renewable Energy (EERE), *Ethanol Basics,* http://www.afdc.energy.gov/afdc/ethanol/basics.html

[2] DOE EERE, Biomass Program webpage, Retrieved from http://www1.eere.energy.gov/biomass/biofuels_initiative.html

[3] DuPont and Danisco, (May 14, 2008). Press Release, *DuPont and Genencor Create World-Leading Cellulosic Ethanol Company*, http://www.danisco.com/wps/wcm/connect/genencor/genencor/media_relations/investor_257_en.htm

[4] Range Fuels, Our First Commercial Plant webpage, Retrieved from http://www.rangefuels.com/our-first-commercial-plant.html

[5] Green Car Congress, (June 28, 2006).*U.S. Automakers Pledge to Double Output of Biofuel Vehicles by 2010*, http://www.greencarcongress.com/2006/06/us_automakers_p.html

[6] U.S. Department of Energy, Alternative Fuels and Advanced Vehicles Data Center (AFDC). Properties of Fuels. Retrieved from http://www.afdc.energy.gov/afdc/pdfs/fueltable.pdf

[7] Bromberg, L, and D.R, Cohen, (2008). Effective Octane and Efficiency Advantages of Direct Injection Alcohol Engines. MIT Laboratory for Energy and the Environment Report LFEE 2008-01 RP. Retrieved from http://web.mit.edu/mitei/lfee/programs/archive/publications/2008-01-rp.pdf.

[8] Renewable Fuels Association, *Statistics*, http://www.ethanolrfa.org/industry/statistics/

[9] *Energy Independence and Security Act of 2007*, (P.L. 110-140, December 19, 2007). Retrieved from: http://frwebgate.access.gpo.gov/cgi-bin/getdoc.cgi?dbname=110_cong_public_laws&docid=f:publ140.110.pdf

[10] MacDonald, Thomas, 2005. *Alcohol Fuel Flexibility—Progress and Prospects*, California Energy Commission, http://www.energy.ca.gov/2005publications/CEC-600-2005-038/CEC-600-2005-038.PDF

[11] The Library of Congress, Summary of the Alternative Motor Fuels Act of 1988, http://thomas.loc.gov/cgi-bin/bdquery/z?d100:SN01518:@@@L&summ2=m&

[12] The program that allows CAFE reductions for production of FFVs was extended by the Energy Act of 2007, which calls for a scheduled phase out of this incentive in 2022.

[13] Motta, Robert, et al., *Alternative Fuel Transit Buses: Final Results from the National Renewable Energy Laboratory (NREL) Vehicle Evaluation Program*, October 1996, http://www.cleanairnet.org/infopool/1411/articles-59985_resource_1.pdf

[14] GAO, December 1999. Mass Transit: Use of Alternative Fuels in Transit Buses. Report to Congressional Committees. Retrieved from http://www.gao.gov/new.items/rc00018.pdf

[15] Bio Fuel Daily, (November 30, 2010). Brazil Invests in Scania Ethanol Buses. Retrieved from http://www.biofueldaily.com/reports/Brazil_Invests_In_Scania_Ethanol_Buses_999.html.

[16] Email communication with Mr. Hans-Åke Danielsson, Scania Press Manager, hans-ake.danielsson@scania.com, (May 5, 2008).

[17] Motta, et al., 1996

[18] *Ibid.*

[19] Velázquez, S, et al., December 2009. Report on Experiences of Ethanol Buses and Fuel Station in Sao Paulo, BEST Project Final Report, CENBIO- Brazilian Reference Center on Biomass, São Paulo, Brazil. http://www.best-europe.org/upload/BEST_documents/info_documents/Best%20reports%20etc/D2.07_Ethanol_Buses_in_SaoPaulo.pdf

[20] *Ibid.*

[21] National Renewable Energy Laboratory, *Hennepin County's Experience with Heavy-Duty Ethanol Vehicles*, NREL/SR-540-22726, (January, 1998). http://www.afdc.energy.gov/afdc/pdfs/hennepin.pdf

[22] Motta, et al., 1996

[23] Underwriters Laboratories, Press Release, *Underwriters Laboratories Announces Development of Certification Requirements for E85 Dispensers*, (October 16, 2007). http://www.afdc.energy.gov/afdc/pdfs/e85_requirements_release_101507.pdf

[24] Motta, et al., 1996

[25] DOE EERE, Checklist of Installing or Converting Equipment to Dispense E85, http://www.afdc.energy.gov/afdc/pdfs/e85_site_checklist.pdf

[26] National Alternative Fuels Hotline, DOE EERE, *Heavy-Duty Vehicle and Engine Resource Guide*, 1996, http://ntl.bts.gov/lib/5000/5800/5816/hvyeng96.pdf

[27] *Ibid.*

[28] Hill, Jason, et al., (July 25, 2006). *Environmental, Economic, and Energetic Costs and Benefits of Biodiesel and Ethanol Biofuels*, Proceedings of the National Academy of Sciences, 103(30):11206-11210, http://www.pnas.org/cgi/content/full/103/30/11206

[29] *Ibid.*
[30] Adler, Paul R., Stephen J. Del Grosso, and William J. Parton, (April, 2007). *Life-Cycle Assessment of Net Greenhouse-Gas Flux for Bioenergy Cropping Systems*, Ecological Applications, 17(3):675-691, http://ddr.nal.usda.gov/bitstream/10113/7752/1/IND43965267.pdf
[31] Retka Schill, Susanne, (August 2007). *Developing a Biofuels Rating System*, Ethanol Producer Magazine. http://www.ethanolproducer.com/article.jsp?article_id=3169&q=&page=1
[32] U.S. Environmental Protection Agency (EPA), (April 2007). *Regulatory Impact Analysis: Renewable Fuel Standard Program*, EPA420-R-07-004, p. 250, http://www.epa.gov/otaq/renewablefuels/420r07004.pdf
[33] Hill, et al., 2006
[34] Flexible fuel vehicle availability can be searched through DOE EERE, *Flexible Fuel Vehicle Availability*, http://www.eere.energy.gov/afdc/vehicles/flexible_fuel_availability.html
[35] National Alternative Fuels Hotline, 1996
[36] Scania corporate Web site, http://www.scania.com/products/bus/engines/alternative_fuels/
[37] National Alternative Fuels Hotline, 1996
[38] Ehrlich, David, (October 10, 2007). *Scania Cuts Price of Ethanol-Powered Buses*, Cleantech Group LLC, http://media.cleantech.com/1902/scania-cuts-price-of-ethanol-powered-buses
[39] Motta, et al., 1996
[40] National Renewable Energy Laboratory, 1998
[41] Motta, et al., 1996
[42] National Renewable Energy Laboratory, (March 2008). *Cost of Adding E85 Fueling Capability to Existing Gasoline Stations: NREL Survey and Literature Search*, NREL/FS-540-42390, http://www.afdc.energy.gov/afdc/pdfs/42390.pdf
[43] *Ibid.*
[44] Motta, et al., 1996
[45] Renewable Fuels Association, *VEETC*, http://www.ethanolrfa.org/resource/federaltaxincentives/veetc/
[46] *Ibid.*
[47] *Ibid.*
[48] DOE EERE, Clean Cities Alternative Fuel Price Report archives, http://www.afdc.energy.gov/afdc/price_report.html.

7.0 Compressed Natural Gas

Compressed natural gas (CNG) is a form of natural gas that has been put under high pressure to increase its energy density. This is done to allow storage volumes that are suitable for vehicular use. Natural gas is widely available from an extensive pipeline network that reaches across much of the country. Specialized refueling equipment is required for delivering natural gas as CNG.

While CNG is the primary focus of this chapter, each section briefly addresses CNG blends with hydrogen, referred to as Hydrogen-enriched Compressed Natural Gas (HCNG). HCNG blends are in pilot stages of development and are promoted as "bridging" fuels to facilitate a future hydrogen economy.

7.1 Fuel Description

Natural gas comes primarily from fossil reserves. Pipeline natural gas has been refined to typically be over 90% methane, with small amounts of other light hydrocarbons including ethane, propane, and butane, as well as inert gases such as nitrogen. Small amounts of odorants are added to natural gas as a safety measure. Pipeline gas composition varies by region and season due to variations in wellhead and refined gas.

Compressed Natural Gas,
{k*uh*m-**prest nach**-er-*uh*l gas}
noun – a mixture of hydrocarbons, principally methane, stored at a high-pressure.

On a volume basis, under normal atmospheric conditions, natural gas contains much less energy than gasoline or diesel fuel. But natural gas energy density is increased by compressing it to very high pressures. Common vehicle storage pressures of CNG are 3,000 to 3,600 pounds per square inch (psi). Energy storage density directly affects vehicle driving range—the greater the amount of stored energy, the greater the driving range.

Pipeline natural gas is often referred to as "dry gas" because the water vapor content has been reduced to levels that are unlikely to condense in the pipeline—this effectively prevents the formations of liquid water in the pipeline and associated corrosion. When natural gas is compressed to 3,600 psi for use in a vehicle, the dew point (i.e., the temperature at which water vapor will form water droplets) increases from well below 0°F to around 60°F. When the temperature of a CNG tank falls below the dew point, water droplets can form inside the tank and mix with contaminants such as carbon dioxide and hydrogen sulfide to cause corrosion. To prevent this, "dry" pipeline natural gas is typically further dried on-site to reduce water vapor to a level that will not cause problems when compressed to 3,600 psi.

Table 7.1 lists the fuel properties of natural gas versus diesel. An octane rating well over 100 makes natural gas well-suited for use in spark-ignited engines.

Table 7.1 Natural Gas and Diesel Fuel Properties

Property	Natural Gas	Diesel
Boiling Temperature (°F)	-260	356 to 644
Autoignition Temperature (°F)	900	600
Cetane Number	N/A	40 to 55
Octane Number (R+M)/2	120	N/A
Flash point (°F)	-306	≥140
Flammability Limits (vapor in air by volume %)	5 to 15	1 to 6
Lower Heating Value (Btu/lb)	20,263	18,394 *(128,450 Btu/gal)*
Relative Weight (same volume) Compared to air = 1 Compared to water = 1	 0.60 0.45 *(as liquid)*	 >3 *(as vapor)* 0.85
Soluble in water	No	No

N/A : Not Applicable

HCNG typically contains 20% to 30% hydrogen by volume, with natural gas making up the balance of the mixture. The addition of hydrogen to natural gas extends the flammability range shown in Table 7.1, and reduces the lower heating value.

Key Point

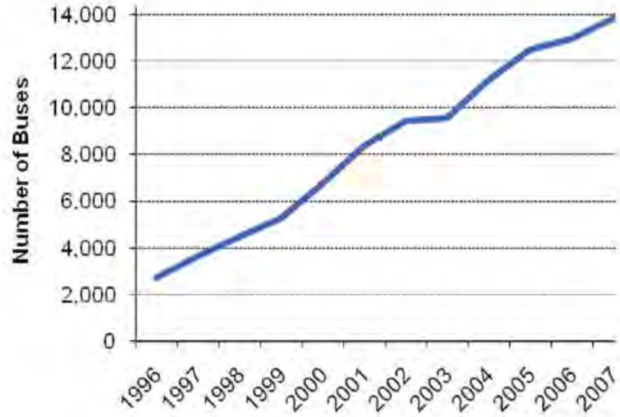
Even in its compressed state, CNG has only about 25% of the energy as the same volume of diesel fuel. That means fuel storage volume for CNG must be about four times that of diesel for the same amount of fuel energy.

7.2 Fuel Usage

CNG has been used as a transit bus fuel for decades. Nationwide, roughly 14,000 transit and paratransit buses operate on natural gas, and most of these use CNG. In 2007, nearly 30% of fixed-schedule transit buses operated on fuels other than diesel—60% of these ran on natural gas.[1] Figure 7.1 shows the steady growth in the number of operating natural gas buses from 1996 to 2007.

NGVAmerica estimates that in 2009, there were over 125 transit agencies operating natural gas buses. The following are some of the largest CNG bus fleets:

Figure 7.1 Number of Operating Natural Gas Buses in the United States, 1996 - 2007



- Los Angeles County Metropolitan Transportation Authority (LACMTA), over 2,500 CNG buses,
- Massachusetts Bay Transportation Authority (MBTA), over 500 CNG buses,
- New York City Transit (NYCT), over 450 CNG buses, and
- Washington Metropolitan Area Transit Authority (WMATA), over 450 CNG buses.

Did You Know?

There are over 9.6 million vehicles powered by natural gas worldwide. The greatest numbers are in Pakistan (2.0 million), Argentina (1.7 million), Brazil (1.6 million), and Iran (1.0 million). These statistics are tracked by the International Association for Natural Gas Vehicles.

Is it Imported?

Only 16% of the natural gas used in the United States is imported, and 88% of the imported gas was shipped by pipeline from Canada and Mexico. The remaining 12% of imported natural gas was delivered to our shores as liquefied natural gas, transported by ship from other countries.

There are several field tests of HCNG buses across the country:

- SunLine Transit began field testing two HCNG buses in 2004, with a fuel mix containing 20% hydrogen. This field test has been in conjunction with Cummins Westport.
- Centre Area Transportation Authority (CATA) began field testing an HCNG bus in 2007 using a 30% hydrogen mix. This field test has been in conjunction with Pennsylvania State University.
- Greater Vancouver Transportation Authority (TransLink) began field testing two HCNG buses in 2007 using a fuel mix with 20% hydrogen.
- San Francisco International Airport is constructing a refueling station in 2010 for 14 shuttle buses that will run on an HCNG blend with 20% hydrogen.

7.3 Safety, Training, and Disposal

Flammability and Toxicity

Natural gas is not toxic, but can cause asphyxiation if a sufficient amount is released in an enclosed area. Under most conditions, flammability is the risk of greatest concern. Under normal atmospheric conditions, natural gas is lighter than air, making released gas rise to the ceiling in enclosed areas. The ability of natural gas to move upward in air is indicated by a specific gravity in air of less than 1, as shown in Table 7.1. Although natural gas is lighter than air at the same temperature, when a substantial amount of natural gas under high-pressure is quickly released, sudden expansion causes the gas to cool. The cool gas may initially be heavier than the surrounding air, causing it to hover near the ground until it warms to near the air temperature. Leaks directed downward could also create momentary high concentrations at ground level.

The possibility of released gas temporarily concentrating anywhere from the floor to the ceiling means flammable mixtures are possible throughout a garage or maintenance facility, or within the confines of a vehicle. Fire and explosion risks are reduced by a combination of means including: early detection (through either smell of the odorants in natural gas or natural gas detectors with alarms), control of ignition sources, use of explosion-proof electrical devices, and ventilation to quickly disperse released gas. Odorant added to natural gas may be smelled when the gas present is well below 5%—the minimum amount of gas needed in air for a flammable mixture, as indicated by the lower flammability limit shown in Table 7.1.

CNG leaks can be characterized as slow or fast leaks, each of which has different risks:

SLOW LEAK

A slow leak results when gas escapes through a small gap such as a loose fuel line fitting. During slow releases, the natural mixing of gas with the surrounding air causes much of the mixture to be too lean to be flammable. In these cases, flammable mixtures are more likely to occur only very near to the point of release.

FAST LEAK

A fast leak may occur as a result of events such as a release from storage or fuel tank pressure relief devices, or rupture of a high pressure line in the refueling system. During these events, flammable mixtures may occur at a substantial distance from the release point—nearer the release point, natural gas may exceed 15% of the air-gas mixture, making it too rich to be flammable.

Larger gas releases can pose an explosion hazard under enclosed or obstructed conditions. There have also been incidents of CNG cylinder explosions due to factors such as corrosion from leaking battery acid, manufacturing defects, and either internal or external damage. The American National Standard for Natural Gas Vehicle Containers (ANSI NGV2) calls for CNG cylinder inspections, and NFPA 52, a national-level code, calls for installation of on-board methane detectors. Although not a national-level requirement, fire suppression systems are also typically installed on CNG buses, and may be an insurance requirement.

In contrast to diesel facilities, fire codes for natural gas facilities typically do the following:

- Restrict open flames,
- Require lighting, heating, and electrical systems that are rated for hazardous environments,
- Require ventilation in enclosed areas, and
- Require use of methane detectors in high-risk areas.

CNG buses and facilities are designed to meet a variety of standards, codes, and advisories, some of which are listed in Table 7.2. An updated list of relevant standards and codes is available at http://www.cleanvehicle.org/technology. Safety characteristics of HCNG are similar to CNG, and the same codes are likely to be used.

A blue CNG diamond decal is often used to inform emergency responders of buses and facilities that contain CNG, though there is no uniform requirement for use or placement of this common marking.

Blue diamond symbol commonly used to identify CNG buses and facilities.

High Pressure

Gas released at very high velocities from pressure or thermal relief devices, or an improper or damaged fitting or high pressure line, can cause tissue damage. Further, the high velocity release of gas from flexible hoses such as during refueling can cause an improperly placed or damaged refueling hose and nozzle to whip around, injuring people and damaging surrounding equipment.

Training

Training for CNG bus operators and maintenance personnel is needed to familiarize them with the CNG dispensing system, bus technology, and safety needs associated with natural gas use. Similar training would be needed for HCNG.

Maintenance needs and schedules for CNG buses are different than for diesel buses. As part of the bus procurement process, most bus manufacturers provide extensive training to transit agencies on the unique aspects of CNG buses. Additional training aids are available through organizations such as the Clean Vehicle Education Foundation, which publishes online technical bulletins and documents such as the "CNG Fuel System Inspector Study Guide," all available through: http://www.cleanvehicle.org/technology.

Table 7.2 Selected Codes, Standards, and Guidelines for CNG Vehicles and Infrastructure

Standard	Description
NFPA 52—Vehicular Gaseous Fuel Systems Code (2010)	Covers CNG, LNG, and hydrogen vehicles (including marine) and fueling facilities.
NFPA 88A—Standard for Parking Structures (2007)	Covers open, enclosed, basement, and underground parking structures.
NFPA 30A—Code for Motor Fuel Dispensing Facilities and Repair Garages (2003)	Covers facilities dispensing both gaseous and liquid fuels at the same facility.
SAE J1616—Recommended Practice for Compressed Natural Gas Fuel (1994)	Recommendations of vehicular fuel composition.
SAE J2406—Recommended Practices for CNG Powered Medium and Heavy-Duty Trucks (2004)	Covers CNG powered medium and heavy-duty trucks (>14,000gvwr).
Design Guidelines for Bus Transit Systems Using CNG as an Alternative Fuel (6/96)	FTA Report that references required codes and provides additional precautions and general information.
NFPA 1—Uniform Fire Code (2009)	The most widely adopted model building code in the U.S. Provides basis for local fire codes.
ANSI NGV1—1994 (with 1997 & 1998 addenda) – Compressed Natural Gas Vehicle Fueling Connection Devices	Assures standardized nozzles and receptacles.
ANSI NGV2—2000 —Basic Requirements for Compressed Natural Gas Vehicle Fuel Containers	Provides container requirements, including periodic visual inspections, in addition to FMVSS 304 requirements
ANSI NGV4.1/CSA 12.5—1999 —NGV Dispensing Systems	Covers natural gas vehicle dispensing systems.
ANSI NGV4.2/CSA 12.52—1999 —Hoses for NGVs and Dispensing Systems	Covers requirements for hose assemblies for natural gas vehicles and dispensing systems.
ANSI NGV4.4/CSA 12.54—1999—Breakaway Devices for Natural Gas Dispensing Hoses and Systems	Covers CNG dispenser shear valves and fueling hose emergency breakaway shutoff devices.
ANSI NGV4.6/CSA 12.56—1999 —Manually Operated Valves for Natural Gas Dispensing Systems	Covers manually operated valves excluding cylinder shut-off valves.
ANSI NGV4.8/CSA 12.8—2002—Natural Gas Vehicle Fueling Station Reciprocating Compressor Guidelines	Applies to CNG fueling station compressor packages that contain reciprocating compressors.
ANSI PRD1—1998 (with 1999 addendum) —Basic Requirements for Pressure Relief Devices for Natural Gas Vehicle Fuel Containers	Applies to pressure relief devices for CNG vehicle fuel containers.
ASME Boiler and Pressure Vessel Code, Section V111 (pressure vessels)	Sections applicable to containers used in CNG refueling stations.
FMVSS 304 (49 CFR 571.304) —Compressed Natural Gas Fuel Container Integrity	DOT Federal Motor Vehicle Safety Standard covering CNG motor vehicle fuel containers.

U.S. Department of Transportation's Transportation Safety Institute (TSI) offers training courses specifically for transit agencies. Their 2011 course listings include "Safety Evaluations for Alternative

Fuels Facilities and Equipment." This 3-day course provides "awareness and training in conducting safety evaluations for alternative-fueled vehicles, support equipment, and facilities using Compressed Natural Gas (CNG), Liquefied Natural Gas (LNG), hydrogen, fuel cells, propane, ethanol, electricity, bio-diesel, and hybrid electric." Another 1-day course offering, "Alternative Fuel Cylinder Inspection," is specific to CNG. Classes are scheduled on an as-needed basis. Those interested should contact TSI.

Disposal

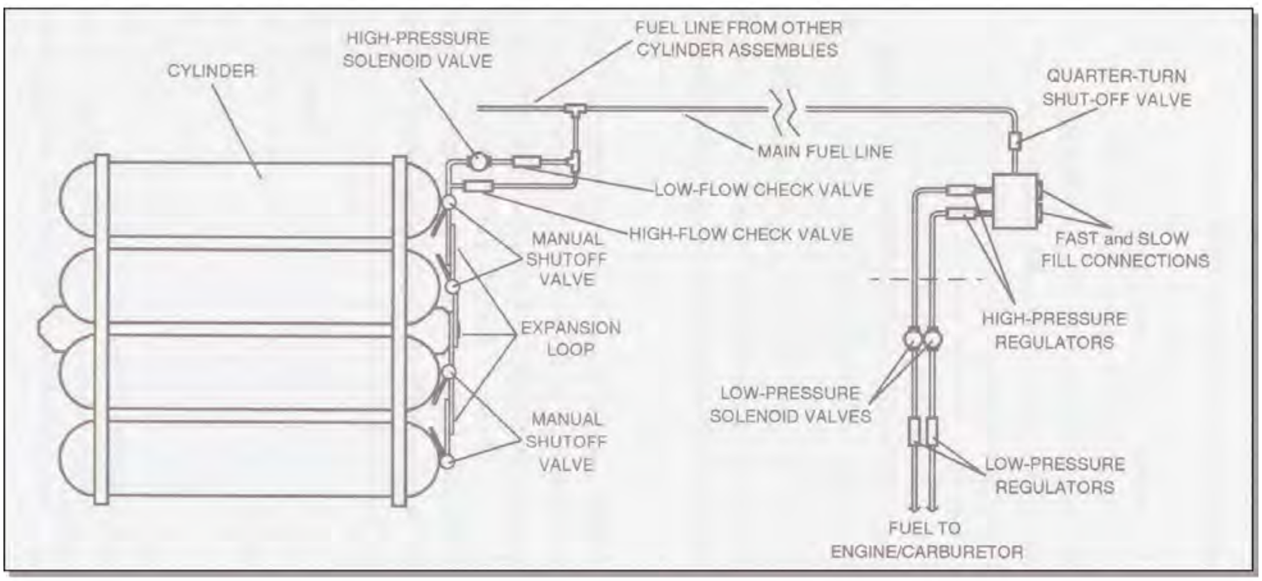
Un-used CNG should be returned to the supplier or a qualified handler of hazardous waste. CNG raises and dissipates when released in open air, but poses fire and explosion hazards until it is diluted to a point below its flammability limit.

7.4 Technology and Performance

The Fuel System

A typical CNG bus fuel system is illustrated in Figure 7.2. It includes high-pressure storage cylinders, high-pressure fuel lines, electronic fuel shut-off solenoids, a multi-stage pressure regulator system, and refueling receptacle connections.

Figure 7.2 Typical CNG Vehicle Fuel System



The high-pressure fuel is released through an electronic solenoid valve that is activated by the vehicle's ignition switch. The fuel is then directed through a series of pressure regulators that lower the fuel pressure. CNG fuel systems have two or three stages of pressure reduction. Pressure reduction causes gas to expand and cool. In many systems, engine coolant is circulated through the final pressure regulator to maintain the gas at a constant temperature, enabling more precise metering. An electronic fuel delivery system meters gas flow into the engine.

HCNG can be used in natural gas engines with some modifications. The main modification is a software recalibration of the engine controller to retard spark timing. The only hardware change may be replacement of the fuel flow sensor to allow larger fuel injection volumes. In some cases, onboard fuel storage may need to be increased.

The Engine

Two different approaches have been used for CNG bus engines with respect to the ratio of air to fuel in the combustion chamber: lean burn and stoichiometric. Lean burn refers to a natural gas mixture with an air-to-fuel ratio that is higher than needed to completely burn the fuel. The extra air dilutes the mixture, reducing temperature and formation of nitrogen oxides (NOx). In contrast, a stoichiometric mixture has just enough air to completely burn the available fuel. The combination of exhaust gas treatment and engine technology, including turbocharging, exhaust gas recirculation, and electronic controls, determines whether engines using lean burn or stoichiometric mixtures have lower tailpipe emissions.

> **Did You Know?**
>
> Some natural gas engines use compression-ignition rather than spark-ignition. These are called **"dual-fuel"** engines because the air-gas mixture in the engine cylinder is ignited by a small injection of diesel fuel. This type of engine is more common in stationary applications. Although dual-fuel bus engines are not currently available in the United States they are used in other countries, reducing diesel needs by 50% to 80% compared to conventional diesel bus engines.

As of 2010, there is only one natural gas engine available for transit buses that meets 2010 EPA emission standards. This engine is the Cummins Westport ISL G. It uses electronically controlled stoichiometric spark-ignition, cooled exhaust gas recirculation (EGR), and a three-way catalyst to reduce emissions of NOx, hydrocarbons (HC), and carbon monoxide (CO). Although they are relatively new to transit buses, three-way catalysts have been common emission control devices on light-duty gasoline vehicles for more than thirty years and are considered a robust and mature emission reduction technology.

In contrast to the Cummins Westport ISL G, many natural gas bus engines certified to earlier EPA emission standards used a lean burn engine technology with an oxidation catalyst.

Onboard Fuel Storage

High-pressure CNG storage cylinders used in transit applications are generally 6 to 12 in. in diameter. Cylinders are located on the roof of low-floor bus designs. For standard bus designs, cylinders are placed either underneath the bus or in the bus skirt-space above the engine. CNG cylinders are usually constructed from aluminum or carbon steel reinforced with overwrapped composite materials to minimize weight. Manual shut-off valves are always provided on CNG cylinders, and must be closed when the cylinders are being serviced. Most of the high-pressure cylinders made today meet the NGV-2 standards of the American National Standards Institute (ANSI). Common locations

CNG bus overhead storage tank placement (Source: New Flyer Website) for methane detectors with alarms include the passenger area, the cylinder storage area, and the engine compartment.

Refueling

The refueling facility for CNG buses incorporates different equipment than what is used for diesel refueling. In the past, fleet managers have had to contract an architect/engineer to design and oversee construction of their refueling facility, hire personnel to operate and maintain the facility, and assume full responsibility for assuring a reliable fuel supply. Today, many transit operators outsource the job of providing fuel, and contract fuel service providers to build, own, and operate a refueling station on the transit property. This arrangement transfers refueling risks from the fleet operator to the fuel service provider. Major transit agencies, including the Los Angeles County Metropolitan Transportation Authority (LACMTA) and Massachusetts Bay Transportation Authority (MBTA), are now contracting with fuel service providers for their CNG bus fleets.

Fast fill CNG refueling in Tacoma, Washington

Refueling onboard CNG tanks to 3,600 psi requires a compressor to raise the pressure of pipeline gas. Gas lines to a facility that has not previously had a natural gas fleet often need upgrading to deliver gas at a sufficient rate—pressure in the upgraded lines is typically between 10 and 60 psi, and pipe diameter may also be expanded. Before compressing the pipeline gas, it is first "conditioned" by a gas dryer to prevent water condensation that may occur at higher pressures. NFPA 52, Standard for Compressed Natural Gas Vehicular Fuel Systems, recommends drying the gas to a dew point at least 10°F below the lowest expected ambient temperature. The gas dryer contains a sorbent that must be periodically regenerated by heating.

The conditioned gas is passed to a multi-stage reciprocating compressor. Heat exchangers between compression stages dissipate some of the heat associated with compression. With proper maintenance, compressors commonly provide over 25 years of service. Compressors are usually powered by electricity, but larger units may use natural gas.

Gas pressure at the compressor outlet is around 4,500 psi. At this pressure, some of the heavier hydrocarbons in natural gas condense to liquids along with trace amounts of compressor oil. These liquids are removed by a coalescing filter that needs periodic draining. The compressor size and needs for gas storage are affected by whether the refueling facility is designed for fast or slow filling. Table 7.3 summarizes the primary differences between fast and slow (or time) fill facilities.

Table 7.3 Comparison of Slow and Fast Fill CNG Refueling

	Slow Fill	Fast Fill
Time to Refuel	12+ hours	3 to 10 minutes
Attendance	Unattended— *Gas first flows to the tank with the lowest pressure; when all tanks reach the same pressure, they are simultaneously filled to maximum pressure, and the compressor automatically turns off.*	Attended— *Refueling attendant needs are similar to conventional diesel refueling.*
Gas Metering	For entire fleet	For each vehicle
Equipment	• Gas dryer • Multi-stage compressor with heat exchangers • Receiver tank • Manifold /fill posts • Hoses and nozzles	• Gas dryer • Multi-stage compressor with heat exchangers • Cascade of storage tanks • Refueling island(s) • Hoses and nozzles
Electricity for the Compressor*	Can be set for off-peak to take advantage of lower electricity rates.	As needed, during peak and off-peak rate periods.
Spatial Area Needs	Less area needed – • No refueling islands • Parking is combined with refueling • *Optional: storage for emergency fast fill*	More area needed – • Refueling islands • Separate parking area • Cascade of storage tanks
Completeness of Fill	More complete— *Gradual compression allows more heat dissipation, lower temperature allows more gas to be put in the tank.*	Less complete – *Temperature increases with gas compression, reducing the amount of gas that can be put in the tank.*
Common Fleet Size	Less than 40 – *compressor size for larger fleets is equal to fast-fill design.*	Dozens to hundreds

* Larger compressors may be powered with natural gas rather than electricity.

Slow-fill stations for light and medium-duty vehicles may use self-contained compression and dispensing units referred to as vehicle refueling appliances (VRA). Each VRA can fill several vehicles, and can be combined with additional units as the CNG fleet grows.

For smaller fast-fill stations (more typical for light-duty vehicles), refueling is essentially from the cascade of storage tanks, which is recharged as needed by the compressor. In larger stations (more typical for transit bus fleets), the incremental cost of compressor capacity is less than the cost of additional storage cylinders, so buses are refueled primarily from the compressor. But in these cases, a cascade of storage cylinders is typically included to reduce compressor cycling.

Performance

Performance and drivability of CNG buses is similar to diesel buses, although slight reductions in acceleration and hill climbing ability may be noticed. CNG engines have peak power ratings similar to comparable diesel engines, but the lower volumetric efficiency of CNG engines at low engine speeds results in a small decrease in torque. Both reduced low-speed torque and increased bus weight due to heavier fuel tanks contribute to acceleration reductions. In some situations, this can be a major decision criterion for bus procurement. For example, in 2006 the City of San Francisco decided to purchase hybrid electric buses instead of CNG buses due in part to the hybrids' superior hill-climbing capabilities.[2]

The latest stoichiometric CNG engines with cooled EGR may have improved low-end torque due to increases in knock-limited brake mean effective pressure (BMEP). Cummins Westport claims a 30% increase in low-speed torque for its stoichiometric, cooled EGR engine compared to its previous lean-burn engine.[3]

The heavier weight of CNG fuel tanks negatively affects both acceleration and fuel economy. Reductions in fuel economy are also a result of the lower engine efficiencies of spark-ignited versus compression-ignited engines. CNG bus fuel economy is often reported in terms of "diesel gallon equivalents," or DGE. Based on APTA's annual survey of transit properties, CNG buses averaged 2.5 miles per DGE compared to 3.6 mpg for diesel buses—representing a 30% lower fuel economy with CNG.[1]

Diesel Gallon Equivalents (DGE)

On an energy-equivalent basis:

1 gallon diesel = 126.67 cubic feet natural gas at atmospheric pressure

1 gallon diesel = 0.58 cubic feet natural gas at 3,600 psi

1 gallon diesel = 4.34 gallons natural gas at 3,600 psi

Fuel economy of the SunLine Transit HCNG buses (using a 20% hydrogen blend) has been reported to be

Site Visit!

A CNG hybrid electric bus entered commercial service in 2008 for the San Diego Metropolitan Transit System (MTS). The 40-ft low-floor prototype bus cost $1 million. Funding was provided by state and local grants.

. . . and another!

A CNG plug-in hybrid was unveiled in early 2010 in Mumbai, India, by India's second largest commercial vehicle manufacturer, Ashok Leyland. The bus provided service during the 2010 Commonwealth Games in New Delhi.

the same as for CNG buses on an energy equivalent basis, and about 12% lower than for CNG buses on a per volume basis.[4]

7.5 Maintenance, Reliability, and Storage

Maintenance

Some maintenance needs and schedule differences that are relevant for CNG buses include the following:

- Periodic spark plug replacements for spark-ignited engines (in contrast to typically lower-maintenance compression-ignition diesel engines)
- Possible greater frequency of brake and suspension component replacements as a result of the heavier weight of CNG buses compared to diesel buses
- Annual visual inspection of onboard CNG fuel tanks (per ANSI/NGV2)
- Recommended emptying of onboard CNG tanks before working on the fuel system
- Periodic maintenance of the refueling equipment (gas dryer, compressor, etc.)

Reliability

Reliability, as measured by miles between road calls (MBRC), varies significantly between bus models and for different types of service, regardless of fuel type. This makes it difficult to confidently compare the reliability of CNG and diesel buses. The concerns in developing conclusions regarding the relative reliability of CNG and diesel buses are discussed in a 1999 LACMTA report.[5] LACMTA reviewed several reports on bus reliability and operating costs that suggested CNG buses were more reliable and less costly to operate than diesel buses. In contrast, LACMTA's review of these reports found that the observed reliability and operating cost differences were due to warranties covering newer CNG buses but not the older diesel buses and the expected differences in reliability with vehicle age.

Comparisons of newer CNG buses to older diesel buses are also seen in more recent reports. A study published in 2006 on WMATA diesel and CNG buses reported an increase in the MBRC of 10 CNG buses versus 5 diesel buses—but the diesel buses were from a different manufacturer and were 1 to 3 years older than the CNG buses.[6] Reliability of CNG buses was also reported to be better than diesel buses in another study published in 2006 on NYCT buses—but this comparison was also between newer CNG buses and older, different model diesel buses.[7] Hence, neither of these more recent studies provides confident conclusions on the relative reliability of diesel and CNG buses that are the same model and model year.

How is it Stored?

CNG is stored in tanks, often referred to as cylinders, designed to meet safety standards for storage of high pressure gases. Included is a pressure relief valve that automatically vents gas when temperatures (and associated pressures) are unusually high, such as in a fire. Venting gas under these conditions prevents cylinder explosion.

The results of a recent survey of transit authorities conducted by the U.S. Department of Transportation Federal Transit Administration (FTA) suggest that current CNG engines are viewed as "durable and reliable"—without providing a direct comparison in the relative reliability of CNG and diesel buses.[8]

There is insufficient experience with HCNG to confidently assess potential maintenance and reliability differences compared to CNG. The ongoing field tests have reported no significant issues to date.

Storage

Typical CNG storage pressures are 3,000 to 3,600 psi. CNG storage tanks are designed in cylindrical shapes because this design allows a stronger tank construction to assure safe containment of high pressure gas. All high pressure tanks are equipped with a thermal relief device (TRD) and/or a pressure relief device (PRD). A TRD has a fusible plug that melts when the temperature exceeds a set level, such as when a tank is engulfed in flames. A PRD has a rupture disc that ruptures when pressure inside the tank reaches set levels. A PRD releases tank contents when the temperature inside the tank rises, causing pressure build-up, such as in a fire, or when a tank is filled beyond the set capacity (i.e., over-filled). Proper training and maintenance are important guards against refueling overpressure.

When a PRD or TRD is actuated, all the gas in the tank will be released within a few minutes, and the devices must then be replaced (i.e., they are not valves that can be opened and re-closed). Gas released from PRDs and TRDs is typically directed through a line that vents it upwards and away from people. Vented gas may be heard as a loud hissing sound.

Storage tanks for HCNG are the same as those for CNG. In some cases, storage capacity may need to be expanded for HCNG to compensate for its lower energy density.

7.6 Emissions

Emissions are addressed as currently regulated pollutants and greenhouse gases. Currently regulated air pollutants fall under the Clean Air Act. They include hydrocarbons (HC), nitrogen oxides (NOx), particulate matter (PM), non-methane hydrocarbons (NMHC), and carbon monoxide (CO). Currently regulated pollutants cause harmful effects on local and regional levels. In contrast, greenhouse gases (GHG) have global effects on temperatures.

A CNG bus from Boulder, Colorado, is emissions tested on the WVU transportable dynamometer.

Regulated Pollutants

CNG and diesel bus emissions of regulated pollutants have become increasingly similar over the last decade. Historically, the benefits of CNG were due to the more complete burn of the light hydrocarbons that comprise natural gas. As regulations of tailpipe emissions became more stringent, diesel engine technology evolved to meet new standards through a combination of electronic controls and exhaust gas treatment. CNG engine technology and exhaust gas treatment have also evolved in response to the most recent step in the phased-in emission standards. Because CNG engines have emissions characteristics that are different from diesel engines, they need different exhaust treatment systems.

EPA urban bus engine standards have changed several times over the lifespan of the oldest buses on the road – new emissions standards became effective in 2004, 2007, and 2010. With each of these changes, there were changes in diesel emission controls. Only the most stringent emission levels, which were phased in from 2007 to 2010, required significant changes for CNG buses. Half of all engine sales in 2007 through 2009 were to meet the 2010 standards, so comparing like model years is not always appropriate.

As the standards and associated emission control systems have changed, so has the relative difference in diesel and CNG emissions. For example, a typical 2006 CNG bus emits less CO and NOx than a 2006 diesel bus, but in 2010, diesel buses may have lower CO emissions than natural gas buses. To achieve 2007 standards for PM, diesel buses needed the addition of a diesel particulate filter (DPF). CNG buses used the same technology needed for prior standards (i.e., lean-burn engine controls and an oxidation catalyst). To achieve 2010 emission standards, diesel buses need both a DPF and selective catalyst reduction (SCR). Comparable CNG engines (i.e., the Cummins ISL G) use stoichiometric cooled exhaust gas recirculation (EGR) with a three-way catalyst (TWC).

Currently, available emissions measurements from model year (MY) 2010 buses are quite limited. This is a significant consideration for comparisons of emissions differences between natural gas and diesel buses because these engines were required to meet more stringent emissions regulations beginning in 2010. For a preliminary comparison of 2010 natural gas and diesel bus emissions, U.S. EPA certification data for MY2010 on-road engines with power ratings of 300 to 350 horsepower were compared. Table 7.4 shows the average certification test emissions as converted to grams/mile based on EPA conversion factors. These emissions estimates are used as default values in the FuelCost2 model. These estimates should be updated as more emission measurements are reported for 2010 buses.

Table 7.4 Natural Gas Engine Emissions: EPA MY2010 Certification Tests

	g/bhp-h *	g/mile
Carbon Monoxide	6.53	21.91
Nitrogen Oxides	0.07	0.22
Particulate Matter	0.00	0.00
Non-Methane Hydrocarbons	0.02	0.02

* Emissions estimates based on EPA certification test data for model year 2010 highway engines between 300 and 350 horsepower available at http://www.epa.gov/oms/crttst.htm. Units of g/bhp-h are converted to g/mile using the EPA conversion factor for gasoline (spark-ignition) engines.[9]

The SunLine Transit HCNG test buses have about 50% lower NOx and non-methane hydrocarbon emissions than similar CNG buses.[10] These comparisons are of buses that do not have the latest NOx control technologies. Emissions differences between HCNG and CNG buses are expected to be reduced on buses equipped with SCR.

Greenhouse Gases

The GHG emission of greatest concern from diesel buses is carbon dioxide (CO_2). While CO_2 is also emitted from CNG buses, methane emissions are the greater GHG concern. The global warming potential of methane is over 20, versus 1 for CO_2, indicating that methane is over 20 times more effective at trapping heat than CO_2.[11] GHG emissions are often reported in CO_2 equivalents for easier comparison on emissions in terms of heat-trapping ability.

GHG emissions are best compared over the fuel lifecycle, referred to as well-to-wheels. This is commonly broken into two components: well-to-tank, and tank-to-wheels. Well-to-tank includes GHG emission from fuel exploration, development, and production, to refining, delivery to refueling sites, and the actual refueling process. Tank-to-wheels emissions are from onboard sources, primarily the tailpipe (as a result of combustion). Although not typically applicable to CNG buses, tank-to-wheels also includes evaporation from the fuel tank.

GHG emissions from well-to-tank for both diesel and CNG are in the range of 20% to 30% of their total lifecycle GHG emissions. Well-to-tank GHG emissions are estimated to be 12% higher for CNG than for diesel.[12] GHG emissions from CNG refueling operations can be further increased with events such as compressor malfunctions and refueling accidents, making training and maintenance an important component for control of GHG emissions.

The greatest portion of GHG lifecycle emissions from both CNG and diesel buses is from the tailpipe. Tank-to-wheels GHG emissions vary with engine technology. The tank-to-wheels emissions shown in Table 7.5 were measured on board during a drive cycle typical for Vancouver Transit Authority buses.[13] The diesel buses were equipped with 2006 Cummins ISL 280 engines, particle filters, and no oxidation catalyst. CNG buses were equipped with 2006 lean-burn Cummins C-Gas Plus (ICG 280) engines and an oxidation catalyst. In this study, GHG tailpipe emissions were 8% lower for the CNG versus diesel buses – this relationship will likely not be the same for MY2010 and beyond.

Table 7.5 GHG emissions from 2006 CNG and Diesel Buses

		CO_2 Equivalent g/mile*		
		Diesel	CNG	Change with CNG
Well-to-Tank				
	Total	**636**	**711**	**12% increase**
Tank-to-Wheels				
	CO_2	2,258	1,872	17% reduction
	CH_4	3	230	76-fold increase
	N_2O	46	14	69% reduction
	Total	**2,306**	**2,117**	**8% reduction**
Total Well-to-Wheels				
	Total (Net)	**2,942**	**2,828**	**4% reduction**

* Assumes 1 g CH_4 = 23 g CO_2; 1 g N_2O = 296 g CO_2

Some studies of tailpipe emissions in older buses have found higher GHG emissions from CNG buses than from diesel buses (e.g., MY2000 and 2001 buses,[14] and MY2002 to 2004 buses[15]). A study comparing GHG emissions from CNG buses with stoichiometric versus lean-burn engines (MY2002 and MY2004) found GHG tailpipe emissions to be 30% lower from the stoichiometric engines.[15] This suggests the potential importance of CNG engine design and control technology on GHG tailpipe emissions.

Cummins Westport, the manufacturer of the only currently available urban bus natural gas engine, has reported that its 2010-compliant natural gas ISL G engine provides a 17% reduction in GHG tailpipe emissions compared to the cleanest comparable diesel engines.[16] This improvement is primarily from reductions in unburned methane emissions. Since methane is a much more potent GHG than CO_2 (the primary GHG from diesel engines), GHG emissions are unlikely to be reduced by such a substantial amount in MY2010 diesel buses.

For the purposes of choosing a default value for lifecycle GHG emissions in the FuelCost2 cost model that was developed as part of the current project, it is estimated that MY2010 CNG buses with stoichiometric engines will offer GHG reductions in the range of 10% to 20% compared to MY2010 diesel buses. The middle value of 15% GHG reduction is used as a default value.

7.7 Cost and Availability

CNG buses are available in a variety of transit bus models from manufacturers such as Orion (a Daimler brand), New Flyer Industries, Blue Bird Corporation, North American Bus Industries, El Dorado National, Champion Bus, and Optima. Fuel service providers that arrange for design, construction, maintenance, and operation of on-site CNG refueling facilities have also become quite common among CNG bus transit fleets. When assessing the costs of CNG bus operations, capital and operating costs must be addressed for both the buses and the depot, including refueling and maintenance.

Vehicle Costs

Capital costs for CNG buses were around $30,000 more than for diesel buses in 2007. This cost difference is projected to decrease to between $22,000 and $26,000 in 2012.[17] In the accompanying FuelCost2 lifecycle cost model, the default value for a 40-ft CNG bus is $25,000 more than for a comparable diesel bus.

Maintenance costs for CNG buses have been reported by WMATA to be between $0.52 and $0.58 per mile compared to $0.59 per mile for diesel buses.[18] Similar costs for New York City Transit CNG buses have been estimated as $1.29 per mile, with propulsion-related maintenance estimated as $0.349 per mile.[19]

Overall fuel costs for CNG buses compared to diesel buses are indicated by a comparison of the average retail station fuel prices across the country for CNG and diesel. In 2009, CNG retail prices were $1.91 per Diesel Gallon Equivalent (DGE), while average retail diesel prices were $2.51.[20]

Did You Know?

There are over 775 retail CNG stations in the United States today.

Refueling and Maintenance Costs

CNG refueling cost components and their contribution to total refueling costs based on a fleet of 50 buses are the following:[21]

- Station capital cost—when amortized over an expected station life of 20 years, this represents around 20% to 30% of total refueling costs.
- Operation and maintenance (O&M)—in addition to physical operation and maintenance, this includes electricity costs for gas compression. Generally, O&M represent 20% to 30% of total refueling costs.
- Fuel costs—in recent years, these costs have represented roughly half to two-thirds of total refueling costs.

In 2001, WMATA commissioned a new $4 million CNG fueling station to serve a fleet of 164 CNG buses at its Bladensburg, Maryland, depot. The refueling facility incorporated three compressors and was operated and maintained by a contractor for $360,000 annually. This cost does not include approximately $300,000 of annual electricity costs for running the compressors. An additional $11.6 million was required for modifying the maintenance facility to accommodate CNG buses.[22]

More recently, the Orange County Transportation Authority announced that it has contracted with a CNG service provider to design, build, and operate a new CNG refueling station to serve 63 CNG buses and provide 500,000 DGE annually; the cost of the contract is $3.6 million.[23]

CNG facility costs have been modeled in *TCRP Report 132* (TCRP Project C-15) as a base cost of $1,000,000 plus $15,000 per CNG bus.[24] Facility operational costs for CNG are higher than diesel due in large part to the costs of electricity for the compressor. It was further estimated in *TCRP Report 132* that additional facility operations costs per year for CNG are roughly equal to 6% of CNG infrastructure costs. Assuming a per bus average annual mileage of 37,000, typical additional facility operational costs for CNG of $0.05 per mile have been calculated as default values for use in FuelCost2.

TCRP Report 132 also provides low, mid, and high estimates for propulsion system maintenance of diese and CNG buses meeting MY2007 standards. The propulsion system maintenance costs for diesel range from $0.13 to $0.19 per mile, while similar costs for CNG range from $0.14 to $0.35 per mile. Although the low-range maintenance cost estimates are similar, the high-end estimates are 84% greater for CNG than for diesel buses. The mid-cost estimates in *TCRP Report 132* are used as default values in the accompanying FuelCost2 model (i.e., $0.16 per mile for diesel and $0.18 per mile for CNG).

Cost estimates for CNG adoption are shown in Table 7.6. These are general estimates for initial comparison purposes. For actual project planning and budget purposes, specific costs for CNG bus fleets, refueling stations, and maintenance facilities should be determined.

Table 7.6 CNG Bus Cost Estimates

Item	CNG
New Vehicle ($)	$375,000
Facility Conversion ($/50 Buses) [a]	$1.75 million
Fuel ($/DGE) [b]	$1.91
Fuel economy (mi/DGE) [a]	2.7
Propulsion System Maintenance ($/mile) [a]	0.18
Facility Maintenance and Operation ($/mile) [a]	0.23

a Estimates derived from Clark, N., Zhen, F. and Wayne, W. S., et al. (December 2009). *TCRP Report 132: Assessment of Hybrid-Electric Transit Bus Technology*. Transportation Research Board of the National Academies, Washington, D.C. Fuel economy based on average speed of 3.4 mph.

b Based on Clean Cities Alternative Fuel Price Report, average retail price (including taxes) in 2009.[25]

HCNG costs are not estimated in this report, and this fuel option is not included in the FuelCost2 model that accompanies this report. As a fuel that is in the pilot stages of development, HCNG projects are typically supported by substantial federal or state-level grants.

7.8 Summary

Compressed Natural Gas

Pros	Cons
There is much transit experience with CNG—it has been used for decades by transit properties across the country.	Safety concerns regarding fire and explosion are greater for CNG than for diesel. Additional training of bus operators and mechanics is required.
Natural gas fuel typically costs less than diesel fuel on an energy equivalent basis.	Capital costs for facility conversion to CNG are quite high (i.e., millions of dollars) and CNG buses cost around $25,000 more than diesel buses.
Current CNG engines are viewed as "durable and reliable."	Maintenance costs are typically higher for CNG buses than for comparable diesel buses.
Emissions of GHG are roughly 10% to 20% lower with CNG buses than diesel buses when using typical pipeline gas. GHG may be more substantially reduced with use of biomethane, such as from landfills.	Emissions of regulated pollutants are similar for CNG and diesel buses as of MY2010, which may make the additional capital costs of CNG more difficult to justify.
Natural gas supply may be more reliable than diesel because nearly 85% of natural gas is domestically produced while only about 30% of diesel has domestic origins. Natural gas use may also offer greater benefits for the regional economy than diesel.	CNG contains only about 25% of the energy content of diesel fuel, and requires about four times the fuel volume of diesel for comparable driving ranges.

CNG References

[1] American Public Transportation Association (May 2009). *Public Transportation Fact Book*. Retrieved from http://www.apta.com/RESOURCES/STATISTICS/Pages/transitstats.aspx

[2] Bowman, B. (June 2, 2006). *Muni Cleans Up its Act: Adding 56 Hybrid Buses: New Diesel-Electric Coaches Cut Exhaust, Boost Fuel Economy*. San Francisco Chronicle. Retrieved from http://www.sfgate.com/cgi-bin/article.cgi?f=/c/a/2006/06/02/BAGDVJ67UV1.DTL

[3] Cummins Westport, Inc., (March 7, 2010). *ISL G, Every Alternative*. Retrieved from http://www.everytime.cummins.com/assets/pdf/4103996.pdf

[4] Welch, Alan. Transition to Hydrogen with NGV Technology. Presented at the Natural Gas Vehicle Technology Forum, August 2-4, 2005, Retrieved from http://www.afdc.energy.gov/afdc/pdfs/alan_welch.pdf

[5] Los Angeles County Metropolitan Transportation Authority (LACMTA), Transit Operations Department (August 31, 1999). *Fuel Strategies for Future Bus Procurements, Final Report*. Prepared for the LACMTA Board of Directors. (This report was not found on-line, but the delivery memo that accompanied this report can be viewed at http://boardarchives.metro.net/BoardBox/Box%2003/00000578.pdf.)

[6] Chandler, K., E. Eberts, and M. Melendez (2006). *Washington Metropolitan Area Transit Authority: Compressed Natural Gas Transit Bus Evaluation*, NREL Technical Report NREL/TP-540-37626. Retrieved from http://www.nrel.gov/docs/fy06osti/37626.pdf

[7] Barnitt, R. and K. Chandler (2006). *New York City Transit (NYCT) Hybrid (125 Order) and CNG Transit Buses*, NREL Technical Report NREL/TP-540-40125. Retrieved from http://www.nrel.gov/vehiclesandfuels/fleettest/pdfs/40125.pdf

[8] U.S. Department of Transportation, Federal Transit Administration (April 2007). *Useful Life of Transit Buses and Vans*, Report Number FTA VA-26-7229-07.1. Retrieved from http://www.fta.dot.gov/documents/Useful_Life_of_Buses_Final_Report_4-26-07_rv1.pdf

[9] U.S. Environmental Protection Agency (May 1998). *Update Heavy-Duty Engine Emission Conversion Factors for MOBILE6: Analysis of BSFCs and Calculation of Heavy-Duty Engine Emission Conversion Factors*. EPA420-P-98-015. Retrieved from: http://www.epa.gov/oms/models/mobile6/m6hde004.pdf

[10] Welch, Alan. Transition to Hydrogen with NGV Technology. Presented at the Natural Gas Vehicle Technology Forum, August 2-4, 2005, Retrieved from http://www.afdc.energy.gov/afdc/pdfs/alan_welch.pdf

[11] U.S. Department of Energy, Energy Information Administration (October 2008). *Documentation for the Emissions of Greenhouse Gases in the United States 2006*, U.S. DOE/EIA – 0638 (2006), p. 208. Retrieved from http://www.eia.doe.gov/oiaf/1605/ggrpt/documentation/pdf/0638(2006).pdf

[12] U.S. Department of Transportation, Federal Transit Administration (July 2, 2007). *Transit Bus Life Cycle Cost and Year 2007 Emissions Estimation, Final Report*, FTA-WV-26-7004.2007.1. Retrieved from http://www.fta.dot.gov/documents/WVU_FTA_LCC_Final_Report_07-23-2007.pdf

[13] Graham, L.A., G. Rideout, D. Rosenblatt, and J. Hendren (2008). *Greenhouse Gas Emissions from Heavy-Duty Vehicles. Atmospheric Environment, 42*, 4665-4681.

[14] Melendez, M., J. Taylor, and J. Zuboy (December 2005). *Emission Testing of Washington Metropolitan Area Transit Authority (WMATA) Natural Gas and Diesel Transit Buses*, Technical Report NREL/TP-540-36355, National Renewable Energy Laboratory. Retrieved from http://www.nrel.gov/docs/fy06osti/36355.pdf

[15] Nylund, N., K. Erkillä, M. Lappi, and M. Ikonen (October 15, 2004). *Transit Bus Emission Study: Comparison of Emissions From Diesel And Natural Gas Buses*, Research Report PRO3/P5150/04. VTT Processes. Retrieved from http://www.vtt.fi/inf/pdf/jurelinkit/VTTNylund.pdf.

[16] Westport News Release (February 6, 2006). *Cummins Westport Receives U.S.$350,000 for Engine Demonstration*. Retrieved from http://www.westport.com/news/index.php?id=301&return_to=/news/index.php

[17] Clark, N., Zhen, F. and Wayne, W. S., et al. (December 2009). *TCRP Report 132: Assessment of Hybrid-Electric Transit Bus Technology*. Transportation Research Board of the National Academies, Washington, D.C., page 11.

[18] Chandler, K., E. Eberts, and M. Melendez (2006). *Washington Metropolitan Area Transit Authority: Compressed Natural Gas Transit Bus Evaluation*, NREL Technical Report NREL/TP-540-37626. Retrieved from http://www.nrel.gov/docs/fy06osti/37626.pdf

[19] Barnitt, R. and K. Chandler (2006). *New York City Transit (NYCT) Hybrid (125 Order) and CNG Transit Buses*, NREL Technical Report NREL/TP-540-40125. Retrieved from http://www.nrel.gov/vehiclesandfuels/fleettest/pdfs/40125.pdf

[20] U.S. Department of Energy (2009). *Clean Cities Alternative Fuel Price Report*, 2009 quarterly reports. Retrieved from http://www.afdc.energy.gov/afdc/price_report.html

[21] Grace, P., (October 2006). *Creative Financing & Fuel Options for CNG Transit Fleets*. Clean Energy Fuels. Presentation.

[22] Chandler, et al. (2006).

[23] Business Wire (2008, February 5). *Clean Energy to Build and Operate "Green" Natural Gas Fueling Station for Orange County Transportation Authority for Growing Fleet of Contracted Fixed Route Buses.*

[24] Clark, N., Zhen, F. and Wayne, W. S., et al. (December 2009). *TCRP Report 132: Assessment of Hybrid-Electric Transit Bus Technology*. Transportation Research Board of the National Academies, Washington, D.C., page 12.

[25] U.S. Department of Energy (2009). *Clean Cities Alternative Fuel Price Report*, 2009 quarterly reports. Retrieved from http://www.afdc.energy.gov/afdc/price_report.html

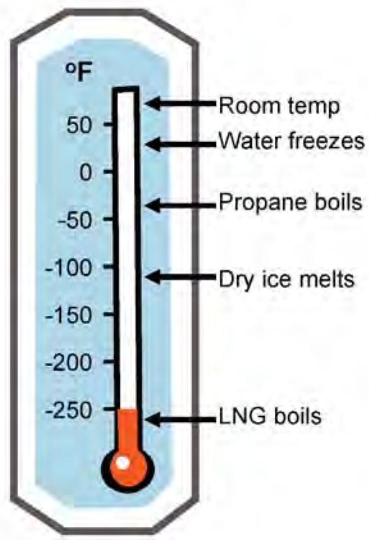
8.0 Liquefied Natural Gas

Liquefied Natural Gas, or LNG, is natural gas that has been cooled to very low temperatures to form a liquid that has a much higher energy density than compressed gas. The higher energy density means that less space is needed for storing fuel on an LNG bus than on a CNG bus. An extensive pipeline network provides natural gas throughout much of the country. Specialized refueling equipment is needed for LNG vehicles. Under the Energy Policy Act, LNG is defined as an alternative fuel.

Multiple-use fuel lines surround an LNG Dallas Area Rapid Transit (DART) bus at the fueling bay.

8.1 Fuel Description

LNG is natural gas that has been condensed to a liquid in a process called liquefaction. Just as steam condenses to water at 212°F (100°C), natural gas forms LNG at -260°F (-162°C). Liquids held at temperatures below -100°F (-73°C), such as LNG, are referred to as cryogenic liquids. LNG is colorless, and weighs about half as much as water. Odorants may be added to LNG after liquefaction to make it easier to detect leaks.



Most LNG is produced at large liquefaction facilities that benefit from economies of scale. Feedstock for LNG is usually pipeline gas from fossil fuel reserves, but biogas can also be used.

> **Liquefied Natural Gas,**
> {**lik**-wuh-fahyd **nach**-er-*uh*l gas}
> *noun*—a mixture of hydrocarbons, principally methane, that has been condensed to a liquid to reduce its volume for storage and transport.

Natural gas is composed mainly of methane, but it also contains small amounts of heavier hydrocarbons, water, and inert gases. Liquefaction plants in the U.S. typically produce LNG that is 98% or more methane. Because this amount is not standard across the globe, methane content is a particularly important specification when dealing with international suppliers. Bulk LNG is transported over the ocean in large, specialized LNG carriers. Specialized tanker trucks are used for transporting LNG over land.

Is it Imported?

LNG imports currently make up only about 1% of the natural gas used in the United States, but this is expected to increase. According to the U.S. Department of Energy, the United States imported less than 0.2 trillion cubic feet (tcf) of natural gas as LNG in 2002—this is expected to increase to 4.8 tcf by 2025.[1]

The energy density of LNG is about 600 times greater than that of natural gas under ambient conditions, and 2.4 times greater than that of compressed natural gas (CNG). Even so, LNG has only about 60% of the energy contained in an equal volume of diesel fuel.

Table 8.1 lists the fuel properties of LNG versus diesel fuel.[1, 2] With an octane rating well over 100, LNG has excellent properties for a vehicle fuel. The high octane rating allows for better performance and higher efficiencies in spark-ignited engines.

Did You Know?

Landfill gas produced from anaerobic digestion of organic materials such as wastewater or animal manure can also be used to produce LNG.

Table 8.1 LNG and Diesel Fuel Properties

Property	LNG	Diesel
Boiling Temperature (°F)	-260	356 to 644
Autoignition Temperature (°F)	900	600
Cetane Number	N/A	40 to 55
Octane Number (R+M)/2	120	N/A
Flash point (°F)	-300	≥140
Flammability Limits (vapor in air by volume %)	5 to 15	1 to 6
Lower Heating Value (Btu/gal)	74,400 *(as liquid)*	128,450
Relative Weight (same volume) Compared to air = 1 Compared to water = 1	 0.60 0.45 *(as liquid)*	 >3 *(as vapor)* 0.85
Soluble in water	No	No

N/A: Not Applicable

8.2 Fuel Usage

The American Public Transportation Association (APTA) estimated that there were 1,130 LNG buses and paratransit vehicles in operation in 2005 and that about 10% of all non-diesel fuel used in transit buses was LNG.[3] Table 8.2 lists active LNG bus fleets. These are located in Arizona, California, and Texas, with bus model years ranging from 1994 to 2007. The largest fleet is owned by the Regional Public Transportation Authority (Valley Metro), an organization of 14 local governments. The Valley Metro LNG fleet operates in Phoenix, Tempe, and other nearby communities. It is serviced by three refueling stations.

*Table 8.2 Transit Properties with Active LNG Bus Fleets**

Transit Fleet	Location	Active LNG Fleet Buses		
		Number	Model Years	Manufacturers
City of El Paso (Sun Metro)	El Paso, TX	31	1994, 1997	New Flyer, Blue Bird
Dallas Area Rapid Transit (DART)	Dallas, TX	182	1998, 2002	NOVA Bus Corp
Big Blue Bus	Santa Monica, CA	108	2002, 2005, 2007	NABI, New Flyer
Orange County Transportation Authority	Orange, CA	232	2000, 2001	NABI
Regional Public Transportation Authority (Valley Metro)	Phoenix, AZ	490	1998-2004	New Flyer, El Dorado, NABI

* Based on reports from 2005 to 2009.

8.3 Safety, Training, and Disposal

Flammability and Toxicity

LNG vapors are flammable, and although they are non-corrosive and non-toxic, large releases in an unventilated, confined area can cause asphyxiation. Physical contact with LNG liquid, cold vapor, or cold equipment can cause cryogenic burns that are similar to heat burns but have different first aid recommendations.

LNG vapors are flammable when their concentrations in the air are between 5% and 15% by volume. When LNG vapors are initially released, they are heavier than air, and tend to stay near the ground, increasing the chances of exposure to ignition sources such as hot exhaust tailpipes. As the vapors warm, they become lighter than air, and rise to the ceiling.

In addition to the potential flammability hazard caused by accidental LNG releases, the periodic venting of boil-off gas from LNG tanks is another significant safety issue. It is necessary to address this issue in all LNG vehicle parking, storage, and maintenance facilities. The use of vent lines, along with recapture or controlled release of boil-off gas, is one method of handling boil-off gas.

LNG is often odorless because odorants solidify and separate out during the liquefaction process. There are methods for adding odorants after liquefaction, but because odorants solidify at LNG temperature, the result can be very low odor levels from an LNG vapor release (such as boil-off gas), and much higher odor levels from the final evaporations of a liquid spill.

Did You Know?

When LNG evaporates, the gas mixture is referred to as "vapor" to reflect its liquid origins. LNG vapors are natural gas, which is lighter than air at the same temperature. But in the initial stages of an LNG release, the vapor is much colder and heavier than the surrounding air, causing it to sink to the ground. Water in the air may condense within the vapor cloud, creating fog. As the cloud warms, it will rise, and the vapors will disperse.

Because the fuel characteristics of LNG and CNG at ambient conditions are similar, many of the required building modifications that apply to CNG facilities also apply to LNG facilities. Facility improvements needed for use of LNG include the following:

- Methane detectors and alarms,
- Increased ventilation,
- Relocation of ignition sources such as heaters, and
- Installation of explosion-proof electrical components.

Primary guidance for LNG facility safety is the *NFPA 59A: Standard for the Production, Storage, and Handling of Liquefied Natural Gas (LNG),* which includes guidance on fire suppression systems and emergency shutdown capabilities. Table 8.3 lists this and other codes and recommendations for LNG operations.

Key Point

Boil-off gas is the result of the gradual vaporization of liquid inside an LNG tank. If vapor in the tank is not used, and tank pressure reaches the trigger point for the pressure relief device (PRD), vapors are released through the PRD. Unlike CNG, releases from LNG tanks are expected, and boil-off gas may be collected through vent lines for use.

Table 8.3 Selected Codes, Standards, and Guidelines for LNG Vehicles and Infrastructure

Standard	Description
NFPA 30A—Code for Motor Fuel Dispensing Facilities and Repair Garages—2003	Covers facilities dispensing both gaseous and liquid fuels at the same facility.
NFPA 57—Liquefied Natural Gas (LNG) Vehicular Fuel Systems	Covers LNG fuel systems on vehicles of all types, associated fueling facilities, and LNG to CNG facilities, with LNG storage in ASME containers of 70,000 gallons (265 m^3) or less.
NFPA 59A—Production, Storage, and Handling of Liquefied Natural Gas (LNG)	Covers the construction, installation, and operation of equipment for the production, storage, and handling of LNG.
FTA Guidelines—Design Guidelines for Bus Transit Systems Using Liquefied Natural Gas as an Alternative Fuel—1997	An FTA Report that references required codes and provides additional precautions and general information.
NFPA 1—Uniform Fire Code—2009	The UFC is the most widely adopted model building code in the United States. Provides the basis for local fire codes.
SAE J2343—Recommended Practices for LNG Powered Heavy-Duty Trucks—1997	Provides recommendations for LNG-powered heavy duty trucks as well as some guidelines for maintenance facility equipment and procedures.
SAE J2645—Liquefied Natural Gas (LNG) Vehicle Metering and Dispensing Systems—2003	Provides details on LNG Vehicular Fuel Metering and Dispensing.

Training

Most bus manufacturers provide extensive training for transit agencies as part of the LNG bus procurement process. Vehicle drivers and support personnel should be trained to understand LNG tank boil-off characteristics in relation to where and how long vehicles are parked, in addition to any procedures necessary to maintain vent line connections and capture boil-off gas.

Because LNG is a cryogenic fuel stored at extremely low temperatures, refuelers and maintenance staff must be instructed on the use of personal protective equipment (PPE) such as insulated gloves and face shields.

Maintenance staff must understand which maintenance procedures require emptying the vehicle fuel tank(s), and refuelers must understand when it is preferable to postpone refueling.

U.S. Department of Transportation's Transportation Safety Institute (TSI) offers training courses specifically for transit agencies. Their 2011 course listings include "Safety Evaluations for Alternative Fuels Facilities and

Equipment." This 3-day course provides "awareness and training in conducting safety evaluations for alternative-fueled vehicles, support equipment, and facilities using Compressed Natural Gas (CNG), Liquefied Natural Gas (LNG), hydrogen, fuel cells, propane, ethanol, electricity, bio-diesel, and hybrid electric." Classes are scheduled on an as-needed basis. Those interested should contact TSI.

Disposal

LNG is a gaseous fuel that dissipates when released into ambient conditions. Capture and re-use of vented or released LNG vapors is generally preferable. In the event of a large spill or a continuous, uncontained leak, under some conditions the fuel may be intentionally burned as part of an overall risk mitigation strategy and to reduce the release of greenhouse gases.

8.4 Technology and Performance

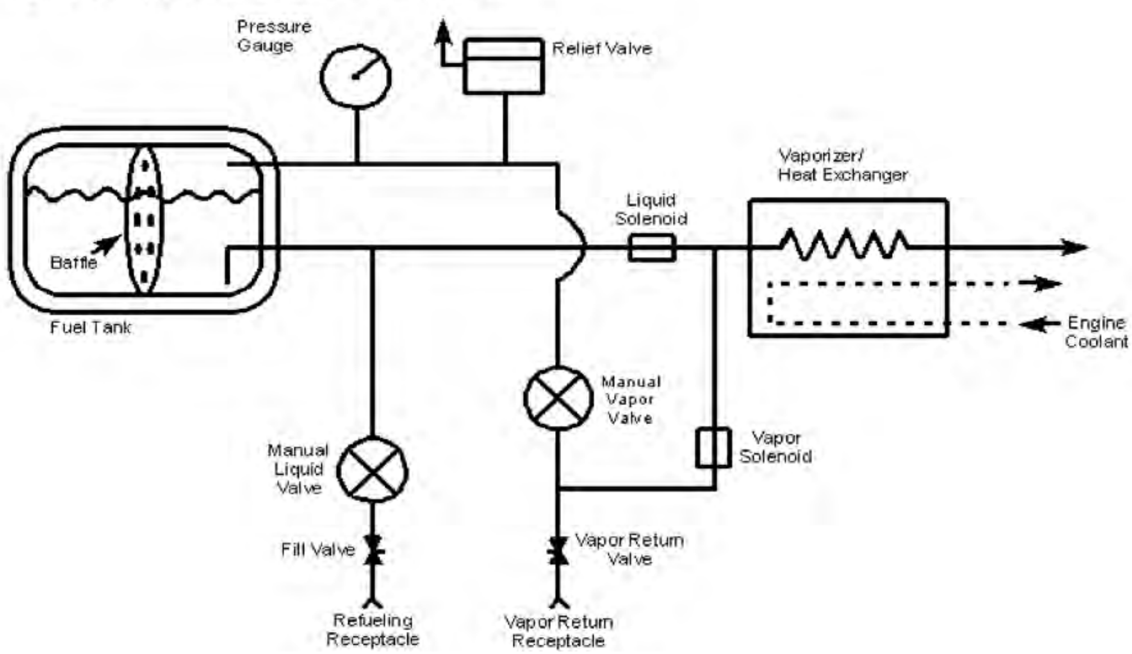
LNG buses use spark-ignited natural gas engines—the same engines used by CNG buses. In 2010, the only natural gas engine available in the United States for full-size transit buses is the Cummins Westport ISL G. This stoichiometric, 8.9 L engine is equipped with a three-way catalyst to meet 2010 emissions standards.

In addition to engines designed for use with natural gas, LNG buses include fuel tank(s) that may be installed either on the roof or underneath the bus. In low-floor designs, fuel tanks may also be placed in the "attic" above the engine compartment. Methane detectors are placed in the passenger area, the engine bay, and in the tank storage areas to identify fuel leaks. The buses also have fire suppression systems with interlocks to prevent them from starting while refueling or during fuel system maintenance.

The Fuel System

LNG vehicle fuel system components typically include an onboard cryogenic fuel tank; a fuel tank with refilling valve; a relief valve; a fuel pump; fuel lines; a fuel vaporizer; a heat exchanger; a pressure regulator; and a natural gas engine as seen in Figure 8.1. LNG is stored in the fuel tank at an extremely low

Figure 8.1 Typical LNG Vehicle Fuel System



temperature. It travels from the tank in either vapor or liquid form to the fuel delivery system. When there is sufficient vapor pressure in the fuel tank, vapors are preferentially drawn to fuel the engine; otherwise, liquid is drawn from a separate fuel line. The preferential use of LNG vapors means that, depending on the frequency and conditions of vehicle use, boil-off gas may be consumed rather than released through the relief valve. The switch to liquid LNG usually occurs within the first few minutes of vehicle operation.

Regardless of whether the fuel flows out of the tank in vapor or liquid form, it passes through a combined vaporizer and heat exchanger. This serves to both vaporize any remaining liquid and to raise the vapor temperature. Hot engine coolant is typically used as the heat source for the vaporizer and heat exchanger, but electrical heat has also been used in some systems. After passing through the heat exchanger, the pressure of the warmed gaseous fuel is reduced by the pressure regulator prior to injection into the engine. From this point forward, the CNG and LNG fuel systems are the same, requiring precisely metered electronic fuel injections into the natural gas engine.

Refueling

Figure 8.2 illustrates a conceptual LNG refueling station.[4] The facility includes a large vertical LNG storage tank, the volume of which depends on fleet size and fuel demand. High tank turnover rates are preferred because they minimize fuel boil-off losses. Boil-off management is a significant consideration for storage tanks. If a suitable tank throughput is maintained, boil-off should not be a significant issue. Occasional pressure buildup can be handled safely by venting a small amount of vapor from the tank through a relief valve with a low release rate. These emissions can be directed to a safe location for flaring, or added to the fuel conditioning process during vehicle refueling.

Figure 8.2 Conceptual LNG Refueling Station

Some refueling facilities also incorporate conditioning equipment (a vaporizer and small storage tanks) for ensuring proper fuel temperature and pressure for vehicle dispensing. The storage tank, conditioning equipment, and vaporizer are located in an impoundment area to contain fuel releases if they should occur. A small glycol boiler, which provides the heat for vaporizing and conditioning the fuel, is located outside the impoundment area. Fuel delivery to the vehicle is typically performed using fuel dispensers which can also meter the amounts of fuel delivered.

LNG vehicle refueling procedures are significantly different from those for CNG or diesel vehicles, although the fuel transfer rate from LNG dispensers is similar to conventional diesel fuel dispensers. The LNG refueling process has improved substantially since the 1990s, when an open-vent refueling system released significant amounts of fuel. Current LNG dispensers incorporate dual-line systems for transferring liquid LNG to the vehicle tank and capturing released LNG vapor from the vehicle tank during refueling. This closed loop system lowers the potential for human contact with the fuel and reduces fuel loss.

Before refueling begins, the current practice is to cool down the LNG liquid transfer line to limit vapor formation in the vehicle tank. To do this, liquid LNG is first recycled within the dispenser and transfer hose assembly. Vapor that is generated is returned to the bulk LNG storage tank. The recycling process is automated. When recycling is completed, the liquid transfer line is connected to the vehicle tank refueling receptacle, and the vapor line is attached to the vehicle tank vent line receptacle. Valves associated with the vehicle receptacles are opened to allow liquid and vapor fuel flow. The dispenser pump is then turned on and LNG is transferred into the vehicle tank.

When the tank is full, liquid LNG will start to escape through the vent line, where a sensor detects liquid flow and automatically shuts off the dispenser pump. Finally, the valves on the vehicle's liquid and vapor receptacles are closed. Using this refueling process, the potential for contact with the fuel is low, but it is still often recommended that refuelers use personal protection equipment (PPE). This may include face and eye protection, protective garments, insulated gloves, and safety footwear.

Performance

Performance and drivability of LNG buses is similar to diesel buses. Similar to CNG transit buses, LNG buses have slight reductions in acceleration and hill climbing ability compared to diesel buses.

These performance differences are reduced with the latest stoichiometric cooled EGR equipped natural gas engines through improvements in low-end torque. One manufacturer claims a 30% increase in low-speed torque for the stoichiometric controlled, cooled EGR engine compared to the previous lean-burn controlled engine.[5]

Diesel Gallon Equivalents (DGE)

On an energy-equivalent basis:

1 gallon diesel = 126.67 cubic feet natural gas at atmospheric pressure

1 gallon diesel = 1.7 gallons of LNG

The fuel economy of LNG buses is negatively impacted by their incremental weight gains and their inherently less efficient spark-ignited engines (spark ignition, compared with compression ignition combustion cycles, is less efficient). In a recent survey conducted by APTA, it was reported that LNG buses had fuel economy that was, on average, 53% lower (1.7 mpg) than diesel buses (3.6 mpg).[3] The U.S. Department of Transportation's (DOT) Federal Transit Administration (FTA) reported similar average fuel economy values (1.64 mpg for LNG buses versus 3.64 mpg for diesel buses) in its recent Report to Congress on alternative fuels for transit vehicles.[6]

8.5 Maintenance, Reliability, and Storage

Maintenance and Reliability

While many of the maintenance needs of LNG buses are the same as for diesel buses, there are some differences. Primary differences include the additional maintenance needed for spark-ignited engines, including periodic replacement of spark plugs and other ignition system components. LNG buses are also heavier than diesel buses due to the added weight of LNG tanks and the reinforced bus structure that supports the additional weight. For that reason, long-term brake and suspension component wear may increase. As part of routine maintenance procedures, LNG fuel system components should be checked for cracks or leaks, although LNG fuel system component life should not be an issue. Unlike CNG fuel storage cylinders, LNG tanks do *not* have to be DOT pressure-tested and certified every two years.

In a study completed by the National Renewable Energy Laboratory (NREL) in 2000 on the DART fleet, maintenance costs for LNG engine- and fuel-related systems were 8% higher than for comparable diesel buses. No significant differences were found in brake system maintenance costs. In terms of road calls, the LNG buses had, on average, a 50% shorter mean distance between road calls (MBRC) compared to the diesel buses for engine- and fuel-related systems.[7]

Storage

Bulk storage tanks for LNG are addressed in National Fire Protection Association (NFPA) 59A, which recommends an impound area around the storage tank(s). The function of the impound area is to capture any fuel that may spill from the tank, and to minimize the possibility of endangering personnel, adjoining property, and adjoining structures. Impounding areas are formed by natural barriers, dikes, or impounding walls, and are designed to contain the total volume of liquid in all of the storage tanks located inside the impoundment. Impounding areas are also recommended for LNG transfer areas, such as those designed for unloading LNG tanker trucks.

In both bulk storage and onboard LNG tanks, fuel gradually vaporizes, creating boil-off gas and increasing pressure in the tank. If fuel is not removed, tank pressure will reach levels that trigger release of boil-off gas from the pressure relief device(s). The duration between the time the fuel was last removed and the time when the pressure relief valve opens is known as the tank holding time. This typically ranges between four and seven days. While boil-off gas has been released into the air, it is increasingly being directed through vent lines for capture and use.

How is it Stored?

LNG is stored in cryogenic tanks under slightly elevated pressure (i.e., 10 psi) at temperatures around -250°F. These tanks have an outer shell and an inner pressure shell separated by an insulated vacuum. The inner shell may have baffles to limit sloshing of the liquid fuel. The tanks are also fitted with liquid-fuel-level gauges, pressure relief valves, and over-pressure burst discs. The pressure relief valve (or device) releases boil-off gas when necessary, and then automatically closes. In contrast, the burst disc opens only in extreme over-pressure cases to prevent an explosion—it cannot re-close, and it will release all fuel in the tank.

8.6 Emissions

Emissions are addressed in the following two sub-sections. The first discusses local and regional pollutants that are currently regulated under the Clean Air Act (i.e. hydrocarbons (HC), nitrogen oxides (NOx), particulate matter (PM), non-methane hydrocarbons (NMHC), and carbon monoxide (CO)). The second sub-section discusses pollutants that contribute to global warming (i.e., greenhouse gases (GHG)).

LNG buses use natural gas engines that are the same as those used for CNG buses, and these engines are certified to meet the same emission standards for both fuel types. Thus, LNG buses have the same tailpipe emissions characteristics as CNG buses, and data on CNG tailpipe emissions are also applicable to LNG buses. Since more studies have been conducted with CNG buses than with LNG buses, much of the emissions discussion is based on CNG studies.

Regulated Pollutants

LNG and diesel bus emissions of regulated pollutants have become increasingly similar over the last decade. Historically, the benefits of LNG were due to the more complete burn of the light hydrocarbons that comprise natural gas. As regulations of tailpipe emissions became more stringent, diesel engine technology evolved to meet new standards through a combination of electronic controls and exhaust gas treatment. Natural gas engine technology and exhaust gas treatment have also evolved in response to the most recent step in the phased-in emission standards. Because natural gas engines have emissions characteristics that are different from diesel engines, they need different exhaust treatment systems.

EPA urban bus engine standards have changed several times over the lifespan of the oldest buses on the road – new emission standards became effective in 2004, 2007, and 2010. With each of these changes, there were changes in diesel emission controls. Only the most stringent emission levels, which were phased in from 2007 to 2010, required significant changes for LNG buses. Half of all engine sales in 2007 through 2009 were to meet the 2010 standards, so comparing like model years is not always appropriate.

As the standards and associated emission control systems have changed, so has the relative difference in diesel and natural gas bus emissions. For example, a typical 2006 natural gas bus emits less CO and NOx than a 2006 diesel bus, but in 2010, natural gas buses may emit more CO than diesel and less NOx. To achieve 2007 standards for PM, diesel buses needed the addition of a diesel particulate filter (DPF). LNG buses used the same technology needed for prior standards (i.e., lean-burn engine controls and an oxidation catalyst). To achieve 2010 emission standards, diesel buses need both a DPF and selective catalyst reduction (SCR). Comparable natural gas engines (i.e., the Cummins ISL G) use stoichiometric cooled exhaust gas recirculation (EGR) with a three-way catalyst (TWC).

At the time of this writing, available emissions measurements from MY2010 buses are quite limited. This is a significant consideration for comparisons of emissions differences between natural gas and diesel buses because these engines were required to meet more stringent emissions regulations beginning in 2010. For a preliminary comparison of 2010 natural gas and diesel bus emissions, U.S. EPA certification data for MY2010 on-road engines with power ratings of 300 to 350 horsepower were compared. Table 8.4 shows the average certification test emissions as converted to grams/mile based on EPA conversion factors. These emissions estimates are used as default values in the FuelCost2 model. These estimates should be updated as more emission measurements are reported for 2010 buses.

Table 8.4 Natural Gas Engine Emissions: EPA MY2010 Certification Tests

	g/bhp-h*	g/mile
Carbon Monoxide	6.53	21.91
Nitrogen Oxides	0.07	0.22
Particulate Matter	0.00	0.00
Non-Methane Hydrocarbons	0.02	0.02

*Emissions estimates based on EPA certification test data for model year 2010 highway engines between 300 and 350 horsepower available at http://www.epa.gov/oms/crttst.htm. Units of g/bhp-h are converted to g/mile using the EPA conversion factor for gasoline (spark-ignition) engines.[8]

Greenhouse Gases

The GHG emission of greatest concern from diesel buses is carbon dioxide (CO_2). While CO_2 is also emitted from LNG buses, methane emissions are the greater GHG concern. The global warming potential of methane is over 20, versus 1 for CO_2, indicating that methane is over 20 times more effective at trapping heat than CO_2.[9] GHG emissions are often reported in CO_2 equivalents for easier comparison on emissions in terms of heat-trapping ability.

In the past, LNG (i.e., methane) losses during bulk fuel transfers and refueling were substantial because much of the vapor generated during the fuel transfer process was allowed to escape to the air. Given the high global warming potential of methane, this meant that LNG buses had very high GHG emissions compared to CNG and diesel.

For the purposes of this discussion, the newer LNG transfer methods with recirculation of LNG vapors are assumed. Given the newer fuel transfer methods, when the LNG systems fully capture boil-off gas, their on-site and tailpipe GHG emissions are similar to those from CNG buses. For that reason, the CNG studies of GHG emissions discussed below are applicable to LNG buses.

GHG emissions are best compared over the fuel lifecycle, referred to as well-to-wheels. This is commonly broken into two components: well-to-tank, and tank-to-wheels. Well-to-tank includes GHG emission from fuel exploration, development, and production, to refining, delivery to refueling sites, and the actual refueling process. In the case of LNG, this also includes the liquefaction process. Tank-to-wheels emissions are from onboard sources, primarily the tailpipe (as a result of combustion). Tank-to-wheels also includes evaporation from the fuel tank, or in the case of LNG buses, boil-off gas that is not captured.

GHG emissions from well-to-tank for both diesel and natural gas are in the range of 20% to 30% of their total lifecycle GHG emissions, not including LNG liquefaction. Well-to-tank GHG emissions are estimated to be 12% higher for CNG than for diesel.[10] This includes GHG emissions associated with compressing natural gas for CNG applications. As a simplifying assumption for the purposes of this discussion, it is assumed that GHG emissions are similar for compression and liquefaction.

The greatest portion of GHG lifecycle emissions from both CNG and diesel buses (and by extension, LNG buses) is from the tailpipe. Tank-to-wheels GHG emissions vary with engine technology. The tank-to-wheels emissions shown in Table 8.5 were measured on board during a drive cycle typical for Vancouver Transit Authority buses.[11] The diesel buses were equipped with 2006 Cummins ISL 280 engines, particle filters, and no oxidation catalyst. CNG buses were equipped with 2006 lean-burn Cummins C-Gas Plus (ICG 280) engines and an oxidation catalyst. In this study, GHG tailpipe emissions were 8% lower for the CNG versus diesel buses—this relationship will likely not be the same for MY2010 and beyond.

Table 8.5 GHG Emissions from 2006 Natural Gas and Diesel Buses

		CO_2 Equivalent g/mile*		
		Diesel	Natural Gas	Change with Natural Gas
Well-to-Tank				
	Total	**636**	**711**	**12% increase**
Tank-to-Wheels[30]				
	CO_2	2,258	1,872	17% reduction
	CH_4	3	230	76-fold increase
	N_2O	46	14	69% reduction
	Total	**2,306**	**2,117**	**8% reduction**
Total Well-to-Wheels				
	Total (Net)	**2,942**	**2,828**	**4% reduction**

* Assumes 1 g CH_4 = 23 g CO_2; 1 g N_2O = 296 g CO_2

Cummins Westport, the manufacturer of the only full-size transit bus natural gas engine that is currently available, has reported that its 2010-compliant natural gas ISL G engine provides a 17% reduction in GHG tailpipe emissions compared to the cleanest comparable diesel engines.[12] This improvement is primarily from reductions in unburned methane emissions. Since methane is a much more potent GHG than CO_2 (the primary GHG from diesel engines), GHG emissions are unlikely to be reduced by such a substantial amount in MY2010 diesel buses.

For the purposes of choosing a default value for lifecycle GHG emissions in the FuelCost2 cost model, it is estimated that MY2010 LNG buses with stoichiometric engines will offer GHG reductions in the range of 10% to 20% compared to MY2010 diesel buses. Recognizing the probability of the occasional uncaptured release of boil-off gas during LNG operations, and of vapor releases during the bulk fuel transfer process, it is roughly estimated that the reduction in lifecycle GHG for LNG buses is half of the lowest end of this range. Thus for LNG, the default GHG reduction in FuelCost2 is set at 5% compared to conventional diesel buses. It should be noted that actual measurements of fugitive LNG vapors were not available to better inform this estimate.

8.7 Cost and Availability

When assessing the costs of LNG bus ownership, it is necessary to consider not only costs for the vehicle and its operation, but also the costs for refueling infrastructure and maintenance facility modifications.

Vehicle Costs

LNG buses are more expensive than diesel buses because special modifications are necessary to store LNG on board. Three bus manufacturers currently offer LNG buses: New Flyer Industries, North American Bus Industries (NABI), and El Dorado National, although there is only one natural gas engine currently available for full-size transit buses. LNG buses offered by El Dorado and NABI are $30,000 to $40,000 more than comparable diesel buses, while LNG buses offered by New Flyer are $50,000 higher than comparable diesel buses. The higher New Flyer costs are largely attributed to the use of multiple smaller roof-mounted fuel tanks versus a single large fuel tank.

LNG bus operating costs are primarily composed of maintenance and fuel costs, but only limited information on these costs is available. Between the late 1990s and 2004, the National Renewable Energy Laboratory performed several studies on heavy-duty LNG vehicle fleets, including transit buses, refuse trucks, and long haul trucks. Fuel costs during the time period covered by the studies were $0.90 to $1.45/gallon for diesel fuel and $0.82 to $2.27/diesel gallon equivalent for LNG—significantly lower than today's costs. More importantly, the data reported in these studies apply to early LNG bus designs, and are not indicative of the currently available LNG technologies. For that reason the information is not presented in this document.

For the purposes of default values in the FuelCost2 model, the LNG bus price is set at $40,000 more than the conventional diesel bus price, and operating and maintenance costs are the same as for CNG buses, not including fuel costs. The fuel price for LNG is provided as $1.40 per gallon LNG. This is based on the average 2009 commercial price of natural gas reported by the U.S. Department of Energy plus an additional $0.75 per gallon for LNG, which is similar pricing to that paid by Sun Metro (El Paso, TX) for LNG trucked to their bulk storage tanks.[13]

Refueling Station and Maintenance Facility Costs

Natural gas is widely available throughout the U.S. due to an expansive pipeline system. The pipeline distribution system tends to keep fuel transport costs relatively stable, but natural gas wellhead prices tend to fluctuate seasonally with demand. Prices in fact doubled from 2002 to 2007 (from $2.95 to $6.39 per 1,000 cubic ft).[14] It is also notable that LNG is not widely available as a vehicle fuel. One of the variables in LNG prices for fleet operations is the cost of transporting the fuel from the liquefaction facility where it is produced to the fleet location—a factor dependent on the distance between the production facility and the fleet.

In a recent cost-benefit analysis conducted for Sun Metro on its natural gas supply options, the cost of trucking LNG to its LNG storage tanks was compared to construction of a small-scale liquefaction facility. Over a 10-year analysis period, construction and operation of the liquefaction facility (18,000 gallon per day LNG) was found to cost nearly 30% less than trucking and bulk storage of LNG deliveries.[15] (Note: Sun Metro currently trucks LNG to its bulk storage tanks to directly supply a small, decreasing fleet of LNG buses and to be vaporized to supply a much larger, increasing fleet of CNG buses).

The construction of an LNG fueling station is expensive, but it is less expensive than a comparable CNG fueling station. For example, to install a 60,000 gallon LNG station to fuel its fleet of 200 LNG buses, the City of Phoenix Public Transit Department in 1997 spent $3.5 million; adjusted for inflation, this is equivalent to $4.7 million in 2009.[16] Similarly, Dallas Area Rapid Transit spent $7.5 million ($9.3 million adjusted for inflation) in 2000 to construct LNG fueling stations at two depots and to modify maintenance facilities for serving LNG buses.

The safety-associated costs of facility conversion to LNG (e.g., electrical system upgrades) are incrementally more expensive for older facilities than when incorporated into new facility designs prior to construction. For example, the 1997 facility upgrades to serve a fleet of 200 LNG buses at the City of Phoenix Public Transit Department cost $750,000 (approximately $1 million adjusted for inflation).

No new LNG stations have been constructed by transit agencies in the past several years. Today, most transit fleets have third party natural gas fuel providers construct, operate, and maintain fuel stations. Under this arrangement, the fuel price includes the station capital and operational costs.

Table 8.6 provides cost estimates for LNG bus facilities and operations. These costs should be used only for rough project estimation purposes because they are based on a limited number of fleet experiences.

Table 8.6 LNG Cost Estimates

Item	LNG
New Vehicle ($)	$390,000 [a]
Facility Conversion (50 Buses) ($)	$1.5 million
Fuel ($/gal LNG) ($/ DGE)	1.40 2.38
Fuel economy (mpg)	2.7 [b]
Propulsion System Maintenance ($/mile)	0.18 [b]
Facility Maintenance and Operation ($/mile)	0.20 [c]

a. Bus prices estimated as $40,000 more than a diesel bus price.
b. LNG and CNG engine systems are identical, so CNG data used as a surrogate.
c. Facility O&M estimated as the midpoint of CNG and diesel facility O&M costs.

8.8 Summary

Liquefied Natural Gas

Pros	Cons
Natural gas is widely available across the country.	Specialized storage and refueling equipment is needed.
LNG has excellent properties for spark-ignition engines.	LNG storage volumes are about 1.7 times larger than those for the same amount of energy from diesel.
LNG produces lower emissions of certain pollutants than diesel.	Periodic venting of boil-off gas from LNG tanks is a safety consideration for bulk storage, vehicle parking, and maintenance facilities.
Acceleration and low-end torque are likely to be improved with the latest stoichiometric natural gas engines.	LNG buses generally have slower acceleration than comparable diesel buses.
Biogas or landfill gas can be used to produce LNG, making it a renewable fuel.	As a cryogenic liquid, LNG requires unique training and safety procedures.
Maintenance and reliability characteristics for LNG buses should be similar to those for CNG buses.	Garage facilities may require ventilation modifications and methane detection devices for safe servicing of LNG buses.

LNG References

[1] Foss, M. (October 2003). *LNG Safety and Security*. Center for Energy Economics. Retrieved from: http://www.beg.utexas.edu/energyecon/lng/documents/CEE_LNG_Safety_and_Security.pdf

[2] Murphy, M., (January 1999). *Motor Fuel Options for Heavy Vehicle Diesel Engines: Fuel Properties and Specifications*. U.S. Department of Energy.

[3] American Public Transportation Association (May 2007). *Public Transportation Fact Book, 58th Edition*.

[4] Thompson, L. (March 2008). *LNG As a Transportation Fuel.* Alternative Fuel Vehicle Institute Webcast, Natural Gas Vehicle Institute.

[5] Cummins Westport, Inc. (January 2008). *Every™ Alternative. ISL G. Natural Gas Engines for Bus and Truck*. Retrieved from: http://www.cumminswestport.com/pdf/CWI-ISL_G_Brochure_MED.pdf

[6] Federal Transit Administration (December 2006). *Alternative Fuels Study: A Report to Congress on Policy Options for Increasing the Use of Alternative Fuels in Transit Vehicles.* U.S. Department of Transportation. Retrieved from: http://www.fta.dot.gov/documents/Alternative_Fuels_Study_Report_to_Congress.pdf

[7] Chandler, K., Norton, P. and Clark, N. (October 2000). *Dallas Area Rapid Transit's (DART) LNG Bus Fleet: Final Results, Alternative Fuel Transit Bus Evaluation*. National Renewable Energy Laboratory, NREL/BR-540-28739. Retrieved from: http://www.nrel.gov/vehiclesandfuels/fleettest/pdfs/28739.pdf

[8] U.S. Environmental Protection Agency (May 1998). *Update Heavy-Duty Engine Emission Conversion Factors for MOBILE6: Analysis of BSFCs and Calculation of Heavy-Duty Engine Emission Conversion Factors*. EPA420-P-98-015. Retrieved from: http://www.epa.gov/oms/models/mobile6/m6hde004.pdf

[9] U.S. Department of Energy, Energy Information Administration (October 2008). *Documentation for the Emissions of Greenhouse Gases in the United States 2006*, U.S. DOE/EIA – 0638 (2006), p. 208. Retrieved from http://www.eia.doe.gov/oiaf/1605/ggrpt/documentation/pdf/0638(2006).pdf

[10] U.S. Department of Transportation, Federal Transit Administration (July 2, 2007). *Transit Bus Life Cycle Cost and Year 2007 Emissions Estimation, Final Report*, FTA-WV-26-7004.2007.1. Retrieved from http://www.fta.dot.gov/documents/WVU_FTA_LCC_Final_Report_07-23-2007.pdf

[11] Graham, L.A., G. Rideout, D. Rosenblatt, and J. Hendren (2008). *Greenhouse Gas Emissions From Heavy-Duty Vehicles. Atmospheric Environment, 42*, 4665-4681.

[12] Westport News Release (February 6, 2006). *Cummins Westport Receives U.S.$350,000 for Engine Demonstration*. Retrieved from http://www.westport.com/news/index.php?id=301&return_to=/news/index.php

[13] R.W. Beck, (2009). Cost Benefit Analysis for Sun Metro CNG/LNG Supply. Prepared for City of El Paso Engineering Department. Retrieved from: https://www2.elpasotx.gov/sunmetro/agenda/06-02-09/06020911D.pdf

[14] Energy Information Administration, U.S. Department of Energy. Retrieved from: http://www.eia.doe.gov/

[15] R.W. Beck, (2009). Cost Benefit Analysis for Sun Metro CNG/LNG Supply. Prepared for City of El Paso Engineering Department. Retrieved from: https://www2.elpasotx.gov/sunmetro/agenda/06-02-09/06020911D.pdf

[16] U.S. Department of Labor, Bureau of Labor Statistics (n.d.). *Online consumer price index calculator*. Retrieved from: http://data.bls.gov/cgi-bin/cpicalc.pl.

Guidebook for Evaluating Fuel Choices for Post-2010 Transit Bus Procurements 9-1

9.0 Hydrogen—Internal Combustion Engine

Hydrogen Internal Combustion Engines (HICE, or H_2ICE) are thought of as an intermediary step on the path to using hydrogen fuel cells for transit vehicles. HICE buses are powered by an internal combustion engine that is fueled by hydrogen gas. Hydrogen is stored onboard as a compressed gas, as a liquid, or in solid-state materials using chemical processes such as adsorption.

A 40-ft hybrid-electric HICE bus, operated by SunLine Transit in Thousand Palms, California

HICE technology has been developed for several reasons. Fuel cells still require an uncertain amount of time (possibly decades) before they are fully developed and mass produced. To bridge this gap in the hydrogen transportation economy, HICE was developed to provide many of the benefits of fuel cell vehicles in the near future. Some of the benefits of using HICE technology include the following:

- Accelerating the development of a hydrogen infrastructure,
- Using a new fuel (hydrogen) in a mature engine technology (the internal combustion engine),
- Near-zero "tailpipe" emissions,
- Reduction of petroleum-based fuel needs, and
- Demystifying hydrogen for the public.

Hydrogen {**hahy**-dr*uh*-j*uh*n} *noun*–
A chemical element that forms a colorless, odorless, highly flammable diatomic gas (H_2) at a standard temperature and pressure that is the lightest of all gases.

Several companies are developing HICE engines (Ford, BMW, Mazda, MAN, Westport Innovations, and Quantum) and others are implementing them into vehicles (Ford, MAN, ISE Corporation), from passenger cars, to cutaway van-type shuttle buses, to full-size transit buses.

Key Point

HICE vehicles are often viewed as a ***bridge technology*** between vehicles powered by internal combustion engines fueled with petroleum-based fuels and vehicles powered by fuel cells. HICE may encourage development of a hydrogen infrastructure that may later be used for vehicles powered by fuel cells.

9.1 Fuel Description

Did You Know?

Hydrogen is the most abundant element in the universe. The stars, including our sun, are composed mainly of hydrogen.

Hydrogen is an abundant element, but it is not freely available on its own. Instead, it must be separated by various processes from other compounds. Potential hydrogen sources range from complex compounds such as petroleum-based fuels to simpler compounds such as natural gas and water.

Due to the wide variety of potential feedstocks and methods used to extract hydrogen from them, HICE energy requirements and lifecycle emissions vary widely. The most environmentally benign way to produce pure hydrogen would be to use renewable power (e.g., solar, hydro, or wind) to power an electrolyzer in order to produce hydrogen from water.

Table 9.1 shows some of the key fuel properties of hydrogen compared to diesel. The high octane rating allows high compression ratios (>14) to be used, which increases energy efficiency. The wide flammability limits of hydrogen also allow operation in an ultra-lean mode.[1, 2]

Table 9.1 Hydrogen and Diesel Fuel Properties[3]

Property	Hydrogen	Diesel
Boiling Temperature ($^{\circ}$F)	-423	356 to 644
Autoignition Temperature ($^{\circ}$F)	932	600
Cetane Number	N/A	40 to 55
Octane Number	130+	N/A
Flash point ($^{\circ}$F)	N/A	≥140
Flammability Limits (vapor in air by volume %)	4.1 – 74.0	1.0 – 6.0
Lower Heating Value (Btu/lb)	52,217	18,394
Relative Weight (same volume) Compared to air = 1	0.07	>3 *(as vapor)*
Soluble in Water	No	No

HICE engines do not require the level of hydrogen purity needed to operate fuel cells (i.e., over 99.9%). Because the purification of hydrogen can be quite costly, a wider range of hydrogen sources may be economically viable for HICE vehicles than for fuel cell vehicles. As hydrogen levels decrease from 96% to 60%, engines continue to operate properly, but with decreased power.[4]

9.2 Fuel Usage

HICE buses are currently at the demonstration phase of development, so no fleets use them in large numbers. Between 2005 and 2008, Ford produced around 30 E-450 shuttle buses with HICE 6.8-liter V-10 engines. Eight of these were for the State of Florida as part of the Florida Hydrogen Highway Initiative.[5, 6] In early 2010, ten of these were still operating at various locations in Canada, but only two remained in operation in the United States. These are both located in Allentown, PA; one is operated by Air Products and Chemicals, and the second by Lehigh Valley Hospital. The most common reasons for discontinued operation were cost and refueling issues (i.e., fuel availability).[7]

Is it Imported?

Hydrogen is produced regionally, mainly for industrial uses. Although hydrogen can be produced using numerous resources, the primary feedstock is currently natural gas, 16% of which is imported.

In the United States, a 40-ft hybrid HICE (HHICE) bus developed by ISE Corporation has been in fleet operation at SunLine Transit in Thousand Palms, California, since 2004.[8]

A HICE bus at a refueling station in Berlin, Germany (Source: HyFLEET:CUTE Website).

In Europe, the HyFLEET:CUTE program included 14 HICE buses in its demonstration fleet of fuel cell buses in Berlin. HyFLEET tested two different engines produced by MAN: 4 buses had naturally aspirated (200 hp) engines, while 10 buses had turbocharged/direct-injection (270 hp) MAN engines. One of the buses with the turbocharged engine also had a fuel cell APU for auxiliary power production. By the end of the study in 2009, these buses had traveled 430,000 km and logged 30,000 service hours. The buses with naturally aspirated engines worked well, but the ones with turbocharged engines suffered from fuel injector problems.[9, 10, 11]

9.3 Safety, Training, and Disposal

Flammability and Toxicity

Hydrogen has wide flammability limits (4.1% to 74.0% by volume at 60°F and 1 atm). It is not toxic, but a large volume release can displace enough air to cause asphyxiation. Hydrogen gas is colorless, has no smell, and is lighter than air. It will rise and dissipate if released outdoors, but it can accumulate in confined areas. When hydrogen stored under high pressure is released to the air, the hydrogen gas expands which causes the surrounding air to cool – this may cause a vapor cloud to form. Hydrogen leaks may also be detected by the accumulation of frost on the tank or lines around the leak.

Hydrogen diffuses 3.8 times faster than natural gas, and rises six times faster, meaning the concentration of hydrogen decreases relatively quickly to below the flammability limit.[12] Buildings such as storage garages and maintenance bays must nevertheless have hydrogen sensors and proper ventilation systems to make sure that gas is quickly and safely exhausted in the event of either small gas releases from routine maintenance or the failure of a fuel storage or fueling system. Maintenance areas must be modified to remove all potential sources of sparking to prevent fire and explosion in the event of a hydrogen buildup.[13]

Because hydrogen burns very quickly, it can produce a loud noise that can be mistaken for an explosion. If a pool of liquid hydrogen or a continuous leak of gaseous hydrogen is ignited, the flame will be colorless, and very difficult to see.

High Pressure

Gas released at very high velocities from pressure or thermal relief devices, or an improper or damaged fitting or high pressure line, can cause tissue damage. Further, the high velocity release of gas from flexible hoses such as during refueling can cause an improperly placed or damaged refueling hose and nozzle to whip around, injuring people and damaging surrounding equipment.

Training

The training requirements for HICE buses have not been widely discussed since they are still at the prototype/pre-production stage of development. The engine and fuel storage technology is similar to that of CNG buses, so required training ought to be similar. Government and industry are developing codes and standards related to hydrogen fuel production, distribution, and use for hydrogen-fueled fuel cell buses. The safety and training recommendations and requirements developed through this process should provide information that can be used to train staff to safely maintain and operate HICE buses.

Federal Motor Carrier Safety Administration (FMCSA) of the U.S. DOT has published the following three reports that provide a good beginning for addressing hydrogen safety in bus operations:

- *Guidelines for Use of Hydrogen Fuel in Commercial Vehicles, Final Report.* Report Number FMCSA-RRT-07-020, November 2007. Available at http://www.fmcsa.dot.gov/facts-research/research-technology/report/Guidelines-H2-Fuel-in-CMVs-Nov2007.pdf

  Summary: This 81-page report provides an introduction to hydrogen fuel as used in combustion engines and fuel cells. It includes basic fuel properties and conversion factors, fuel system components, safety and emergency response, and guidelines for design and operation of hydrogen systems on vehicles and as part of refueling facilities and maintenance facilities.

- *Changes to Consider in the Federal Motor Carrier Safety Regulations and North American Standard Inspection Procedures to Accommodate Hydrogen as an Alternative Fuel.* Report Number FMCSA-RRT-07-027, December 2007. Available at http://www.fmcsa.dot.gov/facts-research/research-technology/report/FMCSA-H2-Regs-and-Inspections-Final-Report-Nov2007.pdf

  Summary: This 26-page report examines existing FMCSA regulations governing commercial vehicle fuel systems, discusses gaps, and presents considerations for changes in these regulations for hydrogen fuel. It also examines modifications in commercial vehicle inspections and carrier reviews that should be considered for hydrogen fuels.

- *System Safety Plan for Commercial Vehicle using Hydrogen as an Alternative Fuel.* Report Number FMCSA-RRT-07-025, November 2007. Available at http://www.fmcsa.dot.gov/facts-research/research-technology/report/System-Safety-Plan-CMVs-Hydrogen-Final-nov07.pdf
  Summary: This 28-page report provides guidance for the development of a System Safety Plan (SSP) for use by vehicle fleet operators to ensure long-term safe operation of vehicles using hydrogen.

U.S. DOT's Transportation Safety Institute (TSI) offers training courses specifically for transit agencies. Their 2011 course listings include "Safety Evaluations for Alternative Fuels Facilities and Equipment." This 3-day course provides "awareness and training in conducting safety evaluations for alternative-fueled vehicles, support equipment, and facilities using Compressed Natural Gas (CNG), Liquefied Natural Gas (LNG), hydrogen, fuel cells, propane, ethanol, electricity, bio-diesel, and hybrid electric." Another 1-day course offering, "Alternative Fuel Cylinder Inspection," is specific to CNG, but the inspection guidance would be similar for high pressure hydrogen cylinders. Classes are scheduled on an as-needed basis. Those interested should contact TSI.

Disposal

Hydrogen gas is lighter than air, so if fuel is lost or intentionally vented outdoors, it will rise and quickly dissipate to safe concentrations. Un-used hydrogen fuel should be returned to the supplier.

9.4 Technology and Performance

HICE Engine Technology

HICE engines are spark-ignition engines that operate on the Otto combustion cycle, just like engines that run on gasoline. The engines can be built on either gasoline or diesel engine block designs, though both cases require an ignition source such as a spark plug or glow plug to initiate combustion. Due to the properties of hydrogen, several engine components must be modified for safe operation and to meet reliability and durability requirements. Some of the modified engine components include: specifically designed fuel system, injectors, and spark plugs, a higher energy ignition coil, and the use of low ash formulation oil with extra corrosion inhibitors.[14]

The following approaches are used to introduce hydrogen into engine cylinders:

- **Port Fuel Injection**—uses a hydrogen injector on the intake manifold. Similar to gasoline port fuel injection but with increased injection volumes to compensate for hydrogen's lower energy density. These engines are theoretically able to achieve 84% of baseline gasoline engine power; pre-ignition of the fuel has resulted in actual power output that is only 65% of a gasoline engine.[15, 16]
- **Direct Fuel Injection**—injects fuel directly into each cylinder, allowing a higher percentage of the cylinder volume being filled by hydrogen, which results in a higher power density compared to port fuel injection. Direct fuel injection reduces pre-ignition and backfiring, and uses a higher compression ratio which improves efficiency, and lowers costs. Due to the higher compression ratios and power output, these hydrogen engines are compared to diesel engines. The theoretical specific power of a direct injection HICE engine is 20% higher than a comparable gasoline engine.

- **Boosting technologies**—(e.g., supercharging or turbocharging) can be used to increase the specific power of both port fuel injected and direct fuel injected engines. The specific power ratios compared to the gasoline and diesel engines (i.e., 84% and 120%) are increased by multiplying by the boost pressure ratio ($p_{boost}/p_{ambient}$).

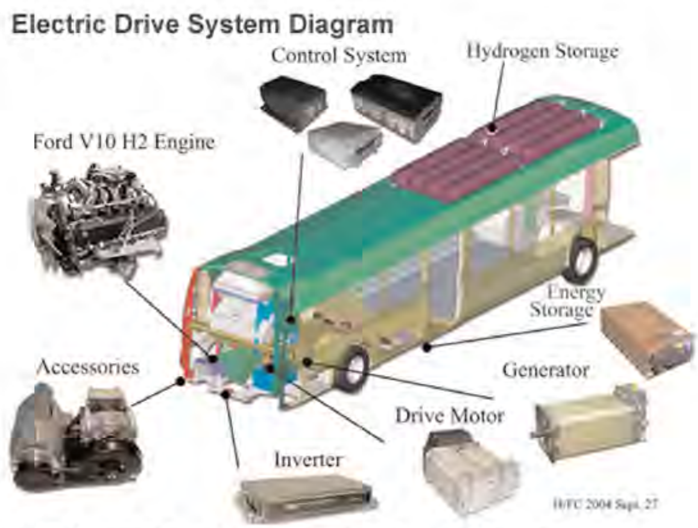
Table 9.2 Comparison of Powertrain Differences Between Diesel and Hydrogen Internal Combustion Engine Buses

Component	Diesel Bus	Hydrogen Internal Combustion Engine Bus
Energy source and storage method	Diesel fuel in tank	High-pressure or liquefied hydrogen tanks
Propulsion power source	Diesel engine	Spark ignition engine
Drivetrain	Multiple geared transmission	Multiple geared transmission

A key limiting performance aspect of HICE bus technology identified during the Ford HICE shuttle bus demonstration was the space required for onboard hydrogen fuel storage. The balance between fuel storage space and passenger/cargo capacity resulted in significant reductions in driving range between refueling compared to conventional buses. A hybrid electric powertrain may help extend the driving range.

Hybrid-Electric HICE Buses

Since HICE buses use a powertrain that is nearly identical to that used by conventional engines, hybrid-electric drive systems can also be used to improve fuel economy and drive power. These buses are known as hybrid-electric HICE buses (HHICE). As with diesel-electric hybrid buses, hybrid technology in HICE buses lowers fuel usage, fuel storage requirements, and exhaust emissions. It also potentially allows for engine downsizing. On the other hand, HHICE buses have higher capital costs than regular HICE buses. Early prototype HHICE buses were very expensive, on the order of $1 million per bus, though prices would likely go down if HHICE buses go into full production.[17]



A 40-ft HHICE Bus (Source: SunLine Transit Website).

9.5 Maintenance, Reliability, and Storage

Maintenance

The maintenance requirements of HICE buses have not been widely discussed since the technology is still at the prototype/pre-production stages of development. Technicians would have to be trained to understand the fuel and the procedures required to safely work on hydrogen-fueled buses. However, the majority of the technology used for a HICE bus is the same as, or very similar to, that used in current diesel and CNG buses. For example, production HICE buses would use heavy-duty diesel-based engines, gaseous fuel storage and delivery systems, and a conventional drivetrain. HICE bus maintenance should therefore not be significantly different than for these buses.

The maintenance areas for hydrogen-fueled buses must be modified to ensure safe operating conditions. The requirements for storage of gaseous-fueled hydrogen vehicles are similar to the requirements for natural gas-fueled vehicles. The maintenance areas must be fitted with hydrogen sensors and ventilation equipment suitable for use in environments with hydrogen gas, such as sealed fan motors and switches to eliminate the potential of sparking which could ignite the gas. Ventilation must be sufficient to quickly exhaust the hydrogen to reduce gas concentrations to safe levels (below 4.1%).

Reliability

The reliability of HICE buses has not been widely investigated since they are still at the prototype/pre-production stages. However, the majority of the technology that would likely be used on a production HICE bus is the same as, or very similar to, that used in current diesel and CNG buses. For example, production HICE buses would use a heavy-duty diesel based engine, gaseous fuel storage and delivery systems modified from robust and mature CNG technology, and a conventional drivetrain. Due to these and other similarities, it could be assumed that HICE buses would also have comparable reliability.

Storage

There are three ways to store hydrogen fuel: as a compressed gas, as a liquid, or in solid-state materials using chemical processes such as adsorption. Compressed gas storage is the most common method for all HICE vehicle prototypes, and the only method currently used for HICE bus prototypes. Under this method, hydrogen is stored in high pressure (typically 5,000–10,000 pounds per square inch) wound carbon fiber cylinders, similar to those used for storing CNG on buses. Though several cylinders are likely necessary to store an adequate amount of hydrogen for a HICE bus, there should be ample available space on the roof.

How is it Stored?

Standard storage and handling procedures are similar for compressed natural gas and hydrogen gas.

Hydrogen can be stored as a liquid by reducing the temperature to -423°F in a process similar to how natural gas is liquefied. Liquefying the fuel increases the energy storage density, reducing the amount of space needed for fuel storage. However, the additional components required to keep the fuel at -423°F take up some of the saved space. BMW has used this method for its demonstration 7-Series passenger cars.

Hydrogen can also be stored in solid-state materials, such as hydride materials. One such material is essentially the same as what is used in the anodes of nickel metal hydride (NiMH) batteries. NiMH battery manufacturer ECD Ovonic developed a metal hydride hydrogen storage system for vehicles which requires less volume than a compressed gas system. However, this system weighs more because the technology is only able to store approximately 1 to 3% by weight of hydrogen. So far these systems have only been used in prototype light-duty vehicles. Mounting such a heavy system on a bus's roof could lower its stability and potentially lead to a loss in passenger carrying ability.

Table 9.3 shows the storage volume and weight for carrying 10 kg of hydrogen using different storage technologies. For comparison purposes, the energy equivalent volume and storage weight is also shown for diesel.[18]

Table 9.3 Comparison of Hydrogen Fuel Storage System Weight and Volume

	Earlier Systems		Recent Systems	
	Weight (kg)	Volume (L)	Weight (kg)	Volume (L)
Diesel (9 Gallons)	40	55	40	55
Compressed Hydrogen Gas	5,000 psig		10,000 psig	
	260	500	230	250
Liquefied Hydrogen	Metallic (Stainless Steel)		Lightweight Carbon Fiber Construction	
	220	300	80	250
Hydride	5,000 psig		10,000 psig	
	260	500	230	250

9.6 Emissions

Emissions are addressed in two sub-sections below. The first section discusses local and regional pollutants that are currently regulated under the Clean Air Act [i.e., hydrocarbons (HC), nitrogen oxides (NOx), particulate matter (PM), and carbon monoxide (CO)]. The second section discusses pollutants that contribute to global warming [i.e., greenhouse gases (GHG)].

Regulated Pollutants

Hydrogen is a simple diatomic molecule (H_2) and does not contain carbon, unlike other fuels such as petroleum diesel, biodiesel, natural gas, propane, etc. As a result, tailpipe emissions of CO, HC, and PM (all of which contain carbon) are near zero.[19, 20, 21] A minute amount of lubrication oil enters the combustion chambers under normal engine operation, resulting in very low, almost unmeasurable emissions.

Conventional diesel engines are tuned to strike a balance between NOx and PM emissions. Because hydrogen produces no PM emissions, HICE buses can have their engines and aftertreatment systems (if present) tuned just for low NOx levels. Three combustion strategies are used to manage NOx emissions. Figure 9.0 presents a depiction of the relative NOx emission trend with increasing air/fuel ratio and the relevant NOx control techniques.[22]

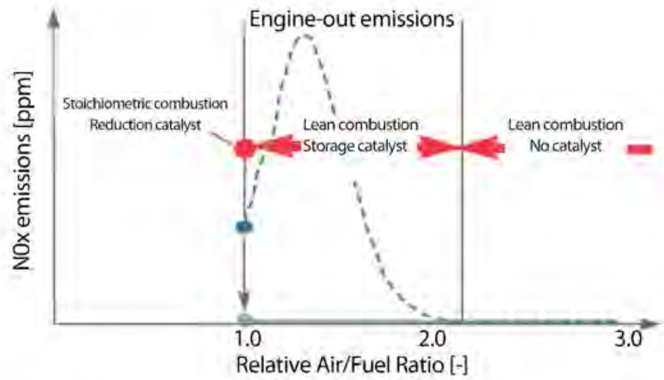


Figure 9.0 Primary HICE NOx Control Options

As the figure shows, the three potential operating regions are:

1. Ultra-lean (high air/fuel ratio) operation (no aftertreatment needed);
2. Lean operation (air/fuel ratio) with a lean-NOx trap (LNT); and
3. Stoichiometric operation (air/fuel ratio of 1.0) with a three-way catalyst.

Lean operation is beneficial for minimizing engine out NOx emissions, however the power density suffers. The engine tuning can adjust the air/fuel ratio depending on the power requirements, moving between any, or all, of these modes to produce the necessary power while minimizing NOx emissions. The resulting emissions are "significantly below SULEV levels".[23, 24] For example, the BMW 6.0L V12 operating on the FTP drive cycle produced less than 0.002 g/mile of NOx (10% of the super low-emission vehicle [SULEV] II level).[25] The Ford 6.8L V10 shuttle bus engine with LNT system produced 0.007 g/mile, 30% lower than SULEV.[26]

In the accompanying FuelCost2 model, emissions values are rounded to the one-hundredths place, and default values for HICE regulated emissions are 0.01 g/mile for NOx, and 0.00 g/mile for other regulated pollutants.

Greenhouse Gases

Hydrogen is a simple diatomic molecule (H_2) and does not contain carbon, unlike other fuels such as petroleum diesel, biodiesel, natural gas, propane, etc. As a result, vehicle-level tailpipe emissions of carbon-based GHG are near-zero. Tailpipe emissions of carbon dioxide (CO_2), the primary GHG from vehicles, have been reported to be less than 1% of CO_2 emissions from conventional vehicles.[27, 28] The non-zero emission levels are the result of a minute amount of lubrication oil entering the combustion chambers under normal engine operation.

Although emissions from HICE vehicle tailpipes are near-zero, emissions during the production of hydrogen fuel must also be included when calculating lifecycle emissions. The methods to produce hydrogen fuel vary, as do their emissions. There are two primary sources of emissions during hydrogen production. The first is the GHG (including CO_2) that may be produced during generation of the electricity used by the hydrogen production facility. Power generation emissions vary with the fuel source, and may be essentially zero with use of renewable energy.

The second source of GHG during hydrogen production is CO_2 produced as a result of the chemical separation of hydrogen from various compounds. Four different methods that can be used for this separation are the following:

- **Steam Reformation.** Hydrogen is produced from hydrocarbon fuels such as natural gas, gasoline, or propane. This process ultimately yields one molecule of CO_2 for every four of H_2. Steam reformation of natural gas accounts for 95% of current hydrogen production.
- **Partial Oxidation Reformation.** This process also uses hydrocarbon fuels, but requires lower energy input than steam reformations. The process itself creates one molecule of CO_2 for every three of H_2.[29]
- **Gasification of Coal or Biomass.** Using the gasification process, the ratio of CO_2 to H_2 depends on the feedstock.[30]
- **Electrolysis of Water.** This method uses electrolysis to directly split water molecules into oxygen and hydrogen, and results in no GHG production other than that associated with the generation of electricity.[31]

Diesel-Gallon Equivalents (DGE)

On an energy-equivalent basis:

1 gallon diesel = 2.5 lb hydrogen

1 gallon diesel = 1.13 kg hydrogen

For a general estimate of lifecycle GHG emissions, the combined GHG emissions from the most common form of hydrogen production (i.e., steam reforming of natural gas) and fuel distribution are estimated to be approximately 20% lower for fuel cell vehicles than for diesel vehicles on a per mile basis.[32] HICE buses use two to three times more hydrogen per mile than fuel cell buses. This suggests that GHG associated with hydrogen production for HICE buses on a per mile basis are 160% of GHG associated with diesel production on a per mile basis. Tank-to-wheels GHG from diesel vehicles are estimated to represent 80% of the total lifecycle GHG associated with these vehicles.[33] In contrast, tank-to-wheels GHG from hydrogen vehicles are estimated to represent less than 1% of the total lifecycle GHG associated with hydrogen vehicles. Together, this suggests that the lifecycle GHG emissions reduction associated with hydrogen buses, from fuel production to engine combustion, are 68% lower than from diesel buses—this is the default value used in the FuelCost2 model.

9.7 Cost and Availability

The cost for a HICE bus is much higher than for a conventional bus since the technology is at the prototype/pre-production stages. For example, the Ford HICE E-450 shuttle bus costs approximately $250,000, or roughly 100% to 150% higher than a conventional gasoline version.[34] If sales volumes increase, it is possible that cost would come down. However, the high cost of storing hydrogen will prevent the cost from matching the baseline vehicle cost.[35] As a default value for a HICE bus price in the accompanying FuelCost2 model, the diesel bus cost estimate is doubled. Table 9.4 summarizes estimated bus, refueling station, and operations and maintenance costs for HICE buses and diesel buses.

Table 9.4 Hydrogen Internal Combustion Engine Bus Cost Estimates

Item	HICE	Diesel
New Vehicle ($)	700,000	350,000
Facility Conversion ($/ 50 Buses)	1.8 million [a]	Not applicable
Fuel ($/kg, hydrogen)	7.00	Not applicable
Fuel ($/gal)	Not Applicable	2.51[c]
Fuel Economy (miles/kg) (miles/DGE)	2.4 [b] 2.7	Not applicable 3.2[d]
Fuel Economy (mpg)	Not applicable	3.3[d]
Propulsion System Maintenance ($/mile)	0.18 [a]	0.16[d]
Facility Maintenance and Operation ($/mile)	0.23[a]	0.18[d]

a. Due to the limited experience with HICE buses, these costs are estimated to be the same as for CNG costs as reported in Clark, N., Zhen, F. and Wayne, W. S., et al. (December 2009). *TCRP Report 132: Assessment of Hybrid-Electric Transit Bus Technology*. Transportation Research Board, Washington, D.C.
b. Based on Ford HICE shuttle fuel economy scaled to a 40-ft bus as described in the text.
c. Based on Clean Cities Alternative Fuel Price Report, average retail price (including taxes) in 2009.[36]
d. Clark, N., et al. (December 2009). *Assessment of Hybrid-Electric Transit Bus Technology*, TCRP C-15.

The Ford HICE shuttle buses are reported to have a 13% better fuel economy than their gasoline counterparts.[37] A 40-ft (full size) gasoline transit bus is estimated to have a fuel economy of 2.4 miles per DGE of gasoline assuming an average speed of 13 mph and 3 months hotel load per year. This was increased by 13% to yield 2.7 miles per DGE of hydrogen, which is approximately 2.4 miles per kilogram of hydrogen (using the conversion factor of 1.13 kg hydrogen per DGE).[38]

9.8 Summary

HICE

Pros	Cons
HICE may act as a bridge technology to hydrogen fuel cells, allowing for the development of a hydrogen infrastructure.	HICE may become out-of-date as costs and reliability of fuel cell buses improve.
HICE buses are mechanically very similar to current diesel and CNG buses, which are proven technologies.	HICE buses remain at the development/pre-production phase. It is unknown when or if HICE buses will be mass produced.
The cost of HICE buses should go down as the technology is improved and the market develops.	Until HICE buses become mass produced, their costs will remain high compared to conventional buses.
HICE tailpipe emissions for both regulated pollutants and GHG are near-zero.	The emissions of pollutants, including GHG, that result from producing hydrogen must be accounted for when comparing lifecycle emissions.
HICE buses can use a hybrid-electric powertrain to further decrease fuel use and emissions.	The cost of a hybrid HICE bus would be higher than the price of a non-hybrid HICE bus, which is already more expensive than conventional diesel buses.

Hydrogen References

[1] Munshi, S. (2007). *HCNG and Hydrogen MD/HD Engine Programs*. Presented at the CALSTART-WestStart Hydrogen Internal Combustion Engine Symposium, Los Angeles, CA.

[2] White, C. (2007). *H2ICE Emissions and Near-ZEV Performance*. Presented at the CALSTART-WestStart Hydrogen Internal Combustion Engine Symposium, Los Angeles, CA.

[3] U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy (n.d.). *Properties of Fuels*. Retrieved from: http://www.eere.energy.gov/afdc/pdfs/fueltable.pdf

[4] Keenan, G. (2006). *Dispensing and Blending Hydrogen Stations*. Presented at the CALSTART-WestStart Hydrogen Internal Combustion Engine Symposium, 2006, San Diego, CA.

[5] Ford Motor Company Press Release (February 18, 2005). *Ford Vehicles Help Florida Jump Start its Hydrogen Highway*. Retrieved from: http://media.ford.com/article_display.cfm?article_id=20292&make_id=trust

[6] Ford Motor Company (2007). *For a More Sustainable Future: Connecting with Society, Ford Motor Company, 2006/7 Sustainability Report*. Retrieved from: http://www.fordcomsearch.ford.com/cs.html?url=http://www.ford.com/doc/2006-07_sustainability_report.pdf

[7] Eco Friendly Mag (February 23, 2010). Ford H2ICE Shuttle Bus Update. Retrieved from: http://www.ecofriendlymag.com/sustainable-transporation-and-alternative-fuel/ford-h2ice-shuttle-bus-update/

[8] SunLine Transit (n.d.). *SunFuels – Alternative Fueling Station*. Retrieved from: http://www.sunline.org/home/index.asp?page=172

[9] U.S. Department of Transportation, Federal Transit Administration (March 2009). *A Report on Worldwide Hydrogen Bus Demonstrations, 2002-2007*, FTA-GA-04-7001-2009.01. Retrieved from: http://www.fta.dot.gov/documents/ReportOnWorldwideHydrogenBusDemonstrations_2002to2007.pdf

[10] Kentzler, M. (November 17, 2009). *The Achievements of the Worlds' Largest Hydrogen Powered Bus Fleet*. Presented at the HyFleet:CUTE Conference, November 17-18, 2009, Hamburg, Germany. Retrieved from: http://www.global-hydrogen-bus-platform.com/InformationCentre/Downloads

[11] Maierhofer, B. (November 17, 2009). *Alternative Drive Systems for Public Transport*. Presented at the HyFleet:CUTE Conference, November 17-18, 2009, Hamburg, Germany. Retrieved from: http://www.global-hydrogen-bus-platform.com/InformationCentre/Downloads

[12] U.S. Department of Energy, Hydrogen Program (n.d.). *Hydrogen & Our Energy Future*, DOE/EE-320. Retrieved from: http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/hydrogenenergyfuture_web.pdf

[13] U.S. Department of Transportation, Federal Transit Administration (August 2005). *Analysis of Electric Drive Technologies for Transit Applications: Battery-Electric, Hybrid-Electric, and Fuel Cells*, FTA-MA-26-7100-05.1. Retrieved from: http://www.navc.org/Electric_Drive_Bus_Analysis.pdf

[14] Natkin, R. (2007). *The Design, Development, Validation, and Delivery of the Ford H2ICE E-450 Shuttle Bus*. Presented at the CALSTART-WestStart Hydrogen Internal Combustion Engine Symposium, Los Angeles, CA.

[15] Munshi, S. (2006). *Heavy Duty Engines*. Presented at the CALSTART-WestStart Hydrogen Internal Combustion Engine Symposium, San Diego, CA.

[16] Hall, W. (2007). *BMW Hydrogen Near Zero Emission Vehicle Development*. Presented at the CALSTART-WestStart Hydrogen Internal Combustion Engine Symposium, Los Angeles, CA.

[17] Munshi, S. (2006). *Heavy Duty Engines*. Presented at the CALSTART-WestStart Hydrogen Internal Combustion Engine Symposium, 2006, San Diego, CA.

[18] Hall, W. (2007). *BMW Hydrogen Near Zero Emission Vehicle Development*. Presented at the CALSTART-WestStart Hydrogen Internal Combustion Engine Symposium, Los Angeles, CA.

[19] Munshi, S. (2007). *HCNG and Hydrogen MD/HD Engine Programs*. Presented at the CALSTART-WestStart Hydrogen Internal Combustion Engine Symposium, Los Angeles, CA.

[20] Natkin, R. (2007). *The Design, Development, Validation, and Delivery of the Ford H2ICE E-450 Shuttle Bus*. Presented at the CALSTART-WestStart Hydrogen Internal Combustion Engine Symposium, Los Angeles, CA.

[21] Wysor, J. (2006). *A Perspective on Emissions*. Presented at the CALSTART-WestStart Hydrogen Internal Combustion Engine Symposium, 2006, San Diego, CA.

[22] White, C. (2007). *H2ICE Emissions and Near-ZEV Performance*. Presented at the CALSTART-WestStart Hydrogen Internal Combustion Engine Symposium, Los Angeles, CA.

[23] Munshi, S. (2007). *HCNG and Hydrogen MD/HD Engine Programs*. Presented at the CALSTART-WestStart Hydrogen Internal Combustion Engine Symposium, Los Angeles, CA.

[24] White, C. (2007). *H2ICE Emissions and Near-ZEV Performance*. Presented at the CALSTART-WestStart Hydrogen Internal Combustion Engine Symposium, Los Angeles, CA.

[25] Hall, W. (2007). *BMW Hydrogen Near Zero Emission Vehicle Development*. Presented at the CALSTART-WestStart Hydrogen Internal Combustion Engine Symposium, Los Angeles, CA.

[26] Munshi, S. (2006). *Heavy Duty Engines*. Presented at the CALSTART-WestStart Hydrogen Internal Combustion Engine Symposium, San Diego, CA.

[27] White, C. (2007). *H2ICE Emissions and Near-ZEV Performance*. Presented at the CALSTART-WestStart Hydrogen Internal Combustion Engine Symposium, Los Angeles, CA.

[28] Natkin, R. (2007). *The Design, Development, Validation, and Delivery of the Ford H2ICE E-450 Shuttle Bus*. Presented at the CALSTART-WestStart Hydrogen Internal Combustion Engine Symposium, Los Angeles, CA.

[29] U.S. Department of Energy, Hydrogen Program (n.d.). *Hydrogen & Our Energy Future*, DOE/EE-320. Retrieved from: http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/hydrogenenergyfuture_web.pdf

[30] U.S. Department of Energy, Hydrogen Program (n.d.). *Hydrogen & Our Energy Future*, DOE/EE-320. Retrieved from: http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/hydrogenenergyfuture_web.pdf

[31] Wysor, J. (2006). *A Perspective on Emissions*. Presented at the CALSTART-WestStart Hydrogen Internal Combustion Engine Symposium, San Diego, CA.

[32] Joseck, J. (March 2009). Well-to-Wheels Greenhouse Gas Emissions and Petroleum Use. DOE Hydrogen Program Record# 9002. Retrieved from: http://www.hydrogen.energy.gov/.../9002_well-to-wheels_greenhouse_gas_emissions_petroleum_use.pdf

[33] Skone, T.J., and Gerdes, K. (November 2008). *Development of Baseline Data and Analysis of Life Cycle Greenhouse Gas Emissions of Petroleum-Based Fuels, Appendix J*. National Energy Technology Laboratory (DOE/NETL-2009/1346).

[34] Natkin, R. (2007). *The Design, Development, Validation, and Delivery of the Ford H2ICE E-450 Shuttle Bus*. Presented at the CALSTART-WestStart Hydrogen Internal Combustion Engine Symposium, Los Angeles, CA.

[35] Williams, R. (2006). *Placing Hydrogen ICE Vehicles—Lessons Learned*. Presented at the CALSTART-WestStart Hydrogen Internal Combustion Engine Symposium, San Diego, CA.

[36] U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy (2009). *Clean Cities Alternative Fuel Price Report*, 2009 quarterly reports. Retrieved from: http://www.afdc.energy.gov/afdc/price_report.html

[37] Associated Press (July 10, 2007). *Ford: Hydrogen-powered cars in five years*. Retrieved from: http://www.msnbc.msn.com/id/19700154/

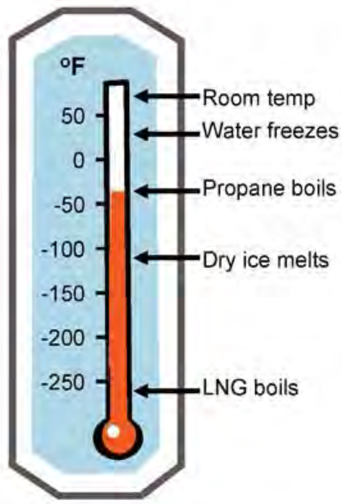
[38] Chandler, K., and Eudy, L., 2008. Alameda-Contra Cost Transit District (AC Transit) Fuel Cell Transit Buses: Third Evaluation Report Appendices. National Renewable Energy Laboratory (NREL) Technical Report NREL/TP-560-43545-2. Retrieved from http://www.nrel.gov/docs/fy08osti/43545-2.pdf.

10.0 Propane

Propane, also known as liquefied petroleum gas (LPG) or autogas, can be used to power buses and other vehicles. It is a by-product of natural gas processing and crude oil refining. Propane has been a commercial alternative transportation fuel for several decades as a result of its domestic availability, distribution infrastructure, high energy density, and clean-burning qualities. It is the third most-common motor fuel worldwide.

At Zion National Park propane buses shuttle 2.5 million visitors annually.

Propane, { proh-**peyn** } noun – a colorless, flammable gas, C_3H_8, of the alkane series, occurring in petroleum and natural gas: used chiefly as a fuel and in organic synthesis. One of the liquefied petroleum gases (LPGs).



Propane accounts for about 2% of the energy used in the U.S., of which less than 2% is used for transportation fuel. When used to power vehicles, propane is stored as a liquid onboard in low pressure tanks and burned as a gas in the engine. There are more than 270,000 on-road propane vehicles in the United States and more than 10 million worldwide. Propane vehicle technology is well established, and propane fueling stations are found throughout the United States, with the greatest concentration in Texas. The U.S. Department of Energy's Alternative Fuels and Advanced Vehicles Data Center maintains a list of propane fueling stations by state on their website. Propane is defined as an alternative fuel under the Energy Policy Act of 2005.

Key Point

Switching to LPG vehicles can extend engine life, reduce maintenance costs, and may reduce some types of emissions.

10.1 Fuel Description

LPG is produced as a by-product of natural gas processing and crude oil refining. LPG is a variable mixture of gases that are "graded" based on their chemical composition. When used as a transportation fuel in the United States, LPG is typically HD5 grade, which is defined by the Gas Processor's Association to be at least 90% propane (C_3H_8), and no more than 5% propylene and 5% other gases (i.e., butane, methane, etc.). Throughout this discussion, HD5 grade LPG will be assumed, although it should be mentioned that in some regions (i.e., California), the HD10 grade of LPG (containing up to 10% propylene) is available, and meets the engine manufacturer specifications for some propane engines. Much of the HD5-grade fuel sold in the United States is more than 90% propane, but the current grading system does not distinguish propane content above 90%.

Propane is colorless and odorless. An odorant (typically ethyl mercaptan) is often added for leak detection. Propane becomes a liquid when subjected to modest pressure (120 psi) or cooling. The energy density for propane when it is a liquid is 270 times greater than for when it is a gas, making its liquid phase more efficient for storage and transport.

Propane has a high octane rating (105) and excellent properties for spark-ignited internal combustion engines. It also has one of the highest energy densities and lowest flammability ranges of all alternative fuels. Table 10.1 compares some key properties of propane and diesel fuel.

Table 10.1 Propane and Diesel Fuel Properties[1]

Property	Propane	Diesel
Boiling Temperature (°F)	-44	356 to 644
Autoignition Temperature (°F)	842	600
Cetane Number	N/A	40 to 55
Octane Number ([R+M]/2)	105	N/A
Flash point (°F)	-156	≥140
Flammability Limits (vapor in air by volume %)	2.2 to 9.5	1.0 to 6.0
Lower Heating Value (Btu/gal)	84,250	128,550
Relative Weight (same volume) Compared to air = 1 Compared to water = 1	 1.5 0.51	 >3 *(as vapor)* 0.85
Soluble in Water	No	No

10.2 Fuel Usage

According to the American Public Transportation Association's Fact Book (2007), there were a total of 310 propane (or LPG) transit buses and 161 paratransit buses in use in 2005.[2] In subsequent editions of the Fact Book, the number of propane buses has not been reported separately. With the exception of two 1997 model year 35-ft buses, the buses have been 20 to 30 ft long and primarily manufactured by Thor Industries. Currently, there are no propane-powered 40-ft or larger transit buses produced in the United States. This is due to a lack of heavy-duty propane engines. Most current propane engines can only meet the power and torque requirements of 20- to 30-ft buses. Table 10.2 presents a summary of some of the larger North American transit fleets using propane transit buses.

Table 10.2 North American Propane Transit Bus Fleets

Agency	# Buses	Type	Operational Status
Los Angeles Department of Transportation, Los Angeles, CA	18 6 3	30' ElDorado National 30' Goshen Coaches 24' ElDorado National	In use since 2002 In use since 2002 In use since 2003
VIA Metropolitan Transit, San Antonio, Texas	16	30' Champion low floor	In use since 2000
Laguna Beach Municipal Transit, Transit, Laguna Beach, CA	6 12	26' ElDorado National National Various makes and lengths	In use since 2004 Special event use since 1990
City of Mesquite, Mesquite, TX	3 2	25' Goshen GCII 26' & 28' E350	In use since 2005 In use since 2002
Corpus Christi Regional Transit Authority, Corpus Christi, TX	5	30' Champion low floor	In use since 2000
City of Brownsville, Brownsville, TX	3	30' low floor transit coaches	In use since 2004
West Contra Costa County Transit, Pinole, CA	2	35' Champion	In use since 1997

Propane has been the most popular alternative fuel choice for school buses in the United States, but there is no formal tracking of the number of these buses in current operation. There are 10 million propane-powered vehicles (most of which are light-duty) on the road in Europe, where drivers can toggle between propane and gasoline with the push of a button.[3] Chevrolet has recently introduced the Spark in India, a propane-powered passenger car which can switch to using gasoline when propane is not available.[4] Chevrolet and GMC could produce light-duty propane trucks in the United States as soon as 2012.[5] Hybrid electric LPG/gasoline engines are already on the market in India and Europe, and may become available in the United States in the future.

10.3 Safety, Training, and Disposal

Safety

Propane is a flammable liquid and gas. If a leak occurs, the liquid will quickly vaporize, cooling the surrounding air. Both propane liquid and vapors can cause frostbite. The vapors will typically stay near to the ground where they may travel and be ignited by pilot lights, heaters, smoking, or electrical equipment. Propane is non-toxic and generally vaporizes before it can present a significant threat to soil, surface water, or groundwater. Proper ventilation and leak detection sensors are required in buildings such as garages and maintenance bays in case of indoor leaks.

Safety recommendations include grounding fuel tanks and fuel lines during refueling to prevent the buildup of an electrostatic charge that could spark and ignite propane vapors. Additional recommendations for propane facilities include the following:

- Explosion proof (classified) wiring and electrical equipment in low areas,
- Ventilation rates sufficient to remove released gas, and
- Propane detectors and alarms.

An alternative to explosion-proof devices and wiring would be a strict policy of closing off vehicle propane tanks and purging the fuel system before any indoor maintenance. Routine maintenance activities could be performed outdoors.

Training

Since propane is stored under pressure, special training is required to avoid the safety hazards mentioned above. The training requirements for propane and compressed natural gas are very similar. Codes and standards have been developed for all aspects of propane fuel production, distribution, and use. NFPA 58, *Liquefied Petroleum Gas Code*, is a primary source used by local fire authorities. This code calls for self-conducted audits of the safety of propane installations, referred to as a Fire Safety Analysis (FSA). Guidance on conducting an FSA is provided in the *Fire Safety Analysis Manual for LP-Gas Storage Facilities*, available at http://www.nfpa.org/assets/files//PDF/Research/2008FSAManual.pdf.

Is It Imported?

Roughly half of the propane available in the U.S. is produced at U.S. refineries during petroleum processing, and half is produced at gas processing plants during natural gas processing. About two-thirds of the petroleum processed at U.S. refineries is imported, while natural gas processing uses almost all domestic gas.

U.S. Department of Transportation's Transportation Safety Institute (TSI) offers training courses specifically for transit agencies. Their 2011 course listings include "Safety Evaluations for Alternative Fuels Facilities and Equipment." This 3-day course provides "awareness and training in conducting safety evaluations for alternative-fueled vehicles, support equipment, and facilities using Compressed Natural Gas (CNG), Liquefied Natural Gas (LNG), hydrogen, fuel cells, propane, ethanol, electricity, bio-diesel, and hybrid electric."

Disposal

Un-used propane should be returned to a certified dealer for proper disposal. Propane is denser than air, so in the event of a release, it may collect in low areas prior to dispersal. Control of the vapor cloud to prevent ignition and uncontrolled burning, or explosion, are primary objectives in the event of a release.

10.4 Technology and Performance

Propane has a low cetane number and high octane number, meaning it is more conducive for use in spark-ignition engines. In older propane engines, the fuel is vaporized and mixed with air before it enters the combustion chamber. Newer propane engine designs may maintain pressure throughout the fuel system to allow liquid fuel injection, which may increase power output. The fuel systems for propane and natural gas are often quite similar with the major difference being that CNG systems have a higher volumetric fuel flow rate for a given load due to its lower energy content. Similar to CNG, propane vehicle fuel systems are fitted with sensors and shut-off valves that automatically prevent the escape of propane if the fuel line ruptures as in an accident. Other safety valves and detectors allow fuel to flow only when the engine is operating.

Given propane's lower octane rating compared to CNG, propane engines use a lower compression ratio or a lower turbocharger boost pressure, resulting in lower power output. Fuel economy is typically comparable for propane and CNG buses because the lower engine efficiency of a propane bus is offset by its lighter fuel storage system compared to a similar CNG vehicle.

Propane buses typically get between 15% to 30% fewer miles per gallon of fuel than comparable diesel buses. As with all fuel types, fuel economy varies significantly for many reasons. One study by the National Renewable Energy Laboratory estimates that Type D ("transit"-style) school buses get 5.0 miles per gallon when running on engines converted to use propane, compared to 6.6 miles per gallon when running on comparable diesel engines.[6] In contrast, VIA Metropolitan Transit of San Antonio has reported a fuel economy of 2.35 miles per gallon with its Champion 30-ft Solo buses.[7]

Although no heavy-duty OEM propane engine is available in North America, Cummins-Westport manufactures a medium-duty engine for export to Mexico and Latin America. The 5.9 liter B propane engine produces 195 hp and 420 ft-lb of torque and is certified to the EPA 2007 and CARB low-NOx emission standards for heavy-duty engines. The engine is based on the Cummins 5.9 liter diesel engine but is modified for spark ignition operation. It uses much of the existing fuel and ignition system components of the natural gas version of the same engine. The engine is suitable for powering transit buses in the 16,000 to 28,000 lb gross vehicle weight (i.e., 20 to 30 ft in length).

Did You Know?

Because propane is cleaner burning than gasoline and diesel when there is no treatment of exhaust gas, it has historically been the fuel of choice for use in indoor equipment such as fork lifts. It is also used for barbeque grills, household appliances, and even for heating the air that lifts hot-air balloons.

Cummins-Westport discontinued North American sales of the B propane engine on January 1, 2010, the date that EPA 2010 emissions standards became effective. Considering that propane engine emissions typically fall between those of natural gas and diesel engines, both of which have been modified by manufacturers to meet the new regulations, it is likely that the technology exists to produce a heavy-duty engine that would meet EPA standards. However, in improving designs to meet the 2010 deadline, most engine manufacturers have chosen to focus on the larger markets for natural gas- and diesel-powered engines.

The alternatives to the diesel-based Cummins-Westport engine are conversion systems available for General Motors 8.1 liter V-8 and Ford 6.8 liter V-10 gasoline engines. These engines are used in GM and Ford medium- and heavy-duty chassis which can be used in 20- to 30-ft buses for paratransit applications. Some propane conversion kits have been certified to meet EPA 2010 emissions standards.

Table 10.3 Comparison of Powertrain Differences between Diesel and Propane Buses

Component	Diesel Bus	Propane Bus
Energy source and storage method	Diesel fuel in tank	Liquid propane stored in pressurized tanks at 300 psi
Propulsion power source	Diesel engine	Gasoline- or diesel-based engine modified to operate with propane
Drivetrain	Multiple geared transmission	Multiple geared transmission

The driving range of propane buses may be less than that of diesel buses if propane tanks are not sized to compensate for the lower energy density of the fuel. The performance considerations for natural gas generally apply to propane as well, except that propane has a lower octane rating which may result in lower, knock-limited torque ratings.

How is it Stored?

The size and placement of LPG tanks may be an issue for some buses. Because they are pressure vessels, LPG tanks are necessarily cylindrical, making them difficult to package efficiently. LPG has a lower energy density than gasoline or diesel, so its onboard tanks have to be larger. The higher strength and larger size of LPG fuel tanks impose a moderate weight penalty compared with equivalent diesel tanks. Compared to CNG tanks, LPG tanks are lighter and smaller for the same energy capacity.

10.5 Maintenance, Reliability, and Storage

Maintenance

One major reason to use propane in buses is to lower maintenance costs. Similar to CNG, propane's high octane rating, low fuel carbon content, and oil contamination characteristics have been shown to result in propane engine life of up to two times longer than gasoline engine life. Because the propane and air mixture is gaseous, cold start problems associated with liquid fuel are eliminated. Technicians must be trained to understand the fuel and the procedures required to safely work on propane buses.

A maintenance garage for propane buses should have explosion-proof (classified) wiring and electrical equipment in all low areas (up to 18 inches above ground level). Building ventilation must be able to remove propane gas from ground level. An alternative to explosion-proof wiring and devices is a strict policy of closing off vehicle propane tanks and purging the fuel system before performing indoor maintenance. Maintenance facilities should also be equipped with flammable gas detectors. These can detect concentrations of propane before the vapors reach flammable levels. Routine maintenance activities can be performed outdoors as well.

Reliability

The reliability of propane transit buses has not been widely investigated since there are few propane buses in use. The various transit fleets that operate propane buses have not publicized any significant reliability concerns. Further, propane use by school buses has been increasing over the last 15 years, suggesting that reliability is acceptable. Due to the similarities between propane and CNG buses, it is reasonable to assume that their reliability is comparable.

Storage

Propane is stored as a liquid gas under pressure. Storage tanks are constructed of carbon steel and designed to meet standards developed by the American Society of Mechanical Engineers (ASME) for pressure vessels. Propane storage tanks are roughly 20 times more puncture resistant than conventional diesel and gasoline tanks. When a propane tank is filled, liquid propane fills about 80% of the tank. The remaining space is for the expansion of propane gas which occurs when temperatures in the tank increase, such as throughout a normal day. Tank pressure varies depending on both temperature and how much propane is in the tank—tank pressures are commonly in the range of 50 to 175 psi.

Propane storage requirements are covered in NFPA 58, *Liquefied Petroleum Gas Code*. Safety features of propane tanks include an Overfilling Prevention Device (OPD). This device shuts off the flow of gas to a cylinder after 80% capacity has been reached. Both on-board fuel tanks and bulk storage tanks also have a pressure relief valve(s) to vent gas if pressure in the tank becomes excessive. The Uniform Fire Code (NFPA 1) addresses safety distance around bulk storage tanks. On-board tanks must also comply with U.S. Department of Transportation regulations (*49 CRF 171-190*) which call for periodic recertification and testing of fuel tanks.

10.6 Emissions

Emissions are addressed in the following two sub-sections. The first section discusses local and regional pollutants that are currently regulated under the Clean Air Act [i.e., hydrocarbons (HC), nitrogen oxides (NOx), particulate matter (PM), and carbon monoxide (CO)]. The second section discusses pollutants that contribute to global warming [i.e., greenhouse gases (GHG)].

Regulated Pollutants

Propane engines generally have lower emissions than counterpart diesel engines, although generally not as low as natural gas engines. According to the U.S. DOE, propane vehicles emit about one-third fewer reactive organic gases than gasoline fueled vehicles. Nitrogen oxide and carbon monoxide emissions also are 20% and 60% lower, respectively, than from conventional vehicles. Toxic pollutants, CO, and non-methane hydrocarbon (NMHC) emissions are also typically lower.[8] Experimental propane buses operated by the Orange County Transportation Authority (OCTA) in the early 1990s underwent chassis dynamometer emissions tests that indicated very low NOx emissions.

At the time of this writing, available emissions measurements from model year (MY) 2010 buses are quite limited. This is a significant consideration for comparisons of emissions differences between propane and diesel buses because these engines were required to meet more stringent emissions regulations beginning in 2010. For a preliminary comparison of 2010 propane and diesel bus emissions, U.S. EPA certification data for MY2010 on-road engines with power ratings of 300 to 350 horsepower were compared. For propane engines, these represent aftermarket conversion kits. Table 10.4 shows the average certification test emissions as converted to grams/mile based on EPA conversion factors. These emissions estimates are used as default values in the FuelCost2 model. These estimates should be updated as more emission measurements are reported for 2010 buses.

Table 10.4 Propane Engine Emissions: EPA Model Year 2010 Certification Tests *

	g/bhp-h	g/mile
Carbon Monoxide	4.04	13.55
Nitrogen Oxides	0.12	0.39
Particulate Matter	0.00	0.00
Non-Methane Hydrocarbons	0.05	0.17

* Emissions estimates based on EPA certification test data for model year 2010 highway engines between 300 and 350 horsepower available at http://www.epa.gov/oms/crttst.htm. Units of g/bhp-h are converted to g/mile using the EPA conversion factor for gasoline (spark-ignition) engines.[9]

Greenhouse Gases

Compared to buses fueled with conventional diesel and gasoline, propane buses produce less greenhouse gases over their lifecycle. A study by Argonne National Laboratory found that light-duty propane vehicles produce 21% to 24% less GHG than gasoline vehicles.[10] A more recent study by The Propane Education and Research Council examines lifecycle GHG for several propane uses, including light- and medium-duty engines. It found similar lifecycle GHG emissions for diesel and propane-fueled engines.[11] For the purposes of a default value in the accompanying FuelCost2 model, the lifecycle GHG emissions from propane-powered buses are assumed to be the same as from diesel buses.

10.7 Cost and Availability

Because of the limited availability of commercial propane engines, there are no full-size (40-ft) propane buses available in the United States. For paratransit bus applications, there is only one OEM propane engine available, while two other engines can be converted to run on propane.

Diesel Gallon Equivalents (DGE)

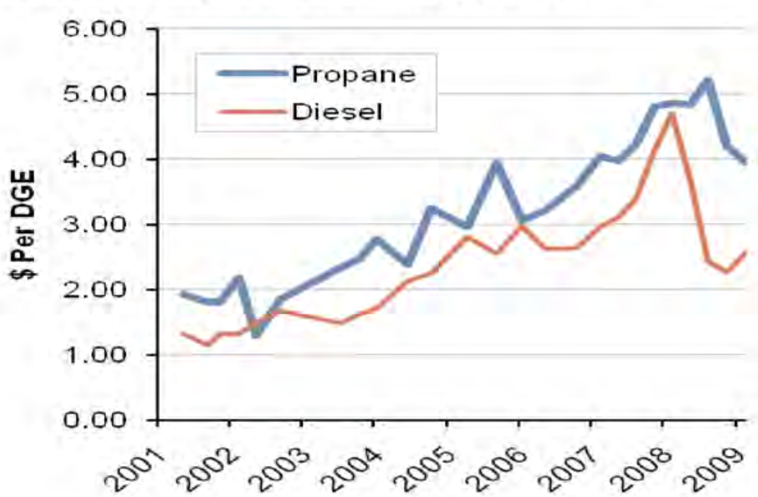
On an energy-equivalent basis:

1 gallon diesel = 1.54 gallons propane

Historically, the incremental cost of 30-ft propane buses has been approximately $25,000 to $45,000. In 2003, the City of Brownsville, Texas, procured three 30-ft transit coaches for $265,000 each. According to the manufacturer's estimates this price is between $20,000 and $25,000 higher than that of a similarly equipped diesel model. OCTA's experience from the 1990s indicates an approximate incremental cost of $30,000. A 2008 FTA report on shuttle buses shows that the average propane shuttle cost is comparable to that of diesel shuttles ($69,058 versus $67,229) and is higher than that of gasoline shuttles ($50,711).[12] While the range of shuttle lengths in this report was 20 to 30 ft, the median shuttle length was only 23 ft.

Propane fueling facilities and modifications to maintenance facilities require additional capital costs. In 2004, VIA Metropolitan Transit installed a single 30,000 gallon propane tank and five propane dispensing bays at a cost of $114,790 to fuel its fleet of 67 30-ft Champion propane buses. Although these costs vary substantially depending on the specific circumstances and equipment, a typical estimate for a 200-bus transit fleet is $300,000 for modifications to one maintenance garage and $700,000 for one propane fueling facility.

Figure 10.1 Propane and Diesel Prices, 2001 to 2009



The price of propane depends on factors including whether the purchase is at the wholesale (e.g., fleet) or retail level, the quantity being purchased, the timing relative to yearly and seasonal propane market fluctuations, the location within the United States, and state taxes. Data from the DOE Clean Cities Alternative Fuel Price Reports show that the 2009 national average price for propane was $2.62 per gallon, or $4.04 per diesel gallon energy equivalent (DGE). For comparison, in 2009 the average cost of gasoline was $2.24 per gallon ($2.50 per DGE), while for diesel it was $2.51 per gallon. Propane used to power buses is eligible for the Alternative Fuels and Excise Tax Credit, which periodically requires congressional approval for continuation. Sources such as the DOE Alternative Fuels and Advanced Vehicles Data Center and the National Propane Gas Association are good sources for information regarding current incentives. Historical prices of propane and diesel are shown in Figure 10.1.

Operating costs for propane buses, relative to diesel buses, depend primarily on fuel costs and maintenance costs. Fuel costs should be higher for propane buses than for diesel buses based on current prices. Maintenance costs for propane buses are not well documented and may be lower than gasoline and diesel buses due to less formation of carbon deposits in the engine and reduced engine wear during cold-starts.

Blue Bird's propane-powered Vision school bus uses the GM Vortec 8.1 liter engine with liquid injection. The Blue Bird Vision is a conventional Type C school bus with an overall length of 24 to 39 ft, and a gross vehicle weight rating (GVWR) of up to 31,000 lb, making it the largest OEM propane-powered bus available. For comparison purposes, the Blue Bird Vision is also available with diesel engines, such as the Cummins ISB-10. The propane-powered Vision has a fuel economy rating of 6.6 mpg, compared to 9.9 mpg for the diesel-powered version.[13] This 30% reduction in fuel economy is the basis for the propane fuel economy shown in Table 10.5 and is also used to estimate fuel economy in the FuelCost2 model.

Table 10.5 Propane Bus Cost Estimates

Item	Propane	Diesel
New Vehicle ($)	380,000[a]	350,000
Facility Conversion (50 Buses) ($)	875,000[b]	Not applicable
Fuel ($/gal)	2.62[c]	2.51[c]
Fuel economy (mpg) (miles/DGE)	2.3[d] 3.4	3.2 3.2
Propulsion System Maintenance ($/mile)	0.18[e]	0.16
Facility Maintenance ($/mile)	0.18[e]	0.18

a. Estimated to be $30,000 more than diesel bus.
b. Estimated to be half the cost of a CNG facility.
c. Based on Clean Cities Alternative Fuels Price Reports average retail for 2009.
d. Full-size transit bus propane fuel economy is estimated to be 30% lower than baseline diesel fuel economy on a miles per gallon basis.
e. Estimated to be the same as for CNG buses, which have similar spark-ignition engines.

10.8 Summary

Propane

Pros	Cons
Propane has a long history of use in light-duty and medium-duty vehicles and is particularly popular for school buses, making this a relatively mature and available technology.	In 2010, there are no propane engines available in the United States in the size range used by 40-ft transit buses.
Propane engines have historically had lower emissions than counterpart gasoline and diesel engines. Emission benefits today depend on exhaust treatment technology.	The fuel economy of propane buses is roughly 25% lower than for diesel buses.
In some regions of the country, propane is a domestic fuel. Although it is typically from petroleum sources, it can be produced from renewable biomass.	Propane use requires specialized safety, maintenance, and disposal measures.
Propane buses may have lower maintenance costs and bus capital costs that are less than 1% higher than for diesel buses.	Additional costs associated with the refueling infrastructure and changes to maintenance facilities must also be considered.
Based on local availability and fuel price, propane may be an economical fuel choice for transit buses.	There are only two propane engine conversions and one OEM propane engine available for powering 20- to 30-ft buses in 2010.

Propane References

[1] U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy (n.d.). *Properties of Fuels*. Retrieved from: http://www.eere.energy.gov/afdc/pdfs/fueltable.pdf.

[2] American Public Transportation Association (2007). Public Transportation Fact Book, 58th Edition. Retrieved from http://www.apta.com/resources/statistics/Documents/FactBook/APTA_2007_Fact_Book.pdf

[3] GM Europe (March 2009). *Chevrolet extends LPG portfolio throughout Europe*. Retrieved from: http://www.gmeurope.info/geneva09/downloads/chevrolet/en/pdf/EN_LPG.pdf

[4] *The Hindu* (June 13, 2009). GM India launches LPG version of Chevrolet Spark. Retrieved from: http://www.hindu.com/thehindu/holnus/006200906132051.htm

[5] Healey, J. (January 12, 2010). Chevrolet and GMC trucks could soon run on LPG, CNG. *USAToday*. Retrieved from: http://content.usatoday.com/communities/driveon/post/2010/01/chevrolet-and-gmc-trucks-should-soon-run-on-lpg-cng/1

[6] Laughlin, M. (April 2004). *Economic Analysis of Alternative Fuel School Buses*, DOE/GO-102004-1870. U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy. Retrieved from: http://www.nrel.gov/docs/fy04osti/35764.pdf

[7] TIAX LLC (December 2003). *The Transit Bus Niche Markets for Alternative Fuels: Module 5: Overview of Propane (LPG) as a Transit Fuel, Clean Cities Coordinator Kit*. Retrieved from: http://www.eere.energy.gov/afdc/pdfs/mod05_lpg.pdf

[8] U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, FreedomCAR & Vehicle Technologies Program (August 2003). *Just The Basics: Liquefied Petroleum Gas*. Retrieved from: http://www1.eere.energy.gov/vehiclesandfuels/pdfs/basics/jtb_lpg.pdf

[9] U.S. Environmental Protection Agency (May 1998). *Update Heavy-Duty Engine Emission Conversion Factors for MOBILE6: Analysis of BSFCs and Calculation of Heavy-Duty Engine Emission Conversion Factors*. EPA420-P-98-015. Retrieved from: http://www.epa.gov/oms/models/mobile6/m6hde004.pdf

[10] Wang, M.Q., and H.S. Huang (1999). *A Full Fuel-Cycle Analysis of Energy and Emissions Impacts of Transportation Fuels Produced from Natural Gas*. Center for Transportation Research, Argonne National Laboratory. Retrieved from: http://www.transportation.anl.gov/pdfs/TA/13.pdf

[11] The Propane Education and Research Council (2007). *Propane Reduces Greenhouse Gas Emissions: A Comparative Analysis*. Retrieved from: http://www.propanecouncil.org/uploadedFiles/Propane_Reduces_GHG_Emissions_(2007).pdf

[12] U.S. Department of Transportation, Federal Transit Administration (December 21, 2007). *An Evaluation of the Market for Small-to-Medium-Sized Cutaway Buses*, MI-26-7280.07.1. Retrieved from: http://www.fta.dot.gov/documents/MI-26-7280.07.1_FINAL_REPORT.pdf

[13] Blue Bird (n.d.). *Blue Bird Propane-Powered Vision®: The Propane-Powered Vision Advantage*. Retrieved from: http://www.blue-bird.com/uploadedFiles/Blue-Bird/Products/School/Vision/Propane-BeniftsBrochure-0708.pdf

11.0 Dimethyl Ether

Dimethyl Ether (DME) is a potential fuel for transit buses, but as of 2010, has only been used as a demonstration fuel. DME is gaseous at room temperature and pressure but can be easily liquefied for storage. DME is most commonly produced from natural gas. It can also be produced from coal, and has the potential to be produced from a wide range of feedstocks including biomass.

A DME-fueled bus is prepared for service in Shanghai (File Photo, China Daily)

DME has been used globally for many years in non-transportation industries. It is commonly used as an aerosol propellant for cosmetic and medical products such as inhalers. It can also replace or supplement natural gas for residential heating and cooking needs. DME is being considered for use as a transportation fuel by many governments around the world, with early success in demonstration vehicles.

Dimethyl Ether, { dahy-**meth**-*uh*l **ee**-ther } *noun* – a simple hydrocarbon fuel that is stored as a liquid under pressure. It can be produced from a variety of feedstocks, including coal, natural gas, and biomass.

11.1 Fuel Description

Dimethyl ether is a simple molecule (CH_3–O–CH_3) that exists as a gas at room temperature. Like propane, DME is liquefied when subjected to modest pressure (roughly 90 pounds per square inch, or psi). A pressurized storage tank keeps DME in its liquid phase. DME has a sweet, ether-like odor and is colorless. Due to the mildness of DME's odor, it has been suggested that an odorant be added when it is used as a transportation fuel to aid in leak detection.

DME is usually produced in a two-step process in which natural gas (or another carbon-based material such as coal, biomass, or organic waste) is converted to methanol. In the second step, methanol is

Key Point

DME-fueled engines are not yet commercially available. Currently, they are in demonstration phase of development in China, Japan, and Europe. In the United States research and development of DME as a vehicle fuel is taking place on a much smaller scale.

purified and converted to DME. A "direct", one step process has more recently been developed, but is less commonly used.[1,2] Table 11.1 displays the basic properties of DME and diesel.

Table 11.1 Dimethyl Ether and Diesel Fuel Properties[3, 4]

Property	DME	Diesel
Boiling Temperature (°F)	-13	356 to 644
Autoignition Temperature (°F)	455	600
Cetane Number	55 to 60	40 to 55
Flash point (°F)	- 41.8	140 to 176
Flammability Limits (vapor in air by volume %)	3.4 to 18	1.0 to 6.0
Lower Heating Value (Btu/gal)	66,615	128,450
Relative Weight (same volume)		
Compared to air = 1	1.6	>3 *(as vapor)*
Compared to water = 1	0.66	0.85
Soluble in water (by volume)	Yes, up to 8%	No

DME has a cetane rating of 55 to 60, making it well-suited for compression ignition engines. The combination of DME's high cetane rating and low boiling point of -13°F gives it the following advantages as a fuel:

- Fast mixing of fuel and air,
- Lower levels of ignition delay, and
- Good starting in cold weather.

When used as a vehicle fuel, DME needs additives to increase lubricity and reduce wear of sliding engine parts.

Did You Know?

DME is already used around the world as a propellant in aerosol cans. As a result, DME's effects on human health and the environment have already been thoroughly tested.

11.2 Fuel Usage

No commercially available engines today are designed specifically for DME. Most of the projects demonstrating DME as a transportation fuel have been in compression ignition (diesel) engines in Europe, China, and Japan. DME use as a fuel has also been demonstrated in spark-ignition (gasoline) engines with fuel blends of 70% propane and 30% DME. DME could also be used as a hydrogen source for fuel cells.

Companies including Nissan and Volvo have demonstrated heavy vehicles that are DME-fueled. Volvo developed the first DME-powered bus when they converted a B10BLE bus to use a DME engine as part of a project for the Danish Road Safety and Transportation Agency and the Danish Environmental Protection Agency.

A DME demonstration project conducted by a corporate consortium is underway in Sweden, with the larger objective of demonstrating the full technological chain required to produce, distribute, and use bio-DME (DME produced from biomass) as a vehicle fuel. As part of this project, a bio-DME production plant is being constructed by Chemrec and is expected to begin production from black liquor (a pulp and paper industry byproduct) in 2010.[5] Four DME fueling stations are also being built, and between 2010 and 2012, 14 DME-powered heavy-duty trucks will be tested in the field. The trucks will use Volvo's "third generation" DME engine technology with modified 13 liter, 440 hp diesel engines.[6]

China is particularly interested in DME because of its large coal reserves which can be used to synthesize DME. China has invested in a series of large DME production facilities to lower production costs and facilitate competitive pricing of DME with petroleum-based fuels. It is anticipated that in 2010, most of the LPG household heating market in China will be using a fuel blend of 20% DME and 80% LPG. With respect to DME as a replacement fuel for diesel engines, Shanghai opened its first DME refueling station in 2007, and began use of ten DME buses in 2009.[7] Plans for larger-scale use of DME as a transportation fuel are beginning with 100 DME buses in Shanghai that will be on the road in 2010.[8]

DME is not currently being significantly developed as a transportation fuel in the United States, though some research and development is ongoing. The most notable U.S. research to-date was conducted at Pennsylvania State University from 1999 to 2002, where a fuel blend of 25% DME and 75% diesel was demonstrated in the university's shuttle buses.[9]

The development of a large-scale DME distribution infrastructure, including fueling stations, is viewed as a major challenge for DME use as a vehicle fuel. As with other new alternative fuels, DME is being first targeted to centrally refueled heavy-duty fleets such as transit.

Site Visit!

As a part of China's effort to promote DME as a transit fuel, a goal has been set to have 100 DME buses on the road for the 2010 Shanghai World Expo. The first 10 DME buses began carrying Shanghai passengers in February, 2009. Other Chinese cities, including Zhangjiagang, Guangzhou, Beijing, and Nanjing, have expressed interest in DME transit buses as well. China has already invested in several large DME production plants to meet the expected growing demand for DME as both a heating fuel and a transportation fuel. The Chinese DME is produced from coal.

11.3 Safety, Training, and Disposal

Safety

DME is a flammable liquid and gas. It can form explosive mixtures with air. As with other fuels stored as liquid under pressure, a fuel release quickly vaporizes, cooling the surrounding air. Both DME liquid and vapors can cause frostbite. DME vapors are heavier than air, and similar to propane, may travel and be ignited by pilot lights, heaters, smoking, or electrical equipment.

Codes and regulations that specifically address the use and storage of DME as a transportation fuel have not been developed. Recognizing the fuel property similarities between DME and propane (a primary component of Liquefied Petroleum Gas (LPG)), LPG codes and regulations provide a starting point for DME safety recommendations.

Safety recommendations include grounding fuel tanks and fuel lines during refueling to prevent the buildup of an electrostatic charge that could spark and ignite DME vapors.[10] In case of an indoor leak, such as in a garage or maintenance bay, proper ventilation and leak detection sensors are likely to be required. Following recommendations for LPG facilities, DME maintenance facilities should have:

- Explosion-proof (classified) wiring and electrical equipment in low areas,
- Ventilation rates sufficient to remove released DME gas, and
- DME gas detectors and alarms.

An alternative to explosion-proof devices and wiring would be a strict policy of closing off vehicle DME tanks and purging the fuel system before any indoor maintenance. Routine maintenance activities could be performed outdoors.

Pure DME has a mild odor and is colorless, so an odorant may be added to allow leaks to be detected by smell. Currently, there is no standard odorant for DME, but the same odorants used in LPG have been used in DME demonstration projects.[11]

DME is non-toxic, non-carcinogenic, and non-mutagenic.[12] Most spill scenarios do not present a significant threat to soil, surface water, or groundwater because DME vaporizes relatively quickly.

Training

Maintenance staff, refuelers, and drivers need training to understand the procedures for safe handling of DME. Recommended training topics for LPG can be used as guidance on training needs for DME.

U.S. Department of Transportation's Transportation Safety Institute (TSI) offers training courses specifically for transit agencies. Their 2011 course listings include "Safety Evaluations for Alternative Fuels Facilities and Equipment." This 3-day course provides "awareness and training in conducting safety evaluations for alternative-fueled vehicles, support equipment, and facilities using Compressed Natural Gas (CNG), Liquefied Natural Gas (LNG), hydrogen, fuel cells, propane, ethanol, electricity, bio-diesel, and hybrid electric." While DME is not included, much of the guidance for LPG would likely be relevant for DME. Classes are scheduled on an as-needed basis. Those interested should contact TSI.

Disposal

Un-used DME should be returned to the supplier or a qualified handler of hazardous waste. Released DME vaporizes relatively rapidly, posing fire and explosion hazards until it dissipates in the air to a point that is below its flammability limit.

11.4 Technology and Performance

DME has the potential to be more fuel efficient than diesel on a diesel gallon equivalent (DGE) basis due to its higher cetane rating. On the other hand, the lower energy density of DME means larger fuel tanks are needed to have the same driving range as comparable diesel buses. The weight added by larger storage volumes may reduce the fuel economy benefits achieved with improved engine efficiency. In tests of DME in heavy-duty vehicles, Volvo has stated that fuel economy is similar to that of comparable diesel vehicles on a diesel gallon equivalent basis.[13]

Diesel vehicles can be relatively easily modified to run on DME. The following changes have been used in demonstration vehicles:

- Larger fuel tanks to allow a driving range with DME that is similar to diesel's,
- A pressurized fuel system to maintain DME as a liquid up to the point of injection,
- Specialized fuel injectors that release double the volume of diesel fuel injectors to compensate for DME's reduced energy content,
- Altered engine management software, and
- Large volume Exhaust Gas Recirculation (EGR) system to improve emissions and fuel economy.

The major component differences between buses fueled by DME and diesel are their fuel storage and delivery systems. Similar to LPG fuel systems, DME fuel systems are sealed and pressurized to between 90 and 100 psi. This maintains DME in a liquid phase for storage and delivery to the engine.

A Cummins diesel engine converted to run on DME (Source: Transport Canada Website).

Lower injection pressure, lower maximum cylinder pressure, and pressure rise rate with DME collectively contribute to reduced engine noise and an expected longer engine life compared to diesel.[14] Compared to compressed natural gas, the low storage pressure for DME requires less complicated and expensive fueling and storage equipment. For refueling, a standard LPG receptacle has been used in demonstration projects.[15]

DME characteristics of corrosiveness and viscosity both contribute to fuel leak concerns.[16] The low viscosity of DME means it more easily leaks from pumps and injectors than diesel. DME corrodes certain metals, plastics, and rubbers, and like alcohol fuels, DME can damage certain polymers and elastomers. Materials used with DME have varied among DME demonstration projects. A Danish DME project identified Teflon, graphite, and Kalrez as DME-resistant and used these materials as sealing for valves, caps, and assemblies in lieu of metal-to-metal sealing.[17] A Canadian study identified PTFE (Teflon) and butyl-n (Buna-N) rubber as DME-resistant, but qualified this statement by stating that PTFE can become embrittled (and cause valve failure) when exposed to the low temperatures generated by DME as it vaporizes.[18]

At this time, there are no standards for DME fuel systems, and experience with DME-powered engines is too limited for meaningful performance evaluations. It is expected that DME engine performance characteristics with respect to engine power and acceleration will be comparable to diesel.

11.5 Maintenance, Reliability, and Storage

Maintenance and Reliability

No extensive DME engine maintenance studies have been done to-date. Most demonstration vehicles have been prototype designs. As is expected with a technology at such an early stage of development, these vehicles required more frequent maintenance than their baseline diesel counterparts.

Required maintenance for mature commercial-level DME buses is expected to be comparable to that required by diesel buses. DME fuel storage and injection systems will need to be different, though similar systems have been employed in natural gas and LPG transit buses for many years.

Given the similarity to diesel engines, DME engines can ultimately be expected to have similar maintenance and reliability. In the nearer term, DME characteristics of higher corrosiveness and lower viscosity may cause increased maintenance needs and reduced reliability.

Storage

DME is similar in many respects to LPG with regard to storage and dispensing, but there are some significant differences in material used for seals. In demonstration projects, Teflon, graphite, butyl-n (Buna-N) rubber, and Kalrez have been reported to work well with DME, although the potential for Teflon embrittlement has been raised. In a Danish DME demonstration project, storage and supply systems were very similar to existing LPG systems, with the exception of the purge system.[19]

How is it Stored?

DME is stored as a liquid under pressure, similar to propane storage. Storage pressure is typically around 90 pounds per square inch (psi).

Since DME is not available as a standardized transportation fuel, some DME vehicle users have needed to add lubricity additives and odorants to pure DME purchased from gas companies. Mixing these additives on-site significantly adds to the cost of DME storage and fueling facilities because additional tanks and dispensing, metering, and circulating hardware are needed. If DME use increases, it would be expected that fuel providers would add lubricity enhancers and odorants at the terminal level, so fleets would not have to incur this extra facility expense. This would bring the added expense of additives and odorants to a negligible level.

11.6 Emissions

Emissions are addressed in two sub-sections below. The first section discusses local and regional pollutants that are currently regulated under the Clean Air Act [i.e., hydrocarbons (HC), nitrogen oxides (NOx), particulate matter (PM) and carbon monoxide (CO)]. The second section discusses pollutants that contribute to global warming [i.e., greenhouse gases (GHG)].

Regulated Pollutants

DME-fueled engines inherently have low emissions compared to diesel. The relatively simple chemical structure of the DME compound facilitates combustion that results in virtually no PM (i.e., soot). As a result, DME vehicles do not typically need particulate filters to meet current U.S. EPA standards—although a NO_x catalyst system is needed to meet U.S. EPA 2010 emission standards.

The DME demonstrations in Europe have included emissions measurements, which are compared to European emission standards. A DME-powered bus in Denmark in 2001 easily exceeded Euro 4 emission standards with reductions in PM, NOx, HC, and CO.[20] In a 2001 Canadian study, a DME engine was found to have reduced emissions of regulated pollutants, with the exception of total hydrocarbons (THC).[21] High THC was largely the result of unburned DME. With respect to toxic THC components, the Canadian study found substantial increases in formaldehyde in conjunction with large decreases in other toxic components (i.e., acetaldehyde, acetone, acrolein, and propionaldehyde). Optimization of DME injection and combustion systems and incorporation of an EGR system were identified as means for further emissions reductions, as has been done in more recent demonstrations of DME vehicles.

A heavy-duty DME truck developed by Nissan and tested in collaboration with the Japanese National Traffic Safety and Environment Laboratory met the U.S. EPA 2010 emissions standards as early as 2006. The Nissan DME truck used a large volume Exhaust Gas Recirculation (EGR) system with a high-performance NO_x catalyst system.[22]

Table 11.2 Nissan's Heavy-Duty DME Truck Emissions

	2010 Standard (g/bhp-hr)	DME Truck (g/bhp-hr)	DME Truck (g/mile) *
Carbon Monoxide	15.5	0.157	0.73
Nitrogen Oxides	0.20	0.075	0.35
Particulate Matter	0.01	0.001	0.00
Non-Methane Hydrocarbons	0.14	0.090	0.42

* Emissions reported as g/bhp-hr are converted to g/mile using the EPA conversion factor for diesel (compression ignition) engines.

In FuelCost2, the lifecycle analysis tool that accompanies this report, the default emissions data for DME buses are the same as shown above for Nissan's 2006 demonstration heavy-duty truck.

Greenhouse Gases

Lifecycle greenhouse gas (GHG) emissions from DME use varies significantly depending on the feedstock used for DME production. In general, lifecycle GHG associated with coal-based DME appears to be significantly higher than lifecycle GHG associated with conventional diesel. Lifecycle GHG emissions from natural gas-based DME appears to be roughly the same as from conventional diesel, while biomass-based DME may offer substantial reductions (e.g., 75% or greater) in GHG compared to conventional diesel.[23] For the purposes of this report, it is assumed that DME used as a transportation fuel in the United States will be produced from biomass. The conservative estimate of a 75% reduction in GHG with bio-DME use compared to conventional diesel is used as a default value in the FuelCost2 model that accompanies this report.

11.7 Cost and Availability

Currently, there are no large-scale production facilities in the United States for DME production as a transportation fuel. DME production costs vary depending on which methods and feedstocks are used. In China, where there is ample coal available as a feedstock and several large DME production facilities, the price of DME is around 10% lower than diesel.[24] At least one biofuels expert in the Netherlands has estimated that DME production costs are likely to be slightly less per gallon than synthetic diesel costs, but this cost advantage may be negated by the lower energy density of DME.[25] Similarly, Chemrec, the company that is constructing the demonstration bio-DME plant in Sweden, projects that the price of biomass-based DME will be less than the price of diesel on an energy equivalent basis.[26] For the purposes of this report, a more conservative estimate of DME priced equal to diesel on an energy basis will be used.

Diesel-Gallon Equivalents (DGE)

On an energy-equivalent basis:

1 gallon diesel = 1.9 gallons DME
1 gallon diesel = 10.4 lb DME

With respect to bus prices, DME bus prices are likely to be higher than diesel bus prices due to the increased costs associated with the DME storage tank.[27] Since DME and LPG fuel tanks are similar, the default DME bus price in the FuelCost2 lifecycle model assumes similar incremental costs of DME and LPG buses over a comparable diesel bus. Similarly, refueling facility costs are expected to be similar for DME and LPG.

With respect to bus maintenance costs, spark-ignition engines such as those used with LPG generally have slightly higher maintenance costs than compression ignition engines such as used with DME. However, if the leak and corrosion issues with DME continue in commercial buses, overall DME bus maintenance costs advantages compared to LPG may be lost. For the purposes of default values in FuelCost2, DME bus and facility maintenance costs are assumed to be the same as for LPG buses and refueling systems.

Guidebook for Evaluating Fuel Choices for Post-2010 Transit Bus Procurements 11-9

Table 11.3 DME and Diesel Bus Cost Estimates

Item	DME	Diesel
New Vehicle ($)	380,000[a]	350,000
Facility Conversion ($ / 50 buses)	875,000[a]	Not Applicable
Fuel ($/gal) ($/DGE)	1.7 3.2	3.2 3.2
Fuel Economy (miles/gallon) (miles/DGE)	1.45[b] 2.8	2.8 2.8
Propulsion System Maintenance ($/mile)	0.16[a]	0.16
Facility Maintenance ($/mile)	0.18[a]	0.18

a. Estimated to be similar to diesel costs.
b. Estimated as the same as diesel fuel economy on an energy content basis.

11.8 Summary

Dimethyl Ether

Pros	Cons
DME's high cetane rating makes it well-suited for compression-ignition diesel engines.	Currently there are no DME engines commercially available in the United States.
Engine operation is also quiet compared to diesel.	DME prices, availability, and operating costs are difficult to predict.
DME fuel properties are similar to those of LPG, and it is likely that DME fire and safety standards will be similar to LPG's.	DME has corrosive properties that LPG does not have, and requires lubricity additives. No safety, maintenance, or disposal standards currently exist for DME's use in vehicles.
DME engines can be designed to have significant emission advantages compared to diesel engines.	It is not clear if manufacturers would design commercial DME engines to take full advantage of possible emissions benefits, or if they would just design to meet current standards.
DME can be produced from biomass, and has a lower lifecycle GHG emissions than diesel.	DME produced from feedstocks such as coal would have greater GHG emissions than diesel.
DME is being used as a transit bus fuel in Shanghai, China.	No U.S. transit agencies have experience using DME as a transit bus fuel.

Dimethyl Ether References

[1] Refuel / ECN, (n.d.). *Bio-DME*. Retrieved from: http://www.refuel.eu/biofuels/bio-dme/
[2] Japan DME Forum (2004). *About DME: DME production processes*. Retrieved from: http://www.dmeforum.jp/about/process_e.html
[3] Wu, J., Huang, Z., Qiao, X., Lu, J., Zhang, J. and Zhang, L. (March 2008). Study of Combustion and Emission Characteristics of Turbocharged Diesel Engine Fuelled with Dimethylether. *Frontiers of Energy and Power Engineering in China*, 2(1):79-85. Retrieved from: http://www.springerlink.com/content/j48097m2131246x4/
[4] Bailey, B., Eberhardt, J., Goguen, S. and Erwin, J. (n.d.). *Diethyl Ether (DEE) as a Renewable Diesel Fuel*. Retrieved from: http://www.afdc.energy.gov/afdc/pdfs/dee.pdf
[5] Fairley, P. (December 12, 2008). Taking Pulp to the Pump: Gasifying Black Liquor From Pulp Mills Will Accelerate Second-Generation Biofuels. *Technology Review*. Retrieved from: http://www.technologyreview.com/energy/21811/page1/
[6] AB Volvo (2010). Bio-DME. *Sustainability Report 2009*. Retrieved from: http://www.volvogroup.com/group/global/en-gb/responsibility/sustreport09/envcare/renew_fuels/bio_dme/Pages/biodme.aspx
[7] Lampinen, M. (February 18, 2009). China: Shanghai launches ten DME buses into service. *Automotiveworld.com*. Retrieved from: http://www.automotiveworld.com/news/commercial-vehicles/74781-china-shanghai-launches-ten-dme-buses-into-service
[8] Kelly (September 24, 2008). New energy DME bus to run in Shanghai this year. *Gasgoo*. Retrieved from: http://autonews.gasgoo.com/auto-news/1007850/New-energy-DME-bus-to-run-in-Shanghai-this-year.html
[9] Chapman, E., Bhide, S., Boehman, A. and Klinikowsky, D. (April, 2003). *Dimethyl Ether (DME)-Fueled Shuttle Bus Demonstration Project*. DOE Contract DE-FG26-99FT40161, 2003. Retrieved from: http://www.osti.gov/bridge/servlets/purl/819427-yEcm3H/native/819427.pdf
[10] Transport Canada (2001). *A study of dimethyl ether (DME) as an alternative fuel for diesel engine applications*. TP 13788E. Retrieved from: http://www.tc.gc.ca/innovation/tdc/summary/13700/13788e.htm
[11] Hansen, J. B. and Mikkelsen, S. (July 2001). *DME as a Transportation Fuel*. The Danish Road Safety & Transport Agency and The Danish Environmental Protection Agency. Retrieved from: http://www.fstyr.dk/da-DK/Shortcuts/English/~/media/Files/Publikationer/Engelske_pub/dme_eng.ashx
[12] International DME Association (2009). *DME | Benefits*. Retrieved from: http://www.aboutdme.org/index.asp?bid=220
[13] Green Car Congress (June 19, 2006). *AB Volvo to Develop Third-Generation DME Engines for Heavy Vehicles*. Retrieved from: http://www.greencarcongress.com/2006/06/ab_volvo_to_dev.html
[14] Wu, J., Huang, Z., Qiao, X., Lu, J., Zhang, J. and Zhang, L. (March, 2008). Study of Combustion and Emission Characteristics of Turbocharged Diesel Engine Fuelled with Dimethylether. *Frontiers of Energy and Power Engineering in China*, 2(1):79-85. Retrieved from: http://www.springerlink.com/content/j48097m2131246x4/
[15] Hansen, J. B. and Mikkelsen, S. (July 2001). *DME as a Transportation Fuel*. The Danish Road Safety & Transport Agency and The Danish Environmental Protection Agency. Retrieved from: http://www.fstyr.dk/da-DK/Shortcuts/English/~/media/Files/Publikationer/Engelske_pub/dme_eng.ashx
[16] Semelsberger, T.A., Borup, R. L., and Greene, H.L., 2006. Dimethyl ether (DME) as an alternative fuel. Journal of Power Sources, 156:497-511.
[17] Hansen, J. B. and Mikkelsen, S. (July 2001). *DME as a Transportation Fuel*. The Danish Road Safety & Transport Agency and The Danish Environmental Protection Agency. Retrieved from: http://www.fstyr.dk/da-DK/Shortcuts/English/~/media/Files/Publikationer/Engelske_pub/dme_eng.ashx
[18] Transport Canada (1998). *Safety considerations of dimethyl ether (DME) as an alternative diesel fuel*. TP 13456E. Retrieved from: http://www.tc.gc.ca/innovation/tdc/summary/13400/13456e.htm
[19] Hansen, J. B. and Mikkelsen, S. (July 2001). *DME as a Transportation Fuel*. The Danish Road Safety & Transport Agency and The Danish Environmental Protection Agency. Retrieved from: http://www.fstyr.dk/da-DK/Shortcuts/English/~/media/Files/Publikationer/Engelske_pub/dme_eng.ashx

[20] Hansen, J. B. and Mikkelsen, S. (July 2001). *DME as a Transportation Fuel*. The Danish Road Safety & Transport Agency and The Danish Environmental Protection Agency. Retrieved from: http://www.fstyr.dk/da-DK/Shortcuts/English/~/media/Files/Publikationer/Engelske_pub/dme_eng.ashx

[21] Transport Canada (2001). *A Study of Dimethyl Ether (DME) as an Alternative Fuel for Diesel Engine Applications*. TP 13788E. Retrieved from: http://www.tc.gc.ca/innovation/tdc/summary/13700/13788e.htm

[22] Sato, Y. and Nakamura, A. (2006). Conference on the Development and Promotion of Environmentally Friendly Heavy Duty Vehicles such as DME Trucks, Washington, D.C., March 17, 2006. Retrieved from: http://www.jitidc.com/conferences/2006/03/dme_detailed_information.pdf

[23] Wang, M., (2009). Well-to-Wheels Analysis of Biofuels and Plug-In Hybrids. Presentation at the Joint Meeting of Chicago Section of American Society of Agricultural and Biological Engineers and Chicago Section of Society of Automotive Engineers, Argonne National Laboratory, June 3, 2009. Retrieved from http://www.transportation.anl.gov/pdfs/TA/580.pdf

[24] Li, C. (February 17, 2009). Cleaner fuel for buses soon. *China Daily*, p. 4. Retrieved from: http://www.chinadaily.com.cn/cndy/2009-02/17/content_7482000.htm

[25] Fairley, P. (December 12, 2008). Taking Pulp to the Pump: Gasifying black liquor from pulp mills will accelerate second-generation biofuels. *Technology Review*. Retrieved from: http://www.technologyreview.com/energy/21811/page1/

[26] Chemrec Media Release, (September 2, 2009). DME as Diesel Fuel Alternative Gaining Ground as Engine Manufacturers, BioDME Biorefineries Gear Up for Renewable Motor Fuels. Retrieved from http://advancedbiofuelsusa.info/wp-content/uploads/2009/09/dme_as_diesel_substitute_gaining_ground_-_09-02-09_final.pdf

[27] Edwards, R., Larivé, J.-F., Mahieu, V. and Rouveirolles, P. (October 2008). *Well-To-Wheels Analysis of Future Automotive Fuels and Powertrains in the European Context: TANK-TO-WHEELS Report, Version 3: Appendix 1: Vehicle Retail Price Estimation*. EUCAR/COMCAWE/JRC. Retrieved from: http://ies.jrc.ec.europa.eu/uploads/media/V3.1%20TTW%20App%201%2007102008.pdf

12.0 Electric—Trolleybus

A trolleybus operated by San Francisco Municipal Transportation Agency (SFMTA)

Electric trolleybuses (ETB) are powered by electricity received from wires suspended overhead, which are referred to as catenary wires. These buses are electrically isolated from the ground by rubber tires, and have two poles attached to two overhead power wires.[1,2] The two poles distinguish trolleybuses from streetcars, trams, and trolley cars which have a single pole and run on a fixed track that is necessary to complete their electrical circuit.

Electric trolleybuses have several names, such as trackless trolley, trolley coach, trackless tram, or trolley. Some systems are also referred to as "electronic" trolleybuses, recognizing the technological advances in system construction that occurred in the 1920s and later using different media to control electricity (e.g., triodes, diodes, and other semiconductor components). The term "electric trolleybus" is redundant, but ensures differentiation from buses that are built to look like old-time trolleys but do not use catenary wires for power. In this chapter, electric trolleybuses will be referred to simply as "trolleybuses."

12.1 Fuel Description

Strictly speaking, a fuel is something that is consumed to produce energy. A trolleybus uses energy in the form of electricity, which is drawn from the overhead wires. The electric energy carried in the overhead wires can be produced using a wide range of sources and technologies, from combustion of fossil fuels such as coal and natural gas, to renewable solar, wind, and hydropower. Thus, trolley buses do not require onboard fuel except as may be used for backup power units.

Historically, trolleybuses were propelled solely by electric power from overhead wires, but today it is standard to have an additional, onboard auxiliary power unit (APU). The APU, typically a battery pack or a generator set, is sufficient for short detours to drive around accident scenes, construction sites, street festivals, etc.[3,4] To reduce overhead wires, the APU may also be used as part of a regular route for some limited spans.[5]

Some trolleybuses are dual mode—capable of full operation on either electric or another power source (such as a diesel engine). While this type of bus will not be dealt with specifically in this document, the following discussion does address dual-mode bus operation under electric power from overhead wires.

12.2 Fuel Usage

Trolleybuses have been in operation since 1901, and were fairly widespread through the middle of the 1900s. Over 50 cities in the United States have had trolleybuses, but now only 5 cities still operate them. Globally, some 340 cities use trolleybuses.[6,7,8]

In the 1950s and 1960s many U.S. cities discontinued trolleybuses. These decisions were supported by relatively cheap fuel for buses with combustion engines and a desire to remove "unsightly" overhead wires.[9] (Means for reducing the "visual pollution" of overhead wires is discussed in *TCRP Report 07*.) In recent years, the number of trolleybuses has not increased, despite air quality benefits and relatively low operational costs. The Federal Transit Administration (FTA) has concluded that a significant cause for the lack of growth in trolleybus use is the high installation costs for new and expanded electric trolley lines. This issue will be discussed in more detail in Section 12.7.

As may be expected, with decreased use of trolleybuses in the United States, there has been a decrease in U.S. suppliers. New Flyer is currently the only U.S. supplier of trolleybuses – although there are dozens of trolleybus manufacturers across the globe. Table 12.1 presents a summary of the current North American transit fleets that use trolleybuses.

Table 12.1 Current North American Trolleybus Fleets

Agency	# Vehicles	Length	Operational Status
King County Metro Transit, Seattle, WA[10,11,12]	59 100	60′ 40′	Operating since 1940s
San Francisco Municipal Transportation Agency (SFMTA), San Francisco, CA[13]	240 93	40′ 60′	Operating since 1935[14]
South Eastern Pennsylvania Transit Authority (SEPTA), Philadelphia, PA	38	40′	Operating since 1940s (Suspended service from 2002 to 2008, when new vehicles were put in service)
Massachusetts Bay Transportation Authority (MBTA), Boston, MA[15,16]	28	40′	Operating since 1936
Greater Dayton Regional Transit Authority (GDRTA), Dayton, OH[17,18]	57	N/A	Operating since 1933
South Coast British Columbia Transportation Authority (TransLink), Vancouver, British Columbia, Canada[19,20]	188 40	40′ 60′	Operating since 1950s
Edmonton Transit System (ETS), Edmonton, Alberta, Canada	98	N/A	Operating since 1939

N/A = Not Available

12.3 Safety, Training, and Disposal

Safety

Because trolleybuses do not store fuel on board, fuel flammability and toxicity concerns are limited to the backup power source. Electrocution is the primary safety concern. This risk is addressed through system design details such as:

- placing insulators between overhead wire support poles, and
- locating live wire at least 5 ft from the poles (i.e., out of reach from the pole).

In the event of a power grid failure resulting from weather or a traffic accident involving an electric pole, the current generation of trolleybuses has sufficient onboard backup power to move the bus to a safe location until power is restored.

Unlike traditional diesel fueled buses, trolleybuses are virtually silent, lacking the noise of a combustion engine. While this quietness is beneficial for passengers, it poses hazards for unwary pedestrians.

Training

Because maintaining trolleybuses requires different skills compared to other bus types, agencies with other transportation modes face greater training costs for multiple technologies.[21] Electric propulsion systems use electronic circuits with relatively high voltages and currents. For example, the New Flyer trolleybuses operate at 600 VDC—five times greater than the voltage in standard electrical outlets. Maintenance staff must be properly trained to work with this type of system to prevent harmful or potentially fatal electric shocks. Special protective equipment and diagnostic tools are required to work with high-voltage electric drive systems. The U.S. General Accounting Office evaluated the safety concerns associated with electric buses and concluded that electrocution hazards from the high-voltage systems were the primary concern.[22]

Disposal

Unlike other bus types, trolleybuses have no fuel stored onboard as a primary power source. However, there may be a small amount of onboard fuel for a backup generator, which may degrade over time if it is not used. This will require appropriate disposal, based on the fuel type. Alternatively, for buses with backup power from battery packs, proper battery disposal is needed.

Did You Know?

The history of the trolleybus dates back to 1882, when Dr. Ernst Werner von Siemens ran his Elektromonte experimental trolleybus demonstration in a suburb of Berlin, Germany. The first passenger-carrying trolleybus operated in 1901 near Dresden, Germany.

12.4 Technology and Performance

Today's trolleybuses have standard bus chassis, and are typically 40 ft or 60 ft articulated buses, with a maximum speed of around 40 mph. The National Electrical Safety Code (NESC) specifies a minimum height of 18 ft for the overhead contact wires—some state or local codes may require greater heights. An overhead wire height of 18 ft generally allows trolleybuses 12 to 15 ft of maneuverability from the centerline of the overhead wire. Crossings with railroads require greater height, typically 22 to 23 ft, which limits bus maneuverability to 2 to 4 ft. Height exceptions to state code can usually be obtained for low structures.[23]

The overhead wire, also referred to as the overhead contact system (OCS), functions as both a guideway and power supply. The OCS is supported by poles, building eyebolts, and other structural attachments, allowing the strung wire to follow the path of a catenary curve. Thus, the wire system is sometimes referred to as a catenary.

Electrical power is provided to the OCS as direct current (DC), typically 600 to 700 V DC. Unlike alternating current (AC) that is used for the electrical grid and standard power outlets, direct current flows in one direction at a constant strength. Feeder stations placed at regular intervals use rectifiers to convert AC power from the electrical grid to DC power for OCS. The two trolley poles allow current to flow from the supply wire, through the trolleybus, and back to the feeder station through the return wire.

The OCS is divided into sections that can be electrically separated, allowing maintenance of a section without turning off the entire system. The section breaks are dead spaces with insulated neutral wires. Dead spaces are also used in "crossovers" at intersections of straight-path overhead wire, and in "switches" for joining curved and straight wire segments. These dead spaces are strategically located to allow trolleybuses to coast through them with minimal effect on bus movement.

The trolley pole on top of the trolleybus roof has a spring base. The spring maintains tension to keep the trolley shoe current collector (at the end of the trolley pole) in contact with the wire. The trolley pole is pulled behind, rather than pushed ahead by the bus. This reduces the chances of dewiring and damage to the overhead wires. In older systems, the trolley pole contacted the overhead wire with grooved trolley wheels. Today's sliding carbon trolley shoes replace the trolley wheels, reducing sparking, wire wear, and dewirement.

Did You Know?

Boston and Seattle have used dual-mode trolleybuses to enable buses to operate in long tunnels where diesel exhaust may be prohibited.

A trolleybus propulsion system replaces the conventional powertrain (i.e., combustion engine, transmission, fuel tank, and exhaust system) with an electric powertrain that includes a set of trolley poles, a traction motor, and a traction motor controller. Table 12.2 presents a summary of the major mechanical differences between diesel buses and trolleybuses.

Table 12.2 Comparison of Diesel Bus and Trolleybus Powertrains

Component	Diesel Bus	Trolley Bus
Energy source and storage method	Diesel fuel in tank	Electricity via overhead catenary wires accessed with dual roof mounted trolley poles
Propulsion power source (primary)	Diesel engine	Traction motor with motor controller and related power electronics
Propulsion power source (secondary/backup)	None	Auxiliary power unit (battery or diesel engine)
Drivetrain	Multiple geared transmission	Single or multiple geared transmission

Unlike combustion engines, which have low torque at low engine speeds, electric motors provide maximum torque at close to zero motor speed. Although the rated maximum torque output from an electric motor is typically lower than that of a diesel engine, the electric motor's ability to maintain high torque levels over much of its operational range offers excellent power-on-demand and drivability characteristics. The high torque output at low vehicle speeds also gives the buses better acceleration than diesel buses. This torque advantage makes electric motors an ideal choice for hilly areas. The rubber tires provide more traction on hills than fixed-track streetcars, and the electric motor has lower noise than diesel buses, especially while climbing hills.

The traction motor uses DC power, and allows regenerative braking, which captures kinetic energy and feeds it back into the overhead wire or into the onboard backup power battery pack. The motor performs this function by reversing field during deceleration, and operating in reverse as a generator. Regenerative braking increases the vehicle's full-cycle energy efficiency and does not require additional components. A study in Santa Barbara, California, found that more than 30% of traction energy was recovered by regenerative braking of battery-electric buses – a similar amount would be expected with trolleybuses.[21] Other trolleybus equipment (e.g., lights, fans, compressors, etc.) is powered by an onboard inverter that converts DC back to AC, and a transformer that reduces the voltage to appropriate levels.

The quiet, smooth, vibration-free ride provided by all-electric buses has been credited with attracting higher ridership. Santa Barbara, California, and Chattanooga, Tennessee, both saw continual growth in ridership once battery-electric shuttles were put into service. [21]

12.5 Maintenance, Reliability, and Storage

Maintenance

The electric powertrain and transmission system on a trolleybus has fewer maintenance requirements than on a conventional combustion-engine bus.[21] Clearly, this is not the case for dual-mode buses that are able to operate fully with or without the overhead wire system.

Trolley shoes have carbon inserts that are the contact point with overhead wires. These inserts are designed to wear more easily than the overhead contact wires, reducing wear on the overhead wires. Typical service life for carbon inserts on the San Francisco MTA trolleybus system has been reported to be 600 miles.[24]

Reliability

For San Francisco MTA, trolleybus reliability, measured as miles between roadcalls or mechanical breakdowns, is less than half of diesel bus reliability. In 2007 and 2008, MTA trolleybuses averaged about 1,500 miles between failures, while diesel buses averaged about 3,500 miles between failures.[25]

San Francisco MTA states that their trolleybuses require less maintenance and have a longer life than their diesel engine buses.[13] One example of trolleybus powertrain durability is the fact that Seattle refurbished and reinstalled into new trolleybuses trolley train powertrains that had previously logged 67,000 hours, 450,000 miles, and 24 years of service.[34] Another example is SEPTA's purchasing history of trolleybuses: New purchases took place in 1940, 1979, and 2007. Boston MBTA considers the useful life for diesel and CNG buses to be 15 years, while trolleybuses are expected to last 20 years. Even so, MBTA's 2004 purchase of new trolleybuses to replace buses built in 1976 (after 28 years in-service) shows that longevity has exceeded expectations.[15]

Storage

The primary power for trolleybuses is delivered directly from overhead catenary lines when the energy is needed, so questions of primary energy storage are not applicable. Current trolleybus designs, however, use a backup power source such as a diesel generator or battery based auxiliary power unit. The storage requirements for backup diesel fuel are identical to those for current conventional buses. Backup batteries will slowly lose charge through self-discharge reactions when the buses are parked for long periods. Potentially harmful gas evolution, such as hydrogen, is a concern, but it depends on the battery chemistry.

12.6 Emissions

Emissions are addressed in the following two sub-sections. The first sub-section discusses local and regional pollutants that are currently regulated under the Clean Air Act. Tailpipe pollutants, referred to as mobile sources, include hydrocarbons (HC), nitrogen oxides (NO_x), particulate matter (PM), and carbon monoxide (CO). The second sub-section discusses pollutants that contribute to global warming, referred to as greenhouse gases (GHG).

Regulated Pollutants

Trolleybuses are categorized as zero emission vehicles (ZEV), which are defined by the state of California as vehicles that produce no tailpipe or evaporative emissions.[26,27] Minute emissions from heating motor lubricating oil and tire wear are not considered to be tailpipe or evaporative emissions, and are not further considered.

The overall emissions associated with powering a trolleybus depend on the regional electric grid's power generation mix. Electricity can be produced using a wide range of energy sources, ranging from zero-emission renewable sources (e.g., hydropower, wind, solar, etc.) to traditional coal power plants.

Emissions of sulfur oxide (SO_x) are not regulated as tailpipe emissions because on-road vehicles do not produce a significant amount of SO_x. Electric power generators, however, are a substantial source of SO_x emissions, and must not exceed specified limits. The amount of SO_x emission from power generation is greatest from coal electric generators. Using a typical power generation mix, SO_x emissions due to transit can increase with the use of electric buses.[28] However, it should be recognized that there are regional caps on overall SO_x production, so if a utility's SO_x emissions increase, it must purchase SO_x credits from other utilities or industries that are able to lower their SO_x emissions. This limits the increase in regional SO_x production that can occur due to the use of electric buses.

On a per-mile basis, NO_x and PM emissions due to electric vehicles may increase slightly in some regions.[29] Power generation from coal, natural gas, oil, and biomass has NO_x emissions, while generation from nuclear, hydro, and wind does not.

The costs of any emissions control systems required by power generators (or the purchase of emissions credits to offset their emissions) are shared by all of the electric utility's customers, so transit agencies do not incur capital costs for emissions control. Upgrading a centralized power plant with additional emission reduction equipment is more cost effective than equipping and monitoring a large fleet of vehicles, as is necessary for buses with combustion engines using diesel or alternative fuels.

In the FuelCost2 model that accompanies this guide, only tailpipe emissions of regulated pollutants are considered, and trolley buses are assumed to have zero tailpipe emissions.

Did You Know?

In 1900, electric automobiles outnumbered gasoline powered vehicles on the streets of the U.S.

Greenhouse Gases

As with the regulated pollutants, GHG are directly related to the sources of electricity generation. GHG are calculated in terms of lifecycle emissions, meaning from mining or drilling, to plant construction, operation, and decommissioning. All power generators produce GHG emissions, with coal-fired power plants typically producing the most. Nuclear, hydropower, wind, and other renewables only produce GHG emissions associated with the fabrication of materials, construction, and decommissioning.

GHG are often expressed in units of carbon dioxide (CO_2) equivalents to account for differences in the global warming potential (GWP) of different types of GHG (i.e., carbon dioxide, methane, and nitrous oxide). The average amount of each GHG released per unit of electricity generation (as reported by EPA)[30] was multiplied by the GWP to calculate 606 grams of CO_2 equivalents per kWh. This was divided by the 0.17 miles per kWh (the estimated fuel economy for battery electric buses), yielding 3,565 grams of CO_2 equivalents per mile. In contrast, diesel bus lifecycle GHG are estimated to be 2,942 grams of CO_2 equivalents per mile, based on CO_2 equivalents of 636 for well-to-tank GHG,[31] and 2,306 for tank-to-wheels GHG.[32] This relatively poor GHG performance of trolleybuses is attributed to the fuel economy estimate, which is based on information from a single transit agency. Poor contact between the trolley shoe current collector and the overhead wire may contribute to this relatively poor fuel economy.

In the accompanying FuelCost2 model, the default value for lifecycle GHG relative to diesel is 120%, based on the above estimates of lifecycle CO_2 equivalents per mile for each of these bus types.

12.7 Cost and Availability

As with electric rail vehicles (trains, subways, trolleys, etc.), overhead wires and a power distribution system are needed to deliver power to the buses. This infrastructure is expensive to install. According to the FTA:

> The trolleybus is an anomaly in the transit program because the overhead catenary power line for the rubber-tired electric trolleybuses is defined in law as a 'fixed guideway.' A transit agency may use its formula funds to replace trolleybuses or extend trolleybus service to a new area. For any medium or small urbanized area considering trolleybuses for the first time, however, apportioned formula funds are likely to be insufficient for design and construction of the electric power distribution system. A project requesting discretionary funding for new or extended trolleybus electrification is defined in law as a new Capital Investment, which subjects it to a highly competitive process that militates against most urban areas even proposing new trolleybus service.

Thus, the market potential for expanding the application of trolleybuses is limited. However, the FTA states that "the barrier associated with defining the catenary electrical power distribution for trolleybuses as 'fixed guideway' could be eliminated by a technical correction of 49 U.S.C. Section 5302(a)(4). Electric power for trolleybuses could be defined as belonging instead to the category of 'bus-related facilities' that does not require competition within the New Starts program for discretionary funding."

The capital costs for trolleybuses are also very high. 2006 FTA data show that the average 40 ft diesel transit bus cost approximately $274,000. The average price for a diesel 60 ft articulated bus was $534,000. The average trolleybus cost $697,000, roughly 150% higher than a 40 ft diesel bus. The data did not differentiate between bus sizes, so the average bus cost may be artificially higher due to the inclusion of some 60 ft trolleybuses.[33] For a default value in the accompanying FuelCost2 model, the price of a trolleybus will be estimated to be 150% higher than the price of a diesel bus.

The long life of the trolleybus powertrain (propulsion system) contributes to lower lifecycle costs and longer vehicle lifetimes. King County Metro in Seattle refurbished 24-year-old powertrains from decommissioned trolleybuses and installed them in new trolleybuses. The powertrains had approximately 450,000 miles and 67,000 hours of use when they were retrofitted into the new trolleybuses.[34]

New Flyer is the only company that is currently producing trolleybuses for the U.S. market. The company has produced trolleybuses since 1968; however, it did not produce the vehicles between 1992 and 2003. New Flyer reentered the trolleybus market in 2003 with an order from Greater Vancouver Transit Authority (British Columbia, Canada) for both 40 ft and 60 ft articulated trolleybuses. These buses use a detection system to alert the driver in the event of a dewirement. The New Flyer model also has an emergency power unit to power the bus when there are road obstacles, or when it needs to travel away from the overhead lines, for reasons such as road construction, traffic incidents, or maneuvering in the garage facility. The emergency power unit can be either a battery-powered backup generator or a diesel-powered generator set. The maximum speed is limited to 40 mph, but the buses are designed to handle "demanding grades."

The FTA has estimated trolleybus energy usage as 0.17 mile per kWh, or 5.88kWh/mile. This correlates well with information provided by Edmonton Transit System, in which their average electric consumption was 6.45kWh/mile.[35] Applying the 2009 national average price of electricity to the transportation sector of $0.11 per kWh, energy costs for the current generation of electric buses are about $0.65 per mile.[36]

Table 12.3 provides initial estimate costs for the adoption of trolley buses, and these are used as default values in the accompanying FuelCost2 model. These costs should be adjusted for specific planning purposes.

Table 12.3 Trolleybus Cost Estimates

Item	Trolleybus
New Vehicle ($)	875,000
Facility Conversion ($)	100,000[a]
Fuel (electricity, $/kWh)	0.11
Fuel economy (miles/kWh)	0.17
Propulsion System Maintenance ($/mile)	0.16[b]
Facility Maintenance ($/ x fleet miles)	0.13[c]

a Limited data available, this is an initial estimate.
b U.S. DOT, Energy Information Administration (May 14, 2010). *Table 5.3 Average Retail Price of Electricity to Ultimate Customers: Total by End-Use Sector.*
c Federal Transit Administration (December 2006). *Alternative Fuels Study: A Report to Congress on Policy Options for Increasing the Use of Alternative Fuels in Transit Vehicles.* U.S. Department of Transportation.

12.8 Summary

Trolleybus

Pros	Cons
Trolleybuses have zero emissions at their point of use.	Capital costs for installing the power distribution system are high.
Energy used to power trolleybuses can be from renewable sources.	The catenary, overhead wire power distribution system can be considered “unsightly.”
Trolleybuses are commonly kept for 25 or more years.	Capital costs for trolleybus coaches are high.
The silent and smooth ride of electric buses has been credited with contributing to ridership increases.	FTA funding for new systems is difficult to obtain due to trolleybus classification as a “fixed guideway.”

Trolleybus References

[1] U.S. Department of Transportation, Federal Highway Administration, December 2006. *Alternative Fuels Study: A Report to Congress on Policy Options for Increasing the Use of Alternative Fuels in Transit Vehicles.* Retrieved from: http://www.fta.dot.gov/documents/Alternative_Fuels_Study_Report_to_Congress.pdf,.
[2] San Francisco Municipal Transit Agency Webpage, Retrieved from: http://www.sfmta.com/cms/mfleet/trolley.htm.
[3] Vossloh Low-Floor Trackless Trolley Buses Data Sheet, Retrieved from: http://www.phillytrolley.org/Kiepe_Trackless_Brochure.pdf.
[4] New Flyer Webpage on Trolley Bus Product, Retrieved from: http://www.newflyer.com/index/trolley.
[5] Kulpa, J.S., Schwartz, A.D., (1995). *TCRP Report 07: Reducing the Visual Impacts of Overhead Contact Systems.* Transportation Research Board, National Academy Press, Washington, DC. Retrieved from: http://onlinepubs.trb.org/onlinepubs/tcrp/tcrp_rpt_07-a-pdf.
[6] Webb, Mary (ed.) (2008), *Jane's Urban Transport Systems 2008-2009*. Jane's Information Group, Coulsdon, Surrey (UK): Jane's Information Group, 883 pp.
[7] *Trolleybus Bulletin No 109: Databook II,* (March 1979) North American Trackless Trolley Association (NATTA), as reported by David Wyatt. Retrieved from: http://home.cc.umanitoba.ca/~wyatt/etb-systems.html.
[8] *Tom's North American Trolleybus Pictures Website*. Retrieved from: http://www.trolleybuses.net/index.htm.
[9] Hylton, Harvey I., (August 10, 2007), Public Transportation in Dayton Ohio 1870 – 2007. Retrieved from: http://www.daytontrolleys.net/history/harveyhylton/hhhist/history.htm
[10] King County Metro Transit Webpage. Retrieved from: http://transit.metrokc.gov/am/vehicles/breda-trolley.html.
[11] King County Metro Transit Webpage. Retrieved from: http://transit.metrokc.gov/am/vehicles/g-trolley.html.
[12] King County Metro Transit Webpage. Retrieved from: http://transit.metrokc.gov/am/history/history-trolley2001.html.
[13] San Francisco Municipal Transportation Agency Website. Retrieved from: http://www.sfmta.com/cms/mfleet/trolley.htm.
[14] San Francisco Municipal Railway, *History of Trolley Buses in San Francisco*, Updated May, 28 2003. Retrieved from: http://www.sfmta.com/cms/ains/trollhist.htm,.
[15] Massachusetts Bay Transit Agency, *Draft Capital Investment Plan 2006-2011*. Retrieved from: http://www.mbta.com/uploadedFiles/documents/CIP_7_11_DRAFT_11_18_05.pdf.
[16] Massachusetts Bay Transit Agency Website. Retrieved from: http://www.mbta.com/about_the_mbta/history/?id=964.
[17] Greater Dayton Regional Transit Authority. Retrieved from: http://www.greaterdaytonrta.org/about_ETB.asp.
[18] Hylton, Harvey I., August 10, 2007, Public Transportation in Dayton Ohio 1870 – 2007. Retrieved from: http://www.daytontrolleys.net/history/harveyhylton/hhhist/history.htm.
[19] TransLink Webpage. Retrieved from: http://www.translink.bc.ca/Transportation_Services/Regional_bus/trolley_bus.asp.
[20] TransLink Webpage. Retrieved from: http://www.translink.bc.ca/Transportation_Services/Regional_bus/default.asp.
[21] Eudy, L., *Challenges and Experiences with Electric Propulsion Transit Buses in the United States*, DOE/GO-102003-1791, National Renewable Energy Laboratory, November 2003.
[22] General Accounting Office, (December 2009). *Mass Transit: Use of Alternative Fuels in Transit Buses*, GAO/RCED-00-18, Washington, D.C.
[23] Kulpa, J.S., Schwartz, A.D., (1995). *TCRP Report 07: Reducing the Visual Impacts of Overhead Contact Systems.* Transportation Research Board, National Academy Press, Washington, DC. Retrieved from: http://onlinepubs.trb.org/onlinepubs/tcrp/tcrp_rpt_07-a-pdf.
[24] Hao, E., (1999). Trolley shoe carbon inserts: Testing for success. *Transportation Research Record: Journal of the Transportation Research Board, No. 1677,* pp 87 – 90.

[25] SFMTA, (2008). Proposition E: Municipal Transportation Quality Review, July 1, 2006 – June 30, 2008. Retrieved from: http://www.sfmta.com/cms/rtqr/documents/12-1-09Item11FY07-FY08TransportationQualityReview.pdf.

[26] California Environmental Protection Agency, Air Resources Board (March 28, 2008*)*. *Fact Sheet: The Zero Emission Vehicle Program* - 2008. Retrieved from: http://www.arb.ca.gov/msprog/zevprog/factsheets/2008zevfacts.pdf

[27] California Codes, Vehicle Code § 22511 (g). Retrieved from: http://www.leginfo.ca.gov/calaw.html

[28] Minnesota Pollution Control Agency, 2007. Air Emissions Impacts of Plug-In Hybrid Vehicles in Minnesota's Passenger Fleet. Retrieved from: http://www.state.mn.us/mn/externalDocs/Commerce/Air_Emissions_Impacts_of_PlugIn_Hybrid_Vehicles_in_Minnesotas_Pass_032907013010_PCA_PHEV_emissions_FINAL_2.pdf

[29] Minnesota Pollution Control Agency, (2007). Air Emissions Impacts of Plug-In Hybrid Vehicles in Minnesota's Passenger Fleet. Retrieved from: http://www.state.mn.us/mn/externalDocs/Commerce/Air_Emissions_Impacts_of_PlugIn_Hybrid_Vehicles_in_Minnesotas_Pass_032907013010_PCA_PHEV_emissions_FINAL_2.pdf

[30] U.S. Environmental Protection Agency, (2008). eGRID2007 Version 1.1, Year 2005 Summary Tables. Retrieved from: http://www.epa.gov/cleanrgy/documents/egridzips/eGRID2007V1_1_year05_SummaryTables.pdf

[31] U.S. Department of Transportation, Federal Transit Administration (July 2, 2007). *Transit Bus Life Cycle Cost and Year 2007 Emissions Estimation, Final Report*, FTA-WV-26-7004.2007.1. Retrieved from http://www.fta.dot.gov/documents/WVU_FTA_LCC_Final_Report_07-23-2007.pdf

[32] Graham, L.A., G. Rideout, D. Rosenblatt, J. Hendren, (2008). Greenhouse gas emissions from heavy-duty vehicles. Atmospheric Environment, 42:4665-4681.

[33] 2006 Federal Transit Administration Statistical Summary, Vehicle Purchases by Type of Fuel and Type of Bus. Retrieved from: http://www.fta.dot.gov/documents/pg._95-t-12_n_13-2006.xls.

[34] Metro Employee Historic Vehicle Association Website. Retrieved from: http://www.mehva.org/bus1008.html.

[35] Edmonton Transit System Webpage. Retrieved from:http://www.edmonton.ca/portal/server.pt/gateway/PTARGS_0_0_381_214_0_43/http%3B/CMSServer/COEWeb/getting+around/ets+in+the+community/ets+and+the+environment/ETS+Trolleys.htm.

[36] U.S. Department of Energy, Energy Information Administration (May 14, 2010). *Table 5.3 Average Retail Price of Electricity to Ultimate Customers: Total by End-Use Sector, 1996 through February 2010*. Retrieved from http://www.eia.doe.gov/cneaf/electricity/epm/table5_3.html

13.0 Electric—Battery

This chapter addresses transit buses that are powered solely by an electric motor using energy that is stored in an onboard battery pack. Other energy storage devices, such as ultracapacitors and flywheels, have been demonstrated for electric vehicles, but their technical and economic drawbacks have limited their development and commercialization.[1, 2] Ultracapacitors and flywheels both have very high power capabilities, but their limited energy storage only allows a driving range of a few miles.

Battery compartment of a 30-ft electric transit bus.

Other types of electric powered buses are addressed in other chapters of this Guidebook; these include:

- Trolley buses, which rely on electric motors, but receive electricity from overhead electric power lines.
- Fuel cell buses, which also have electric motors, but produce electricity from the electrochemical reaction of oxygen and hydrogen in an onboard fuel cell system.
- Hybrid-electric buses, which have electric motors in addition to traditional combustion engines.

Key Point

Smaller, lighter buses are able to achieve a greater driving range from the battery pack than heavier, full-size transit buses. To maintain minimum necessary driving ranges, electric buses have been marketed almost exclusively in the 22- to 30-ft size range, with a maximum speed of 25 to 40 mph. While no full-size battery-electric transit buses have been available in recent years, there are plans for commercial production of a "next-generation" 35-ft battery-electric bus that was set to begin in 2010.

Did You Know?

The weight of a full-size transit bus can be reduced by as much as 10,000 lbs by making the body with a composite material. Such materials have been tested for durability and crash resistance, and are being used in some next-generation battery-electric buses.

13.1 Fuel Description

As a transit bus fuel, electricity must be discussed in a manner different from traditional fuels such as diesel. Diesel is both the energy carrier and storage medium. Electricity, on the other hand, is simply an energy carrier that can be produced using a wide range of sources, from renewable energy sources (solar, wind, hydropower, etc.) to traditional coal power plants. Energy enters an electrochemical battery when it is connected to the electrical grid through a battery charger. This device applies a predetermined algorithm to control current, voltage, and power to charge the battery.

The overall environmental impact of charging the battery depends on the sources of power supplying the grid. Even so, battery-electric buses are often recognized as the most environmentally friendly of all public transportation options, even after accounting for power plant emissions. Battery-electric buses gain additional energy efficiency through the use of "regenerative braking," a process in which the electric motor converts and stores kinetic energy during deceleration.

In general, battery performance can be characterized by four primary parameters:[3]

- **Specific Energy—**A higher specific energy means a longer range for the same battery weight. Specific energy is the ratio of a battery's energy output to its mass, typically expressed in watt-hours per kilogram (Wh/kg)
- **Specific Power**—A higher specific power means greater acceleration for the same battery weight. It is the ratio of a battery's power to its mass, expressed in watts per kilogram (W/kg).
- **Cycle Life**—The number of complete charge-discharge cycles that a battery can go through before its capacity declines to less than 80% of its original capacity.
- **Calendar Life—**The amount of time that a battery will be able to provide sufficient power and capacity for its application.

The cycle life of a battery will vary not only according to its composition, but also according to how it is used in a given configuration. A battery is said to go through a "shallow cycle" when up to 20% of its power is discharged and then recharged; a "deep cycle" on the other hand is when more than 20% of the battery's power is discharged and recharged. A series of deep charge-discharge cycles will affect a battery differently than a series of shallow cycles. Deep discharge battery packs have a cycle life that ranges from 800 (lead-acid) to 4,000 (for advanced lithium-ion).[3,4]

Battery-electric vehicles are designed to operate in deep-discharge mode. They normally begin the day with a full charge and operate until their batteries reach a certain lower discharge limit. Recharging takes place either between shifts or at the end of the day. Typically, the battery control system will not allow discharge levels below the lower discharge limit, and will warn drivers when that limit is approaching.

As of 2006, the only battery types to be used in all-electric buses were lead-acid, nickel-cadmium (NiCd), and sodium nickel chloride batteries. Other battery chemistries, such as nickel metal hydride (NiMH) and lithium-ion (Li-ion), are under development and are also viable options for the future.[5] Table 13.1 summarizes the performances of these battery chemistries. The United States Advanced Battery Consortium (USABC) has set minimum and long-term developmental goals for high-energy batteries for electric vehicles. These were selected to address the market needs for widespread electric vehicle use, and are listed in Table 13.1 for comparison.

Table 13.1 Summary of Electric Bus Battery Characteristics

	Specific Energy Wh/kg (Range)	Specific Power W/kg (Acceleration)	Cycle Life	Cost
Lead-Acid	35	200	500-800	$
Nickel-Cadmium (NiCd)	30	260	1,000	$$$
Nickel Metal Hydride (NiMH)	45-75	850	900	N/A
Sodium Nickel Chloride "Zebra"	95	170	1,000	$$$
Lithium-Ion (Li-ion)	100-180	700-1,300	1,000-4,000	$$$$
USABC Minimum Goals	150	300	1,000	$
USABC Long-Term Goals	200	400	1,000	$

Battery technology has been a key limiting factor for battery-electric vehicles. Issues that have limited the development and commercial application of battery-electric buses include:[6]

- Short range between recharges
- Short battery cycle life that requires at least one expensive battery pack replacement during the bus life
- Poor operational reliability due to battery systems being undercharged, out of balance, or containing deteriorated cells that interfere with proper function
- Substantial maintenance to keep battery systems in top operational form (e.g., frequent load testing, cell balancing, and cell replacement)
- Reduced capacity of most battery types during cold ambient temperatures
- Inaccurate state-of-charge gauges (equivalent to an inaccurate fuel gauge).

To determine the most appropriate battery type for a given application, consideration should be given to the battery performance characteristics, reliability, cost effectiveness (including battery replacements during a bus lifetime), and ability to capture energy from regenerative braking.[3]

The cost and benefit of a thermal and/or electrical battery management system is also an important consideration. Improving temperature and voltage uniformity within the battery pack can optimize performance and charge acceptance (for regenerative braking), reduce maintenance costs, and increase battery pack life.[7,8]

13.2 Fuel Usage

There are currently two battery-electric shuttle bus fleets in operation, as described in Table 13.2. The limited use of battery-electric buses is attributed to high purchase costs, reliability problems, short driving range, and limited acceleration.

Table 13.2 Current North American Electric Battery Bus Fleets

SBMTD: Santa Barbara Metropolitan Transit District		**CARTA**: Chattanooga Area Regional Transportation Authority
		
Santa Barbara, California	**Location**	Chattanooga, Tennessee
20 Electric Buses/Vehicles	**Quantity**	11 Electric Buses/Vehicles
Shuttle bus	**Type**	22-ft shuttle bus
Operational since 1991	**Status**	Operational since 1992

A handful of other fleets have operated battery-electric shuttle buses, but have since switched to diesel or hybrid-electric buses. Some of the reasons given for moving away from battery-electric include:[9]

- **Miami, Florida**—Storms and hurricanes cut electricity service three or four times per year, making it impossible to recharge the buses. Slight flooding (as little as three inches) caused electrical component shorting. The bus manufacturer closed the business, cutting off parts and technical support.
- **Norfolk, Virginia**—Hampton Roads Transit's fleet was difficult to maintain, having particular issues with motor controllers, steering, suspension, and braking systems.
- **Mobile, Alabama**—The Wave Transit's electric bus driving range was initially 60 miles with air-conditioning and 90 miles without it. This range declined to 35 miles with air-conditioning. Numerous problems occurred with a broad range of systems such as batteries, battery chargers, battery chillers, air-conditioning, suspension, and brakes.

- ***Colorado Springs, Colorado***—Poor range and reliability were caused by hilly terrain and battery problems.
- ***Others***—Other fleets noted problems with reliability and cost-effectiveness.

Battery-electric buses may become a more viable option for a wider subset of the transit industry as battery technology improves and purchase costs are reduced.

13.3 Safety, Training, and Disposal

Flammability and Toxicity

Many types of batteries contain toxic materials (e.g., acid, lead , cadmium, nickel, etc.). While these materials are typically sealed inside the battery, they can be a concern when a battery is damaged in a manner that breaches the seal, or if the battery is in a fire that causes it to rupture.

In recent years, the preferred batteries for use in vehicles are sealed batteries, which have negligible gas emissions on overcharge as compared to flooded batteries. Sealed batteries have reduced flammability and explosion concerns, and reduced need for battery storage under ventilated conditions. Only during extreme conditions, such as a cell malfunction, a battery management system failure, or a charger malfunction, will these batteries exceed the normal operating limits and emit gases. The bus manufacturer should be consulted on the type of battery used and appropriate precautions or facility modifications (such as additional ventilation) for battery storage and charging.

There have been rare instances of explosions of lithium-ion batteries used in consumer electronics, and several recalls of these batteries in laptop computers. These rare explosions have been attributed to exposure to high temperatures or short-circuiting within the battery. A slightly different lithium-ion battery technology (using a lithium metal phosphate cathode) is used for vehicle batteries to minimize the chances of explosion. As lithium-ion battery technology continues to mature, the risks of explosion are likely to be further reduced.

Training

Additional skills are required to maintain battery-electric buses, and that equates to an added cost in personnel training. Maintenance workers must receive additional training on the technically complex equipment necessary for maintaining battery systems, as well as on the safety precautions unique to battery-electric powertrain technology.[10]

Electric propulsion systems use electronic circuits with relatively high voltages and currents. For example, the Enova Systems 120kW drive system that is sized for transit buses has a maximum voltage of 425VDC and a maximum current of 480A.[11] Maintenance staff must be properly trained to work with this type of system to prevent harmful or potentially fatal electric shocks. Special protective equipment and diagnostic tools are required to work with high-voltage electric drive systems. The U.S. General Accounting Office evaluated the safety concerns associated with electric buses, and concluded that electrocution hazards from the high-voltage systems were the primary concern.[12] Personnel responsible for charging buses must be trained to properly connect and disconnect the plug.

U.S. Department of Transportation's Transportation Safety Institute (TSI) offers training courses specifically for transit agencies. Their 2011 course listings include "Safety Evaluations for Alternative Fuels Facilities and Equipment." This 3-day course provides "awareness and training in conducting safety evaluations for alternative-fueled vehicles, support equipment, and facilities using Compressed Natural Gas (CNG), Liquefied Natural Gas (LNG), hydrogen, fuel cells, propane, ethanol, electricity, bio-diesel, and hybrid electric." Classes are scheduled on an as-needed basis. Those interested should contact TSI.

Site Visit!

The 2008 Beijing Olympics used a fleet of 50 electric buses, which have a range of 81 miles with the air conditioning on. Running on lithium-ion batteries, and consuming about 1 kWh/mi, the buses were designed by the Beijing Institute of Technology and built by the Jinghua Coach Co. Ltd. Spent batteries were replaced with fully charged ones at the recharging station to allow 24-hour operation of the buses.

Disposal

Battery disposal is an important consideration. According to the Battery Council International, a non-profit organization that promotes the lead-acid battery industry, over 97% of lead used in lead-acid batteries is recycled.[13] There are recycling programs, such as the Rechargeable Battery Recycling Corporation (http://www.rbrc.org), for small, sealed lead-acid, NiCd, NiMH, and Li-ion batteries used in portable electronics. Batteries from electric vehicles are too large to be accepted, but the technology to recycle them does exist. Research into battery recycling is ongoing. For example, the United States Council for Automotive Research (a cooperative group of Chrysler, Ford, and General Motors) has awarded contracts in the past to investigate the feasibility of recycling NiMH and Li-ion batteries used by hybrid-electric and battery-electric vehicles.[14]

13.4 Technology and Performance

Technology

A battery-electric bus propulsion system replaces the conventional powertrain—including the diesel engine, transmission, fuel tank, and exhaust system—with an electric powertrain that includes an electric motor, an electric motor controller, and an electrochemical battery pack. Table 13.3 presents a summary of the major mechanical differences between diesel and battery-electric buses.

Table 13.3 Comparison of Powertrains in Diesel and Battery-Electric Buses

Component	Diesel Bus	Battery-Electric Bus
Energy source and storage method	Diesel in onboard fuel tank	Chemical energy is stored onboard in a battery pack for conversion to electrical energy
Propulsion power source	Diesel engine	Electric motor with motor controller and related power electronics
Drivetrain	Multiple geared transmission	Single or multiple geared transmission

The energy in the batteries must be recharged by connecting the battery pack to a source of electricity. Using the electric grid as an energy delivery system gives electric vehicles tremendous flexibility. It means that power can come from traditional sources such as coal or natural gas, or from renewables such as solar and wind.

Electric motors offer a number of advantages over combustion engines. In terms of propulsion, electric motors provide high levels of torque at low speeds, which allows vehicles to easily accelerate from a stop. Although the rated torque output of an electric motor is typically lower than that of a diesel engine, both an electric motor's ability to maintain high torque levels over much of its entire operational range, and the gear reductions it uses to achieve wheel speeds, offer excellent power-on-demand and drivability characteristics. Other advantages of electric motors include low noise levels, high efficiency, and low maintenance requirements relative to internal combustion engines.

Battery-electric motors also offer the benefit of "regenerative braking," a process that recharges batteries using kinetic energy that would otherwise be lost during braking. To do this, the electric motor reverses field as the vehicle decelerates, acting as a generator to recharge onboard battery packs. Based on an analysis of Santa Barbara Metropolitan Transit District's (MTD) battery-electric fleet, more than 30% of traction energy can be recovered with regenerative braking.

Performance

Current electric buses have a maximum speed of 25 to 45 mph.[15] Battery-electric bus driving ranges are substantially affected by the battery chemistry, duty-cycle, topography, and climate (i.e., whether or not air-conditioning is required). Driving ranges per charge span are from 35 to 80 miles.[16]

Electric bus range and speed are mainly determined by battery technology limitations, especially energy storage density and overall battery system weight and volume. Next-generation technology may allow larger battery-electric buses without excessive weight additions and efficiency losses.

> **Did You Know?**
>
> Battery-electric buses are so quiet that their silence is considered by some to be a safety hazard to pedestrians.

Increases in ridership on electric shuttles in Santa Barbara and Chattanooga have been attributed to preferences for the quiet, smooth, vibration-free ride that these buses provide. These agencies have also promoted the emissions benefit of electric buses to attract new customers. The fact that ridership has stayed high over time is evidence that public support can be maintained even after the technological novelty of an electric bus has passed.[6]

The Federal Transit Administration (FTA) provides an estimate of 0.51 miles per kilowatt-hour (kWh) for electric shuttle buses, which is equivalent to 1.96 kWh per mile.[17]

13.5 Maintenance, Reliability, and Storage

Maintenance

According to a study by the FTA, electric-drive buses (including battery-electric buses) have widely variable maintenance costs. On the one hand, electric-drive buses have low maintenance requirements for their drivetrains and transmissions.[18] Electric motors require little maintenance because they essentially have only one moving part (as opposed to the hundreds found in internal combustion engines).[19] On the other hand, battery-electric buses may require costly battery replacements. Because costs vary so widely, the FTA study assumed that diesel and electric battery maintenance costs were identical.

Reliability

Battery reliability is a central concern, so battery selection is of primary importance. Battery pack reliability can be improved with a battery management system that controls temperature and voltage. Other significant problems that have reduced electric bus reliability have been with common systems used on conventional buses (e.g., steering, suspension, or brakes). In some cases, poor vehicle design has resulted in excessive maintenance. When the best commercially-available and transit-tested components are integrated properly into a battery-electric bus, lifecycle costs are expected to be competitive with diesel buses.[20]

How is it Stored?

Electricity is stored onboard the vehicle in an electrochemical battery pack. There are many developing battery technologies, and traditional lead-acid batteries are being replaced by nickel-cadmium and sodium nickel chloride batteries. Nickel metal hydride and lithium-ion batteries, commonly used in portable electric devices, are also becoming increasingly popular as vehicular batteries show promise for the future.

Storage

Batteries will slowly lose charge through self-discharge reactions when buses are parked. For some battery technologies, release of dangerous gases (such as hydrogen) is possible, and manufacturer recommendations with respect to ventilation and charging protocols should be followed.

13.6 Emissions

Emissions are addressed in the following two sub-sections. The first sub-section discusses local and regional pollutants that are currently regulated under the Clean Air Act. Tailpipe pollutants, referred to as mobile sources, include hydrocarbons (HC), nitrogen oxides (NO_x), particulate matter (PM), and carbon monoxide (CO). The second sub-section discusses pollutants that contribute to global warming, referred to as greenhouse gases (GHG).

Regulated Pollutants

Battery-electric buses are categorized as zero emission vehicles (ZEV), which are defined by the state of California as vehicles that produce no tailpipe or evaporative emissions.[21,22] Minute emissions from heating motor lubricating oil and tire wear are not considered to be tailpipe or evaporative emissions, and are not further considered.

The overall emissions associated with powering a battery-electric bus depend on the regional electric grid's power generation mix. Electricity can be produced using a wide range of energy sources, ranging from zero-emission renewable sources (e.g., hydropower, wind, solar, etc.) to traditional coal power plants.

Emissions of sulfur oxide (SO_x) are not regulated as tailpipe emissions because on-road vehicles do not produce a significant amount of SO_x. Electric power generators, however, are a substantial source of SO_x emissions, and must not exceed specified limits. The amount of SO_x emissions from power generation is greatest from coal electric generators. Using a typical power generation mix, SO_x emissions due to transit can increase with the use of electric buses.[23] However, it should be recognized that there are regional caps on overall SO_x production—if a utility's SO_x emissions increase, it must purchase SO_x credits from other utilities or industries that are able to lower their SO_x emissions. This limits the increase in regional SO_x production that can occur due to the use of electric buses.

On a per-mile basis, NO_x and PM emissions due to electric vehicles may increase slightly in some regions.[24] Power generation from coal, natural gas, oil, and biomass has NO_x emissions, while generation from nuclear, hydro, and wind does not. Another consideration with respect to overall emissions associated with battery-electric buses is that the demand for battery recharging is often at night, which avoids the production of ground-level ozone from the reaction of sunlight with emissions of NO_x and volatile organic compounds (VOC).[25] But in regions heavily dependent on coal, nighttime charging may also cause higher SO_x emissions because coal is typically a base-load energy source that runs continuously, while less polluting power sources (i.e., natural gas) are more easily turned on and off to meet the higher demand of daytime hours.

The costs of any emissions control systems required by power generators (or the purchase of emissions credits to offset their emissions) are shared by all of the electric utility's customers, so transit agencies do not incur capital costs for emissions control. Upgrading a centralized power plant with additional emissions reduction equipment is more cost effective than equipping and monitoring a large fleet of vehicles with emissions reduction equipment, as is necessary for buses with combustion engines using diesel or alternative fuels.

In the FuelCost2 model that accompanies this guide, only tailpipe emissions of regulated pollutants are considered, and battery-electric buses are assumed to have zero tailpipe emissions.

Greenhouse Gases

As with the regulated pollutants, GHG are directly related to the sources of electricity generation. GHG are calculated in terms of lifecycle emissions, meaning from mining or drilling, to plant construction, operation, and decommissioning. All power generators produce GHG emissions, with coal-fired power plants typically producing the most. Nuclear, hydropower, wind, and other renewables only produce GHG emissions associated with the fabrication of materials, construction, and decommissioning.

GHG are often expressed in units of carbon dioxide (CO_2) equivalents to account for differences in the global warming potential (GWP) of different types of GHG (i.e., carbon dioxide, methane, and nitrous oxide). The average amount of each GHG released per unit of electricity generation (as reported by the EPA)[26] was multiplied by the GWP to calculate 606 grams of CO_2 equivalents per kWh. This was divided by the 0.51 miles per kWh (the estimated fuel economy for battery-electric buses), yielding 1,188 grams of CO_2 equivalents per mile. In contrast, diesel bus lifecycle GHG are estimated to be 2,942 grams of CO_2 equivalents per mile, based on CO_2 equivalents of 636 for well-to-tank GHG,[27] and 2,306 for tank-to-wheels GHG.[28]

In the accompanying FuelCost2 model, the default value for lifecycle GHG relative to diesel is 60%, based on the above estimates of lifecycle CO_2 equivalents per mile for each of these bus types.

13.7 Cost and Availability

Full-size battery-electric transit buses have not been available in recent years. Ebus of Downey, California, manufactures 22-ft shuttle buses that cost about $300,000, with an additional $58,000 for an optional 90kW battery charging unit. The bus can travel a distance of 45 miles before its NiCd battery needs to be charged, which takes 30 minutes. The battery has a life expectancy of up to 2,000 cycles.[29] Based on the FTA estimate of 0.51 miles per kWh, battery-electric buses use around 1.96 kWh per mile.[30] Applying the 2009 national average price of electricity to the transportation sector of $0.11 per kWh, energy costs for the current generation of electric buses are about $0.22 per mile.[31]

Manufacturers have announced plans for next-generation battery-electric buses that will be offered on full-size platforms (i.e., 35 and 40 ft). In 2010, Proterra of Golden, Colorado, is beginning construction on a production plant for a 35-ft bus powered by a Li-ion battery pack.[32] Ebus has stated that they will integrate new fast-charge all-electric, fuel cell electric, or hybrid-electric propulsion systems into larger buses, from mid-size 30-ft to full-size 40-ft platforms. The Ebus approach of integration with existing platforms is distinct from Proterra's approach, which is designing and building an all-electric bus from the ground up, including advanced, lightweight body materials.

Table 13.4 provides initial estimate costs for the adoption of electric battery buses, and these are used as default values in the accompanying FuelCost2 model. These costs should be adjusted for specific planning purposes.

Table 13.4 Electric Battery Bus Cost Estimates

Item	Cost
New Vehicle ($)	400,000[a]
Facility Conversion ($)	100,000[a]
Fuel (electricity, $/KWh)	0.11[b]
Fuel economy (miles/kWh)	0.51[c]
Propulsion System Maintenance ($/mile)	0.09[a]
Facility Maintenance ($/mile)	0.13[a]

a Limited data available, this is an initial estimate.

b U.S. DOT, Energy Information Administration (May 14, 2010). *Table 5.3 Average Retail Price of Electricity to Ultimate Customers: Total by End-Use Sector*.

c Federal Transit Administration (December 2006). *Alternative Fuels Study: A Report to Congress on Policy Options for Increasing the Use of Alternative Fuels in Transit Vehicles.* U.S. Department of Transportation.

13.8 Summary

Electric—Battery

Pros	Cons
Battery-electric buses have zero emissions at their point of use.	Capital costs for buses and associated battery packs are high.
Energy used to power battery-electric buses can be from renewable sources.	Driving range per charge is often less than a quarter of the driving range of conventional buses.
Electric buses have higher energy efficiency in stop-and-go driving compared to conventional buses.	The battery pack typically increases bus weight by 300 to 900 kg.
The silent and smooth ride of electric buses has been credited with contributing to ridership increases.	The battery pack takes up a significant amount of space on the bus.
Technology for rapid charging of battery packs is becoming commercialized.	Full recharging of the battery pack typically takes 6 to 8 hours.

Electric – Battery References

[1] Hamilton, T. (October 19, 2009). Next Stop: Ultracapacitor Buses. *MIT Technology Review*. Retrieved from www.technologyreview.com/energy/23754

[2] Griffith, P. (2007). *Inductive Charging of Ultracapacitor Electric Bus*. Presented at the 23rd International Electric Vehicle Symposium and Exposition, December 2007, Anaheim, California.

[3] Chandler, K., Walkowicz, K. and Eudy, L. (July 2002). *Hybrid-Electric Transit Buses: NYCT Diesel Hybrid-Electric Buses, Final Results.* National Renewable Energy Laboratory, NREL/BR-540-32427. Retrieved from http://www.afdc.energy.gov/afdc/pdfs/nyct_diesel_hybrid_final.pdf

[4] Chu, A. (2007). *Nanophosphate Lithium-Ion Technology for Transportation Applications.* Presented at the 23rd International Electric Vehicle Symposium and Exposition, December 2007, Anaheim, California.

[5] Griffith, P. (2006). *Status of U.S. Battery-Electric Bus Programs.* Presented at the 22nd International Electric Vehicle Symposium and Exposition, October 2006, Yokohama, Japan.

[6] Griffith, P. (2007). *Inductive Charging of Ultracapacitor Electric Bus*. Presented at the 23rd International Electric Vehicle Symposium and Exposition, December 2007, Anaheim, California.

[7] Linden, D. and Reddy, T. (2002). *Handbook of Batteries, 3rd ed.* New York: McGraw-Hill.

[8] Eudy, L. and Gifford, M. (2003). *Challenges and Experiences with Electric Propulsion Transit Buses in the United States*. National Renewable Energy Laboratory, DOE/GO-102003-1791. Retrieved from: http://www.afdc.energy.gov/afdc/pdfs/34323.pdf

[9] Griffith, P. (2006). *Status of U.S. Battery-Electric Bus Programs*. Presented at the 22nd International Electric Vehicle Symposium and Exposition, October 2006, Yokohama, Japan.

[10] Eudy, L. and Gifford, M. (2003). *Challenges and Experiences with Electric Propulsion Transit Buses in the United States.* National Renewable Energy Laboratory, DOE/GO-102003-1791. Retrieved from: http://www.afdc.energy.gov/afdc/pdfs/34323.pdf

[11] Enova Systems (n.d.) Retrieved from http://www.enovasystems.com/index.cfm?section=Products&linkID=3

[12] General Accounting Office (1999). *Mass Transit: Use of Alternative Fuels in Transit Buses*. GAO/RCED-00-18. Retrieved from: http://www.gao.gov/new.items/rc00018.pdf

[13] Battery Council International (n.d.). *Lead Battery Recycling*. Retrieved from: http://www.batterycouncil.org/LeadAcidBatteries/BatteryRecycling/tabid/71/Default.aspx.

[14] United States Council for Automotive Research (2007). *USCAR VRP Contracts with 'OnTo Technology' to Advance Hybrid and Electric Car Battery Recycling*. Retrieved from http://www.uscar.org/guest/article_view.php?articles_id=115.

[15] Griffith, P. (2006). *Status of U.S. Battery-Electric Bus Programs.* Presented at the 22nd International Electric Vehicle Symposium and Exposition, October 2006, Yokohama, Japan.

[16] Chu, A. (2007). *Nanophosphate Lithium-Ion Technology for Transportation Applications*. Presented at the 23rd International Electric Vehicle Symposium and Exposition, December 2007, Anaheim, California.

[17] Federal Transit Administration (December 2006). *Alternative Fuels Study: A Report to Congress on Policy Options for Increasing the Use of Alternative Fuels in Transit Vehicles*. U.S. Department of Transportation. Retrieved from: http://www.fta.dot.gov/documents/Alternative_Fuels_Study_Report_to_Congress.pdf

[18] Federal Transit Administration (2006). *Alternative Fuels Study: A Report to Congress on Policy Options for Increasing the Use of Alternative Fuels in Transit Vehicles*. U.S. Department of Transportation. Retrieved from: http://www.fta.dot.gov/documents/Alternative_Fuels_Study_Report_to_Congress.pdf

[19] Eudy, L. and Gifford, M. (2003). *Challenges and Experiences with Electric Propulsion Transit Buses in the United States*. National Renewable Energy Laboratory, DOE/GO-102003-1791. Retrieved from: http://www.afdc.energy.gov/afdc/pdfs/34323.pdf

[20] Griffith, P. (2006). *Status of U.S. Battery-Electric Bus Programs*. Presented at the 22nd International Electric Vehicle Symposium and Exposition, October 2006, Yokohama, Japan.

[21] California Environmental Protection Agency, Air Resources Board (March 28, 2008). *Fact Sheet: The Zero Emission Vehicle Program - 2008*. Retrieved from: http://www.arb.ca.gov/msprog/zevprog/factsheets/2008zevfacts.pdf

[22] California Codes, Vehicle Code § 22511 (g). Retrieved from: http://www.leginfo.ca.gov/calaw.html

[23] Minnesota Pollution Control Agency, 2007. Air Emissions Impacts of Plug-In Hybrid Vehicles in Minnesota's Passenger Fleet. Retrieved from: http://www.state.mn.us/mn/externalDocs/Commerce/Air_Emissions_Impacts_of_PlugIn_Hybrid_Vehicles_in_Minnesotas_Pass_032907013010_PCA_PHEV_emissions_FINAL_2.pdf

[24] Minnesota Pollution Control Agency, 2007. Air Emissions Impacts of Plug-In Hybrid Vehicles in Minnesota's Passenger Fleet. Retrieved from: http://www.state.mn.us/mn/externalDocs/Commerce/Air_Emissions_Impacts_of_PlugIn_Hybrid_Vehicles_in_Minnesotas_Pass_032907013010_PCA_PHEV_emissions_FINAL_2.pdf

[25] Griffith, P. (2006). *Status of U.S. Battery-Electric Bus Programs*. Presented at the 22nd International Electric Vehicle Symposium and Exposition, October 2006, Yokohama, Japan.

[26] U.S. Environmental Protection Agency, 2008. eGRID2007 Version 1.1, Year 2005 Summary Tables. Retrieved from: http://www.epa.gov/cleanrgy/documents/egridzips/eGRID2007V1_1_year05_SummaryTables.pdf

[27] U.S. Department of Transportation, Federal Transit Administration (July 2, 2007). *Transit Bus Life Cycle Cost and Year 2007 Emissions Estimation, Final Report*, FTA-WV-26-7004.2007.1. Retrieved from http://www.fta.dot.gov/documents/WVU_FTA_LCC_Final_Report_07-23-2007.pdf

[28] Graham, L.A., G. Rideout, D. Rosenblatt, J. Hendren, 2008. Greenhouse gas emissions from heavy-duty vehicles. Atmospheric Environment, 42:4665-4681.

[29] Ebus (n.d.). *Ebus Brochure*. Retrieved from: http://www.ebus.com/Brochure.pdf

[30] Federal Transit Administration (December 2006). *Alternative Fuels Study: A Report to Congress on Policy Options for Increasing the Use of Alternative Fuels in Transit Vehicles*. U.S. Department of Transportation. Retrieved from: http://www.fta.dot.gov/documents/Alternative_Fuels_Study_Report_to_Congress.pdf

[31] U.S. Department of Energy, Energy Information Administration (May 14, 2010). *Table 5.3 Average Retail Price of Electricity to Ultimate Customers: Total by End-Use Sector, 1996 through February 2010.* Retrieved from http://www.eia.doe.gov/cneaf/electricity/epm/table5_3.html

[32] *Green Car Congress* (May 5, 2009). Testing Finds Proterra Electric Transit Bus Achieves More Than 20 mpg Diesel Equivalent. Retrieved from: http://www.greencarcongress.com/2009/05/proterra-20090505.html

14.0 Electric—Hybrid

Hybrid electric buses (HEBs) have two forms of drive power: electrical power, and another power source from a combustion engine. The combustion engine is designed for a particular fuel, and the issues surrounding these fuels are addressed in other chapters of this guide. The portion of the hybrid powertrain that captures lost power during braking (regenerative braking) and stores this energy in onboard batteries for later use is also used on electric battery buses, and is part of many fuel cell bus designs.

Hybrid Electric Buses
Top: Metro Transit, Minneapolis, MN; Bottom: DART, Dallas, TX.

The proportion of HEB power that is electric versus from combustion of an onboard fuel varies with design and drive cycle—some designs and drive cycles allow more collection of regenerative braking power. Design of the hybrid powertrain also affects the proportion of electric power that is from onboard generation versus from offboard charging, as with plug-in hybrid electric vehicles (PHEV). Buses that are PHEV are under development. These buses will be able to store electric power from a standard electrical outlet, in addition to regenerative braking. In this chapter, we will focus on HEBs, rather than PHEV buses.

Onboard storage of electric power may be in electrochemical batteries, ultracapacitors, or microturbine generators. The commercial HEBs of 2010 store electrical power in electrochemical batteries—ultracapacitors and microturbines are still in the demonstration phase of development. In either case, this power is transferred through the electrical powertrain.

HEBs can be designed with several hybrid system architectures, each with many possible variations depending on the hardware specifications, control strategy, and performance goals. West Virginia University (WVU), in association with the Transit Resource Center and the Battelle Memorial Center, recently completed a comprehensive assessment of hybrid-electric transit bus technology for the Transportation Research Board that has been published as *TCRP Report 132*.[1] *TCRP Report 132* includes a review of hybrid-electric bus literature, and provides on-road operational data from four major hybrid fleets: King County Metro Transit, New York City Transit, Washington Metropolitan Area Transit Authority, and Long Beach Transit. The study included 58 diesel, diesel hybrid-electric, gasoline hybrid-electric, and CNG buses from model years 1997 to 2004. *TCRP Report 132* served as a primary information source for this section.

14.1 Fuel Description

In a hybrid-electric bus, the onboard propulsion energy is stored in both the fuel tank and in the energy storage system (e.g., battery or ultracapacitor pack). The energy storage system is replenished by regenerative braking, which operates the electric motor as a generator while the bus is decelerating to capture braking energy to charge the batteries for later reuse. For full operation, HEVs require onboard storage of a fuel for the combustion engine—this fuel type depends on the engine design. For description of the combustion engine fuels, please refer to the appropriate fuel-specific chapters of this guide.

Current electric energy storage systems use devices such as electrochemical batteries and ultracapacitors; however, others such as flywheels may be used. An electrochemical battery (e.g., lead-acid, nickel metal hydride, and lithium-ion) stores electric energy in the form of chemical energy. One purpose of the energy storage system is to absorb and store braking energy, so it is necessary that the battery chemistry be rechargeable. Ultracapacitors, also referred to as supercapacitors or electrochemical double layer capacitors, store energy using an electrochemical reaction similar to batteries, however the energy density is an order of magnitude or more than hybrid-electric vehicle batteries.

The U.S. Department of Energy performance goals for hybrid-electric vehicle batteries include:

- Rapid discharge and recharge;
- Long cycle-life (the number of discharges before failure);
- High specific energy (amount of energy by mass, watt-hours per kilogram);
- High specific power (amount of power by mass, watts per kilogram);
- High energy density (amount of energy by volume, watt-hours per liter);
- High power density (amount of power by volume, watts per liter);
- High charging and discharging efficiency;
- Thermal tolerance;
- Recyclability; and
- Low-cost.

In general, battery performance can be characterized by four primary parameters:[2]

- **Specific Energy**—A higher specific energy means a longer range for the same battery weight. Specific energy is the ratio of a battery's energy output to its mass, typically expressed in watt-hours per kilogram (Wh/kg).
- **Specific Power** —A higher specific power means greater acceleration for the same battery weight. It is the ratio of a battery's power to its mass, expressed in watts per kilogram (W/kg).
- **Cycle Life**—The number of complete charge-discharge cycles that a battery can go through before its capacity declines to less than 80% of its original capacity.

- **Calendar Life** – The amount of time that a battery will be able to provide sufficient power and capacity for its application.

The cycle life of a battery will vary not only according to its composition, but also according to how it is used in a given configuration. A battery is said to go through a "shallow cycle" when up to 20% of its power is discharged and then recharged; a "deep cycle" on the other hand is when more than 20% of the battery's power is discharged and recharged. A series of deep charge-discharge cycles will affect a battery differently than a series of shallow cycles. Deep discharge battery packs have a cycle life from 800 (lead-acid) to 4,000 (for advanced lithium-ion).[3]

While early HEB used lead-acid batteries, other battery chemistries, such as nickel metal hydride (NiMH) and lithium-ion (Li-ion), are growing in use. Table 14.1 summarizes the performances of these battery chemistries. The United States Advanced Battery Consortium (USABC) has set minimum and long-term developmental goals for high-energy batteries for electric vehicles. These were selected to address the market needs for widespread electric vehicle use, and are listed in Table 14.1 for comparison.

Table 14.1 Summary of Electric Bus Battery Characteristics

	Specific Energy Wh/kg **(Range)**	**Specific Power** W/kg **(Acceleration)**	**Cycle Life**	**Cost**
Lead-Acid	35	200	500-800	$
Nickel-Cadmium (NiCd)	30	260	1,000	$$$
Nickel Metal Hydride (NiMH)	45-75	850	900	N/A
Sodium Nickel Chloride "Zebra"	95	170	1,000	$$$
Lithium-Ion (Li-ion)	100-180	700-1,300	1,000-4,000	$$$$
USABC Minimum Goals	150	300	1,000	$
USABC Long-Term Goals	200	400	1,000	$

The cost and benefit of a thermal and/or electrical battery management system is also an important consideration. Improving temperature and voltage uniformity within the battery pack can optimize performance and charge acceptance (for regenerative braking), reduce maintenance costs, and increase battery pack life.[4,5]

14.2 Fuel Usage

Hybrid-electric buses are currently in full-scale production. Annual sales are much lower than diesel buses, but this is the fastest growing bus type. Table 14.2 presents a summary of a few of the large North American hybrid-electric bus fleets.

Table 14.2 North American Hybrid-Electric Bus Fleets

Agency	# Vehicles	Type	Status
King County Metro Transit, Seattle, WA[6]	236 operating	Diesel 60' Allison	Operating since 2002
New York City Transit (NYCT), New York, NY	Over 1,000 operating	Diesel 40' BAE Systems	Operating since 2002
Washington Metropolitan Area Transit Authority (WMATA), Washington, DC	80 operating	Diesel 40' Allison	Operating since 2005
South Eastern Pennsylvania Transit Authority (SEPTA), Philadelphia, PA	Over 400 operating	Diesel 40' Allison	Operating since 2002
Long Beach Transit, Long Beach, CA	47 operating	Gasoline 40' ISE	Operating since 2004
Los Angeles County Metropolitan Transit Authority (LACMTA), Los Angeles, CA	6 operating, over 500 on order	Gasoline 42' ISE	Operating since 2009

Each of the three hybrid-electric transit bus propulsion system manufacturers has secured significant sales to major transit operations. Some fleets provided by each of these manufacturers are the following:

- **Allison Transmission—E^P System**
  Major fleets include King County Metro Transit (Seattle, Washington); Washington Metropolitan Area Transit Authority (Washington, DC); and Southeastern Pennsylvania Transit Authority (SEPTA), Philadelphia.
- **BAE Systems—HybriDrive System**
  Major fleets include New York, San Francisco, Toronto, the Port Authority of New York and New Jersey, Houston, and Ottawa.[7]
- **ISE Corporation—ThunderVolt System**
  ISE has developed many different hybrid bus powertrain configurations; however most have been produced in very small numbers. The gasoline-ultracapacitor hybrid system has the largest sales volume to date. Major fleets include Long Beach, Orange County, Norwalk, Montebello, Gardena, San Bernardino, and Fresno, California.

Is it Imported?

The fuel used to power the onboard combustion engine of hybrid buses is determined by the engine design. These fuels can range from imported petroleum-based fuels, to regional biofuels such as biodiesel.

14.3 Safety, Training, and Disposal

Hybrid-electric buses share the safety concerns associated with the onboard fuel for their combustion engine, and the concerns associated with electric battery buses. For an introduction to safety, training, and disposal for the combustion engine fuel of a HEB, please refer to the appropriate fuel-specific chapter of this guide. Often, the combustion engine fuel of HEB is selected to be the same as one of the fuels already used at a particular site, thus safety and training for this aspect of HEB is already developed.

Flammability and Toxicity

Many types of batteries contain toxic materials (e.g., acid, lead , cadmium, nickel, etc.). While these materials are typically sealed inside the battery, they can be a concern when a battery is damaged in a manner that breaches the seal, or if the battery is in a fire that causes it to rupture.

In recent years, the preferred batteries for use in vehicles are sealed batteries, which have negligible gas emissions on overcharge as compared to flooded batteries. Sealed batteries have reduced flammability and explosion concerns, and reduced need for battery storage under ventilated conditions. Only during extreme conditions, such as a cell malfunction, a battery management system failure, or a charger malfunction, will these batteries exceed the normal operating limits and emit gases. The bus manufacturer should be consulted on the type of battery used and appropriate precautions or facility modifications (such as additional ventilation) for battery storage and charging.

There have been rare instances of explosions of lithium-ion batteries used in consumer electronics, and several recalls of these batteries in laptop computers. These rare explosions have been attributed to exposure to high temperatures or short-circuiting within the battery. A slightly different lithium-ion battery technology (using a lithium metal phosphate cathode) is used for vehicle batteries to minimize the chances of explosion. As lithium-ion battery technology continues to mature, the risks of explosion are likely to be further reduced.

Training

An added cost for hybrid-electric buses is personnel training since additional skills are required to maintain hybrid-electric buses. Maintenance workers must receive additional training on technically complex equipment necessary for maintaining battery systems as well as safety precautions unique to hybrid-electric propulsion technology.[8]

Electric propulsion systems use electronic circuits with relatively high voltages and currents. For example, the Allison E^P hybrid system 120kW drive system for transit buses operates at a maximum voltage of 900 VDC.[9] Maintenance staff must be properly trained to work with this type of system to prevent harmful or potentially fatal electric shocks. Special protective equipment and diagnostic tools are required to work with high-voltage electric drive systems. The U.S. General Accounting Office evaluated the safety concerns associated with electric buses and concluded that electrocution hazards from the high-voltage systems were the primary concern.[10] The same concerns apply for hybrid-electric buses since they also utilize a high voltage battery and powertrain system.

U.S. Department of Transportation's Transportation Safety Institute (TSI) offers training courses specifically for transit agencies. Their 2011 course listings include "Safety Evaluations for Alternative Fuels Facilities and Equipment." This 3-day course provides "awareness and training in conducting safety evaluations for alternative-fueled vehicles, support equipment, and facilities using Compressed Natural Gas (CNG), Liquefied Natural Gas (LNG), hydrogen, fuel cells, propane, ethanol, electricity, bio-diesel, and hybrid electric." Classes are scheduled on an as-needed basis. Those interested should contact TSI.

Disposal

Battery disposal is an important consideration. According to the Battery Council International, a non-profit organization that promotes the lead-acid battery industry, over 97% of lead used in lead-acid batteries is recycled.[11] There are recycling programs, such as the Rechargeable Battery Recycling Corporation (http://www.rbrc.org), for small, sealed lead-acid, NiCd, NiMH, and Li-ion batteries used in portable electronics. Batteries from electric vehicles are too large to be accepted, but the technology to recycle them does exist. Research into battery recycling is ongoing. For example, the United States Council for Automotive Research (a cooperative group of Chrysler, Ford, and General Motors) has awarded contracts in the past to investigate the feasibility of recycling NiMH and Li-ion batteries used by hybrid-electric and battery-electric vehicles.[12]

14.4 Technology and Performance

All hybrid buses have an energy storage system and an electric motor that can provide power for propulsion. The powertrain design determines how and when power is dispersed from the electric motor and from the combustion engine.

Table 14.3 presents a summary of the major mechanical differences between diesel and hybrid-electric transit buses.

Table 14.3 Comparison of Differences between Diesel and Hybrid-Electric Buses

Component	Diesel Bus	Hybrid-Electric Bus
Energy source and storage method	Diesel in onboard fuel tank	Combustion engine fuel in tank (e.g., diesel, gasoline). Battery, ultracapacitor, or other electrical energy storage system.
Propulsion power source	Diesel engine	Combustion engine (for diesel or other fuel types), electric motor with motor controller and related power electronics.
Drivetrain	Multiple geared transmission	Parallel hybrid-electric—Multiple geared or continuously variable transmission. Series hybrid-electric—May not require a geared transmission. May use a multiple geared or continuously variable transmission.

In addition to the combustion engine, other primary components of the hybrid-electric technology are the energy storage system, electric motor, and the powertrain, of which there are two basic types. Each of these is described in the following sections, followed by a discussion of fuel economy.

Energy Storage System

Electrochemical battery packs are the most common energy storage system on hybrid buses. Other types of energy storage systems, such as ultracapacitors, are under development. These two types of energy storage systems are the following:

- **Electrochemical Battery Pack**—The cycle life of a battery is affected by the way it is utilized in a particular configuration. A charged battery has a 100% state-of-charge (SOC) and a discharged battery has a 0% SOC. A battery system in a hybrid-electric vehicle is operated in a much different manner than a battery system in an electric vehicle. The longevity of batteries is compromised by wide swings in battery capacity, such as the full charge/discharge cycling that electric vehicles use. As a result, the battery state-of-charge in hybrid-electric vehicles is maintained in a relatively narrow SOC range, for example from 40% to 60%. This results in utilizing a smaller percentage of the battery capacity, but the lifetime dramatically increases.

- **Ultracapacitors**—Ultracapacitors are able to utilize a large percentage of the energy capacity while still maintaining very long useful lives. One major automotive grade ultracapacitor supplier claims their modules have a useful life of over one million cycles and are capable of remaining useful for up to 10 years; however, these characteristics may be mutually exclusive.[13] The voltage swing is wider than and different from batteries, so will likely need

Did You Know?

The first hybrid vehicle was a gasoline-electric automobile developed in 1899 by Ferdinand Porsche. It was a series hybrid that had a motor mounted in each wheel. Electricity was produced by an onboard generator and stored in batteries.

to incorporate power electronics equipment to maintain the output voltage in the operating range of the electric motor.

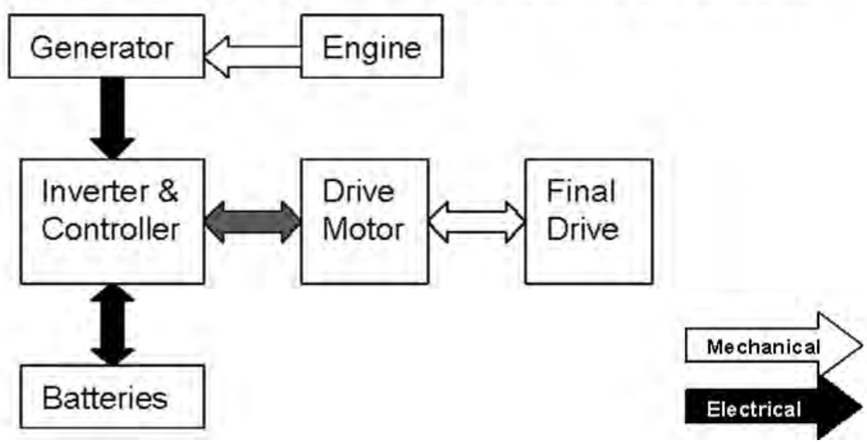
Electric Motor/Generator

The electric motor is used to provide some, or all, of the drive power depending on the hybrid system architecture, as will be discussed below. The electric motor converts electric energy into rotational energy by creating a torque on the motor output shaft. The diesel engine's output power (or torque) is very low at low speeds. Electric motors, however, produce full torque from zero speed. Electric motors are temperature, not current, limited so they are able to produce higher power (as much as double or triple the continuous power rating) for a short period until the motor reaches the maximum operating temperature. These features allow electric motors to accelerate the bus more quickly than a diesel engine can.[14] The wide torque band of electric motors, compared to diesel engines, have allowed many electrically driven vehicles to not require a variable gear transmission like diesel buses use.[1] The motor is also used as a generator during braking (i.e., regenerative braking) to recover braking energy and store it in the energy storage system. A motor can also be connected directly to the diesel engine drive shaft which is used as a generator for series hybrid-electric vehicles.

Series Hybrid-Electric Powertrain

In a series hybrid-electric vehicle, the combustion engine is not mechanically connected to the drive wheels. The engine's output shaft is connected to an electric generator that provides power to electric motor(s) that drive the bus or that charges the energy storage system. In this configuration, the electric motor provides all of the propulsion force so must be higher power capacity (and thus likely heavier and more expensive) than in a parallel hybrid system. Figure 14.1 provides a schematic of a basic series hybrid system configuration. The arrows indicate the mechanical and electrical energy flow. Both BAE Systems and ISE offer series drive transit buses in the U.S. market.[1]

Figure 14.1 Schematic of Basic Series Hybrid-Electric Bus Powertrain[1]

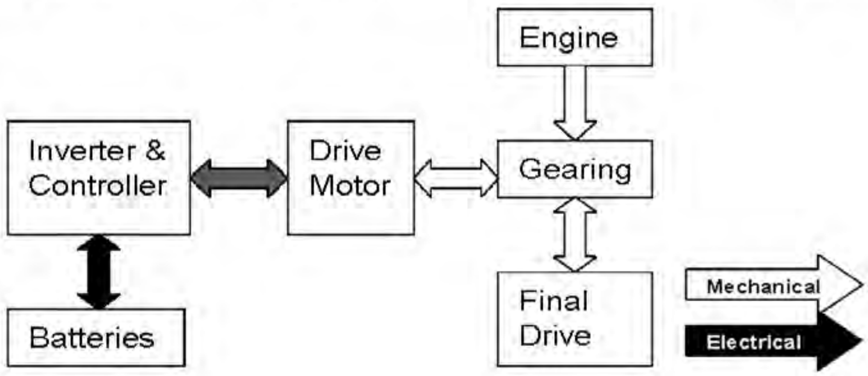


Guidebook for Evaluating Fuel Choices for Post-2010 Transit Bus Procurements 14-9

Parallel Hybrid-Electric Powertrain

In a parallel hybrid-electric vehicle, both the combustion engine and electric motors are mechanically connected to the drive wheels through a mechanical transmission of some design. There are many possible parallel hybrid configurations such as incorporating the electric motors into the transmission housing (pre-transmission type), directly to the driveshaft after the transmission (post-transmission), and many other possible configurations. Both pre- and post-transmission configurations have advantages and disadvantages; however, the required electric motor will have a lower power capacity than in a series hybrid-electric system since a smaller portion of the drive power will go through the electric power path. Figure 14.2 presents a schematic of a parallel hybrid-electric powertrain.[1]

Figure 14.2 Schematic of Basic Parallel Hybrid-Electric Bus Powertrain



Fuel Economy

Hybrid-electric bus powertrains are able to achieve higher fuel economy compared to a conventional diesel bus due to several reasons. Some, or all, of these benefits are possible, but will depend on the hybrid system architecture, system control logic, and drive power requirements to meet the fleet's driving cycle (e.g., hilly versus flat terrain). The control strategy is critical since it determines the amount of energy that is delivered to and from the energy storage system and how the amount of stored energy is maintained.[15]

The potential hybrid system benefits for reducing fuel consumption include:

1. **Engine Load Management**—Due to the additional power available from the energy storage system, the engine may be able to operate only in the most efficient ranges of its operating envelope. In a series hybrid, this may allow the engine to operate at a relatively constant operating point, which removes the emissions and fuel usage inefficiencies related to transient power demands for internal combustion engines.

2. **Combustion Engine Downsizing**—A smaller displacement engine than required for a conventional bus may be used, providing the energy storage system and hybrid powertrain can provide sufficient power to meet the required duty cycle power demands. Smaller displacement engines consume less fuel during idling and part-load operation. They also consume less fuel at full-load operation due to the lower power rating.

3. **Regenerative Braking Energy Recovery**—The electric motor is operated as a generator to provide braking torque when decelerating or going downhill. This allows kinetic energy that would be wasted and dissipated as heat energy by the friction brake system to be recovered and reused for later power demands such as accelerations or maintaining speed on a grade. The WVU study identified this aspect of hybrid system design to be the most significant contribution to fuel economy in most HEB.

As with any transit bus, regardless of the fuel or powertrain, the fuel economy performance depends on many factors such as the number of stops per mile, the average route speed, the route topography (hills vs. flat), etc. Chassis dynamometer fuel economy results can be used to compare different system performances. Some limitations of chassis dynamometer test procedures are that they do not account for air conditioning usage, accessory load, and terrain effects which add error and uncertainty to the data for comparison with in-use data. Comparison of dynamometer testing and in-use data is further complicated because fuel use from idling and operation in the depot was also not captured by the chassis dynamometer testing. Comparing in-use testing results from different fleets is difficult; however comparing the fuel economy performance within a particular fleet operating hybrid-electric buses and other bus types can be used to understand the system's effectiveness.

Diesel hybrid-electric buses in *TCRP Report 132* showed a 14% to 48% fuel economy improvement over diesel buses at different average operation speeds from in-use data. Chassis dynamometer testing on various cycles showed fuel economy improvements ranging from 10% to 76%. The apparent higher potential savings is likely due to the factors mentioned above that dynamometer testing does not include. In general, routes with lower average speeds and more stops and starts yielded higher fuel economy gains since the hybrid system was able to play a larger role in the power recovery and delivery.[1] It is worthy to note that the fuel economy performance of diesel hybrid-electric buses has increased by nearly 50% over the past 7 years. This may show the effect of more sophisticated hybrid system control logic as well as more battery pack data that allow more of the stored energy to be used while still meeting the battery lifetime requirements.

Gasoline hybrid-electric buses, in general, showed an 8% fuel economy improvement over diesel buses (on a diesel gallon equivalent) at different operation speeds from in-use data. Chassis dynamometer testing, however, showed a wide performance range from a 20% fuel economy penalty to a 29% gain compared to diesel buses.[1]

14.5 Maintenance, Reliability, and Storage

The maintenance requirements for hybrid-electric buses are the same as for their conventional combustion engine counterparts but in addition to the maintenance needs of the hybrid powertrain system components. The hybrid system adds complexity and components to the propulsion system that must be maintained or replaced (e.g., battery packs). However, various attributes of hybrid-electric propulsion, such as regenerative braking, yield less brake wear and less stress on the combustion engine and transmission, which may result in reduced maintenance or rebuilds throughout the bus lifetime. Hybrid-electric buses have been used in increasing quantities over the past 6 or more years, however not enough data is available regarding how component replacements or reduced maintenance/rebuilds will affect the lifecycle costs. The energy storage system represents the largest replacement cost (estimated at $27,500).[1]

Hybrid-electric buses have been on the road for over 6 years and are currently being sold in moderate volumes. This experience has led to design improvements that have resulted in maintainability and service procedure improvements.

Several studies have investigated maintenance costs of hybrid bus operation. NREL evaluated two generations of BAE HybriDrive equipped series hybrid-electric buses in the New York City Transit (NYCT) fleet to compare the maintenance costs in the first 2 years of operation. This is valuable because it provides an example of the comparative performance of two technology generations. Additional data are needed to determine the full bus lifecycle maintenance costs that may include replacement of hybrid system components (e.g., battery pack) after the warranty period expires. Maintenance costs includes labor (at $50 per hour) and parts costs.

The second generation hybrids in the NYCT fleet had total maintenance costs that were between 30% and 47% lower, which highlights the reliability and design improvements in the newer generation hybrid system. The second generation hybrid propulsion system (engine, exhaust, electrical system, hybrid system, etc.) maintenance costs were reduced by 55%. These results for the first year, which has a comparison to conventional diesel, are shown in Table 14.4 along with maintenance cost data from Long Beach Transit that compared conventional diesel to gasoline hybrid electric buses.

Table 14.4 Maintenance Cost of Hybrid-Electric Bus Fleets

Maintenance ($/mile)	Diesel	Hybrid	Change (%)
Long Beach Transit (gasoline hybrid)			
Propulsion Only ($/mile)	0.201	0.072	-64
King County Metro Transit (diesel hybrid)			
Total ($/mile)	0.46	0.44	-4
Propulsion Only ($/mile)	0.12	0.13	+8

In *TCRP Report 132*, the mid-level estimate of hybrid bus propulsion system maintenance costs is $0.19 per mile. This value is used as a default value in the FuelCost2 model.

Reliability

Detailed reliability data were also reported for the New York City Transit,[1] King County Metro Transit,[1] and Washington Metropolitan Area Transit Authority[1] diesel hybrid-electric buses, as well as from gasoline hybrid-electric buses from Long Beach Transit.[1] The average monthly mileage, availability, and mean distance between road calls (MBRC) provide information on the reliability of the hybrid-electric buses compared to the baseline diesel buses. Table 14.5 presents a summary of the performance data for these fleets.

Table 14.5 Reliability Summary for Hybrid-Electric Bus Fleets

	Diesel	Hybrid	Change (%)
New York City Transit			
Average Monthly Bus Mileage	2,385	2,461	+3
Miles Between Road Calls (Propulsion Only) (miles)	10,576	10,800	+2
King County Metro Transit			
Average Monthly Bus Mileage	2,949	3,096	+5
Miles Between Road Calls (All) (miles)	5,896	4,945	-16
Miles Between Road Calls (Propulsion Only) (miles)	12,199	10,616	-13
Washington Metropolitan Area Transit Authority			
Average Monthly Bus Mileage	4,576	4,606	+0.6
Miles Between Road Calls (Propulsion Only) (miles)	9,633	4,863	-50
Long Beach Transit			
Average Monthly Bus Mileage	3,295	3,057	-7
Miles Between Road Calls (Propulsion Only) (miles)	14,707	12,037	-18

Storage

Batteries will slowly lose charge through self-discharge reactions when the buses are stored. Potentially harmful gas evolution, such as hydrogen, is potentially a concern, but depends on the battery chemistry. Neither New York City Transit or King County Metro Transit required any facility modifications to accommodate hybrid-electric buses, so this concern may not apply.

14.6 Emissions

Emissions are addressed in the following two sub-sections. The first section discusses local and regional pollutants that are currently regulated under the Clean Air Act (i.e. hydrocarbons (HC), nitrogen oxides (NOx), particulate matter (PM), and carbon monoxide (CO)). The second section discusses pollutants that contribute to global warming (i.e., greenhouse gases (GHG)).

Regulated Emissions

Emissions from current hybrid-electric buses from model years 1997 to 2004 included in *TCRP Report 132* provide good evidence as to the effectiveness of hybrid-electric systems for reducing exhaust emissions on a percentage reduction basis.[1] These reductions are largely associated with reduced use of the combustion engine. Further, hybrid buses generally preferentially use electric power at slower speeds, when combustion engines have reduced efficiencies. Test results of diesel hybrid-electric buses equipped with 2010 model year engines have not been published. Past results provide a glimpse of the possible emission reductions on MY 2010 and later certified engines.

Guidebook for Evaluating Fuel Choices for Post-2010 Transit Bus Procurements 14-13

Data from eight studies evaluated in *TCRP Report 132* found that diesel hybrid-electric buses were found on average to have NOx emissions roughly 50% to 60% lower than conventional diesel buses. The emission rate on a grams per mile basis decreases as the average cycle speed increases, but the NOx reduction effectiveness was essentially constant. Starting in 2007, with the phase-in of compliance to be completed by 2010, all transit bus engines must be certified to produce very low NOx emissions. It would be speculation to estimate the performance of hybrid-electric powertrains on reducing NOx in these engines, but due to the dramatic regulated reductions for all engines, the mass basis emissions will likely be much less significant than in pre-2010 engines.

NOx emissions from the gasoline hybrid-electric bus were roughly 10 times lower than diesel-hybrid electric buses, CNG, and liquefied natural gas buses.[1]

As reported in *TCRP Report 132*, the combined effect of diesel particulate filter (DPF) usage, regenerative braking, less transient operation, and optimized engine control allowed diesel hybrid-electric buses to dramatically reduce PM emissions. The emission rate on a grams per mile basis decreases as the average cycle speed increases. In fact, it was found that PM emission varied by a factor of 15 between the New York bus cycle and the heavy-duty Urban Driving Dynamometer Schedule (UDDS) cycle (from high to low emission rates).[16] This fact highlights the point that emissions data must be compared to data from the same cycle to make an accurate comparison. Gasoline hybrid-electric buses do not require a DPF, and test results show PM emissions equivalent to diesel hybrid-electric buses equipped with a DPF.

New EPA heavy-duty engine emissions standards have been phased in over the last few years and came into full effect in 2010. These standards have promoted substantial changes in diesel engine emissions, and emissions measurements from buses meeting the 2010 standard are very limited at the time of this writing. As a result, the magnitude of emissions improvement with hybrid electric powertrains in 2010 buses cannot be stated with certainty. For the purposes of providing default values in the accompanying FuelCost2 model, an emissions reduction of 25% compared to the default emissions for the combustion engine is used to provide an initial, conservative estimate.

Greenhouse Gases

Carbon dioxide emissions are the primary GHG emission from hybrid-electric bus tailpipes. These emissions are primarily due to the fuel combustion, and they represent roughly 80% of the lifecycle GHG emissions associated with conventional transportation fuels. The remaining 20% is due to fuel production and transportation. Reductions in fuel use directly affect GHG production. Based on the fuel economy improvement discussion above, diesel hybrid-electric buses have shown GHG reduction of between 12% to 32% in-use and 9% to 43% in chassis dynamometer testing compared to a conventional diesel bus. Gasoline hybrid-electric buses show roughly an 8% GHG benefit compared to a conventional diesel bus. For the purposes of providing a default value for hybrid-electric bus lifecycle GHG emissions relative to diesel buses, a 25% reduction in fuel use will be assumed and applied to the default GHG emissions value for the combustion engine using the selected fuel type.

14.7 Cost and Availability

Bus Purchase Cost

Over the past few years, reported premiums for hybrid-electric buses have ranged from 40% to 100%. For example, in 2007, the Southeastern Pennsylvania Transit Authority placed an order for 400 diesel hybrid-electric buses using the Allison hybrid system, with an average bus cost of roughly $531,000, or a 94% price premium.[17] The Washington Metropolitan Area Transit Authority 40 ft diesel buses cost $349,000 (2006), while the Allison hybrid system equipped buses cost approximately $522,000, a 50% price premium. King County Metro Transit uses 60 ft articulated diesel hybrid-electric buses. A conventional diesel bus cost $445,000 while a diesel hybrid-electric bus cost $645,000, a 45% price premium.[1] BAE HybridDrive equipped buses in New York City Transit's fleet cost $385,000 (2002 and 2004), a 41% price premium.[1] The ISE Corporation powered gasoline hybrid-electric bus used by Long Beach Transit cost $550,000 (2005), a 100% price premium over a diesel bus estimated at $300,000 today.[1,18]

The cost premium for hybrid electric buses is expected to decline as this technology becomes more widely commercialized. In *TCRP Report 132*, a 7% to 30% reduction in hybrid bus costs is projected between 2007 and 2012. These reductions are due to technology maturation and equipment manufacturer recovery of their initial investments in the technology. As a default price in the FuelCost2 model, a 30% premium for hybrid electric bus costs compared to conventional diesel buses will be assumed. This is based on the range of hybrid premiums projected in *TCRP Report 132*. Thus, given a diesel bus cost of $350,000, hybrid-electric buses are estimated to cost $455,000. The $105,000 premium will be added to hybrids selected with other fuel types.

Facility Modifications

The only facility modification necessary for New York City Transit was the installation of two lead-acid battery conditioner units at $70,000 each. No additional safety or ventilation modifications were needed. King County Metro Transit and Washington Metropolitan Area Transit Authority did not require any facility modifications for the hybrid-electric buses. Long Beach Transit did not require any major facility improvements to accommodate the hybrid-electric buses, but they did install safety equipment to allow maintenance staff to work on the roofs where the energy storage systems are located. A fueling station may be required for fleets considering hybrid-electric buses that use a fuel type that is different than what they currently use.

Additional diagnostic equipment is needed for HEB maintenance. *TCRP Report 132* estimates these costs to be $5,000 for every 50 buses.

Guidebook for Evaluating Fuel Choices for Post-2010 Transit Bus Procurements

Table 14.6 Hybrid-Electric and Diesel Bus Costs

Item	Hybrid	Diesel
New Bus [a]	$455,000	$350,000
Facility Conversion/Equipment ($/50 buses) [a]	5,000	--
Fuel economy (mpg) [b]	4.01	3.30
Propulsion System Maintenance ($/mile) [a]	0.19	0.16
Facility Maintenance ($/mile) [c]	0.18	0.18

a. Based on Clark, N., Zhen, F. and Wayne, W. S. (December 2009). *TCRP Report 132: Assessment of Hybrid-Electric Transit Bus Technology*. Transportation Research Board of the National Academies, Washington, D.C.

b. Assumes a 25% fuel economy improvement compared to conventional diesel.

c. Facility maintenance costs assumed to be similar for hybrids and their convention counterparts on a per mile basis.

14.8 Summary

Hybrid Electric

Pros	Cons
Hybrid electric buses have lower tailpipe emissions than their conventional counterparts.	More stringent emission standards for all buses mean the total amount of emissions that can be reduced is much smaller than in the past.
Recent increases in hybrid electric buses helps ensure availability of parts.	Hybrid electric technology is not as mature as conventional powertrain technology.
The hybrid electric technology can be used in conjunction with any combustion engine fuel.	Hybrid electric buses cost roughly 30% more than their conventional counterparts.
Fuel economy improvements with the hybrid electric powertrain mean lower fuel costs.	Facility modifications and additional diagnostic equipment and training are needed, albeit modest compared to other alternative fuels.
Ridership increases on some routes are reported to be due to the "green" perception of hybrids.	Additional staff training will be needed regarding electrocution hazards and hybrid powertrain diagnostics.

Hybrid Electric References

[1] Clark, N., Zhen, F. and Wayne, W. S. (December 2009). *TCRP Report 132: Assessment of Hybrid-Electric Transit Bus Technology*. Transportation Research Board of the National Academies, Washington, D.C.

[2] Chandler, K., Walkowicz, K. and Eudy, L. (July 2002). *Hybrid-Electric Transit Buses: NYCT Diesel Hybrid-Electric Buses, Final Results.* National Renewable Energy Laboratory, NREL/BR-540-32427. Retrieved from http://www.afdc.energy.gov/afdc/pdfs/nyct_diesel_hybrid_final.pdf

[3] Chu, A. (2007). *Nanophosphate Lithium-Ion Technology for Transportation Applications.* Presented at the 23rd International Electric Vehicle Symposium and Exposition, December 2007, Anaheim, California.

[4] Linden, D. and Reddy, T. (2002). *Handbook of Batteries, 3rd ed.* New York: McGraw-Hill.

[5] Eudy, L. and Gifford, M. (2003). *Challenges and Experiences with Electric Propulsion Transit Buses in the United States*. National Renewable Energy Laboratory, DOE/GO-102003-1791. Retrieved from: http://www.afdc.energy.gov/afdc/pdfs/34323.pdf

[6] King County Metro Webpage, (April 25, 2008). *New Flyer Articulated Hybrid Bus,* http://transit.metrokc.gov/am/vehicles/hy-diesel.html, accesses.

[7] BAE Systems Press Release, *Newer New York City Buses with BAE Systems' Hybrid Propulsion Cost Less to Own and Operate, U.S. Government Says,* http://www.baesystems.com/Newsroom/NewsReleases/autoGen_10816172629.html, February 6, 2008.

[8] Eudy, L., *Challenges and Experiences with Electric Propulsion Transit Buses in the United States*, DOE/GO-102003-1791, National Renewable Energy Laboratory, November 2003.

[9] Allison Transmission Hybrid E^{P}40 Datasheet, http://www.allisontransmission.com/servlet/DownloadFile?Dir=publications/pubs&FileToGet=SA3576EN.pdf.

[10] General Accounting Office, (December 1999) *Mass Transit: Use of Alternative Fuels in Transit Buses*, GAO/RCED-00-18, Washington, D.C.

[11] Battery Council International (n.d.). *Lead Battery Recycling*. Retrieved from: http://www.batterycouncil.org/LeadAcidBatteries/BatteryRecycling/tabid/71/Default.aspx.

[12] United States Council for Automotive Research (2007). *USCAR VRP Contracts with 'OnTo Technology' to Advance Hybrid and Electric Car Battery Recycling*. Retrieved from http://www.uscar.org/guest/article_view.php?articles_id=115.

[13] Maxwell website, http://www.maxwell.com/ultracapacitors/index.asp, accessed April 24, 2008.

[14] Husain, I., *Electric and Hybrid Vehicles Design Fundamentals*, 2003.

[15] Ciccarelli, T. et al., *Assessment of Hybrid Configurations and Control Strategies in Planning Future Metropolitan/Urban Transit Systems*, SAE Paper 2001-01-2502., 2001.

[16] Clark, N. et al., *Factors Affecting Heavy-Duty Diesel Vehicle Emissions*, Journal of the Air & Waste Management Association, Vol. 52, 2002.

[17] Southeastern Pennsylvania Transit Authority Press Release, (September 27, 2007). *Red, Blue and Green All Over: SEPTA Board Approves Purchase of Hybrid Bus Fleet,* http://www.septa.com/news/press_releases/20070927a.html,

[18] Long Beach Transit website, http://www.lbtransit.com/about/environment.aspx, accessed April 25, 2008.

Guidebook for Evaluating Fuel Choices for Post-2010 Transit Bus Procurements 15-1

15.0 Electric—Fuel Cell

Fuel cells are reaction chambers for the electrochemical conversion of hydrogen gas and oxygen into electricity. Electricity generated from onboard fuel cells can be used to power electric motors that propel a bus. In contrast to electric battery vehicles, which store electric energy from an off-board source in onboard batteries, fuel cell vehicles produce electric energy onboard. The use of hydrogen as a propulsion fuel has been pioneered by the U.S. Space Program, which uses fuel cells to provide most of the electric power in the space shuttle.[1] Vehicular applications for fuel cells are now under development. This emerging technology is currently used in some demonstration fleets, and commercial availability began in 2010.

A CTTRANSIT zero emission hydrogen fuel cell bus outside its garage in Hartford, Connecticut.

There are two possible sources for the hydrogen used by fuel cells:

- Onboard storage of pure hydrogen, and
- Onboard conversion of hydrogen-rich fuels (e.g., methanol, natural gas, gasoline, etc.) to hydrogen gas by a reformer.

While the majority of current fuel cell buses use onboard storage of compressed hydrogen gas from off-board sources, the development of reformers for hydrogen production from onboard hydrogen-rich fuels is progressing. For that reason, this discussion will cover buses both with and without reformers. It is also important to note that a fuel cell can be used on its own to power a bus, or it can be combined with a hybrid electric powertrain to increase efficiency and allow for the recovery of braking energy.

15.1 Fuel Description

Composed of one proton and one electron, hydrogen is the most basic element. Hydrogen gas is a diatomic molecule, which means that it contains two hydrogen atoms. Although it is an abundant resource, hydrogen easily combines with other materials, so it rarely exists on its own for more than a very brief time before combining with another molecule. As a result, various processes are necessary to separate hydrogen from the compounds that contain it. Potential sources of hydrogen range from complex compounds such as hydrocarbon fuels (e.g. natural gas, propane, or petroleum based fuels) to basic substances such as water.

In order to operate properly and to maintain performance for a sufficient length of time, fuel cells require hydrogen with a purity level of 99.9% to 99.999%. Impurities decrease power production potential. An even larger concern, though, is that impurities may also lead to a permanent degradation of the fuel cell performance by "poisoning" the membrane electrode assembly catalyst layer. Carbon monoxide or sulfur, for example, will bind to catalyst active sites, which will reduce the number of sites available for hydrogen reaction to take place.

Table 15.1 shows some of the key properties of hydrogen compared to diesel fuel. The electrochemical process that fuel cells use to produce power is different from combustion, so values such as cetane rating are not relevant to fuel cells.

Table 15.1 Hydrogen and Diesel Fuel Properties

Property	Hydrogen	Diesel
Boiling Temperature (°F)	-423	356 to 644
Autoignition Temperature (°F)	932	600
Flash point (°F)	-423	≥140
Flammability Limits (Volume %, 60°F, 1 atm)	4.1 to 74.0	1.0 to 6.0
Lower Heating Value (Btu/lb)	18,676	18,394
Relative Weight (same volume) Compared to air = 1	0.07	>3 *(as vapor)*
Soluble in Water	No	No

Did You Know?

Hydrogen is considered an energy ***carrier***, like electricity. Electricity can be produced using a wide range of materials, such as fossil fuels, nuclear fission, wind, and moving water. Hydrogen gas is also produced from a variety of substances, including fossil fuels, biomass, and even water.

Hydrogen can be stored as a gas, liquid, or solid using three different methods that are briefly described below.

GAS

Storing hydrogen as a compressed gas has been the most common approach. The high-pressure cylinders are typically 5,000 to 10,000 pounds per square inch. While the cylinders can be made of steel, carbon fiber wound cylinders are preferred for their lighter weight, similar to those used on compressed natural gas (CNG) buses. Like CNG buses, fuel cell buses are likely to need several cylinders to store enough compressed gas for adequate driving range. In both fuel cell and CNG buses, the fuel is stored on the roof, an arrangement that provides ample space for the necessary quantity of cylinders. This convenience currently makes the use of compressed hydrogen gas more appealing than liquid hydrogen for transit buses.

LIQUID

Hydrogen condenses to a liquid at -423°F. The liquefaction process is similar to that used for liquefied natural gas (LNG). Liquefying the fuel increases the energy storage density, thus decreasing the volume required for fuel storage. One problem with this approach is that the bulk of the additional components needed to maintain the fuel at -423°F diminishes the advantage of the higher energy density of liquefied hydrogen. Optimizing storage tank design and using lightweight carbon fiber tanks rather than stainless steel has been projected by BMW to enable storage volume decreases of approximately 20%.

SOLID

Hydrogen can be stored as a solid by allowing it to combine with hydride materials. A metal hydride hydrogen storage system has been developed by ECD Ovonic for vehicles. Although this system requires less volume than a compressed gas system, its weight is higher because with the current technology, hydrogen only comprises 1% to 3% of the total storage system weight. To date, these systems have been used in light-duty demonstration vehicles, but not in fuel cell buses. The extra weight of these systems means a potential loss of passenger carrying ability; and mounting such a massive system on the roof of a bus is likely to make it less stable.

Table 15.2 shows the storage volume and weight for carrying 10 kg of hydrogen using different storage technologies. For comparison purposes, the energy equivalent volume and storage weight is also shown for diesel.[2]

Table 15.2 Comparison of Hydrogen Fuel Storage System Weight and Volume

	Earlier Systems		Recent Systems	
	Weight (kg)	Volume (L)	Weight (kg)	Volume (L)
Diesel (9 Gallons)	40	55	40	55
Compressed Hydrogen Gas	5,000 psig		10,000 psig	
	260	500	230	250
Liquefied Hydrogen	Metallic (Stainless Steel)		Lightweight Carbon Fiber Construction	
	220	300	80	250
Hydride	5,000 psig		10,000 psig	
	260	500	230	250

Rather than storing hydrogen onboard, other fuels can be used as a hydrogen carrier. Methanol has been most commonly used for this purpose. The methanol is stored on the vehicle and processed in an onboard fuel reformer, with hydrogen gas as one of its products. Reformers are also being developed to allow the use of fuels other than methanol, including gasoline, diesel, natural gas, and propane.

15.2 Fuel Usage

Because fuel cell buses are in the demonstration phase of development, there are no fleets that are currently using them in large numbers. Table 15.3 presents a summary of some North American transit fleets utilizing hydrogen fuel cell buses.

Table 15.3 North American Hydrogen Fuel Cell Bus Fleets

Technology	Agency	# Buses	Length	Operational Status
PEM fuel cell with onboard compressed hydrogen gas	Santa Clara Valley Transportation Authority (VTA), Santa Clara, CA, and San Mateo County Transportation District (SamTrans), San Mateo, CA	3	40′	Operating since 2005
PEM fuel cell with onboard compressed hydrogen gas and a hybrid-electric powertrain	Alameda-Contra Costa Transit District (AC Transit), San Francisco, CA	3	40′	Operating since 2006
	SunLine Transit Agency, Thousand Palms, CA	1 1	40′ 30′	Operating since 2006
	Connecticut Transit (CTTransit), Hartford, CT	1	40′	Operating since 2006
Battery dominant system with a PEM fuel cell and onboard compressed hydrogen gas	Hickam Air Force Base, Honolulu, HI[3]	1	30′ shuttle	Operating since 2004
	University of Delaware, Newark, DE[4]	1	22′ shuttle	Operating since 2007
PAFC with onboard liquid methanol and a hybrid-electric powertrain	Georgetown University, Washington, DC	5	3, 30′ 2, 40′	Operating since 1995

PEM—Proton Exchange Membrane; PAFC—Phosphoric Acid Fuel Cell

Battery dominant buses are essentially battery electric buses that use a small fuel cell (approximately 20kW) auxiliary power unit as a range extender. A major reason for this approach is to reduce the overall vehicle costs, which are substantially affected by the fuel cell size. Because the two buses in this category are shuttle buses, they are used in a less rigorous manner than a typical transit bus, having lower maximum speeds, lower power requirements, and a shorter driving range. Technically, these buses are closer in design to electric battery buses, and therefore will not be discussed further in this section.

Several other fuel cell bus demonstrations have been carried out in Japan (8 buses), Italy (1 bus), Spain (1 bus), and Brazil (1 bus). A large combined program encompassing the Clean Urban Transportation for Europe program (CUTE; 27 buses), Australia's Sustainable Transport Energy Program (STEP; 3 buses), and Iceland's Ecological City Transport System (ECTOS; 3 buses) is the largest demonstration effort to date. This program was recently extended for one year to gather additional data as well as to include hydrogen internal combustion engine buses for comparative analysis.[5]

15.3 Safety, Training, and Disposal

Flammability and Toxicity

Hydrogen has wide flammability limits (4.1% to 74.0% by volume at 60°F and 1 atm), but it is not toxic. Because hydrogen burns very quickly, its combustion can produce a loud noise that can be mistaken for an explosion. Hydrogen gas is lighter than air, and it will rise and dissipate if released outdoors. It diffuses nearly four times faster than natural gas and rises six times faster. As a result, the concentration of released hydrogen gas typically quickly decreases below the flammability limit.[6] All storage and maintenance facilities must have hydrogen sensors and proper ventilation systems to ensure that the gas is quickly and safely exhausted in the event of a gas release. Such releases can occur on a small scale, from routine maintenance, or on a larger scale, when fueling system or storage failures occur inside a building such as a maintenance bay or storage garage. In addition, maintenance areas must be modified to remove all potential sources of sparking. This precaution will help prevent a fire or explosion in the event of a hydrogen buildup.[7]

A fuel cell bus at Santa Clara VTA is filled with compressed hydrogen.

Training

All staff must be trained to understand hydrogen's properties as well as the operational changes that are necessary to safely work with or around hydrogen fuel and hydrogen vehicles. A fuel cell vehicle operates in a significantly different manner than one with a diesel engine. Maintenance staff will require a substantial amount of specialized training to learn how the system works and how to diagnose and repair issues. Government and industry are developing codes and standards relating to hydrogen fuel production, distribution, and use, as well as many other aspects of hydrogen. The safety and training recommendations and requirements developed through this process will provide the information required for staff to safely maintain and operate fuel cell buses.

Federal Motor Carrier Safety Administration (FMCSA) of the U.S. Department of Transportation has published the following three reports that provide a good beginning for addressing hydrogen safety in bus operations:

- *Guidelines for Use of Hydrogen Fuel in Commercial Vehicles, Final Report.* Report Number FMCSA-RRT-07-020, November 2007. Available at http://www.fmcsa.dot.gov/facts-research/research-technology/report/Guidelines-H2-Fuel-in-CMVs-Nov2007.pdf
  This 81-page report provides an introduction to hydrogen fuel as used in combustion engines and fuel cells. It includes basic fuel properties and conversion factors, fuel system components, safety and emergency response, and guidelines for design and operation of hydrogen systems on vehicles and as part of refueling facilities and maintenance facilities.

- *Changes to Consider in the Federal Motor Carrier Safety Regulations and North American Standard Inspection Procedures to Accommodate Hydrogen as an Alternative Fuel.* Report Number FMCSA-RRT-07-027, December 2007. Available at http://www.fmcsa.dot.gov/facts-research/research-technology/report/FMCSA-H2-Regs-and-Inspections-Final-Report-Nov2007.pdf
  This 26-page report examines existing FMCSA regulations governing commercial vehicle fuel systems, discusses gaps, and presents considerations for changes in these regulations for hydrogen fuel. It also examines modifications in commercial vehicle inspections and carrier reviews that should be considered for hydrogen fuels.
- *System Safety Plan for Commercial Vehicles using Hydrogen as an Alternative Fuel.* Report Number FMCSA-RRT-07-025, November 2007. Available at http://www.fmcsa.dot.gov/facts-research/research-technology/report/System-Safety-Plan-CMVs-Hydrogen-Final-nov07.pdf
  This 28-page report provides guidance for the development of a System Safety Plan (SSP) for use by vehicle fleet operators to ensure long-term safe operation of vehicles using hydrogen.

U.S. Department of Transportation's Transportation Safety Institute (TSI) offers training courses specifically for transit agencies. Their 2011 course listings include "Safety Evaluations for Alternative Fuels Facilities and Equipment." This 3-day course provides "awareness and training in conducting safety evaluations for alternative-fueled vehicles, support equipment, and facilities using Compressed Natural Gas (CNG), Liquefied Natural Gas (LNG), hydrogen, fuel cells, propane, ethanol, electricity, bio-diesel, and hybrid electric." Another 1-day course offering, "Alternative Fuel Cylinder Inspection," is specific to CNG, with inspection guidance that would be similar for high pressure hydrogen cylinders. Classes are scheduled on an as-needed basis. Those interested should contact TSI.

Disposal

Hydrogen gas is lighter than air. If fuel is released outdoors, it will rise and quickly dissipate to safe concentrations. Un-used fuel should be returned to the supplier.

15.4 Technology and Performance

Fuel Cell Technology A fuel cell is a device that produces energy by enabling an electrochemical reaction between two substances. During this reaction, the free electrons are forced through an outside current loop to create a useable electrical current that can power an electric motor. Two types of fuel cells are presently used in fuel cell buses, both of which are fueled by gaseous hydrogen.

Proton Exchange Membrane (PEM) PEM fuel cells store gaseous hydrogen in high-pressure cylinders to use directly in the fuel cell. Figure 15.1 presents a schematic of the design and operation of a PEM fuel cell. By far the most common type, PEM fuel cells are used in most of the current fuel cell buses.

Phosphoric Acid Fuel Cell (PAFC) These fuel cells use liquid fuels such as methanol as both the hydrogen carrier and the storage medium. The hydrogen gas for the fuel cell is produced on-board using a reformer system. This method allows use of a more conventional fueling infrastructure and a fuel with a higher energy density. A 150 gallon methanol fuel tank can

Guidebook for Evaluating Fuel Choices for Post-2010 Transit Bus Procurements 15-7

provide a 350 mile range. The downside of using an onboard fuel reformer is that it involves extra cost, weight, installation space, and system complexity. Earlier generations of light-duty fuel cell vehicles used this method, but later models have used high-pressure gas storage.

Regardless of the method used to provide the hydrogen gas, both PEM and PAFC designs produce a reaction between hydrogen gas and oxygen to generate a useable electric current and water vapor. Because oxygen naturally exists in the form (O_2) required by the fuel cell, it is taken directly from the air.

Hydrogen fuel cells are viewed by some as the long-term transportation solution to decrease or eliminate petroleum dependence, and to move to a sustainable fuel that will improve air quality and the environment. But there are still many challenges related to fuel cells and onboard fuel storage. Although these challenges are being addressed, development of production ready fuel cells that can match the reliability, durability, and cost effectiveness of today's diesel engines may take a decade or more.[8]

Figure 15.1 Schematic Diagram of PEM Fuel Cell Operation

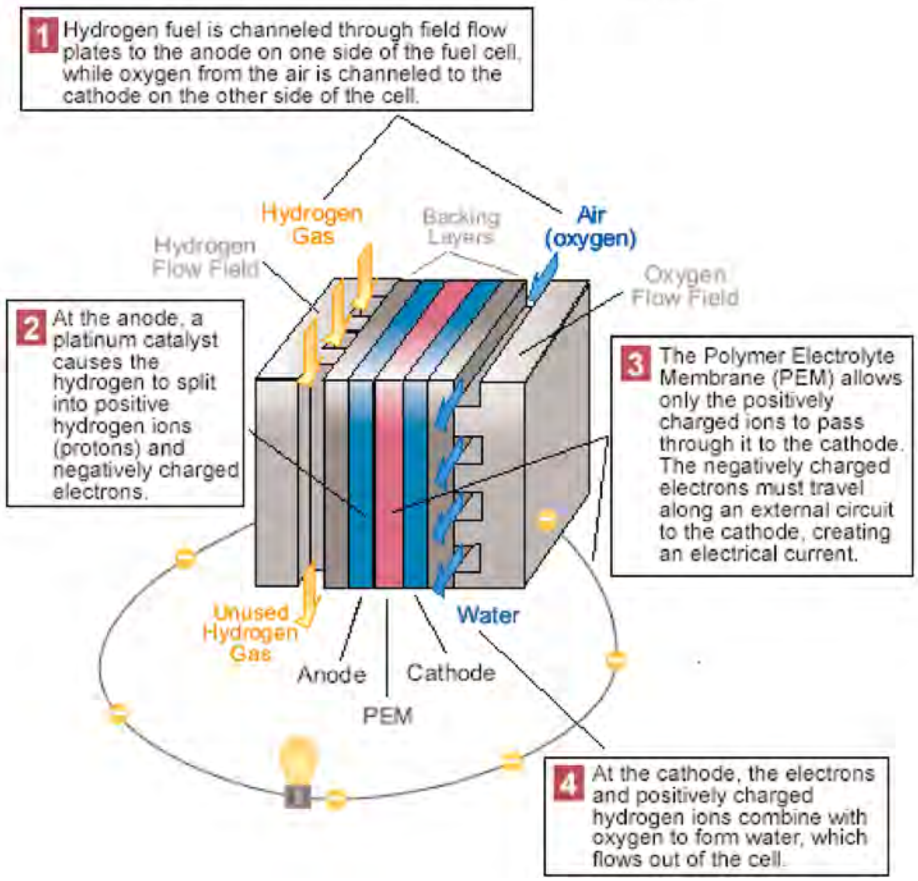


Table 15.4 presents a summary of the major mechanical differences between diesel internal combustion and hydrogen fuel cell transit buses.

Table 15.4 Comparison of Powertrains in Diesel and Fuel Cell Buses

Component	Diesel Bus	Fuel Cell Bus
Energy source and storage method	Diesel fuel in tank	High-pressure or liquefied hydrogen tanks
Propulsion power source	Diesel engine	Fuel cell, electric motor with motor controller, and related power electronics
Drivetrain	Multiple geared transmission	Single or multiple geared transmission

Fuel Economy

As with any transit bus, regardless of the fuel or powertrain, the fuel economy performance of a fuel cell bus depends on many factors, including the number of stops per mile, the average route speed, the route topography (hills vs. flat), etc. For this reason, a comparison of the fuel economy performance *within* a particular fleet that operates both fuel cell buses and other bus types can offer a rough idea of their relative effectiveness. For example, the same fuel cell hybrid electric bus design is in use at Connecticut Transit, AC Transit, and SunLine Transit. The Connecticut Transit bus saw a fuel economy improvement of 100% compared to the diesel baseline buses, with a result of 7.0 miles per kilogram of hydrogen, or 7.9 miles per diesel gallon equivalent (DGE).[9] The AC Transit bus was reported to have a fuel economy improvement of between 63% and 89%, or approximately 6.97 miles per DGE, depending on the route, compared to the diesel bus fuel economy of 4.03 mpg.[10] The SunLine fuel cell bus achieved a fuel economy of 8.33 miles per DGE, compared to 3.29 miles per DGE for the CNG baseline buses, a 253% improvement.[11, 14] These buses are designed with a large capacity battery pack that is recharged each night. The reports did not mention whether the energy that was used to charge the batteries was included in the fuel economy calculations. The fuel economy improvement will be less if the electric energy was not accounted for.

The buses operated at Santa Clara Valley Transportation Authority do not have a hybrid electric propulsion system. With no battery, the vehicles cannot recover braking energy or modulate the power demand from the fuel cell to increase efficiency. As a result, the fuel consumption of those buses was 3.12 miles per kilogram of hydrogen, which is equivalent to 3.52 miles per DGE. The diesel control buses had a fuel economy of 3.98 mpg.[12]

Guidebook for Evaluating Fuel Choices for Post-2010 Transit Bus Procurements 15-9

15.5 Maintenance, Reliability, and Storage

Maintenance

The maintenance requirements for fuel cell buses are significantly different from conventional diesel buses. Fuel cells and diesel engines are both complex devices, but their respective technologies are in disparate stages of maturity. The diesel engine has over a century of development that has resulted in a reliable, durable, and maintainable design. Vehicular application of fuel cells, on the other hand, is still in its early stages. Developing a fuel cell that is compact, cost effective, and meets the reliability and durability goals of a diesel engine is a major challenge. Because the technology is under development, fuel cell buses have substantially increased maintenance requirements in comparison to diesel engine buses.

> **Did You Know?**
>
> Fuel cells were invented in the 1800s, but were not commercially developed until the U.S. Space Program began to use them in the 1950s. For most of their existence, fuel cells have been limited to space and stationary power applications.

An electric motor such as on a fuel cell bus has essentially one moving part in contrast to the many moving parts in an internal combustion engine. As a result, electric motors generally require much less maintenance. The resulting high reliability helps to mitigate the increased maintenance needs of the fuel cell.[13] A hybrid electric system has additional components, higher complexity, and extra maintenance requirements. A properly designed battery pack with reliable battery modules and a management system, however, can result in a reliable unit. A properly functioning battery pack will be maintained by the battery management system, which significantly reduces demands on maintenance staff. Another benefit of utilizing a hybrid electric system is that the fuel cell can be operated at (or close to) steady-state operation, which extends the useful life of the fuel cell stack.

Detailed medium-term (approximately 1 ½ years) maintenance and operational data have been collected by the National Renewable Energy Laboratory (NREL) on several U.S. fuel cell bus demonstrations, including AC Transit and SunLine Transit. Table 15.5 shows that the total maintenance costs for the fuel cell buses at AC Transit were $0.59/mile compared to $0.44/mile for the diesel baseline buses, representing a 34% increase in maintenance costs. The maintenance costs for the propulsion system alone were $0.08/mile for the fuel cell bus and $0.10/mile for diesel buses (a 20% decrease), but these results are skewed because component failures that required the replacement of the batteries and fuel cell stack were covered under the warranty.[10,11] SunLine Transit also experienced component failures that were replaced under warranty, but still reported significantly higher maintenance costs compared to the CNG baseline buses.[14]

Table 15.5 Maintenance Cost Summary for AC Transit and SunLine Transit Fuel Cell Buses

AC Transit			
	Diesel	**Fuel Cell***	**Change***
Total ($/mile)	0.44	0.59	34%
Propulsion Only ($/mile)	0.10	0.08	-20%
Power plant (e.g. Fuel Cell / Diesel Engine Only) ($/mile)	0.02	0.04	100%

SunLine Transit			
	CNG	**Fuel Cell**	**Change**
Total ($/mile)	0.27	0.46	70%
Propulsion Only ($/mile)	0.07	0.24	243%
Power plant (e.g. Fuel Cell / Diesel Engine Only) ($/mile)	0.04	0.09	125%

** Does not include costs covered under warranty.*

Reliability

Detailed reliability data were also reported for the AC Transit and SunLine Transit fuel cell bus demonstrations. The average monthly mileage, availability, and mean distance between road calls (MBRC) provide information on the reliability of the fuel cell buses compared to the baseline diesel and CNG buses. Table 15.6 presents a summary of the performance data for these two fleets.

Table 15.6 Reliability and Availability Summary for AC Transit and SunLine Transit Fuel Cell Buses[11]

AC Transit			
	Diesel	**Fuel Cell**	**Change**
Average Monthly Bus Mileage	2,720	1,067	-61%
Availability	n/a	61	--
Miles Between Road Calls (All) (miles)	4,474	1,395	3.2 times lower
Miles Between Road Calls (Propulsion Only) (miles)	10,670	1,649	6.5 times lower

SunLine Transit			
	CNG	**Fuel Cell**	**Change**
Average Monthly Bus Mileage	4,418	2,056	-53%
Availability	87	65	-25%
Miles Between Road Calls (All) (miles)	10,604	1,194	8.8 times lower
Miles Between Road Calls (Propulsion Only) (miles)	37,872	1,322	28 times lower

The fuel cell bus performance significantly lags behind the conventional diesel bus and CNG performance in all reliability categories. The majority of the downtime at AC Transit was attributed to fuel cell issues (53%) and battery issues (16%).[10,11] At SunLine Transit, the majority of the downtime was attributed to issues with the fuel cell (29%), batteries (19%), and the hybrid system (6%).[14]

The lower mileage accumulation of the fuel cell buses compared to the diesel buses at AC Transit can be explained in part by the fact that the fuel cell buses are operated only during the daytime hours and on weekdays to ensure that the properly trained staff are available for driving and maintaining the buses. At any given time, only two of the three buses are in operation. That means one bus is always available for maintenance, training, or for special events. The battery and fuel cell failures and component replacements dramatically reduced the reliability and availability of the buses. Due to long lead times for replacement parts to arrive, some buses were dormant for several months.[10]

Storage

The storage requirements for hydrogen gas are similar to those for natural gas. If vehicles are stored indoors, the garage must be fitted with hydrogen sensors and appropriate ventilation equipment. For environments in which hydrogen gas is stored, ventilation equipment should include sealed fan motors and switches to eliminate the potential of sparking, which could ignite the gas. All other electrical equipment and wiring must also be inspected and modified if necessary to eliminate potential sparking sources. Ventilation must be sufficient to quickly exhaust the hydrogen in order to reduce the gas concentrations to safe levels.

15.6 Emissions

Emissions are addressed in two sub-sections below. The first section discusses local and regional pollutants that are currently regulated under the Clean Air Act [i.e. hydrocarbons (HC), nitrogen oxides (NOx), particulate matter (PM), and carbon monoxide (CO)]. The second section discusses pollutants that contribute to global warming [i.e., greenhouse gases (GHG)].

Diesel-Gallon Equivalents (DGE)

On an energy-equivalent basis:

1 gallon diesel = 2.5 lb hydrogen

1 gallon diesel = 1.13 kg hydrogen

Regulated Pollutants

The only "tailpipe" emission produced by hydrogen fuel cell buses is water vapor, which is not a pollutant. As with electric battery buses and trolleybuses, however, the full cycle emissions lie upstream in the fuel production processes. Therefore, the lifecycle emissions vary depending on the method(s) used to produce the hydrogen. To achieve zero emissions, hydrogen would need to be produced using renewable energy such as wind or solar power to operate an electrolysis process in which electric power is used to directly split water molecules into hydrogen and oxygen molecules.

In the FuelCost2 model that accompanies this guide, only tailpipe emissions of regulated pollutants are considered, and fuel cell buses are assumed to have zero tailpipe emissions.

Greenhouse Gases

While there are no greenhouse gases (GHG) emissions from the "tailpipe" of fuel cell buses, there are GHG emissions associated with the production of the hydrogen carrier used in the fuel cells. However, the lifecycle GHG associated with fuel cell buses must take into account the GHG emitted during production and transport of the hydrogen carrier used by the fuel cells. This may be a liquid fuel such as methanol, or hydrogen gas.

This discussion focuses on GHG emissions from hydrogen production and transportation since onboard hydrogen serves as the carrier for most current fuel cell buses. The methods to produce hydrogen vary, as do their emissions. There are two primary sources of emissions during hydrogen production. The first is the GHG (including CO_2) that may be produced during generation of the electricity used by the hydrogen production facility. Power generation emissions vary with the fuel source, and may be essentially zero with use of renewable energy.

The second source of GHG during hydrogen production is CO_2 produced as a result of the chemical separation of hydrogen from various compounds. Four different methods that can be used for this separation are summarized below:

- **Steam Reformation.** Hydrogen is produced from hydrocarbon fuels such as natural gas, gasoline, or propane. This process ultimately yields one molecule of CO_2 for every four of H_2. Steam reformation of natural gas accounts for 95% of current hydrogen production.
- **Partial Oxidation Reformation.** This process also uses hydrocarbon fuels, but requires lower energy input than steam reformations. The process itself creates one molecule of CO_2 for every three of H_2.[15]
- **Gasification of Coal or Biomass.** Using the gasification process, the ratio of CO_2 to H_2 depends on the feedstock.[16]
- **Electrolysis of Water.** This method uses electrolysis to directly split water molecules into oxygen and hydrogen, and results in no GHG production other than that associated with the generation of electricity.[17]

For a general estimate of lifecycle GHG emissions, the combined GHG emissions from the most common form of hydrogen production (i.e., steam reforming of natural gas) and fuel distribution are estimated to be approximately 20% lower for fuel cell vehicles than for diesel vehicles on a per mile basis.[18] Tank-to-wheels GHG from diesel vehicles are estimated to represent 80% of the total lifecycle GHG associated with these vehicles.[19] In contrast, tank-to-wheels GHG from hydrogen vehicles are estimated to represent less than 0% of the total lifecycle GHG associated with hydrogen vehicles. Together, this suggests that the lifecycle GHG emissions reduction associated with hydrogen buses, from fuel production to engine combustion, are 84% lower than from diesel buses – this is the default value used in the FuelCost2 model.

15.7 Cost and Availability

Fuel cell buses are available in small quantities. As is expected for a new technology in its developmental stage, the costs are significantly higher than for a conventional diesel bus. For example, a baseline diesel bus used at AC Transit costs $323,000, while the fuel cell bus cost $3.2M, nearly 10 times higher.[10] This bus is the same model as those used by Connecticut Transit and SunLine Transit, so the costs were similar.[14] The buses participating in the combined European and Australian CUTE/STEP/ECTOS programs are slightly less costly at $2.5M.[20]

AC Transit modified its maintenance garage facilities by building a firewall to separate one bay (made for two buses) from the rest of the garage. This modification cost $1.5M. Santa Clara Valley Transportation Authority built a hydrogen fueling station, a separate maintenance facility, and a bus wash for the fuel cell buses, for a combined total of $4.4M.[12] The cost for each building was not listed separately.

As addressed in the maintenance discussion of Section 15.5, a broad range of maintenance costs have been reported for fuel cell buses—from 20% less than diesel to more than 240% more than CNG buses not including costs covered by warranty. Because maintenance costs covered under warranty are not included in the available reports, there are no particularly good estimates of fuel cell bus maintenance costs. For the purposes of a default value in FuelCost2, maintenance costs for fuel cell buses are estimated to be 130% of diesel costs.

Fuel economy of fuel cell buses is roughly estimated to be double the fuel economy of their baseline counterparts on a per DGE basis (see discussion in Section 15.4). No estimates of facility maintenance costs were found for fuel cell bus operations. As an initial estimate, facility costs are estimated to be the same as for a conventional diesel facility. Table 15.7 summarizes the default value costs used in the accompanying FuelCost2 model.

Table 15.7 Hydrogen Fuel Cell Bus Cost Estimates

Item	PEM Cell Bus (Hydrogen onboard)	PAFC Bus (Methanol or other liquid onboard)
New Vehicle ($)	2,500,000	3,500,000
Facility Conversion ($/50 buses)	1,500,000	500,000
Fuel (hydrogen, $/kg)	7.00	Depends on liquid
Fuel economy (miles/DGE)	5.59	5.59
Propulsion System Maintenance ($/mile)	0.21	0.21
Facility Maintenance ($/mile)	0.18	0.18

15.8 Summary

Fuel Cells

Pros	Cons
The only tailpipe emission from fuel cell buses is water vapor which is not considered to be a pollutant.	Fuel cell buses are in the demonstration phase of development – as such, maintenance costs are increased and reliability is reduced compared to conventional buses.
Fuel cells buses equipped with a reformer offer the potential for fuel flexibility (i.e., fuel switching) based on fuel prices.	Fuel cell bus costs have been roughly 10 times higher than conventional bus. Fuel cell bus costs are highly dependent on fuel cell size and the presence of a reformer (to allow use of fuels other than hydrogen as the fuel cell hydrogen source).
Assuming the most common method of hydrogen production, fuel cell buses yield a roughly 84% reduction in lifecycle GHG compared to conventional diesel buses.	Hydrogen refueling facility costs are in the range of CNG refueling facility costs, which are substantially greater than for liquid fuels.
Fuel cell buses offer the potential for noise reductions, similar to other electricity-powered buses.	Fuel economy of fuel cell buses is roughly estimated to be double the fuel economy of conventional diesel buses on an energy equivalent basis.

Fuel Cell References

[1] www.nrel.gov/hydrogen/photos.html.

[2] Hall, W. (2007). *BMW Hydrogen Near Zero Emission Vehicle Development*. Presented at the CALSTART-WestStart Hydrogen Internal Combustion Engine Symposium, 2007, Los Angeles, CA.

[3] Eudy, L. and K. Chandler, *Hickam Air Force Base-Fuel Cell Vehicles: Early Implementation Experience*; NREL/TP-560-42233, October 2007.

[4] UD Daily Article, *UD Unveils Hydrogen-Powered Bus that Produces No Pollutants*, http://www.udel.edu/PR/UDaily/2007/apr/bus040907.html, April, 9, 2007.

[5] CALSTART-WestStart Hydrogen Bus Source Newsletter, *EU Program Puts Hydrogen Buses Through New Paces*, September 2006

[6] U.S. Department of Energy, Hydrogen Program, *Hydrogen & Our Future*, http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/hydrogenenergyfuture_web.pdf, DOE/EE-320.

[7] U.S. Department of Transportation, Federal Transit Administration, *Analysis of Electric Drive Technologies for Transit Applications: Battery-Electric, Hybrid-Electric, and Fuel Cells*, August 2005.

[8] Berry, N., *SCAQMD, SCAQMD–Hydrogen ICE Projects,* 2007 CALSTART Hydrogen Internal Combustion Engine Symposium.

[9] Connecticut Transit Press Release, *CTTransit Earns Gold Honors for Fuel Cell Bus*, July 13, 2007. Retrieved from http://www.cttransit.com/press/Press.asp?pressID=%7BC8E206C3-FF0D-4DF9-A843-64E75CFBC30C%7D

[10] Chandler, K. and L. Eudy (National Renewable Energy Laboratory), *Alameda-Contra Costa Transit District (AC Transit) Fuel Cell Transit Buses: Evaluation Results Update*, NREL/TP-560-42249, October 2007.

[11] Eudy, L., National Renewable Energy Laboratory, *Fuel Cell Bus Evaluation Results*, Presented at TRB Annual Meeting, January 2008.

[12] Chandler, K. and L. Eudy (National Renewable Energy Laboratory), *Santa Clara Valley Transportation Authority and San Mateo County Transit District-Fuel Cell Transit Buses: Evaluation Results*; NREL/TP-560-40615, November 2006.

[13] Eudy, L., *Challenges and Experiences with Electric Propulsion Transit Buses in the United States*, DOE/GO-102003-1791, National Renewable Energy Laboratory, November 2003.

[14] Chandler, K. and L. Eudy (National Renewable Energy Laboratory), *SunLine Transit Agency – Hydrogen Powered Transit Buses: Evaluation Results Update*; NREL/TP-560-42080, October 2007.

[15] U.S. Department of Energy, Hydrogen Program (n.d.). *Hydrogen & Our Energy Future*, DOE/EE-320. Retrieved from: http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/hydrogenenergyfuture_web.pdf

[16] U.S. Department of Energy, Hydrogen Program (n.d.). *Hydrogen & Our Energy Future*, DOE/EE-320. Retrieved from: http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/hydrogenenergyfuture_web.pdf

[17] Wysor, J. (2006). *A Perspective on Emissions*. Presented at the CALSTART-WestStart Hydrogen Internal Combustion Engine Symposium, 2006, San Diego, CA.

[18] Joseck, J. (March 2009). Well-to-Wheels Greenhouse Gas Emissions and Petroleum Use. DOE Hydrogen Program Record #9002.

[19] Skone, T.J., and Gerdes, K. (November 2008). *Development of Baseline Data and Analysis of Life Cycle Greenhouse Gas Emissions of Petroleum-Based Fuels, Appendix J.* National Energy Technology Laboratory (DOE/NETL-2009/1346).

[20] Scott, P., ISE Corporation, *HICE in Transit Bus Applications*, 2006 CALSTART Hydrogen Internal Combustion Engine Symposium.

Photo Credit:
Photos in this chapter courtesy of DOE/NREL, credit – Leslie Eudy.

Appendix A: Fuel Properties and Cost Table

This table is a compilation of the fuel properties and cost estimate tables presented in the fuel-specific chapters of this Guidebook. Please refer to the appropriate fuel chapter for data references used to create these tables.

Summary of Fuel Properties and Costs for Combustion Engine Fuels

Property	Diesel	B100	Gasoline	E100	Natural Gas	Hydrogen	Propane	DME
Boiling Temperature (°F)	356 to 644	599 to 662	80 to 437	172	-260	-423	-44	-13
Autoignition Temperature (°F)	600	N/A	495	793	900	932	842	455
Cetane Number	40 to 55	48 to 65	Not applicable	0 – 54	N/A	N/A	N/A	55 to 60
Octane Number (R+M/2)	NA	NA	84 to 93	115	120	130+	105	NA
Flash point (°F)	140 to 176	≥ 212	-45	55	-300	N/A	-156	- 41.8
Flammability Limits (vapor in air by volume %)	1.0 to 6.0	not known	1.4 to 7.6	4.3 to 19	5 to 15	4.1 – 74.0	2.2 to 9.5	3.4 to 18
Lower Heating Value (Btu/gal unless stated otherwise)	128,450	119,550	116,090	76,330	20,263 Btu/lb	52,217 Btu/lb	84,250	66,615
Relative Weight (same volume) Compared to air = 1 Compared to water = 1	 >3 *(as vapor)* 0.85	 not known 0.88	 >2.5 *(as vapor)* 0.75	 0.79 *(as vapor)* 1.6	 0.60 0.45 *(as liquid)*	 0.07 not known	 1.5 0.51	 1.6 0.66
Soluble in water (by volume)	No	No	Negligible	Miscible in all proportions	No	No	No	Yes, up to 8%
New Vehicle ($)	350,000	$350,000	262,500	$367,500	$375,000	$390,000	380,000	380,000
Facility Conversion ($/ 50 Buses)	N/A	$400	100,000	$100,000	$1.75 million	$1.5 million	875,000	875,000
Fuel ($/DGE unless stated otherwise)	2.51	$3.57	2.50	$3.19(E85)	$1.91	$2.38	2.62	1.30 2.51
Fuel Economy (miles/DGE)	3.2	3.3	2.4	3.2	2.7	2.7	3.4	3.2
Propulsion System Maintenance ($/mile)	0.16	$0.16	0.18	$0.18	0.18	0.18	0.18	0.16
Facility Maintenance and Operation ($/mile)	0.18	$0.18	0.18	$0.18	0.23	0.20	0.18	0.18

Guidebook for Evaluating Fuel Choices for Post-2010 Transit Bus Procurements

Appendix B: Conversion of Tailpipe Emissions Units

Unit Conversions

As discussed in Section 2.3, it is sometimes necessary to convert emissions data from grams per brake-horsepower-hour (g/bhp-hr) to grams per mile (g/mi) in order to properly estimate vehicle lifecycle emissions. Unfortunately, the best way to do this is not with a single, fixed conversion factor. Rather, conversion factors vary by fuel type and type of emission. Furthermore, for all emissions types, the conversion factors increase with increasingly heavy-duty cycles. As a practical matter, this means that to convert engine emissions data (g/bhp-hr) to tailpipe emissions data (g/mi), an estimate of the in-use fuel economy is needed in addition to data from the engine test.

During engine certification tests, emissions are measured as g/bhp-hr along with the pounds of fuel consumed per unit of power (lb/bhp-hr), also referred to as the brake-specific fuel economy (BSFE). The preferred method for estimating tailpipe emissions from engine emissions is to calculate conversion factors as the fuel density (lb/gal) divided by the product of BSFC (lb/bhp-hr) and fuel economy (mi/gal). This yields conversion factor units of bhp-hr/mi, which, when multiplied by engine emissions (g/bhp-hr), yields tailpipe emissions as g/mi.[1] The equation for this is shown below:

$$ConversionFactor(bhp \cdot hr / mi) = \frac{FuelDensity(lb / gal)}{BSFC(lb / bhp \cdot hr) \times FuelEconomy(mi / gal)}$$

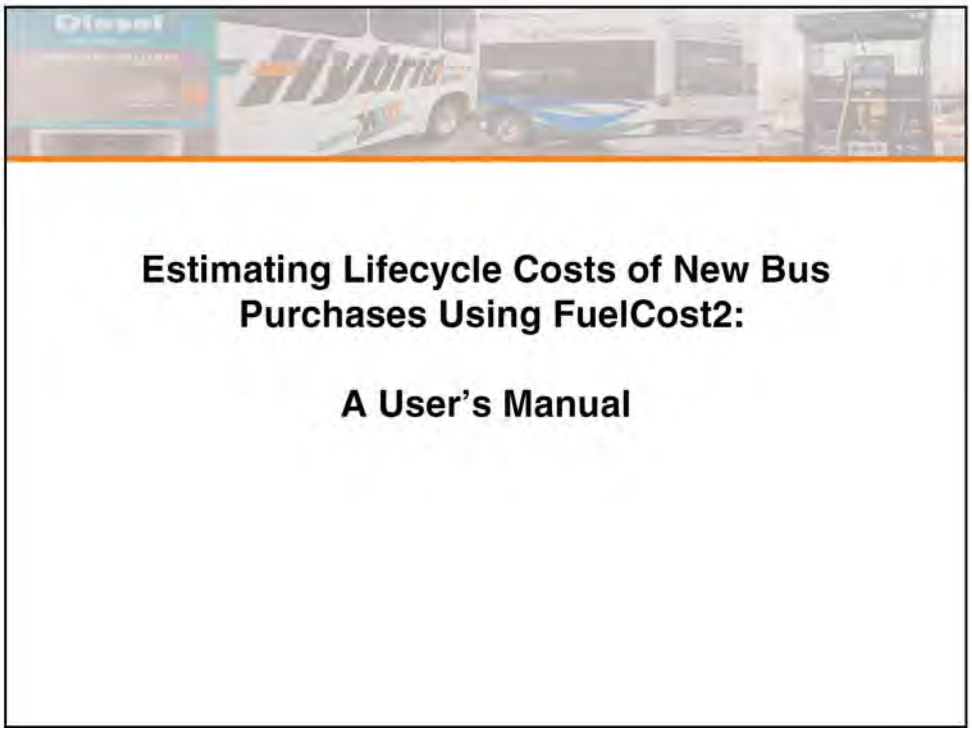
In the above equation, "Fuel Density" is from fuel-specific literature sources, and is also shown in the fuel properties table within the "Fuel Description" section of each fuel-specific chapter in this guide. "Fuel Economy" in the above equation should be based on an estimation of the user's own specific use, and BSFC can be based on EPA engine certification tests or other engine tests.

Be aware that reversing this process to estimate g/bhp-hr based on in-use g/mi measurements for the purpose of comparing in-use measurements to heavy-duty engine emission standards or to certification test results is essentially the same as taking light-duty vehicle in-use g/mi measurements and comparing them to standards or certification tests – in either case, the values are unlikely to be equivalent due to drive cycle differences and expected variation among the vehicles (or engines) of the same make and model regardless of drive cycle.

[1] U.S. Environmental Protection Agency, Air and Radiation (May 1998). *Update Heavy-Duty Engine Emission Conversion Factors for MOBILE6: Analysis of BSFCs and Calculation of Heavy-Duty Engine Emission Conversion Factors*. Retrieved from: http://www.epa.gov/otaq//models/mobile6/m6hde004.pdf

Appendix C: FuelCost2 User's Guide

This user's guide is for FuelCost2, the lifecycle spreadsheet tool that accompanies this Guidebook. The user's guide presented below is a compilation of slides presented at various workshops and webinars given to introduce FuelCost2.



Contents

2

- Introduction to TCRP C-19
- Basic Use of FuelCost2
- Advanced Use of FuelCost2
- Changes that Cause Critical Errors
- Changes for Other Vehicles
- Changing Technology Maturity Ranks

TCRP C-19

Objective

To assist in assessments of alternative fuel buses for 2010 and beyond by updating and expanding *TCRP Report 38* (1998)

- Guidebook
- Cost-model spreadsheet (*FuelCost*)

Fuels/ Powertrains

The Guide and Spreadsheet tool calculates lifecycle costs of 40-ft bus purchase options:

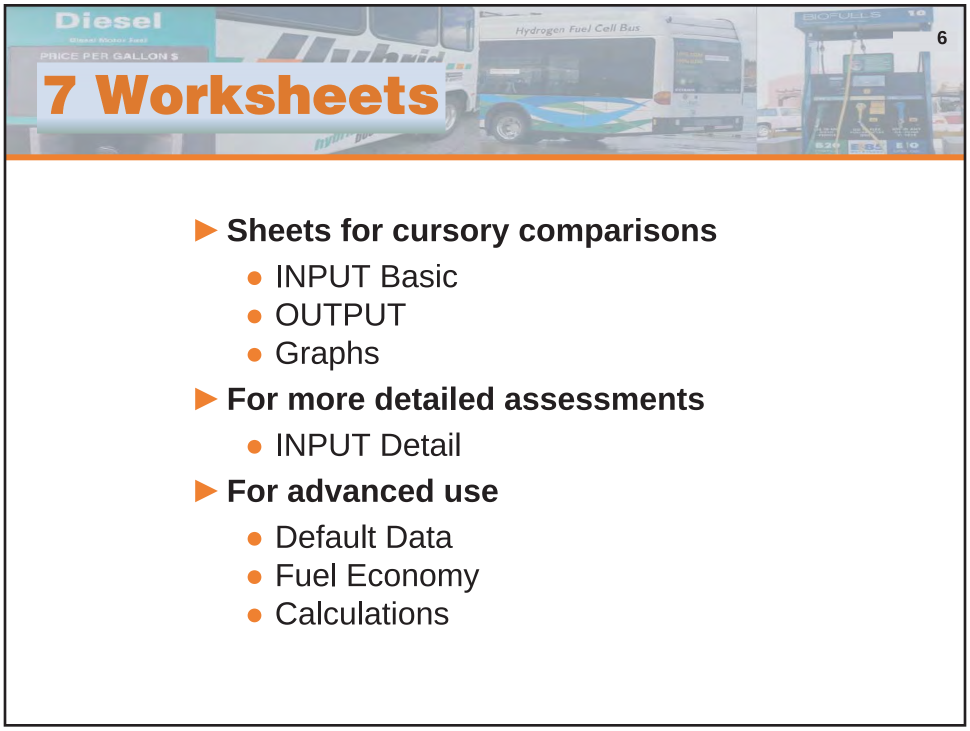
Fuels
- Diesel
- Biodiesel
- Gasoline
- Ethanol
- CNG
- LNG
- LPG
- DME
- Hydrogen

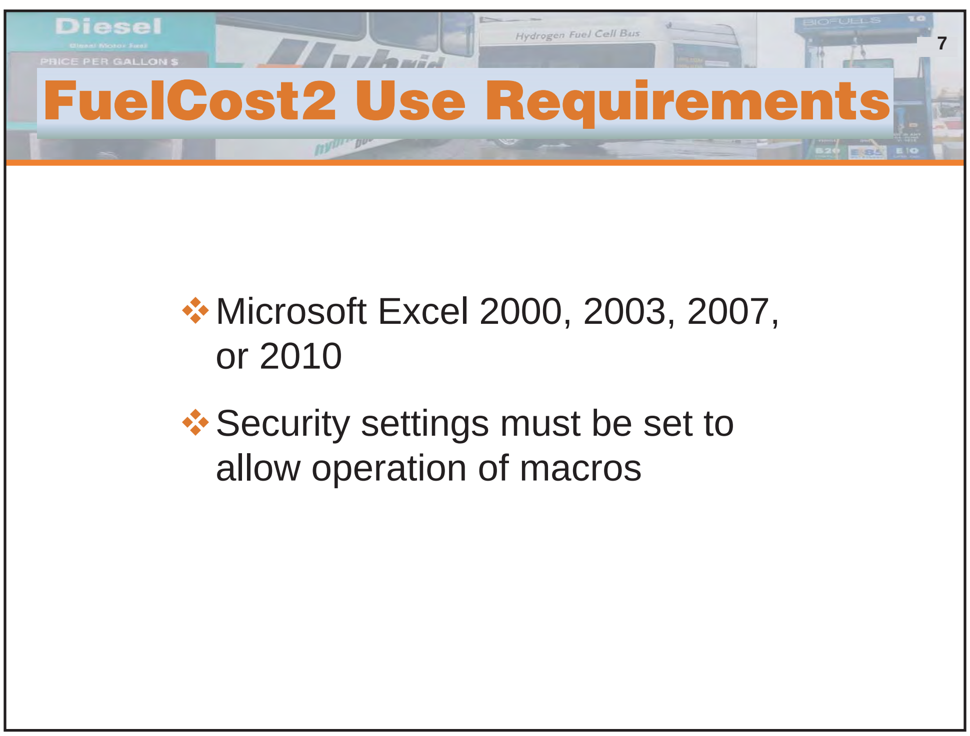
Powertrains
- Conventional
- Hybrid Electric
- All-Electric (battery)
- Catenary electric (trolleybus)
- Fuel Cells

5

The Model: FuelCost2

- **An Excel file**
- **Basic use is largely self-evident** – requires minimal Excel experience
- **More advanced applications possible** – requires moderate Excel experience


Diesel
PRICE PER GALLON $
Hydrogen Fuel Cell Bus
6
7 Worksheets
▶ Sheets for cursory comparisons
● INPUT Basic
● OUTPUT
● Graphs
▶ For more detailed assessments
● INPUT Detail
▶ For advanced use
● Default Data
● Fuel Economy
● Calculations

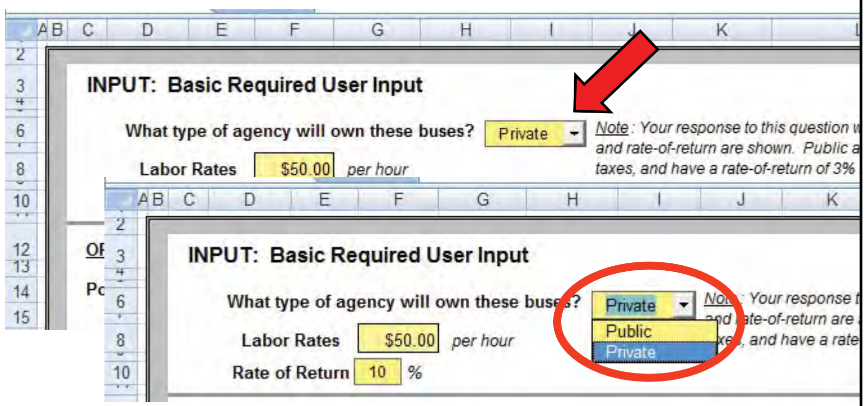

Diesel
PRICE PER GALLON $
Hydrogen Fuel Cell Bus
7
FuelCost2 Use Requirements
❖ Microsoft Excel 2000, 2003, 2007, or 2010
❖ Security settings must be set to allow operation of macros

8

Confirm if Macros are Enabled

1. Click on the “INPUT Basic” sheet (one of the tabs at the bottom of the screen)

2. Click the arrow to the right of the first question – if a drop-down box appears, macros are enabled, otherwise, you must change Excel’s security level.



9

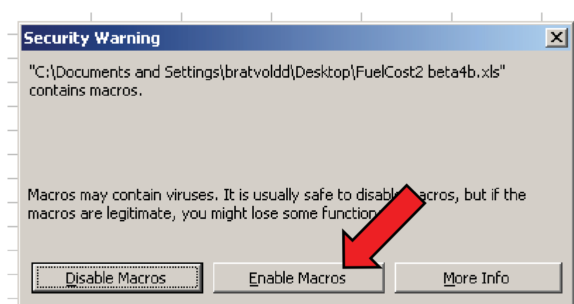
Excel Security Settings: Pre-2007

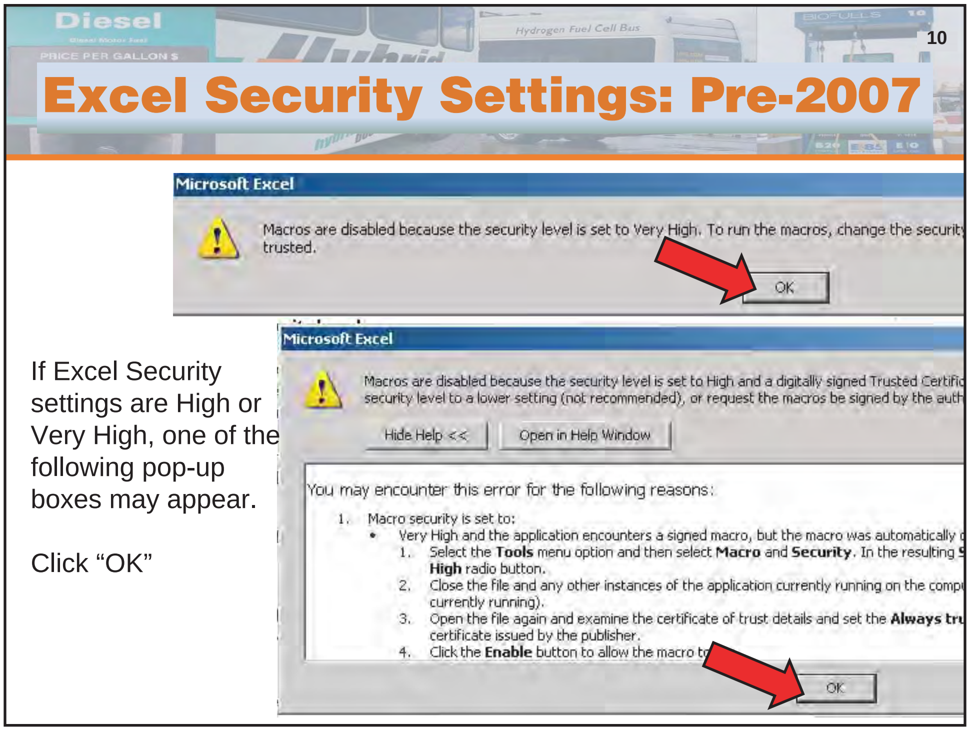
If the Excel Security settings are set to “Low”, there will be no security pop-up boxes, and macros will work.

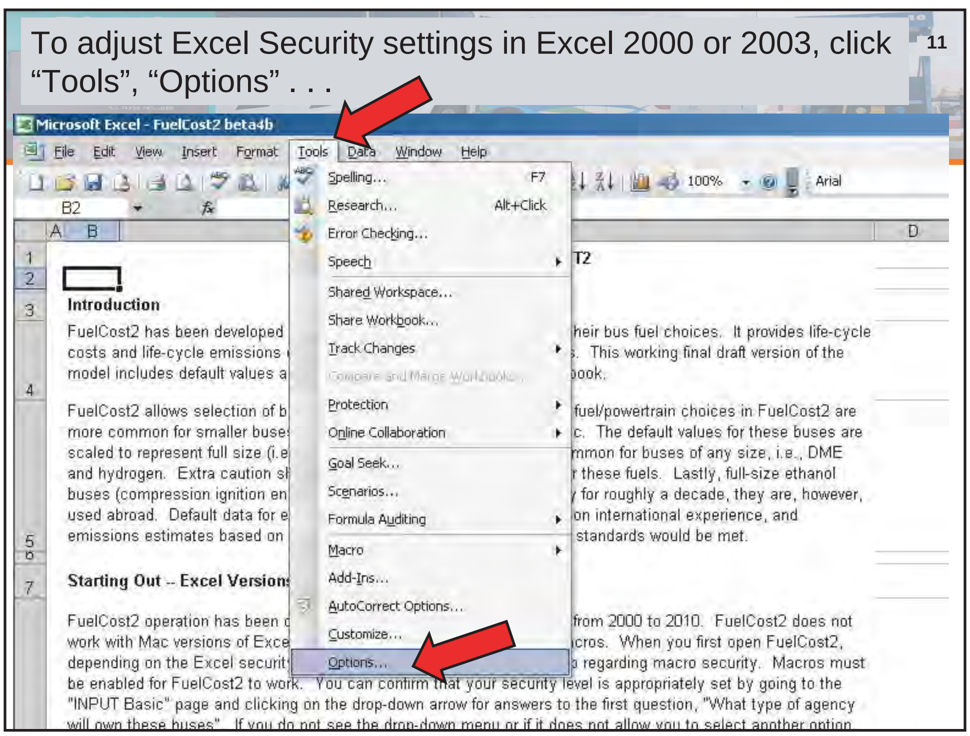
For some older versions of Excel, if the security level is extremely high, no security pop-up boxes may appear, and macros won’t work.

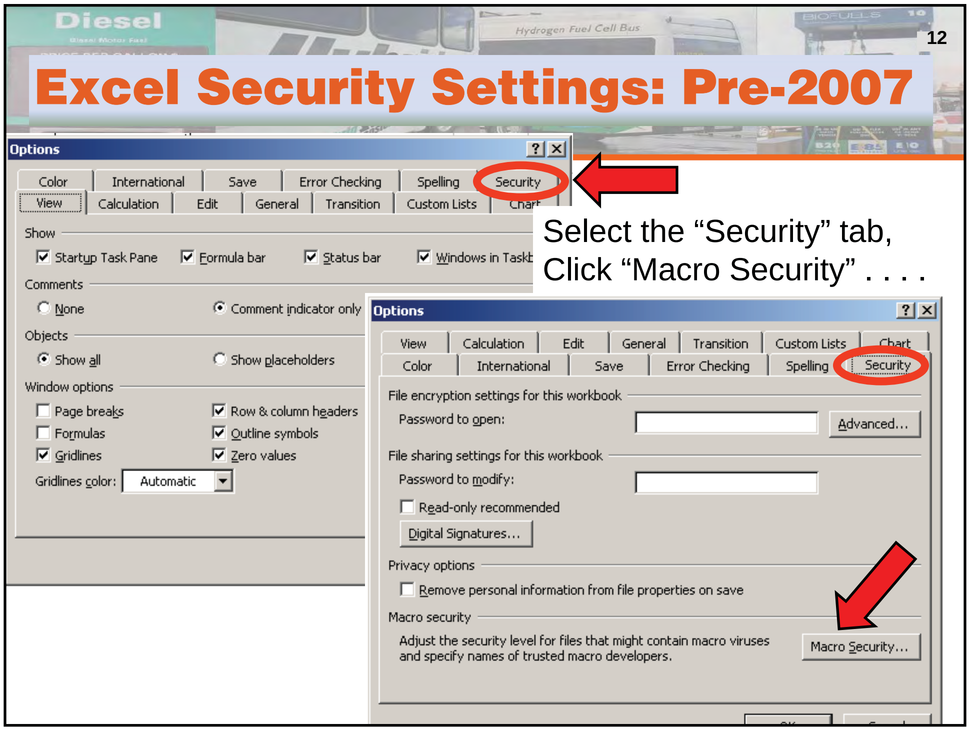
If Excel Security settings are Medium, the following pop-up boxes will appear:

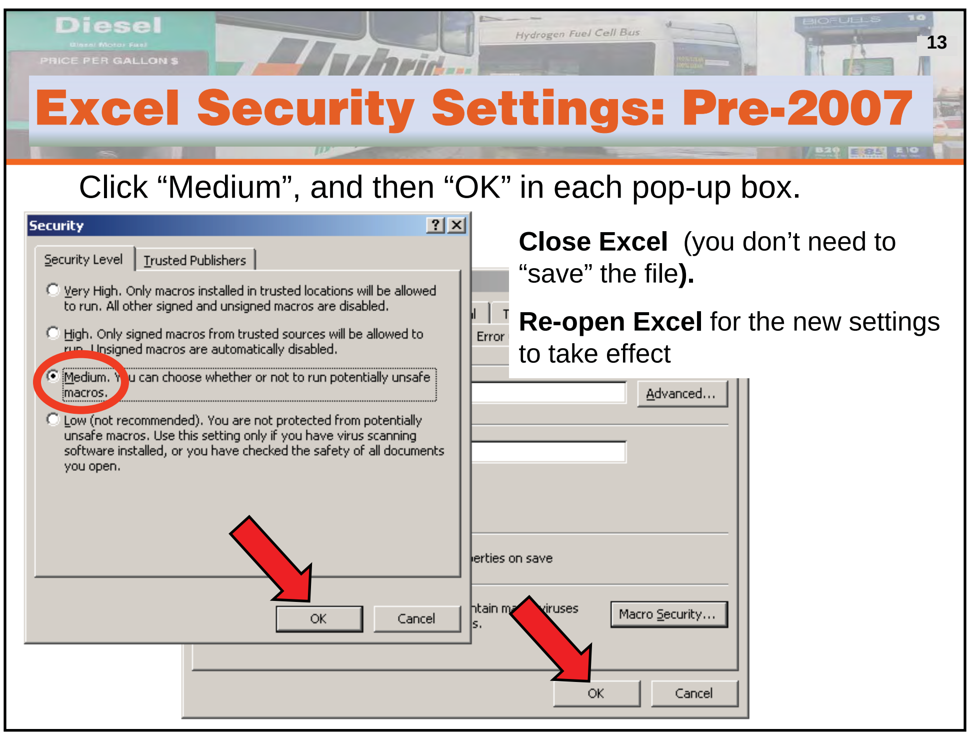
Click “Enable Macros”




10
Excel Security Settings: Pre-2007
Microsoft Excel
Macros are disabled because the security level is set to Very High. To run the macros, change the security
trusted.
OK
Microsoft Excel
Hide Help <<
Open in Help Window
You may encounter this error for the following reasons:
OK
If Excel Security settings are High or Very High, one of the following pop-up boxes may appear.
Click "OK"


11
To adjust Excel Security settings in Excel 2000 or 2003, click "Tools", "Options" . . .
Microsoft Excel - FuelCost2 beta4b
File Edit View Insert Format Tools Data Window Help
Spelling... F7
Research... Alt+Click
Error Checking...
Speech
Shared Workspace...
Share Workbook...
Track Changes
Protection
Online Collaboration
Goal Seek...
Scenarios...
Formula Auditing
Macro
Add-Ins...
AutoCorrect Options...
Customize...
Options...
Introduction
Starting Out -- Excel Version

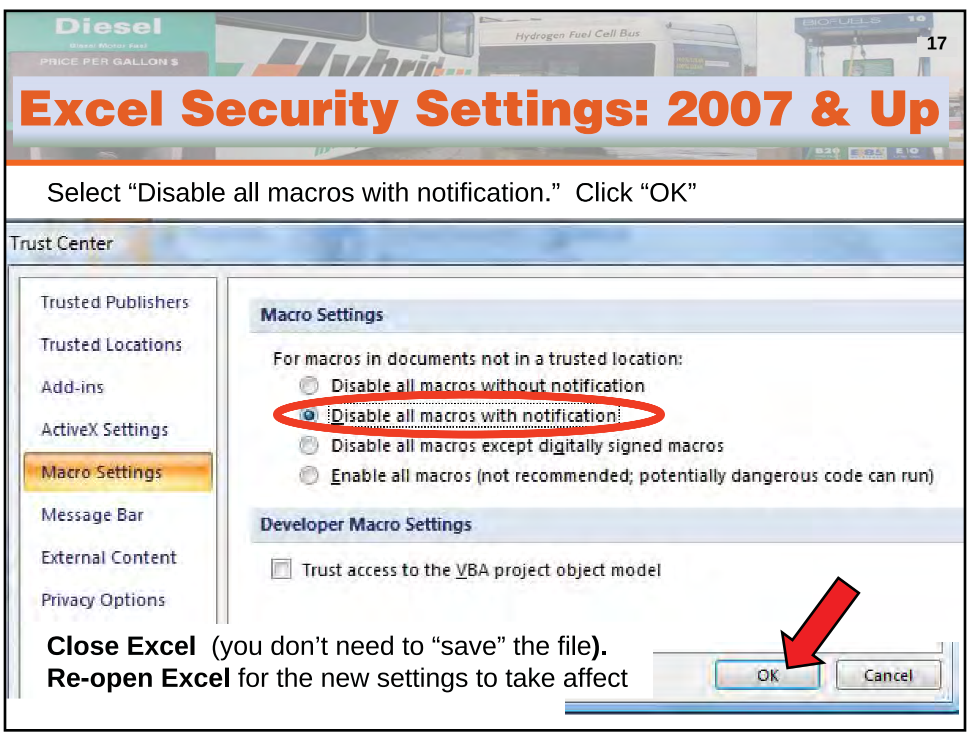

12
Excel Security Settings: Pre-2007
Select the "Security" tab,
Click "Macro Security" . . . .
Options
Color
International
Save
Error Checking
Spelling
Security
View
Calculation
Edit
General
Transition
Custom Lists
Chart
File encryption settings for this workbook
Password to open:
Advanced...
File sharing settings for this workbook
Password to modify:
Read-only recommended
Digital Signatures...
Privacy options
Remove personal information from file properties on save
Macro security
Adjust the security level for files that might contain macro viruses and specify names of trusted macro developers.
Macro Security...


13
Excel Security Settings: Pre-2007
Click "Medium", and then "OK" in each pop-up box.
Close Excel (you don't need to "save" the file).
Re-open Excel for the new settings to take effect
Security
Security Level
Trusted Publishers
Very High. Only macros installed in trusted locations will be allowed to run. All other signed and unsigned macros are disabled.
High. Only signed macros from trusted sources will be allowed to run. Unsigned macros are automatically disabled.
Low (not recommended). You are not protected from potentially unsafe macros. Use this setting only if you have virus scanning software installed, or you have checked the safety of all documents you open.
OK
Cancel
Advanced...
Macro Security...

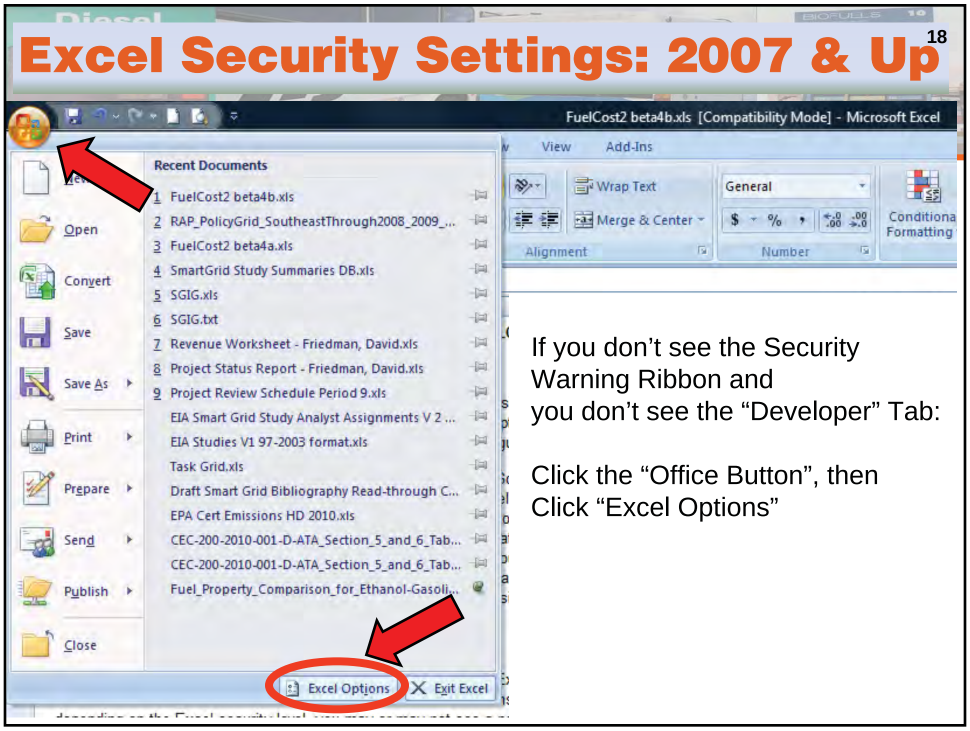

14
Excel Security Settings: 2007 & Up
FuelCost2 beta4b.xls [Compatibili
Home Insert Page Layout Formulas Data Review View Developer Add-Ins
Cut
Copy
Format Painter
Paste
Clipboard
Arial
10
Font
Wrap Text
Merge & Center
Alignment
General
Security Warning Some active content has been disabled. Options...
B2
INSTRUCTIONS FOR FUELCOST2
Introduction
FuelCost2 has been developed to assist transit operators in assessing their bus fuel choices. It provides lif
costs and life-cycle emissions of various bus fuel and powertrain options. This working final draft version of
model includes default values as described in the accompanying guidebook.
FuelCost2 allows selection of bus lenghts of 40 feet and 60 feet. Some fuel/powertrain choices in FuelCost
more common for smaller buses, i.e., gasoline, LPG, and battery electric. The default values for these buse

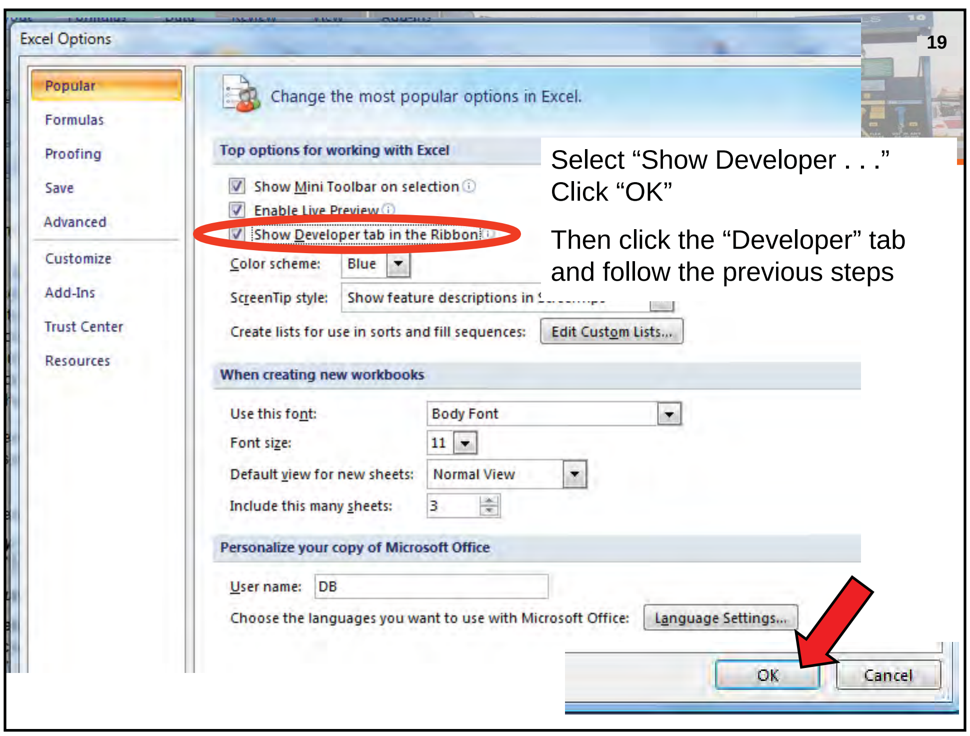

15
Excel Security Settings: 2007 & Up
Microsoft Office Security Options
Security Alert - Macros & ActiveX
Macros & ActiveX
Macros and one or more ActiveX controls have been disabled. This active content might contain viruses or other security hazards. Do not enable this content unless you trust the source of this file.
Warning: It is not possible to determine that this content came from a trustworthy source. You should leave this content disabled unless the content provides critical functionality and you trust its source.
More information
File Path: C:\Users\Owner\Desktop\FuelCost2 beta4b.xls
Help protect me from unknown content (recommended)
Enable this content
Open the Trust Center
OK
Cancel

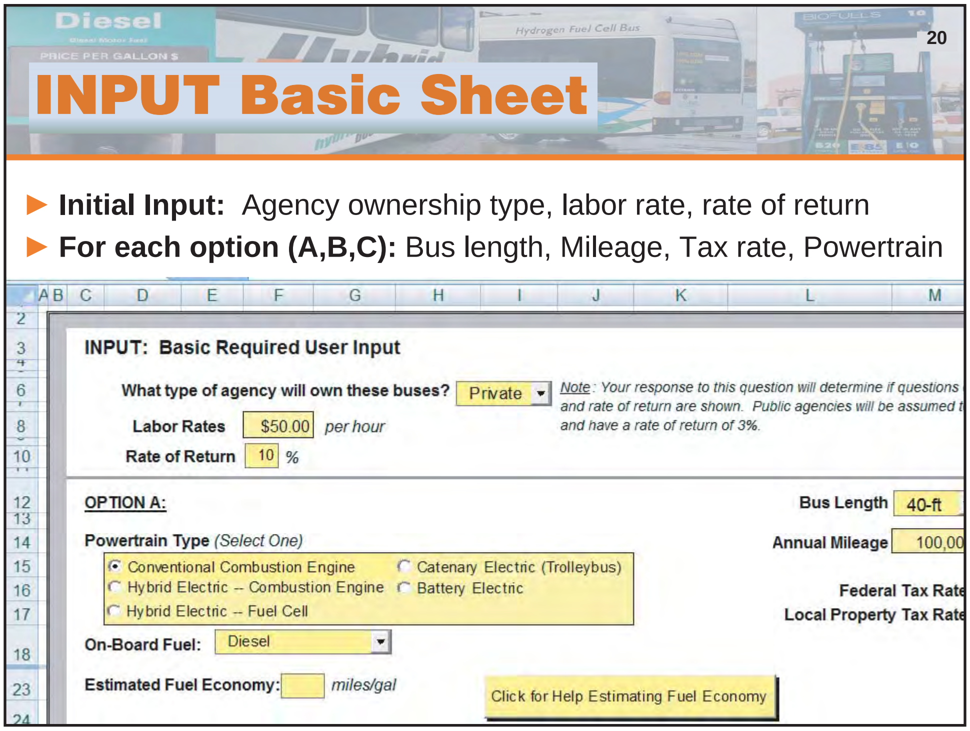

16
Excel Security Settings: 2007 & Up
If you don't see the "Security Warning" Ribbon, Click the "Developer Tab" Then click "Macro Security".
FuelCost2 beta4b.xls [Compatibility Mode] - Microsoft
Home
Insert
Page Layout
Formulas
Data
Review
View
Developer
Add-Ins
Record Macro
Use Relative References
Macro Security
Visual Basic
Macros
Code
Properties
View Code
Run Dialog
Insert
Design Mode
Controls
Source
Map Properties
Expansion Packs
Refresh Data
XML
B2
INSTRUCTIONS FOR FUELCOST2
Introduction
FuelCost2 has been developed to assist transit operators in assessing their bus fuel choices. It provides life-cycle costs and life-cycle emissions of various bus fuel and powertrain options. This working final draft version of the model includes default values as described in the accompanying guidebook.
FuelCost2 allows selection of bus lenghts of 40 feet and 60 feet. Some fuel/powertrain choices in FuelCost2 are more common for smaller buses, i.e., gasoline, LPG, and battery electric. The default values for these buses are scaled to represent full size (i.e., 40 foot) buses. Other fuels are not common for buses of any size, i.e., DME

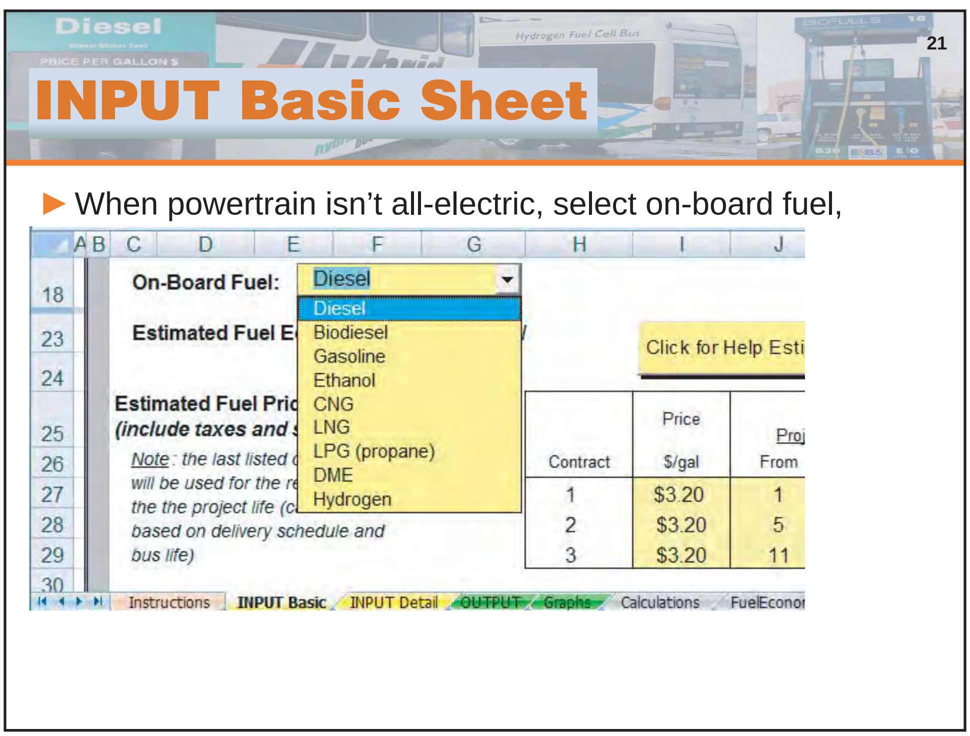

17
Excel Security Settings: 2007 & Up
Select "Disable all macros with notification." Click "OK"
Trust Center
Trusted Publishers
Trusted Locations
Add-ins
ActiveX Settings
Macro Settings
Message Bar
External Content
Privacy Options
Macro Settings
For macros in documents not in a trusted location:
Disable all macros without notification
Disable all macros with notification
Disable all macros except digitally signed macros
Enable all macros (not recommended; potentially dangerous code can run)
Developer Macro Settings
Trust access to the VBA project object model
Close Excel (you don't need to "save" the file).
Re-open Excel for the new settings to take affect
OK
Cancel

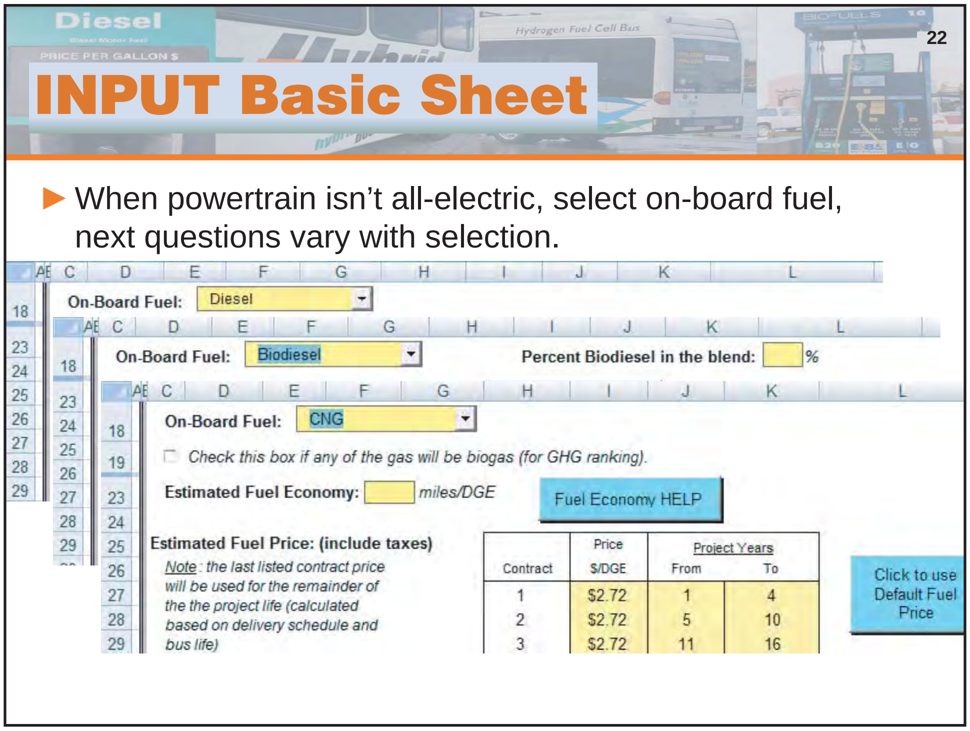
C-10 Guidebook for Evaluating Fuel Choices for Post-2010 Transit Bus Procurements

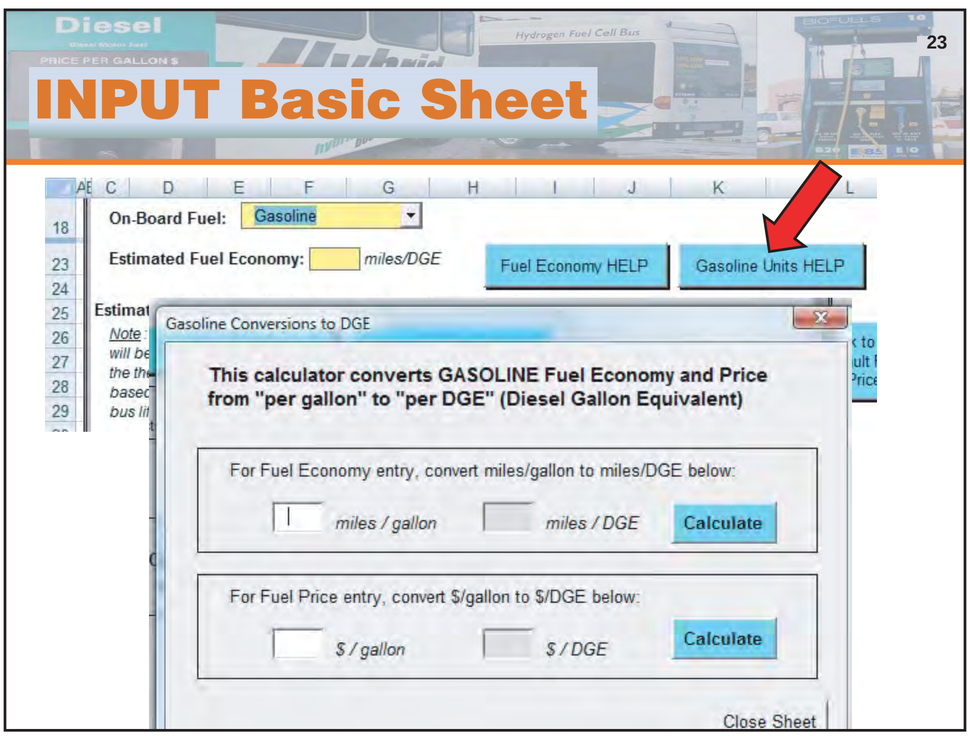


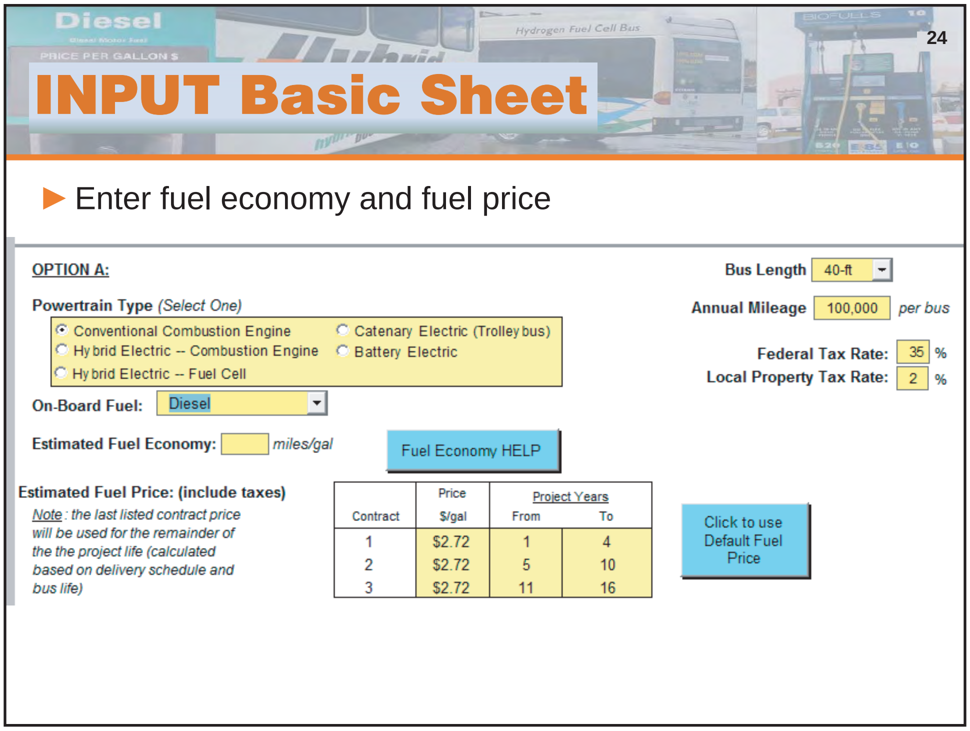


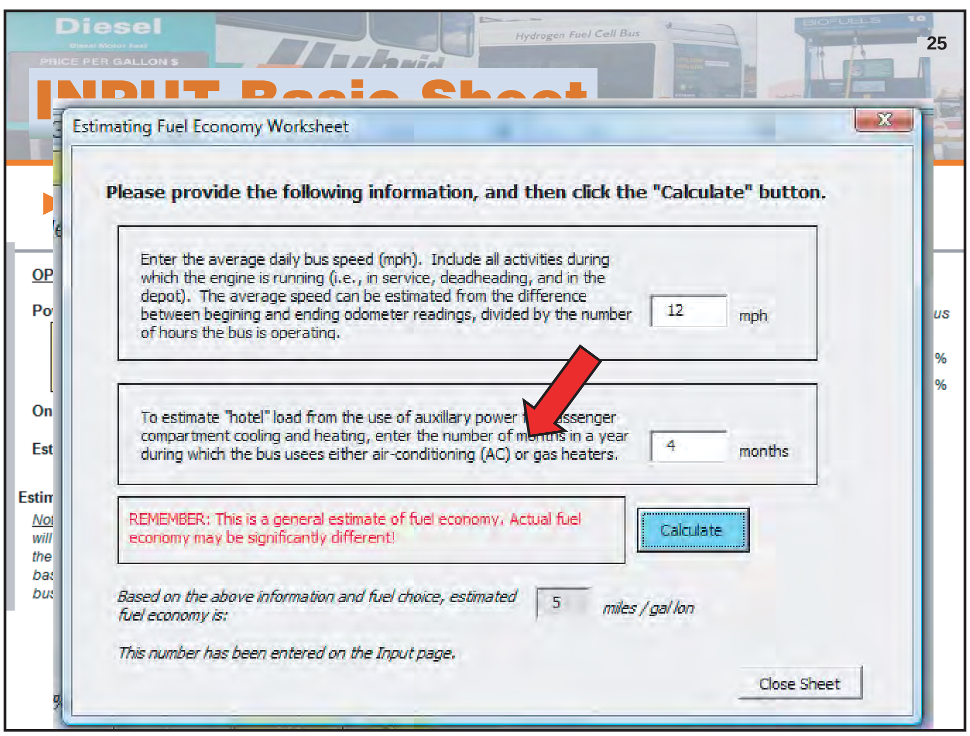

20
INPUT Basic Sheet
▶ Initial Input: Agency ownership type, labor rate, rate of return
▶ For each option (A,B,C): Bus length, Mileage, Tax rate, Powertrain
INPUT: Basic Required User Input
What type of agency will own these buses? Private
Note: Your response to this question will determine if questions
and rate of return are shown. Public agencies will be assumed t
and have a rate of return of 3%.
Labor Rates $50.00 per hour
Rate of Return 10 %
OPTION A:
Bus Length 40-ft
Powertrain Type (Select One)
Annual Mileage 100,00
Conventional Combustion Engine
Catenary Electric (Trolleybus)
Hybrid Electric -- Combustion Engine
Battery Electric
Hybrid Electric -- Fuel Cell
Federal Tax Rate
Local Property Tax Rate
On-Board Fuel: Diesel
Estimated Fuel Economy: miles/gal
Click for Help Estimating Fuel Economy

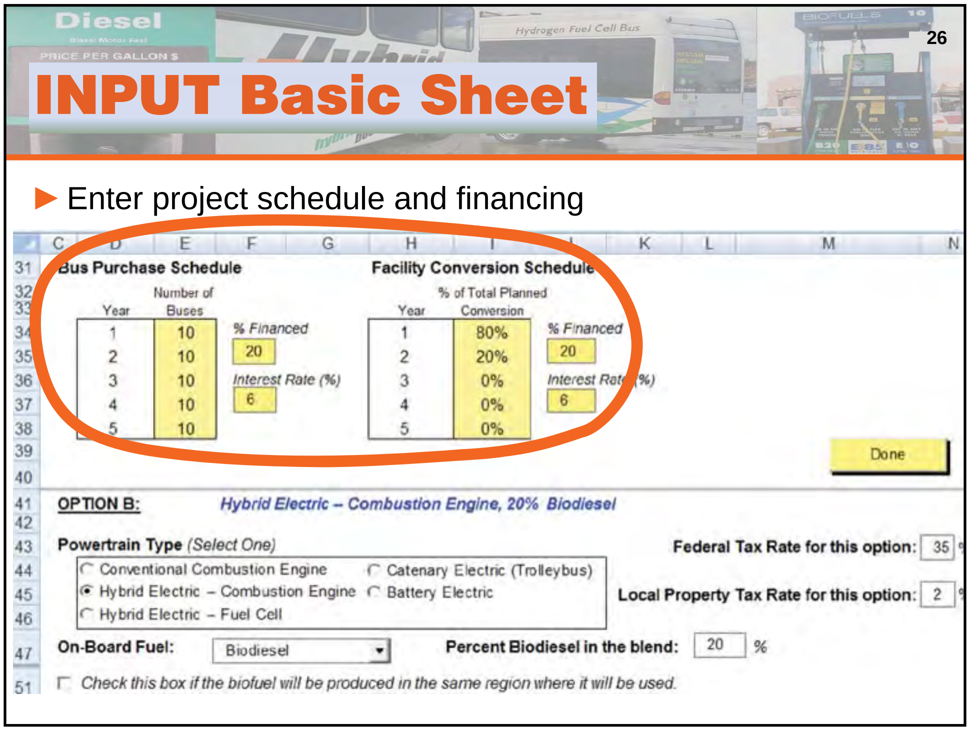

21
INPUT Basic Sheet
▶ When powertrain isn't all-electric, select on-board fuel,
On-Board Fuel: Diesel
Diesel
Biodiesel
Gasoline
Ethanol
CNG
LNG
LPG (propane)
DME
Hydrogen
Estimated Fuel E
Click for Help Esti
Estimated Fuel Pric
(include taxes and s
Note: the last listed
will be used for the re
the the project life (c
based on delivery schedule and
bus life)
Contract
Price $/gal
Proj From
1 $3.20 1
2 $3.20 5
3 $3.20 11
Instructions
INPUT Basic
INPUT Detail
OUTPUT
Graphs
Calculations

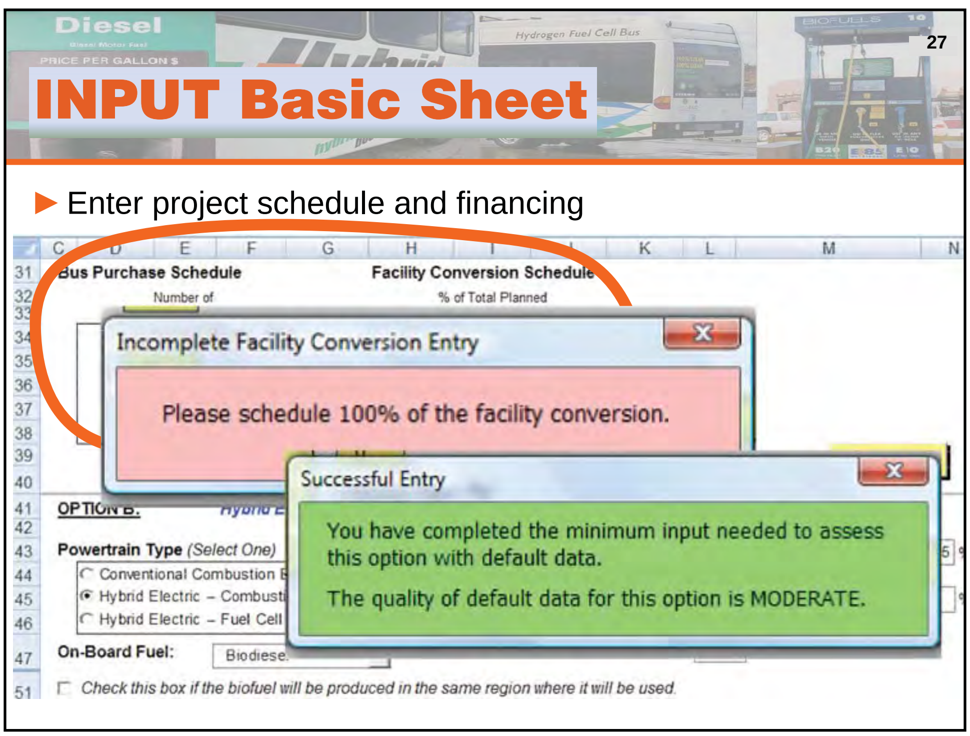

INPUT Basic Sheet
22
When powertrain isn't all-electric, select on-board fuel, next questions vary with selection.
On-Board Fuel: Diesel
On-Board Fuel: Biodiesel
Percent Biodiesel in the blend: %
On-Board Fuel: CNG
Check this box if any of the gas will be biogas (for GHG ranking).
Estimated Fuel Economy: miles/DGE
Fuel Economy HELP
Estimated Fuel Price: (include taxes)
Note: the last listed contract price will be used for the remainder of the the project life (calculated based on delivery schedule and bus life)
Contract | Price $/DGE | Project Years From | To
1 | $2.72 | 1 | 4
2 | $2.72 | 5 | 10
3 | $2.72 | 11 | 16
Click to use Default Fuel Price


INPUT Basic Sheet
23
On-Board Fuel: Gasoline
Estimated Fuel Economy: miles/DGE
Fuel Economy HELP
Gasoline Units HELP
Gasoline Conversions to DGE
This calculator converts GASOLINE Fuel Economy and Price from "per gallon" to "per DGE" (Diesel Gallon Equivalent)
For Fuel Economy entry, convert miles/gallon to miles/DGE below:
miles / gallon
miles / DGE
Calculate
For Fuel Price entry, convert $/gallon to $/DGE below:
$ / gallon
$ / DGE
Calculate
Close Sheet


24
INPUT Basic Sheet
Enter fuel economy and fuel price
OPTION A:
Powertrain Type (Select One)
Conventional Combustion Engine
Hybrid Electric -- Combustion Engine
Hybrid Electric -- Fuel Cell
Catenary Electric (Trolley bus)
Battery Electric
On-Board Fuel: Diesel
Estimated Fuel Economy: miles/gal
Fuel Economy HELP
Estimated Fuel Price: (include taxes)
Note: the last listed contract price will be used for the remainder of the the project life (calculated based on delivery schedule and bus life)
Contract | Price $/gal | Project Years From | To
1 | $2.72 | 1 | 4
2 | $2.72 | 5 | 10
3 | $2.72 | 11 | 16
Click to use Default Fuel Price
Bus Length 40-ft
Annual Mileage 100,000 per bus
Federal Tax Rate: 35 %
Local Property Tax Rate: 2 %


25
Estimating Fuel Economy Worksheet
Please provide the following information, and then click the "Calculate" button.
Enter the average daily bus speed (mph). Include all activities during which the engine is running (i.e., in service, deadheading, and in the depot). The average speed can be estimated from the difference between begining and ending odometer readings, divided by the number of hours the bus is operating.
12 mph
To estimate "hotel" load from the use of auxillary power passenger compartment cooling and heating, enter the number of months in a year during which the bus usees either air-conditioning (AC) or gas heaters.
4 months
REMEMBER: This is a general estimate of fuel economy. Actual fuel economy may be significantly different!
Calculate
Based on the above information and fuel choice, estimated fuel economy is:
5 miles / gal lon
This number has been entered on the Input page.
Close Sheet


26
INPUT Basic Sheet
Enter project schedule and financing
Bus Purchase Schedule
Year
Number of Buses
1 10
2 10
3 10
4 10
5 10
% Financed
20
Interest Rate (%)
6
Facility Conversion Schedule
Year
% of Total Planned Conversion
1 80%
2 20%
3 0%
4 0%
5 0%
% Financed
20
Interest Rate (%)
6
Done
OPTION B:
Hybrid Electric – Combustion Engine, 20% Biodiesel
Powertrain Type (Select One)
Conventional Combustion Engine
Catenary Electric (Trolleybus)
Hybrid Electric – Combustion Engine
Battery Electric
Hybrid Electric – Fuel Cell
Federal Tax Rate for this option: 35
Local Property Tax Rate for this option: 2
On-Board Fuel: Biodiesel
Percent Biodiesel in the blend: 20 %
Check this box if the biofuel will be produced in the same region where it will be used.


27
INPUT Basic Sheet
Enter project schedule and financing
Bus Purchase Schedule
Facility Conversion Schedule
Incomplete Facility Conversion Entry
Please schedule 100% of the facility conversion.
Successful Entry
You have completed the minimum input needed to assess this option with default data.
The quality of default data for this option is MODERATE.
Powertrain Type (Select One)
On-Board Fuel:
Check this box if the biofuel will be produced in the same region where it will be used.

28

After Entering Basic input

- View cursory comparisons (up to 3 options)
  - Lifecycle costs
  - Lifecycle emissions
- Based on use default data
  - **Key Limitation!** *Default data is rarely good for a specific project.*
- Provides a ***starting point*** for comparisons

For higher-level analyses, use “INPUT Detail” sheet

29

INPUT Detail

- Default data provided for each selected option

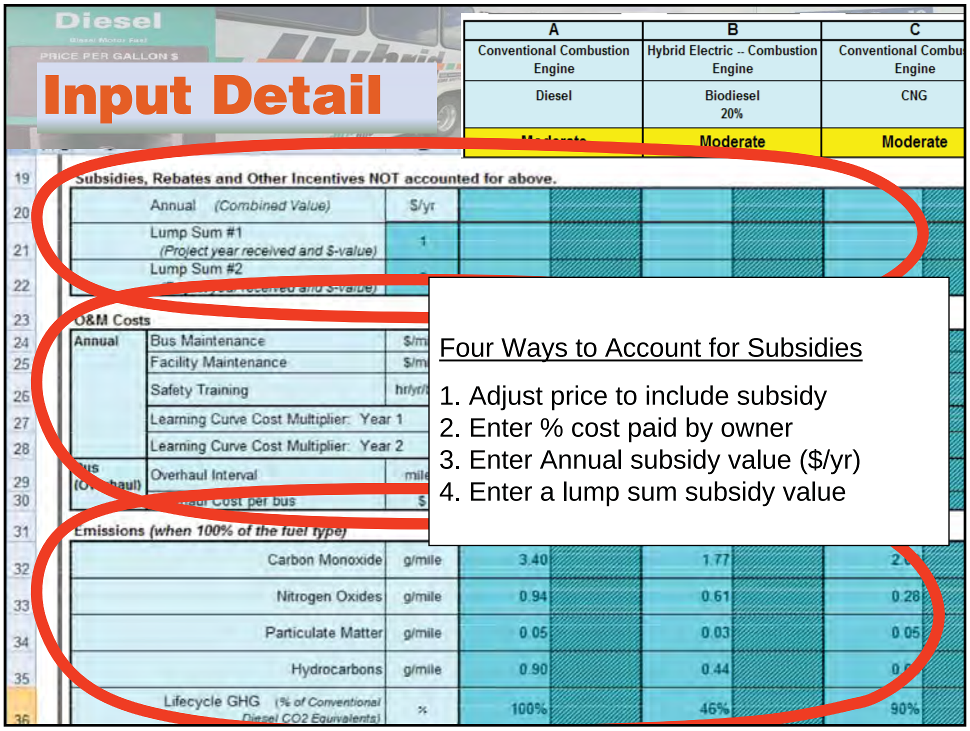
NOTE: No entry is required on this page when the default values are acceptable.
User-entered data will be lost when the option's "Reset" button or "Done" button (on INPUT Basic) is clicked.

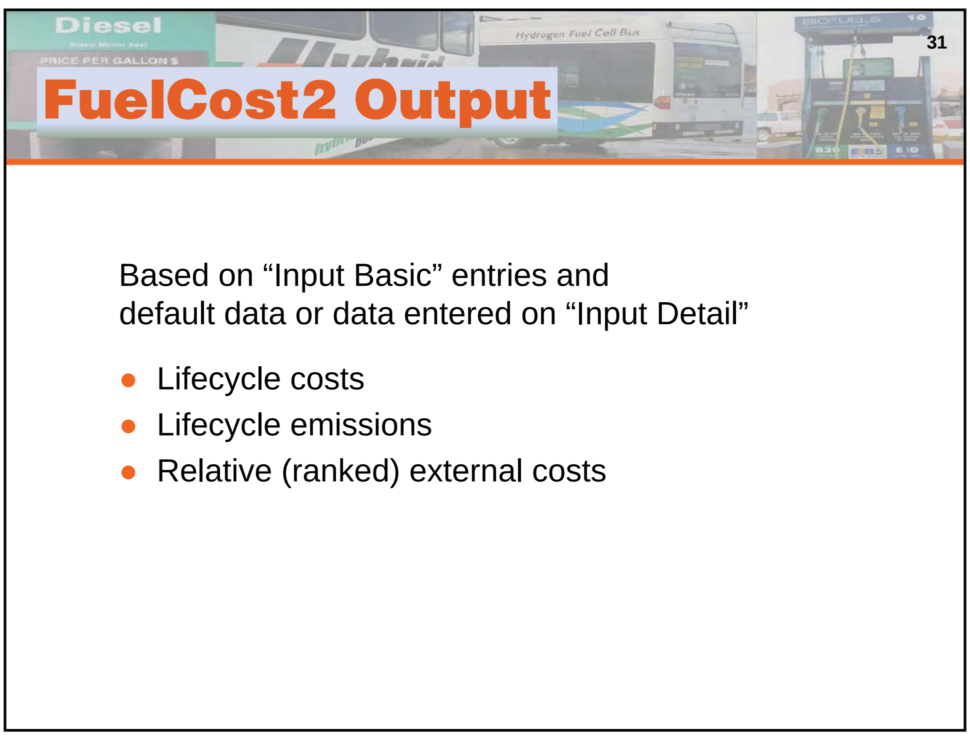
ILED INPUT

ells turn WHITE when edited by the user.

Reset Option A | Reset Option B | Reset Option C

		A		B		C	
Powertrain:		Conventional Combustion Engine		Hybrid Electric -- Combustion Engine		Conventional Combustion Engine	
Fuel:		Diesel		Biodiesel 20%		CNG	
Default Data Quality:		Moderate		Moderate		Moderate	
AL Costs		Cost	% cost paid by purchaser	Cost	% cost paid by purchaser	Cost	% cost paid b purchaser
New Vehicle	$/bus	$ 320,000	20%	$ 384,000	20%	$ 360,000	10%
Converted Vehicle	$/bus	NA	100%	NA	100%	NA	100%
Extended Warranty	$/bus	$ 6,600	100%	$ 7,920	100%	$ 7,425	100%
Depot & Fueling Conversion	$	NA	100%	$ 5,500	100%	$ 1,750,000	100%

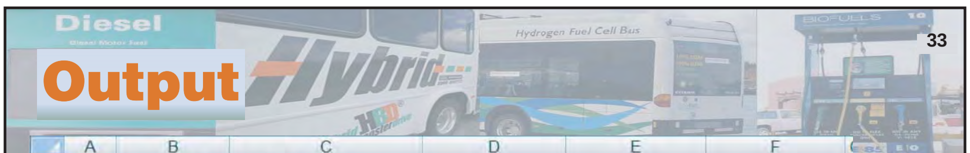

Input Detail
A
Conventional Combustion Engine
Diesel
Moderate
B
Hybrid Electric -- Combustion Engine
Biodiesel 20%
Moderate
C
Conventional Combu Engine
CNG
Moderate
Subsidies, Rebates and Other Incentives NOT accounted for above.
Annual (Combined Value) $/yr
Lump Sum #1 (Project year received and $-value)
Lump Sum #2
O&M Costs
Annual
Bus Maintenance
Facility Maintenance
Safety Training
Learning Curve Cost Multiplier: Year 1
Learning Curve Cost Multiplier: Year 2
Overhaul Interval
Emissions (when 100% of the fuel type)
Carbon Monoxide g/mile 3.40 1.77
Nitrogen Oxides g/mile 0.94 0.61 0.28
Particulate Matter g/mile 0.05 0.03 0.05
Hydrocarbons g/mile 0.90 0.44
Lifecycle GHG (% of Conventional Diesel CO2 Equivalents) % 100% 46% 90%
Four Ways to Account for Subsidies
1. Adjust price to include subsidy
2. Enter % cost paid by owner
3. Enter Annual subsidy value ($/yr)
4. Enter a lump sum subsidy value


FuelCost2 Output
31
Based on "Input Basic" entries and
default data or data entered on "Input Detail"
• Lifecycle costs
• Lifecycle emissions
• Relative (ranked) external costs

Project Life-Cycle Results

SUMMARY

		A	B	C
		Conventional Combustion Engine, Diesel	Hybrid Electric -- Combustion Engine, Biodiesel 20%	Conventional Combustion Engine, CNG
Costs	**Total Cash Outflow**			
	Current $	$ 96,094,327	$ 97,481,145	$ 68,419,000
	Present Value *(10% Rate of Return)*	$ 47,135,172	$ 47,936,241	$ 32,776,376
	Capital Costs			
	Year 1	$1,412,000	$1,702,800	$2,268,500
	Year 2	$1,412,000	$1,696,500	$1,218,500
	Year 3	$0	$0	$0
	Year 4	$0	$0	$0
	Year 5	$0	$0	$0
	Total *(Current $)*	$ 2,824,000	$ 3,399,300	$ 3,487,000
	Other Costs & Offsets *(Total project life)*			
	Interest Payments	$ 90,350	$ 109,510	$ 237,203
	Fuel	$ 72,000,000	$ 68,327,403	$ 46,829,268
	Other O&M	$ 22,200,000	$ 26,873,016	$ 19,169,000
	Tax Deductions ($ value)	$ (1,020,022)	$ (1,228,083)	$ (1,303,471)
	Subsidies/ Rebates	$ -	$ -	$ -
	Total *(Current $)*	$ 93,270,327	$ 94,081,845	$ 64,932,000



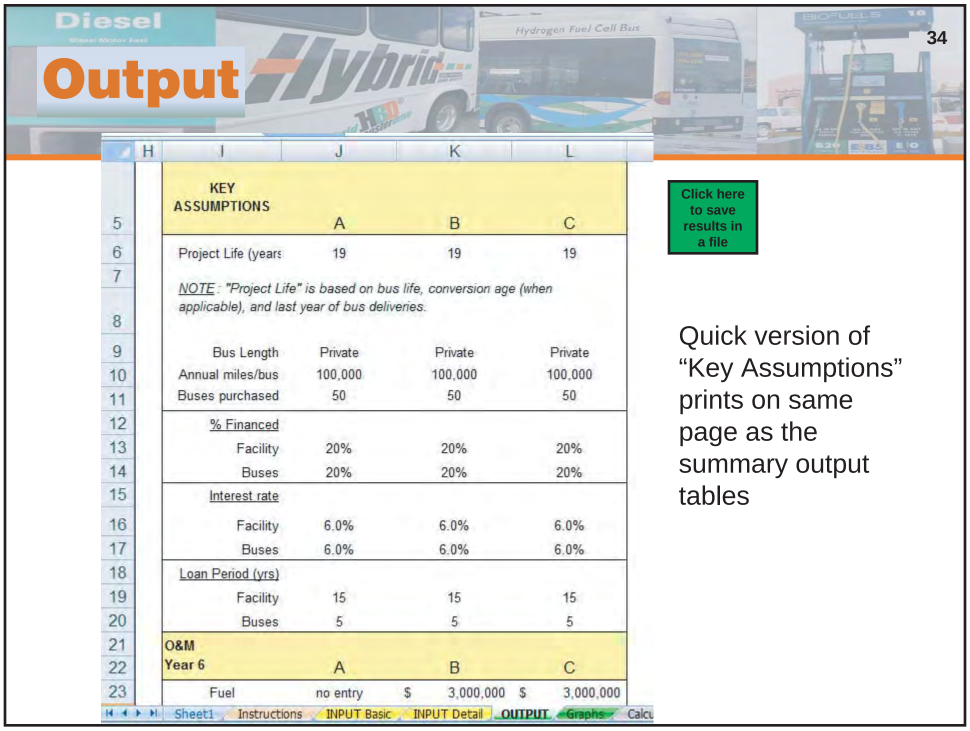
Project Life-Cycle Results

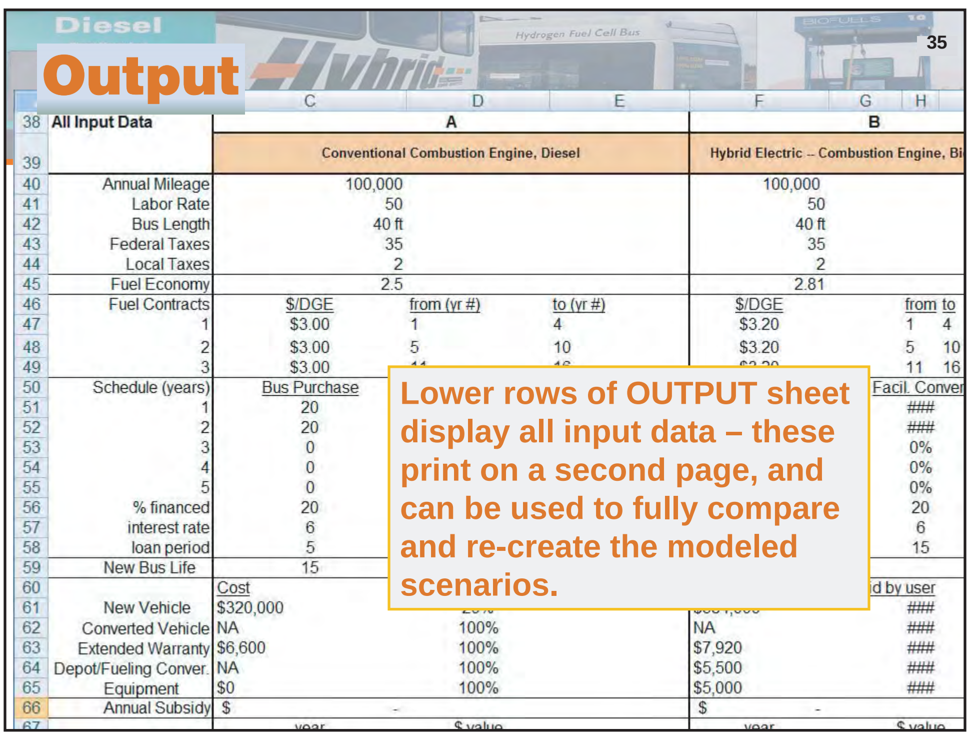
SUMMARY

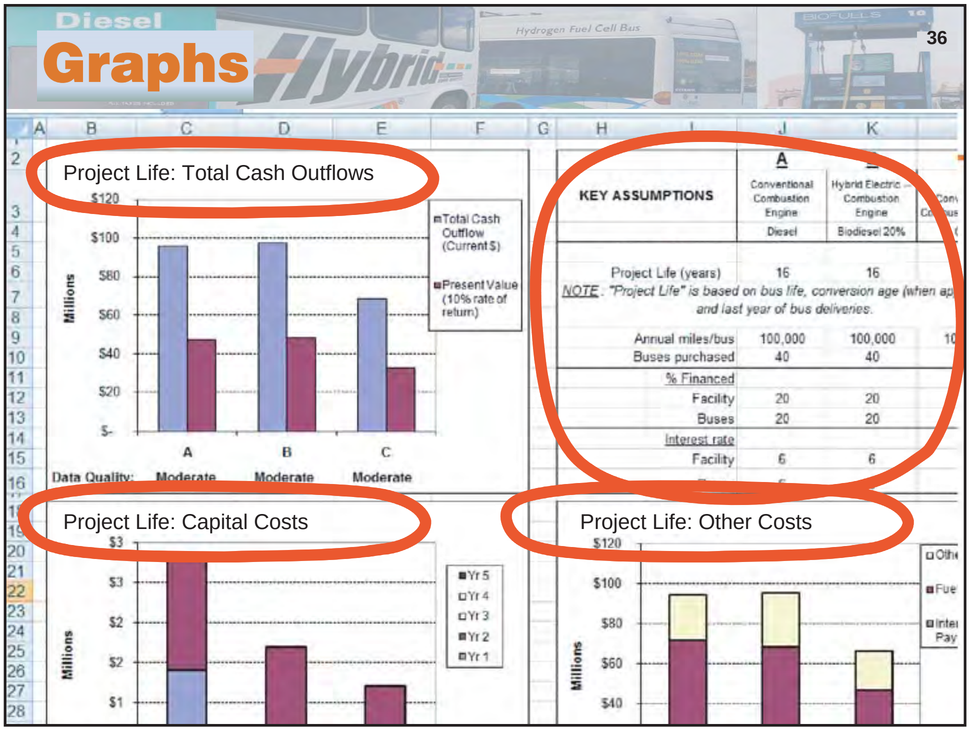
		A	B	C
		Conventional Combustion Engine, Diesel	Hybrid Electric -- Combustion Engine, Biodiesel 20%	Conventional Combustion Engine, CNG
Emissions (Metric tons)	Carbon Monoxide	204.000	106.080	129.920
	Nitrogen Oxides	56.148	36.496	17.967
	Particulate Matter	2.807	1.825	2.995
	Hydrocarbons	54.000	26.325	2.995

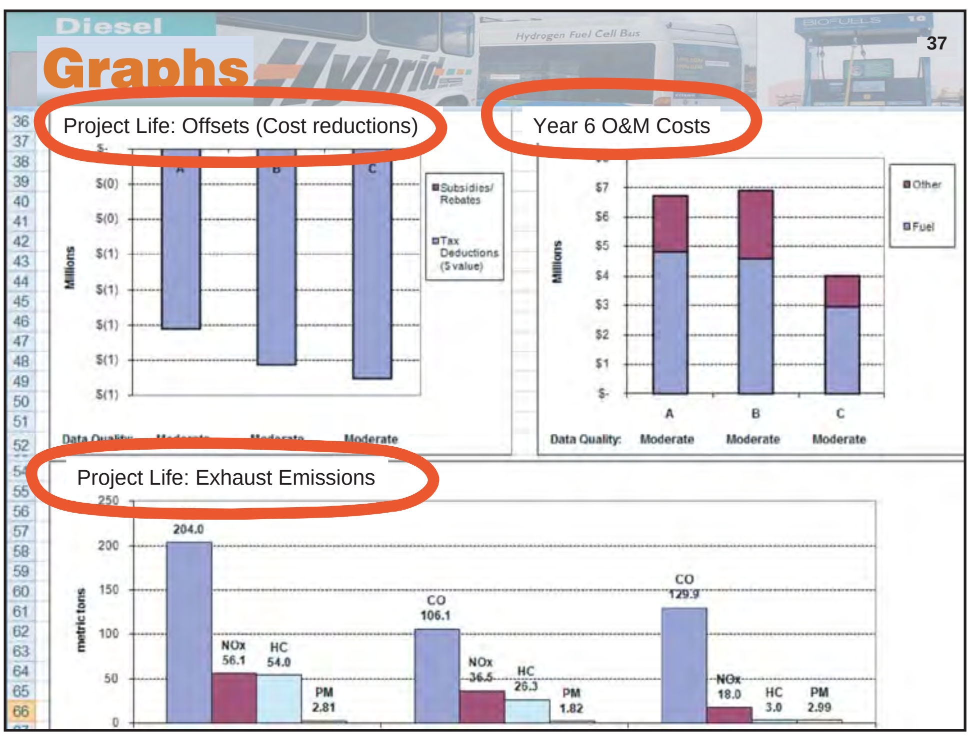
Indirect (External) Costs: Ordered List of Selected Options

	Technology Maturity	Regional Economy	GHG Emissions	NOx Emissions	P Emis
Lowest Indirect Costs	A, C		C	C	E
⬇	B	A, B, C	A	B	A
Highest Indirect Costs			B	A	C


Output
34
KEY ASSUMPTIONS
A B C
Project Life (years 19 19 19
NOTE: "Project Life" is based on bus life, conversion age (when applicable), and last year of bus deliveries.
Bus Length Private Private Private
Annual miles/bus 100,000 100,000 100,000
Buses purchased 50 50 50
% Financed
Facility 20% 20% 20%
Buses 20% 20% 20%
Interest rate
Facility 6.0% 6.0% 6.0%
Buses 6.0% 6.0% 6.0%
Loan Period (yrs)
Facility 15 15 15
Buses 5 5 5
O&M Year 6
Fuel no entry $ 3,000,000 $ 3,000,000
Sheet1 Instructions INPUT Basic INPUT Detail OUTPUT Graphs
Click here to save results in a file
Quick version of "Key Assumptions" prints on same page as the summary output tables


Output
35
All Input Data
A
B
Conventional Combustion Engine, Diesel
Annual Mileage 100,000 100,000
Labor Rate 50 50
Bus Length 40 ft 40 ft
Federal Taxes 35 35
Local Taxes 2 2
Fuel Economy 2.5 2.81
Fuel Contracts $/DGE from (yr #) to (yr #)
1 $3.00 1 4 $3.20 1 4
2 $3.00 5 10 $3.20 5 10
3 $3.00
Schedule (years) Bus Purchase
1 20
2 20
3 0
4 0
5 0
% financed 20
interest rate 6
loan period 5
New Bus Life 15
Cost
New Vehicle $320,000
Converted Vehicle NA 100% NA
Extended Warranty $6,600 100% $7,920
Depot/Fueling Conver. NA 100% $5,500
Equipment $0 100% $5,000
Annual Subsidy $ - $ -
Lower rows of OUTPUT sheet display all input data – these print on a second page, and can be used to fully compare and re-create the modeled scenarios.


36
Graphs
Project Life: Total Cash Outflows
Project Life: Capital Costs
Project Life: Other Costs
KEY ASSUMPTIONS
Project Life (years) 16 16
Annual miles/bus 100,000 100,000
Buses purchased 40 40


37
Graphs
Project Life: Offsets (Cost reductions)
Year 6 O&M Costs
Project Life: Exhaust Emissions

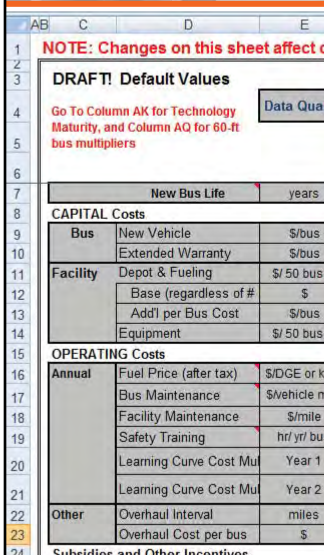
38

Advanced Use of FuelCost2

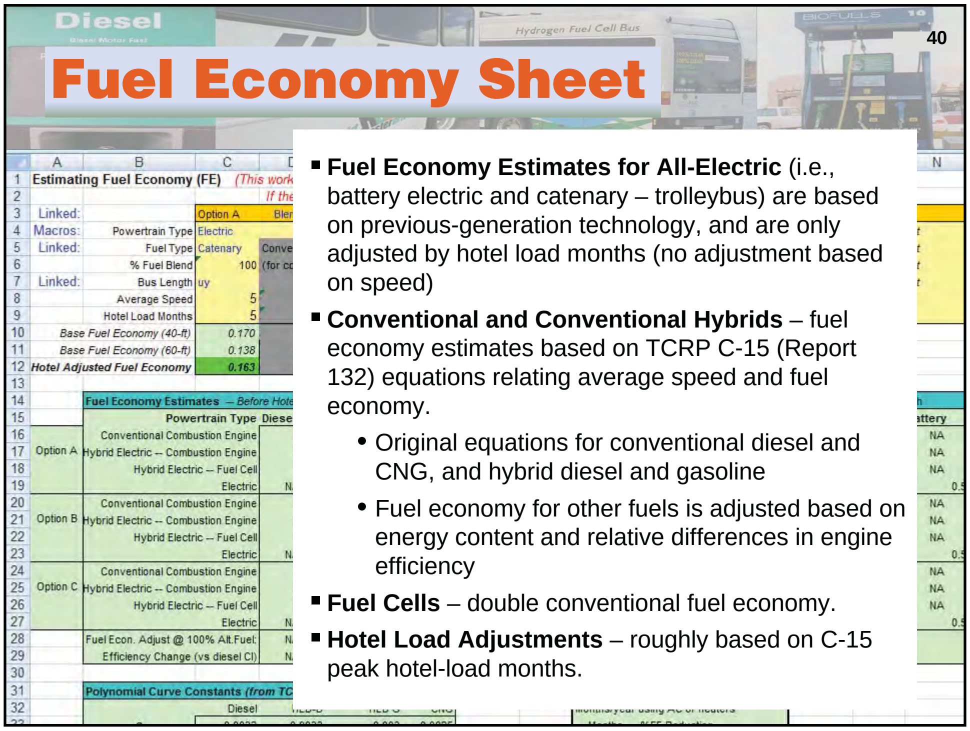
- **Sheets that allow greater tailoring**
  - Default Data
  - Calculations
  - Fuel Economy
- **Password-protected sheets to prevent accidental changes**
- **The password is "test"**

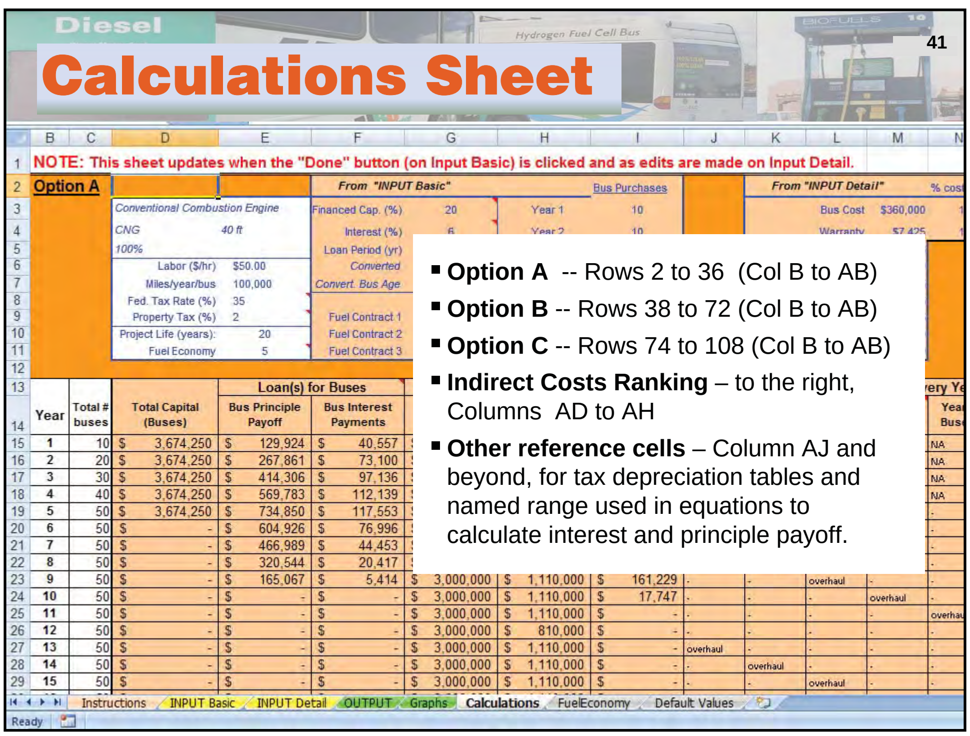
39

Default Data Sheet



- **Row Headers (Column D)** – must include cells with identical headers to "Input Detail", Column D. *(Extra Default Values row headers are okay)*
- **Column Headers (Rows 5 and 6)** – must contain the same text values as shown for powertrain and fuel choices on "INPUT Basic". *(Extra Default Values Column headers are okay)*
- **Data Quality (Row 4)** – conditional formating, for "Moderate" and "Limited".
- **Facility Capital Costs** – The $/50 buses (Row 11) is the same units shown in the Guidebook. Rows 12 and 13 are used by a macro to calculate costs based on the total number of scheduled bus purchases (on "Input Basic")
- **Tech Maturity Rankings and 60-ft bus multipliers** – in the far right columns


40
Fuel Economy Sheet
Fuel Economy Estimates for All-Electric (i.e., battery electric and catenary – trolleybus) are based on previous-generation technology, and are only adjusted by hotel load months (no adjustment based on speed)
Conventional and Conventional Hybrids – fuel economy estimates based on TCRP C-15 (Report 132) equations relating average speed and fuel economy.
Original equations for conventional diesel and CNG, and hybrid diesel and gasoline
Fuel economy for other fuels is adjusted based on energy content and relative differences in engine efficiency
Fuel Cells – double conventional fuel economy.
Hotel Load Adjustments – roughly based on C-15 peak hotel-load months.


41
Calculations Sheet
NOTE: This sheet updates when the "Done" button (on Input Basic) is clicked and as edits are made on Input Detail.
Option A -- Rows 2 to 36 (Col B to AB)
Option B -- Rows 38 to 72 (Col B to AB)
Option C -- Rows 74 to 108 (Col B to AB)
Indirect Costs Ranking – to the right, Columns AD to AH
Other reference cells – Column AJ and beyond, for tax depreciation tables and named range used in equations to calculate interest and principle payoff.

42

Changes that Cause Critical Errors

- **Array equations on the "Calculations" sheet**
  - Array equations have outer curly brackets { }
  - If you click on an array cell as for editing the contents, you must exit the cell by either:
    - Press "Esc", or
    - pressing together: "Ctrl", "Shift", "Enter" (this key combination tells Excel this is an "array" and { } is automatically added.)
  - If you just press "Enter", the { } will be lost, and the equation will no longer work as an array
  - If you press "Enter" accidentally, you can click "Undo"

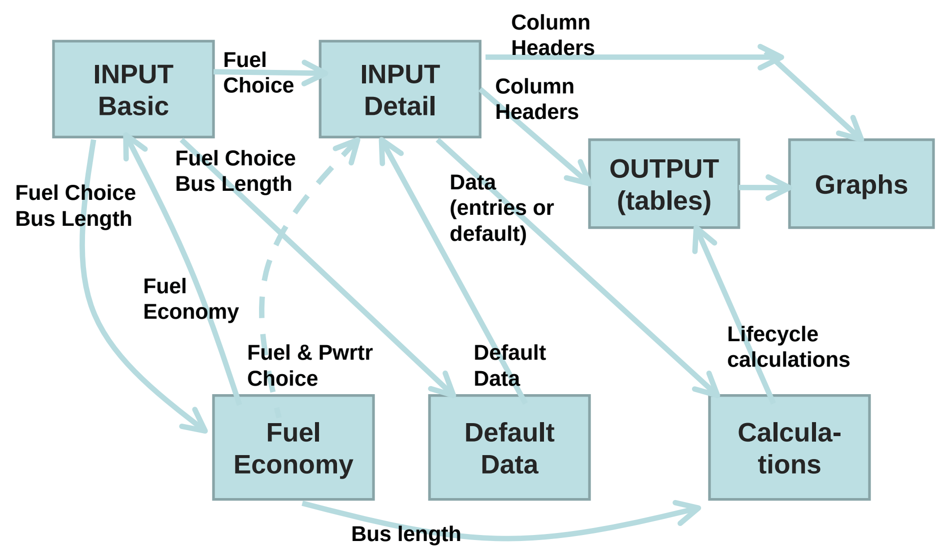
43

Changes that Cause Critical Errors

- **Row and Column Headers on "INPUT Detail" and "Default Values"**
  - Must be the same header text for the macro to properly fill "INPUT Detail"
  - Don't need to be in the same order (the macro uses a "Find" method)
- **Default Values, Row 3**
  - Combines powertrain and fuel (written in white text)
  - Used by the macro to fill in INPUT Detail data

44

Worksheet Flow



45

Changes for Other Vehicles

1. **INPUT Basic Sheet** – change the drop-down choices for Bus Length
2. **Default Values – Two Approaches:**
   - ***Easier*** -- Use a multiplier to convert 40-ft bus data (as is done for 60-ft buses), or
   - ***Harder*** -- Change all data that are affected by bus length to represent new length – this changes the “standard” vehicle shown on Default Data sheet *(currently 40-ft bus)*.
3. **Fuel Economy Sheet** – change equations if you will be using the fuel economy “Help” button on Input Basic

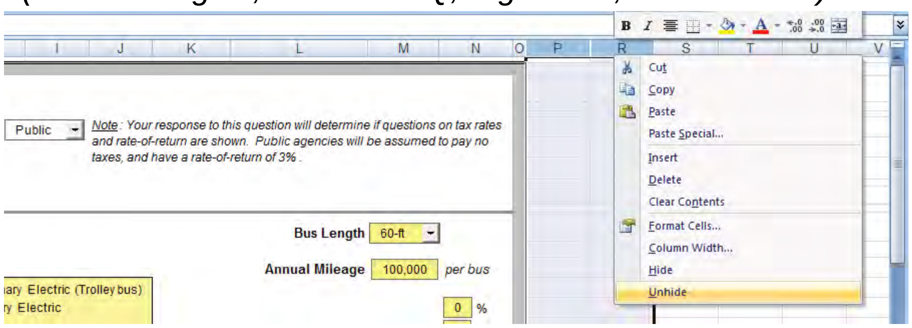
46

1. Change Bus Length Menu

On the INPUT Basic Sheet:

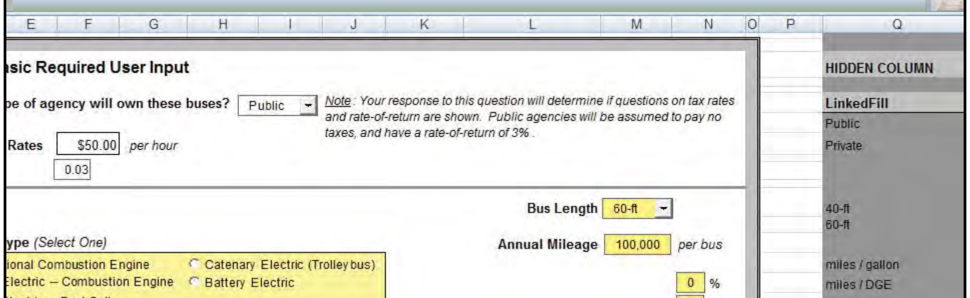
1. Select Columns P:R (they should be highlighted)
2. Right click while keeping mouse over selected area
3. Click "Unhide"

(To "Hide" again, Select Col Q, Right click, Select "Hide")



47

1. Change Bus Length Menu (con't)



INPUT Basic Sheet, Cells Q12:Q13 --

- This is the text used in the Bus Length drop-down menu
- Changes in these cells will change the drop-down menu
- The menu is set to read only 2 "lengths"
- The first "length" (Q12) is the "standard", and refers to the data on DefaultValues sheet
- The second "length" (Q13) is calculated as a multiplier applied to the "standard"

48

2. Easy Way to Adjust Default Data

Adjustments for 25-ft

Item	Multiplier
Bus Life	none
Fuel Economy Adjuster	0.81
New Vehicle	1.5
Extended Warranty	none
Depot & Fueling Conversion	none
Equipment	none
Fuel Price (after tax)	none
Bus Maintenance	none
Facility Maintenance	none
Safety Training	none
Learning Curve Cost: *Muliplier to non-fuel annual costs*	none
Overhaul Interval	none

Apply multipliers to adjust 40-ft bus data to values for another vehicle . . .

DefaultData Sheet – Columns AQ and AR

- Confirm that AR1 shows the new “length” *(needs to match the drop-down list text exactly, doesn’t need to be a length, e.g., “van”)*
- Enter multipliers in Column AR for each item

49

2. Harder Way to Adjust Default Values

DefaultValues Sheet – Columns F to AH

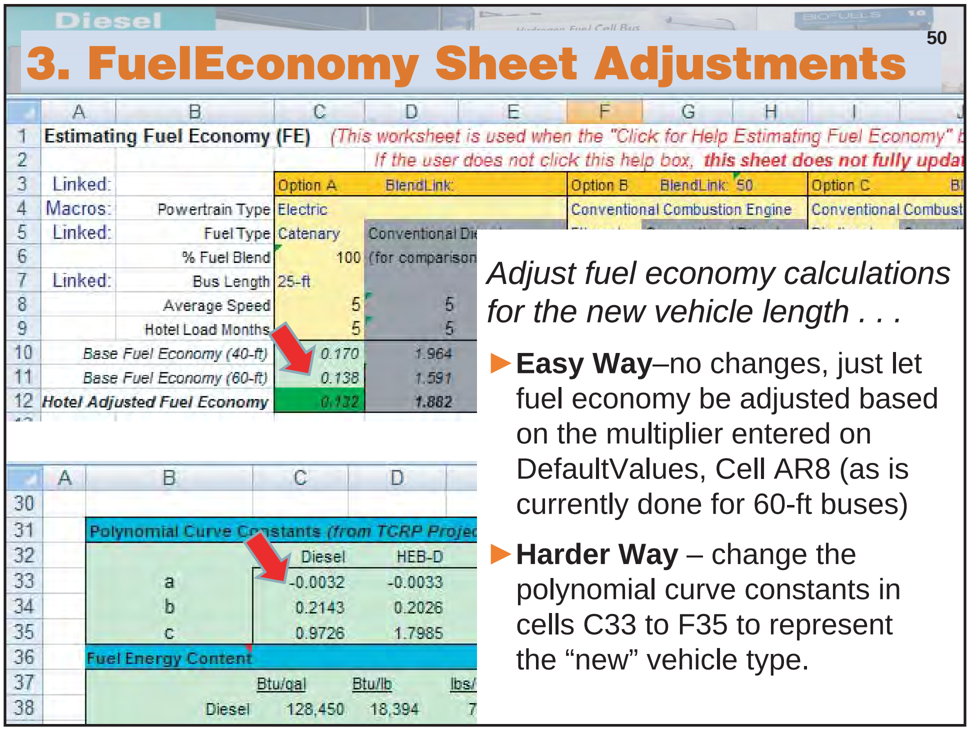
- Makes another vehicle type replace the current standard (i.e.,40-ft bus data)

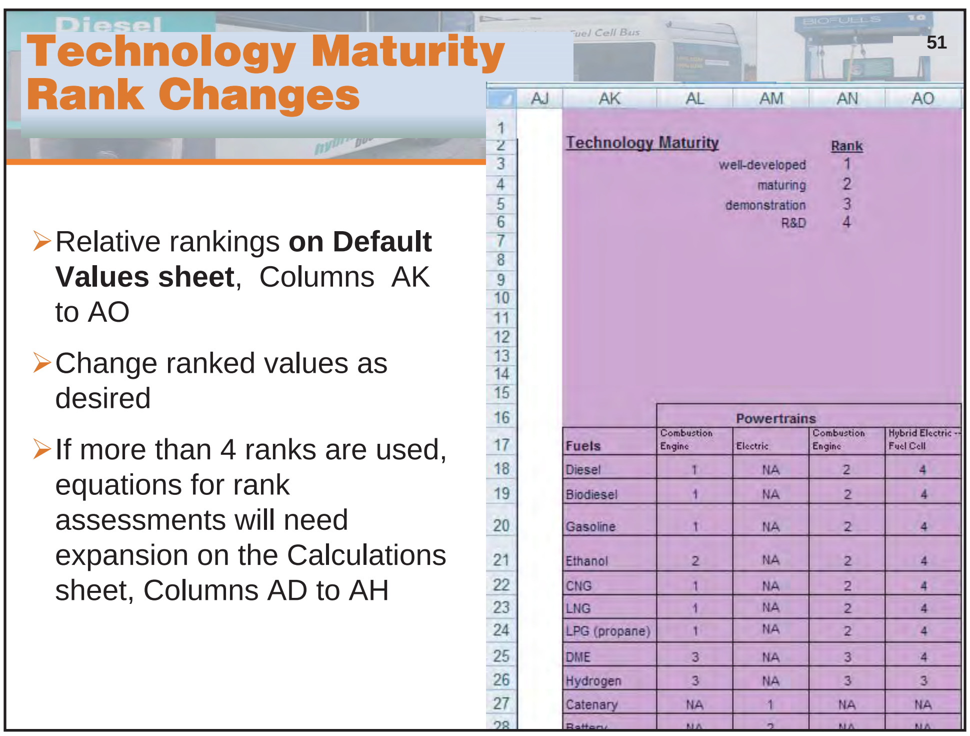
Consider: *(to help assure appropriate relative values)*

- Establish default value for a “base” option, i.e., one column (fuel/powertrain combination) and set other default values relative to the base value

  Example: the price of a new gasoline bus (Cell H9)

  Cell H9 = F6 * 0.75 (where F6 is the price of the conventional fuel)
- Set default values for other powertrains as a value that is relative to a base powertrain (i.e., as an equation)


50
3. FuelEconomy Sheet Adjustments
Estimating Fuel Economy (FE)
(This worksheet is used when the "Click for Help Estimating Fuel Economy"
If the user does not click this help box, this sheet does not fully updat
Linked: Option A BlendLink: Option B BlendLink: 50 Option C
Macros: Powertrain Type Electric Conventional Combustion Engine Conventional Combust
Linked: Fuel Type Catenary Conventional Di
% Fuel Blend 100 (for comparison
Linked: Bus Length 25-ft
Average Speed 5 5
Hotel Load Months 5 5
Base Fuel Economy (40-ft) 0.170 1.964
Base Fuel Economy (60-ft) 0.138 1.591
Hotel Adjusted Fuel Economy 0.132 1.882
Polynomial Curve Constants (from TCRP Projec
Diesel HEB-D
a -0.0032 -0.0033
b 0.2143 0.2026
c 0.9726 1.7985
Fuel Energy Content
Btu/gal Btu/lb lbs/
Diesel 128,450 18,394 7
Adjust fuel economy calculations for the new vehicle length . . .
Easy Way–no changes, just let fuel economy be adjusted based on the multiplier entered on DefaultValues, Cell AR8 (as is currently done for 60-ft buses)
Harder Way – change the polynomial curve constants in cells C33 to F35 to represent the "new" vehicle type.


51
Technology Maturity Rank Changes
Relative rankings on Default Values sheet, Columns AK to AO
Change ranked values as desired
If more than 4 ranks are used, equations for rank assessments will need expansion on the Calculations sheet, Columns AD to AH
Technology Maturity Rank
well-developed 1
maturing 2
demonstration 3
R&D 4
Powertrains
Fuels Combustion Engine Electric Combustion Engine Hybrid Electric – Fuel Cell
Diesel 1 NA 2 4
Biodiesel 1 NA 2 4
Gasoline 1 NA 2 4
Ethanol 2 NA 2 4
CNG 1 NA 2 4
LNG 1 NA 2 4
LPG (propane) 1 NA 2 4
DME 3 NA 3 4
Hydrogen 3 NA 3 3
Catenary NA 1 NA NA

Abbreviations and acronyms used without definitions in TRB publications:

AAAE	American Association of Airport Executives
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ACI–NA	Airports Council International–North America
ACRP	Airport Cooperative Research Program
ADA	Americans with Disabilities Act
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	Air Transport Association
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
DHS	Department of Homeland Security
DOE	Department of Energy
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
HMCRP	Hazardous Materials Cooperative Research Program
IEEE	Institute of Electrical and Electronics Engineers
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
ITE	Institute of Transportation Engineers
NASA	National Aeronautics and Space Administration
NASAO	National Association of State Aviation Officials
NCFRP	National Cooperative Freight Research Program
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
PHMSA	Pipeline and Hazardous Materials Safety Administration
RITA	Research and Innovative Technology Administration
SAE	Society of Automotive Engineers
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005)
TCRP	Transit Cooperative Research Program
TEA-21	Transportation Equity Act for the 21st Century (1998)
TRB	Transportation Research Board
TSA	Transportation Security Administration
U.S.DOT	United States Department of Transportation