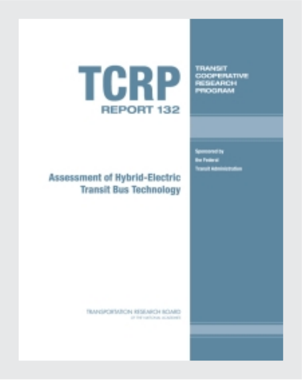

Assessment of Hybrid-Electric Transit Bus Technology

DETAILS

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TRANSIT COOPERATIVE RESEARCH PROGRAM

TCRP REPORT 132

Assessment of Hybrid-Electric Transit Bus Technology

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TRANSIT COOPERATIVE RESEARCH PROGRAM

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

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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 132

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TCRP PROJECT C-15 PANEL
Field of Engineering of Vehicles and Equipment

AUTHOR ACKNOWLEDGMENTS

The research reported herein was performed under TCRP Project C-15 and was led by the Department of Mechanical and Aerospace Engineering at West Virginia University (WVU), with major subcontract support from the Transit Resource Center (TRC), and Battelle Memorial Institute.

Nigel N. Clark, Professor and Berry Chair of Engineering at WVU, was the project director and principal investigator. The other authors of this report were John J. Schiavone, project manager and senior consultant at TRC, and W. Scott Wayne, assistant professor of mechanical and aerospace engineering at WVU, who were co-principal investigators; Feng Zhen, research assistant and PhD candidate at WVU; Kevin L. Chandler, project manager at Battelle; Cliff Chambers, principal at TRC, and Aaron D. Golub, consultant at TRC and assistant professor at the School of Planning and School of Sustainability, Arizona State University. Donald W. Lyons, Mridul Gautam, Gregory J. Thompson, and the staff of the Center for Alternative Fuels, Engines and Emissions at WVU provided valuable input for the C-15 program model.

This report and the C-15 program greatly benefited from the assistance of the managers and staff at six transit agencies (New York City Transit, King County Metro, Washington Metropolitan Area Transit Authority, Long Beach Transit, Dallas Area Rapid Transit, and OC Transpo [Ottawa, Canada]), and three hybrid drive original equipment manufacturers (Allison Transmission, BAE Systems, and ISE Corporation). Significant data used in the C-15 program were gathered through a program funded by the U.S. Department of Energy, conducted by the National Renewable Energy Laboratory (NREL, in Golden, CO), with support from Battelle.

FOREWORD

By Lawrence D. Goldstein
Staff Officer
Transportation Research Board

TCRP Report 132: Assessment of Hybrid-Electric Transit Bus Technology provides decision-making guidelines coupled with a comprehensive life cycle cost model (LCCM) to assist transit managers in evaluating, selecting, and implementing hybrid-electric technology options for transit buses. The guidelines and the accompanying LCC model resulted from the gathering of site data coupled with a comprehensive review of both capital requirements and operating costs of hybrid-electric buses in comparison with those powered by traditional diesel engines. Information grew out of a sound, engineering-based, independent technical evaluation of the costs, performance, and reliability of hybrid-electric transit bus technology in actual service. The LCC model, contained on the accompanying CD-ROM (CRP-CD-71), allows the user to compare the total life cycle costs across several cost categories for up to 6 different "purchase scenarios." These scenarios let the user decide when the purchases will be made, the types of buses to be compared, the work load of the buses, and many other cost inputs in determining benefits and costs associated with alternative purchasing strategies.

The next generation of new bus-propulsion technology is arriving. Hybrid-electric buses are being promoted as more cost effective; more reliable; more energy efficient than conventional diesel and superior to alternative fuel options (e.g., compressed natural gas, liquefied natural gas, propane); and more environmentally friendly. Based on a complex set of alternatives, there is a need to analyze emerging propulsion technologies to assist transit agencies considering hybrid-electric buses.

For several decades transit buses, usually of 40-foot length, have traditionally been powered by diesel engines and driven using automatic transmissions. Over the last 15 years, however, various transit systems have begun to use an assortment of alternative fuels, often while the technologies were under development. Use of alternative fuels has met with varying degrees of success. Based on an increasing need to improve fuel economy while reducing tailpipe emissions, alternate bus powertrain configurations have entered the marketplace and are expected to evolve over the next decade. This report examines developing technology and life cycle cost (LCC) for transit buses using conventional drivetrains with diesel or natural gas engines, and hybrid-electric buses with diesel or gasoline engines. The analysis includes a review of literature pertaining to (a) hybrid bus architecture and energy storage choices and (b) a comparison of existing fuel economy and emissions data for competing technologies. Published data demonstrated that diesel hybrid-electric buses produced lower emissions and consumed less fuel than diesel buses.

The study gathered hybrid-electric bus performance data for real-world bus operations at four sites (New York; Seattle; Long Beach, CA; and Washington, DC), along with data for conventional diesel and natural gas buses to provide a comparison. Seattle buses were

60 feet in length, with the remaining study buses having a length of 40 feet. Further information on bus purchase cost, maintenance cost, and rebuild cost was obtained by consulting manufacturers. A comprehensive bus LCCM was developed in spreadsheet format and used to evaluate transit bus LCC performance, considering both capital and operating costs. This LCC model includes default values and incorporates fuel price projections and a fuel economy model. Default values used in the report may be employed by a transit agency for initial planning purposes and fleet selection, but the model is set up to allow transit operators with more sophisticated data available to optimize route assignments for specific bus technologies, to minimize the cost of operating a mix of technologies in the fleet, to appreciate the impacts of variables such as fuel cost on future operation, and to determine when bus replacement is most desirable from a cost perspective. Major findings are that bus routes, characterized by average speed, have a profound effect on determining the cost advantage of hybrid buses, which offer greatest efficiency advantage during slow, transient operation. In response, the LCC model can be used to determine the threshold speed for which hybrid and conventional buses have equivalent life cycle cost, based on fuel prices. Unpredictable future fuel pricing is the greatest enemy of reliable life cycle cost prediction. In addition, cost of facilities adversely impacts adoption of small fleets of compressed natural gas buses.

The report provides a strong foundation for transit system managers; policymakers; operations and maintenance professionals; and others considering the deployment of, or conversion to, hybrid-electric transit buses who wish to build a dedicated decision-making model for a specific metropolitan area. Coupled with application of the LCC model, it will also provide an impartial resource to facilitate productive discussion between public interest groups, city leadership, and transit system managers.

CONTENTS

SUMMARY

Assessment of Hybrid-Electric Transit Bus Technology

Transit agencies are driven by environmental and economic issues when selecting bus technology, and choices have grown substantially over the last 15 years. Most major U.S. transit agencies rely on 40-ft rear-engined diesel buses with automatic transmissions for revenue service. Compressed natural gas (CNG) buses have been in the marketplace since the early 1990s, and now hybrid-electric buses (HEB) are available in several configurations. Nearly 4,000 HEB are already in service in the United States or were planned to be in service by 2008. Bus activity, in terms of annual mileage accumulation and average operating speed, varies widely from city to city and from route to route, so a single technology solution may not always be the most attractive option. Most U.S. bus depots are currently geared to operate with diesel fuel (either No. 1 or No. 2 fuel), and CNG fueling infrastructure is already available at a limited number of depots. "Full size" bus life is considered to be at least 12 years, and most U.S. bus purchases receive a federal subsidy to relieve capital cost impact. The C-15 program reviewed HEB emissions and fuel economy (FE) and compared the data with emissions and FE from their comparable conventional-drive diesel and natural gas bus counterparts. The researchers also gathered field data from in-use fleets, investigated and projected technology costs, and developed a tool to assist in evaluating the bus life cycle cost (LCC) performance of conventional and advanced bus propulsion technologies with emphasis on HEB.

HEB are generally propelled by two energy sources. Most HEB use diesel engines as the primary energy and power source, with electrical energy stored on board as a second, or auxiliary, source. These configurations are commonly used in the 40-ft standard and 60-ft articulated buses. Gasoline engines have been employed in 40-ft HEB for low-emissions operation in the state of California. Natural gas, hydrogen internal combustion engine (ICE), and fuel cell HEB are still in the early prototype stages and involve a small number of vehicles. Gas turbine hybrid-electric drives have been employed in dozens of 22-ft buses, operating on either diesel or propane. Most HEB use chemical batteries or capacitors as the on-board energy storage system (ESS), and use one or more electric motors to supply partial or total traction force. Flywheels or hydraulic accumulators are used as the ESS in other types of hybrid systems, but these are also in their early demonstration stages. The hybrid system reduces fuel consumption (and hence emissions, for equivalent technology) by recovering energy lost during braking and deceleration, operating the ICE at favorable performance, permitting ICE downsizing, and increasing powertrain efficiency.

Diesel engine technology has become progressively more complex, with particulate matter (PM) restrictions forcing adoption of exhaust filtration (i.e., traps) in 2007, and with oxides of nitrogen restrictions driving the use of urea-selective catalytic reduction after 2010. CNG engines for buses historically use lean-burn technology in the United States, but the most recent engines have moved to stoichiometric operation (in which enough air is supplied to oxidize the fuel completely, but with no excess of oxygen) that includes the fitting of three-way exhaust catalysts.

The research team's analysis confirms that HEB purchase was more expensive than the purchase of diesel or natural gas buses but HEB offer superior fuel efficiency, particularly at low speed. The researchers developed a comprehensive LCC model (the LCCM) in spreadsheet format that can be used to evaluate HEB performance, taking into account both purchase price and operating costs. The model allows direct LCC comparison for up to six different purchase scenarios. The scenarios may include either 40-ft or 60-ft transit buses with similar or different bus technologies. The following five bus technologies are imbedded in the spreadsheet model:

1. Pre-2007 diesel,
2. Conventional diesel,
3. Diesel hybrid-electric,
4. Gasoline hybrid-electric, and
5. CNG buses.

The LCCM includes a broad range of bus cost elements with default values and upper and lower bounds to indicate variability and confidence in default projections. The LCCM also provides the flexibility for users to enter their own cost components as a means of increasing predictive accuracy. In weighing capital costs against fuel efficiency, bus operating speed plays a major role. The national average speed of 12.72 mph is used as a default value in the model, but bus speed differences between transit operations and the variety of routes and speeds within a transit operation imply that the lowest LCC choice is activity dependent. Fuel costs also play a strong role in determining the selection of best technology.

The LCCM is based on a variety of inputs, derived from literature reviews, surveys from bus and hybrid drive manufactures, and information from government agencies and the fuel industry. As a major input, 18 months of real-world bus performance data at three test agencies (New York, NY; Seattle, WA; and Long Beach, CA) were gathered in many categories covering transit bus capital and operation costs. Substantial data also were gathered from a fourth site (Washington, D.C.), which recently had procured buses. Baseline diesel bus costs were established and used to support the evaluation process for alternative technology buses. Additionally, a detailed LCCM user instruction document was created to guide the user in implementing a comparative bus technology evaluation with the LCCM.

The study found that HEB are available in a wide range of bus sizes and are technically feasible for transit service in the United States. HEB can increase fuel efficiency and reduce tailpipe emissions significantly for the transit fleet. Bus LCC is affected substantially by several cost factors, such as purchase incentives, fuel price, bus operation speed and mileage, battery technology, and bus lifespan. It is important to utilize the LCCM with the appropriate operating speeds and fuel cost projections to analyze whether a fleet procurement of HEB or CNG buses is financially sustainable.

Application of the model found that each technology could possibly be a best choice in a real procurement and operation scenario, even when default values are used. Operation speed, air conditioning and heating use, fuel price, purchase incentives, maintenance, and infrastructure availability are important LCC factors. Diesel buses with a conventional drivetrain are usually the least expensive technology, in comparison with HEB and CNG buses—especially during intermediate- and high-speed operation—despite the growing complexity of diesel engine technology. HEB are impacted by high purchase cost and battery replacement cost, but become attractive for their fuel savings when operated at slow speed or over longer life mileage. High fuel price and purchase incentives could also make HEB an attractive and better cost choice for transit operation. Gasoline HEB usually cost 5% to 10% more than diesel HEB overall. They offer a good alternative to diesel HEB for situations in which a hybrid system is desired to achieve fuel efficiency but emissions restrictions might prohibit pre-2010 diesel engine operation. The LCC of CNG buses usually falls between those of diesel and HEB. Operation speed and bus purchase incentives slightly impact CNG LCC. CNG buses become attractive when liquid fuel prices increase but the price of natural gas remains more stable and does not follow the price of diesel. However, price trends for different fuels usually follow one another. Although diesel fueling facilities are available at most current transit garages, a change to CNG buses would necessitate the installation of a compressor station, which must be considered as a capital cost. The study found that to be competitive the purchase scale for CNG buses should be large (over 50 buses) to offset infrastructure costs, unless these costs will not be borne by the bus operator, are reduced by some infrastructure incentives, or CNG infrastructure is already in place.

The LCCM was applied to the four test site scenarios, demonstrating that the model is a useful comparative tool with acceptable accuracy in prediction when default values are used. Since one model cannot perfectly predict all real-world operation; the LCCM is configured to allow the informed user to enter known costs or adjust operational factors to improve accuracy. During this study, the LCCM correctly reflected the differences among technologies found at the four test sites. The LCCM also was reviewed by two additional sites (Dallas Area Rapid Transit and OC Transpo in Ottawa, Canada) before being finalized. The greatest threats to model accuracy in future application will be unpredictable fuel pricing and the degree to which market penetration reduces HEB capital cost.

The C-15 study yielded more detail than would be required by many users. The LCCM tool, as well as additional information on HEB technologies, fuel economy and emissions, and hybrid-electric drivetrain manufacturers available in this report's appendices, are provided with the accompanying CD-ROM and are also available as an ISO image from www.TRB.org.

CHAPTER 1

Background

1.1 Problem Statement and Research Objective

The objective of this research was to develop guidelines to assist transit managers in the assessment, selection, and implementation of hybrid-electric technology options for transit buses. Two distinctly different driving forces exist for the adoption of advanced transit bus technology. First, there is a desire on the part of transit operators and communities to adopt technologies that offer a lower total life cycle cost (LCC). This is measured in terms of reliability (vehicle and infrastructure maintenance); fuel economy; hardware longevity; the capital costs of new bus technologies, changing procedures, diagnostics, hardware, and logistics; and the cost of training operators and mechanics. Second, there are incentives to adopt technologies that offer environmental benefits. In some cases, rulemaking has demanded that the operator follow a pathway that requires emissions levels below those implied by conventional engine certification. Both driving forces are discussed in this study.

1.2 Research Approach

Although hybrid drive technology must take center stage in this report, it is necessary to consider carefully both conventional and alternate technologies that will compete with hybrid technology in the future. This study evaluated diesel (40-ft and 60-ft) and gasoline (40-ft) hybrid-electric buses (HEB), along with comparable conventional diesel and compressed natural gas (CNG) buses, at four U.S. transit agencies.

The research effort yielded two major products. The first is a holistic evaluation of present and emerging hybrid transit bus technology, in which the researchers reviewed transit bus emissions and the fuel economy (FE) impacts of different engine, fuel type, and propulsion technologies on bus emissions performance. This review also addressed hybrid bus technologies, their configurations, important components, and both North American and international implementation.

The second product, directed at the transit operators, provides concise information and a real tool to assist in evaluating the benefits of adopting hybrid bus technology. The tool, based on a spreadsheet, allows direct LCC comparison for up to six different purchase scenarios for either 40-ft or 60-ft transit buses with similar or different bus technologies. A speed-sensitive fuel economy predictor is at the heart of the model. Five technologies are imbedded in the spreadsheet, namely pre-2007 diesel, conventional diesel, diesel hybrid-electric, gasoline hybrid-electric, and CNG. Allowing changes in purchase year (from year 2007 to 2030) for each scenario, the model can evaluate present and future hybrid and conventional bus technology LCC for either a 12-year period or a user-selected lifespan. The model includes a comprehensive range of bus cost elements with default values and upper and lower bounds, and allows users to enter their own cost components if these are well characterized and available to the users. The tool is not only usable by large-scale operations, but also by small municipalities considering the purchase of only a few buses. Two transit operators were used to evaluate the tool, in addition to managers at four transit sites used to gain operations data.

The research work was completed in two phases and involved the following deliverables:

- Task 1: Summarized the existing information available from literature on transit bus emissions across all fuel types.
- Task 2: Conducted a literature search and prepared a summary of the state of the technology for in-service deployment of commercially available hybrid bus fleets.
- Task 3: Prepared a methodology for collecting data on cost and reliability for use in this study.
- Task 4: Prepared a detailed data-collection work plan for Phase 2.
- Task 5: Submitted an interim report documenting Tasks 1 through 4.
- Task 6: Carried out the data collection work plan as approved by the project panel.

- Task 7: Used data collected in Task 6, updated and expanded the LCC analysis from Task 3.
- Task 8: Prepared the draft guidelines.
- Task 9: Prepared the final product.

1.3 Hybrid Technologies and Test Sites

The selection of suitable fleets for evaluation was constrained by existing circumstances. In particular, there were a limited number of HEB operating in North America at the start of the program. In the full-size (longer than 35-ft) bus market, only three manufacturers (Allison, BAE Systems, and ISE) made HEB drives in sufficient numbers. There were also only a few sites that had procured, or were then procuring, hybrid drive technology buses and also had late-model diesel or natural gas technology buses that could be used for comparative purposes. Another challenge for selecting test sites was the need to choose study fleets with an adequate number of hybrid, conventional diesel, and CNG buses to obtain statistically meaningful data and to avoid data sets that were biased by the performance of a single vehicle in a small fleet. To supplement data obtained from the test sites, the study team decided that optimal use should be made of data collected by the DOE/National Renewable Energy Laboratory (NREL) program.

Based on the challenge of finding representative hybrid technologies operating in fleets with comparative buses, the research team selected three Washington Metropolitan Area Transit Authority (WMATA) garage locations that included 40-ft Allison diesel parallel HEB and comparative CNG and diesel buses. Three garage locations at New York City Transit (NYCT) were selected to collect data on comparative 40-ft BAE Systems diesel series HEB, CNG, and diesel buses. Long Beach Transit (LBT), as a site operating ISE gasoline series HEB, was selected to broaden the scope of the hybrid comparison and included two locations. Seattle's King County Metro (KC Metro) was selected to provide 60-ft Allison diesel parallel articulated HEB and diesel buses at two locations. Detailed HEB evaluation results are addressed in Appendix B. Figure 1.1 shows the location of the four test sites and their HEB technologies.

1.4 Brief Review of Hybrid-Electric Bus Technology

This section briefly presents the hybrid-electric bus technology and its configuration. Detailed review of hybrid-electric bus technology is presented in Appendix A. This appendix includes a summary of the state of the art of hybrid-electric bus configuration, key components, and implementation in North America and the world. Included also is a comprehensive transit bus emissions review that covers regulated emissions species, emissions measurement, and studies of hybrid-electric emissions and fuel economy.

1.4.1 Hybrid-Electric Bus Types

In order to improve FE and reduce emissions in urban transportation, several hybrid powertrains have been designed and used in transit service in the United States. Any vehicle with two or more differing energy sources to provide the driving power was considered to be a hybrid vehicle. Usually, one of the sources represents on-board energy storage that can be replenished while driving. Generally, hybrid vehicles use electric power as one of the energy sources, although hydraulic power has recently emerged as a potential contender. An HEB has a propulsion unit, such as an engine, along with one or more electrical motors or generators and an energy storage system (ESS), like a battery. However, architectures might vary widely. Furthermore, hybrid vehicles could be divided into two groups: mild and full.

Figure 1.1. C-15 test site locations and their HEB technologies.

In a mild hybrid, the propulsion source is mainly from the conventional engine. When it is needed, extra power can be taken from the electric motor, which cannot operate independently from the engine. The electric motor can generate electricity for the battery or consume electricity from the battery, but not both at the same time. Mild hybrids are also defined as a vehicle that has 15% of total driveline power from electric, and cannot be a series design (see next section).(*1*) In a full hybrid, the engine and motor offer similar levels of propulsion power—the electric motor can often operate on its own at low speeds.

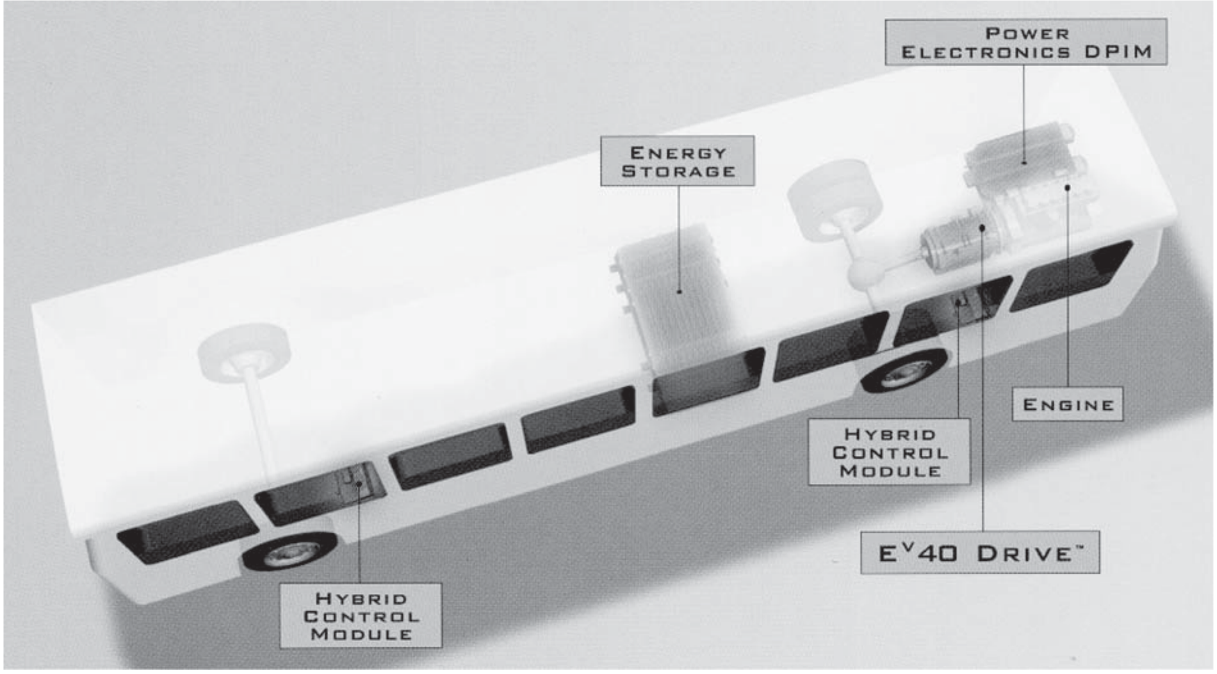
Hybrid vehicles can be defined as *charge sustaining* or *charge non-sustaining* (i.e., *charge depleting*). In a charge-sustaining hybrid, the vehicle can operate independently from the storage device (such as on-board batteries). There is enough energy and power from the engine to drive the vehicle over a reasonable route. In this way, the batteries are not depleted steadily over an extended period of use. In a charge-depleting hybrid, the vehicle cannot operate independently from the storage device, which has to supply energy for propulsion. Since the charge-depleting system is usually intended to extend the driving range, it is often referred to as a *range extender.* Usually the energy storage device is charged periodically from another source. This is often described as a *plug-in hybrid.*

To illustrate typical HEB components, Figure 1.2 shows the layout of a bus using the Allison electric drive EP hybrid propulsion system. The power electronics dual power inverter module (DPIM) converts electrical energy from alternating current (AC) to direct current (DC). In this case, AC is used and produced by the EV drive motor/generators, but only DC can be stored in the ESS. The EV drive includes motors and/or generators that assist in propelling the vehicle. The ESS supplies electrical energy to the EV drive electric motors. The hybrid control module consists of a system controller that processes information from sensors and components and manages the vehicle's propulsion. The hybrid control module also has diagnostic and reprogramming features.(*2*)

A hybrid-electric vehicle (HEV) might also be classified according to system voltage, based on the likelihood of the voltage causing human harm in the event of electrical contact. Vehicles with a voltage of less than 50V are considered low-voltage hybrids. These include vehicles with 42V systems that employee 42V electric auxiliaries; they also may be defined as mild hybrids. Vehicles with a voltage of greater than 50V might be mild or full hybrids, and require higher electrical isolation and design safety standards. High voltage is preferred to reduce current, and hence conductor and inverter size. Heavy-duty HEVs normally have 300V or 600V nominal system voltages. The actual voltage would be higher during battery charging events than during discharging events. Batteries of cells are arranged to match the system voltage.

1.4.2 Hybrid-Electric Drive Configuration

It is not possible for a single powertrain configuration to be suitable for all HEV in all applications and markets. Several architectures were available commercially when this report was being written, and other configurations are possible. These are presented in the remainder of this section.



Source: GM Allison transmissions brochure.

Figure 1.2. Hybrid system components of the Allison EP System™ bus.

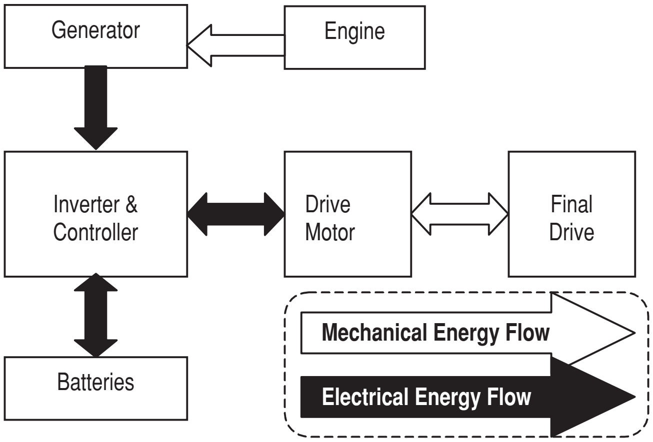


Figure 1.3. Series hybrid-electric drive: simple configuration.

Series Hybrid-Electric Drive

A series HEV typically consists of an engine directly connected to an electric generator (or alternator). Power from the generator is sent to the drive motor and/or energy storage batteries according to their needs. There is no mechanical coupling between the engine and drive wheels. The electric drive motor provides the entire drive force using energy from the energy storage device and/or the engine (which might be a fuel cell), or both. Figure 1.3 shows a basic series hybrid system configuration. The arrows indicate the mechanical and electrical energy flow. Both BAE Systems and ISE offered series drive transit buses in the U.S. market when this report was written. Table 1.1 summarizes the advantages and disadvantages of a series hybrid-electric drive system.

Parallel Hybrid-Electric Drive

In a parallel hybrid-electric drive system both of the power sources (engine and electric motor) are coupled mechanically to the vehicle's wheels. In different configurations, the motor may be coupled to the wheels either through the transmission (pre-transmission parallel design) or directly to the wheels after the transmission (post-transmission parallel design). Each of these has its advantages. A pre-transmission motor is required to operate over a smaller speed range than a post-transmission motor, and it could effectively deliver more torque to the rear wheels at low speed. However, a post-transmission motor offers higher efficiency in transmitting power to the drive wheels, and a greater efficiency in recapturing regenerative braking energy. A design would be possible where both pre- and post-transmission motors are present. In this case, one could even consider the design as a series-parallel combination. Figure 1.4 shows a simple parallel hybrid-electric drive arrangement. Table 1.2 summarizes the advantages and disadvantages of a parallel hybrid-electric drive system.

Complex Architectures

There are more complex hybrid architectures—than series and parallel—already in use. By using two motors, with one or more planetary gear arrangements, a continuously variable transmission system is possible. Two of the rotating mechanical components are linked electrically by motors/generators. In these designs, part of the power is transmitted mechanically, and part is transmitted electrically. Either or both of the motors might exchange energy with the ESS. Control of such a system is more complex than for a simple series or parallel system, but a complex system provides for freedom in managing engine speed and torque versus vehicle speed and power demand. In the light-duty market, the Toyota Prius has demonstrated high FE with a planetary system. The Allison buses currently on the market employ a planetary system with a range shift, which has been termed a *split parallel* (Figure 1.5). Table 1.3 summarizes the advantages and disadvantages of complex hybrid system architectures.

Table 1.1. Advantages and disadvantages of a series hybrid-electric drive system.

Advantages	Disadvantages
Engine configuration is relatively easy and simple to control.	Most suited to city-type driving only.
Engine is able to operate in the region of its peak efficiency more often than in a conventional vehicle.	Large energy loss by generator and motor.
Engine is more efficient at modest speed and at high load, which results in superior FE.	Has a relatively large battery energy loss.
Allows the optimization of engine technology.	Engine, generator, and motor—in addition to the energy storage device—contribute to vehicle mass.
Can reduce severe transient load demands on the engine, which leads to lower emissions.	
Has excellent dynamic performance at low-speed acceleration.	

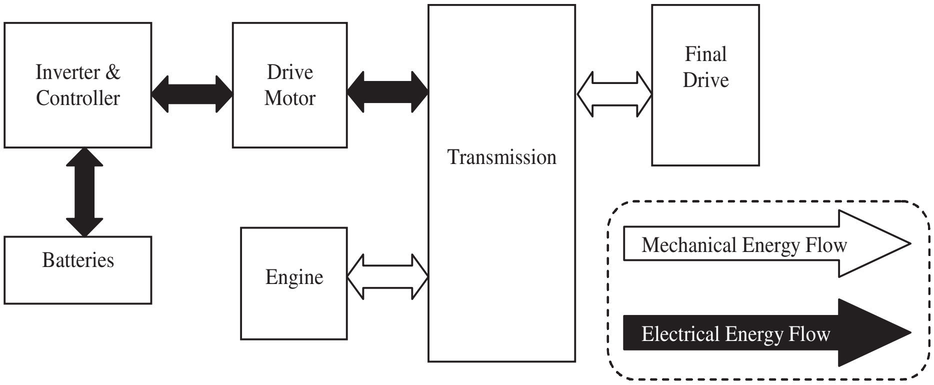


Figure 1.4. Parallel hybrid-electric drive system: simple configuration.

Table 1.2. Advantages and disadvantages of a parallel hybrid-electric drive system.

Advantages	Disadvantages
Offers good energy efficiency during steady-state operation.	The engine cannot completely avoid transient operation because of the direct link between the engine and the wheels.
A small engine and motor help reduce vehicle mass.	Transient operation may result in higher emissions than a series hybrid system produces.
Performs well in high average power and high load conditions.	The design and control is relatively more complex than the series configuration.
Offers a good design compromise where both stop-and-go and cruising operations are likely.	Less braking energy can be captured because motor for parallel system is smaller in size than motor for series system.

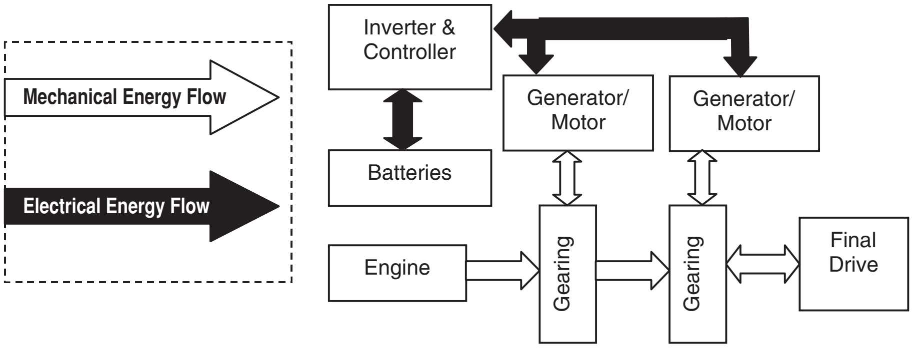


Figure 1.5. Complex hybrid system architecture.

Table 1.3. Advantages and disadvantages of a complex hybrid system architecture.

Advantages	Disadvantages
Offers flexibility in engine operation.	Design is complex.
Provides freedom in managing engine speed and torque versus vehicle speed and power demand.	Control is complex.
Can offer high FE and reduced emissions.	

CHAPTER 2

Life Cycle Cost Model Development

2.1 Overview and Test Site Evaluation Summary

The Life Cycle Cost Model (LCCM) was developed using a variety of inputs, including literature review, surveys, and detailed data gathering. As a major input, 18 months of real-world bus performance data were gathered at three test agencies (NYCT, KC Metro, and LBT) for many categories covering transit bus capital and operation cost. Substantial data also were gathered from a fourth site (WMATA), which had recently procured buses. WMATA acquired buses with different technologies at different times, so that it was possible to collect only nine months of data for the conventional diesel buses. This chapter briefly presents the type of data that were collected from diesel, CNG, and HEB to establish the baseline diesel bus costs and to support the evaluation process for alternative technology buses. These data, along with estimates gathered from the bus industry and projections for fuel pricing, were used to create the LCCM, which is a major product of the C-15 program. A user instructions document was also created to guide the user in implementing the LCCM for a comparative bus technology evaluation. The LCCM was prepared in spreadsheet format.

The reader who wishes to execute the LCCM without learning the details of its creation is referred to Section 2.4.

Several principles guided the creation of the decision tool, which was configured to be most accurate when comparing the cost performance of two different technology options. The spreadsheet model was designed to be able to

- Make comparisons based on generic (i.e., not brand-specific) hybrid, CNG, and diesel propulsion systems.
- Use the baseline established for existing buses and correct it to 2007–2008 year levels for diesel, CNG, and HEB, and use this 2007–2008 base as a starting point for all evaluations.
- Offer a simple user input page and output information.
- Compare several procurement scenarios side by side.
- Distinguish between initial purchases with start-up costs and purchases with ongoing additional procurements where costs have stabilized.
- Handle bus procurements of any size.
- Create outputs in numerical form and, for the most important outputs, graphical form.
- Offer the ability to override default values for most parameters.
- Provide low, medium, and high cost prediction that offers a range rather than a single value.
- Be transparent and readily modified using Excel.

Eighteen months of LCC data were collected from four test sites. Data from two of the sites (NYCT and KC Metro) were obtained from a DOE/NREL study.(*3, 4*) (Note, however, that the initial period of new bus operation, which is not representative of long-term use, was excluded to give a data period of 18 months.) Bus usage, in-field fuel economy, total propulsion-related maintenance cost, and roadcalls of different bus technologies are compared in Table 2.1. Detailed information about bus procurement, route description, in-field data, and charts is available in Appendix B.

2.2 Life Cycle Cost Model

The LCCM is a spreadsheet tool that can predict the capital and operating costs of bus fleets of various technologies. The model incorporates default values, which were chosen by the researchers based on the information from the four sites presented in Table 2.1, as well as information from other sources. The research team's intent was to design the LCCM so the informed user could also override the default values if more accurate entries were available. Default bus speed is set to 12.72 mph and default bus use is 37,000 miles per year, for a default life of 12 years. Other default values are presented in Section 2.2.2. For cost items, the research team adopted low, medium (which is always the default), and high values to

Table 2.1. Summary of bus usage, fuel economy, maintenance, and roadcalls from four test sites.

	NYCT 40-Ft Buses				**KC Metro** 60-Ft Buses		**LBT** 40-Ft Buses		**WMATA** 40-Ft Buses		
Bus Technology	MY2004 D-HEB	MY2002 HEB	MY2002 D-HEB	MY2002 CNG	MY2004 D-HEB	MY2004 Diesel	MY04/05 G-HEB	MY2002 Diesel	MY2006 HEB	MY05/06 CNG	MY2006 Diesel
Bus Usage (Miles per Bus)	2,087	2,240	2,461	2,244	3,096	2,948	3,057	3,295	4,606	2,663	4,576
Fuel Economy (mpg)	3.00	3.22	3.44	1.71	3.21	2.55	3.75*	3.49	3.96	3.21	3.48
Maintenance ($/Mile)	0.158	0.335	0.293	0.269	0.136	0.142	0.072	0.201	0.13	0.29	0.14
Roadcalls (Miles)	8,945	8,669	10,800	7,806	4,954	5,896	12,037	14,707	4,863	6,477	9,633
Study Period	10/04-9/06	10/04-9/05	10/04-9/05	10/04-9/05	4/05-3/06	4/05-3/06	6/05-6/07	6/05-6/07	1/06-5/07	12/05-5/07	8/06-5/07

Notes:
*3.75 is in miles per diesel gallon equivalent. The gasoline HEB traveled 3.34 miles per gasoline gallon.
MY = model year; D-HEB = diesel hybrid-electric bus; G-HEB = gasoline hybrid-electric bus.

provide the user with a reasonable range of predictions. The following sections describe the LCCM, additional data sources used, and model architecture.

2.2.1 Bus Technologies and Purchase Scenarios

The LCCM is configured to provide output for five types of major bus technologies: pre-2007 diesel (as a reference), conventional diesel, CNG, diesel hybrid-electric, and gasoline hybrid-electric buses (HEB). Although data were collected on specific HEB (i.e., Allison, BAE, and ISE), the research team avoided brand name comparisons and instead allowed LCC evaluations to be made by treating hybrids as a generic group of buses for comparison to diesel and CNG buses, which also are categorized as generic bus groups. Since data collection was limited to only four sites, poor or exceptional maintenance practice (i.e., different warranty, bus age, lack of diagnostic capability, varying repair quality) from a single agency representing a specific hybrid product could easily skew the results and incorrectly attribute performance to the technology type. Similarly, road and route conditions would affect conclusions and could introduce bias when considering a small number of sites. Finally, HEB were still evolving at time of data collection and the data collected on the performance of then-current buses may not exactly represent future bus performance.

The LCCM allows simultaneous cost comparisons for up to six purchase scenarios. All purchase scenarios are based upon four overall parameters: bus lifetime, base year, bus length, and inflation index. The model is not configured for direct LCC comparison between short-life buses and long-life buses or between 40-ft and 60-ft buses but is configured to address differences among propulsion technologies. In addition to the four basic bus parameters, each purchase scenario allows entry of different parameters, such as purchase year, operation speed, and bus technology.

2.2.2 Collection of Information and Cost Projections

Data used in the LCCM were obtained through a variety of sources, including data analyses from the test sites presented above, survey questionnaires sent to hybrid original equipment manufacturers (OEMs), and calls made to bus OEMs, other vendors and suppliers, transit agencies, and trade associations. Data in the literature were also reviewed. Although much of the information contained in the model is based on data obtained from actual operational experience, projections had to be made by the research team in those cases where in-use experience was lacking. As more information on all three bus types becomes available in the future, the LCCM is designed so that inputs can be changed by the user as needed. The cost elements used in the model are described in the following subsections.

Vehicle Cost

Each transit agency had different bus procurement requirements when it came to options, extended warranties, OEM-provided training, bus delivery, spare parts, and other services and equipment that influence bus pricing. In particular, equipment that greatly affects the initial bus price consists of Intelligent Transportation System (ITS) features such as automotive vehicle location (AVL), next-stop annunciators, security cameras, automatic passenger counters (APCs), radio and data communications, and other onboard electronic systems. This is a confounding factor in interpreting bus acquisition cost data. For the LCCM, the costs used to reflect each type of bus are based on a vehicle minimally equipped with basic onboard equipment such as air conditioning, multiplexing basic electric destination signs, and standard warranty consisting of one year of coverage for the entire vehicle and two years of powertrain coverage. The cost of extended powertrain warranty is accounted for separately in the LCCM.

The research team found it difficult to determine any significant insurance cost differences based on whether the bus was being operated as a diesel, CNG, or hybrid unit. As a result, the LCCM assumes no cost differences for insurance. However, since insurance cost differences could exist for certain agencies based on their insurance requirements or carrier, the LCCM allows users to add those values to the purchase price as appropriate.

Each of the major bus OEMs was contacted to obtain bus pricing information using the conditions described. Basic bus pricing is used in the model as low, medium, and high values, and a typical pricing differential was maintained between each bus type for comparison purposes. For example, using the diesel bus as a baseline, an incremental cost increase of $30,000 for CNG buses is retained throughout the low, medium, and high price ranges. Because of the various technologies associated with HEB, incremental cost increases of $190,000, $200,000, and $210,000 are used for the low, medium, and high values, respectively, when compared to a standard diesel bus.

The price of all three bus types is based on 2007 models fitted with equipment needed to meet new Environmental Protection Agency (EPA) emissions requirements for engines of that year. Although some 2007 model year buses may have been delivered with 2006 model year engines, all engines built from 2007 onward are required to meet a 0.01 grams per brake horsepower-hour (g/bhp-hr) particulate matter (PM) standard, which requires the manufacturer to employ exhaust filtration. For purchases after 2010, a step change in the range of $4,000 to $8,000 is added to each diesel bus to meet these more stringent 2010 EPA regulations for nitrogen oxides (NOx). CNG bus prices after 2010 do not include a price increase (except for standard inflation) because 2007 CNG engines operating with stoichiometric combustion can already meet 2010 EPA requirements. For hybrid bus purchases in 2012, the LCCM includes a price reduction in the 7% to 30% range (with 15% being the default) based on projections made by hybrid OEMs that hybrid technology costs will go down in time as the technology matures and initial investments in advanced technology are recovered. Low, medium, and high purchase prices that the model uses are shown in Table 2.2.

As with any input, users could run the LCCM with the default pricing value, select other pre-assigned values for each bus type, or input other purchase costs for each bus depending on the cost of specific bus options selected. In addition, the model provides users with the ability to change bus purchase costs. This flexibility allows the model to remain useful even if future prices stray from the model projections.

Other Capital Costs and Facility Costs

Diagnostic Equipment Cost. Costing for diagnostic equipment includes only those special tools and diagnostic equipment items unique to the propulsion system of hybrid buses. The research team assumed that transit agencies had already made investments in diagnostic equipment needed for standard ICEs used in all three bus types and for conventional automatic transmissions used in diesel and CNG buses. In this way, the model differentiates between technologies, because comparative accuracy is of highest concern. The research team obtained costing information for tools and diagnostic equipment unique to hybrid propulsion systems directly from the hybrid OEMs and verified this information with agencies that have purchased such equipment. As engine technology evolves, all bus types would require a similar level of investment in engine diagnostic tools.

Since the ICEs used in hybrids typically were diesel or gasoline, the costing of diagnostic equipment is averaged together for both engine types. An exception is the advanced level of diagnostic equipment applicable to hybrids fitted with gasoline engines that may be unique to an agency's fleet. In this case, costing inputs assume that agencies purchasing gasoline hybrids would opt for more basic diagnostic equipment (i.e., equipment priced more in line with diesel and CNG engines) for the gasoline powered auxiliary power unit (APU). Obtaining the full level of diagnostics for gasoline engines could be as high

Table 2.2. Bus purchase costs in 2007 dollars.

	Diesel		CNG		Hybrid	
	2007	2012	2007	2012	2007	2012
40-Ft, Low	$300,000	$304,000	$330,000	$330,000	$490,000	$416,500
40-Ft, Medium	$310,000	$316,000	$340,000	$340,000	$510,000	$433,500
40-Ft, High	$320,000	$328,000	$350,000	$350,000	$530,000	$450,500
60-Ft, Low	$390,000	$395,200	$429,000	$429,000	$637,000	$541,450
60-Ft, Medium	$403,000	$410,800	$442,000	$442,000	$663,000	$563,550
60-Ft, High	$416,000	$426,400	$455,000	$455,000	$689,000	$585,650

Table 2.3. Diagnostic equipment prices for every 50 buses at one workshop.

	Diesel	CNG	Hybrid
Low	$0	$0	$3,000
Medium	$0	$0	$5,000
High	$0	$0	$7,000

as $20,000. However, it is assumed that agencies with gasoline hybrids would use the services of a local dealer in those isolated cases when more advanced diagnostics are needed. Default diagnostic equipment prices are presented in Table 2.3.

Costs for hybrid diagnostic equipment are calculated for groups of up to 50 hybrid buses at each workshop location based on information provided by the hybrid OEMs. Once multiples of 50 buses are exceeded, the model automatically adds in the cost of another set of diagnostic equipment. As noted, the LCCM is constructed to assume no diagnostic equipment costs for diesel and CNG buses. If diagnostic equipment is desired for multiple locations, users may enter individual costs as needed. Using this concept, the LCCM assigns the following mid-range diagnostic equipment costs for the representative HEB fleet sizes:

- HEB fleet of 1 to 50 with one workshop: $5,000,
- HEB fleet of 1 to 50 with two workshops: $5,000 × 2 = $10,000,
- HEB fleet of 51 to 100 in one workshop: $5,000 × 2 = $10,000, and
- HEB fleet of 61 with 10 in one workshop and 51 in the other: $5,000 + ($5,000 × 2) = $15,000.

Infrastructure and Maintenance Costs. The research team initially considered that cost inputs for infrastructure upgrades were to be included in facility modifications required for both CNG and hybrid buses, with diesel buses not requiring any upgrades. However, as the research for this project progressed it became apparent that lead acid battery storage systems and the battery recharging/reconditioning that went with these systems were no longer used in the latest technology. As a result, infrastructure upgrades for hybrids are no longer an issue and CNG remains as the only bus type requiring infrastructure upgrades.

Understanding that costs for CNG infrastructure (fueling stations and maintenance and storage facilities) could vary greatly depending on several factors such as climate, condition of existing facilities, required fill rate, and code requirements, the task of assigning costs for CNG infrastructure was challenging. As part of a previous FTA study, researchers gathered data on CNG facility cost and found the following information.(*5*) CNG infrastructure costs include two costs—one for depot modification and another for the refueling station. The available data from this FTA study have very wide ranges on both costs: depot modification costs were found to be $500,000 to $15 million and refueling station costs were found to be $320,000 to $7.4 million. The report also had $875,000 for depot modification and $2 million for refueling station cost, as based on a 100-bus purchase. Noting the lack of available data, the cost of electricity for compression ($0.14/DEG [diesel equivalent gallon]) was calculated and is considered the only additional cost for a CNG station. Hence, CNG infrastructure cost for a 100-bus purchase is $2,875,000 and the additional maintenance cost is about $198,000 per year (assuming that CNG buses run 37,000 miles per year at 2.62 miles/DEG). The infrastructure maintenance cost is about 6.8% of the infrastructure cost. The results are fairly close to those from the method developed for the LCCM as described below.

The research team also held discussions regarding CNG infrastructure with agencies of varying sizes operating CNG buses, as well as with representatives from CNG organizations including the Natural Gas Vehicle Institute, NGVAmerica, Trillium, and Clean Energy. After reviewing CNG infrastructure costs from these sources, the team developed a formula by assigning an infrastructure cost of $1 million and then adding $15,000 for each CNG bus purchased. This formula calculates the default CNG infrastructure cost. The low and high costs show a 20% reduction and increment, respectively, to the default cost. Included in these costs are the costs associated with constructing a fueling facility and modifications needed for maintenance and storage facilities such as methane detection, ventilation, electrical modifications, and other needed modifications. Infrastructure maintenance costs are identified separately in the model and are described below. In the case of any expected infrastructure expenses for diesel and HEB, the user has the ability to include the cost.

Using this formula, the following mid-range infrastructure costs are assigned to the representative CNG fleet sizes:

- CNG bus fleet of 25: $1 million + $375,000 = $1,375,000,
- CNG bus fleet of 50: $1 million + $750,000 = $1,750,000,
- CNG bus fleet of 100: $1 million + $1.5 million = $2.5 million, and
- CNG bus fleet of 200: $1 million + $3 million = $4 million.

Additional costs related to the CNG facility are the extra electricity expense to operate the CNG fueling compressors, the cost to rebuild them, and other special operational needs for the CNG fueling facility. Costs varied with each location and the approach used to power compressors but, in the end, 6% of the overall CNG infrastructure cost is used to reflect annual CNG facility maintenance and operating costs. The cost is the differential expense. In other words, the model does not consider the facility maintenance costs for diesel and gasoline bus operation, and assumes no cost associated with them. It should be noted that some CNG providers had arrangements whereby infrastructure and/or annual maintenance and operating costs are included in unit price of the delivered CNG. Subsidies and incentives also are offered to offset CNG infrastructure cost. All of these factors must be considered when the model user either accepts the default value or assigns other CNG infrastructure costs that represent their specific circumstances.

Extended Powertrain Warranty Cost

As noted previously in the section on vehicle costs, the price of all three bus types includes the standard warranty of only one year for the entire vehicle and two years for the drivetrain. Acknowledging that extended drivetrain warranties are popular, the LCCM itemizes these warranties as separate cost items.

Extended powertrain warranty costs are based on how many years of warranty coverage is desired. The cost of the first two years of powertrain warranty coverage is assumed to be included in the original bus purchase price. Costing information is obtained from hybrid OEMs, bus OEMs, and transit agencies. The default (mid-range) cost for extended propulsion warranty coverage provided in the LCCM accounts for the average cost from those providing data.

Extended powertrain warranty costs for hybrid buses encompass coverage for the entire hybrid propulsion system including the APU and ICE. Based on information provided by the hybrid OEMs, a 20% reduction in extended powertrain warranty costs is assumed for purchases made in 2012 because of anticipated improvements in reliability. Extended powertrain warranty costs for diesel and CNG buses cover the ICE and more conventional automatic transmission.

Calculating the actual cost of an extended warranty was somewhat difficult for several reasons. Bus OEMs typically purchased warranties from powertrain vendors, and the OEMs might or might not mark-up those costs to the agency, or may even decide to discount extended warranty costs because of other aspects of a procurement. In addition, because of the competitive nature of bus procurements, some OEMs were reluctant to share detailed warranty costing information. Regardless of sensitivities involved with warranties, all information obtained from OEMs and agencies was analyzed and the ranges used are believed to be representative.

Using a diesel bus as the baseline, extended drivetrain warranty costs for CNG are estimated at 10% higher than diesel, while extended powertrain warranty coverage costs for hybrid buses are much higher (158% to 460%) than diesel. As mentioned above, extended powertrain warranty costs for hybrid purchases made in 2012, however, fell because of anticipated improvements in reliability (106% to 348% higher than diesel in 2007 dollars). The model considers a three-year extended warranty as the default setting. Table 2.4 presents the costs for a three-year warranty for three bus technologies.

Training Cost

Training costs for both operators and mechanics are based on training needed above and beyond what would be required for a traditional diesel bus (i.e., no additional training costs are assumed for diesel buses). All costs are based on the number of trainees and their labor rates (default rates are $50 per hour for both operators and mechanics), and include safety training. With the exception of a CNG bus purchase, which requires 0.5 hours per operator per year for annual safety training, all costs are one-time expenses required only when buses first arrive (i.e., refresher training costs are not included). It is possible that high-voltage electric safety training might emerge for hybrid vehicles, but this is left for the user to quantify.

The research team obtained training labor costs from bus OEMs and transit agencies that have undergone training for CNG and hybrid buses. Since CNG and hybrid bus systems are designed to be relatively seamless to the driver, operator training for both groups is minimal (0.5 to 4.0 hours per operator) and consists primarily of safety training. Maintenance training, also calculated as the number of incremental hours over standard diesel training, ranges from 8 to 12 additional hours per mechanic for CNG, and 16 to 20 additional hours per mechanic for hybrid buses. Agencies should enter the

Table 2.4. Three-year extended warranty costs for buses.

	Diesel	CNG	Hybrid	
Year	2007/2010	2007/2010	2007	2010
Low	$6,000	$6,600	$15,500	$12,400
Medium	$6,750	$7,425	$25,000	$20,000
High	$7,500	$8,250	$42,000	$33,600

Table 2.5. Training hours for bus operators and mechanics.

	Diesel	CNG	Hybrid
Operators—Low	0 hours	0.5 hour + 0.5 hours/year*	1 hour
Operators—Medium	0 hours	1 hour + 0.5 hours/year*	2 hours
Operators—High	0 hours	1.5 hour + 0.5 hours/year*	4 hours
Mechanics—Low	0 hours	8 hours	16 hours
Mechanics—Medium	0 hours	10 hours	18 hours
Mechanics—High	0 hours	12 hours	20 hours

Note: *This additional 0.5 hours/year is required annually for safety training; all other hours are one-time expenses.

number of operators and mechanics that require training and their labor rates, and the LCCM will make the appropriate calculations for each bus type. The default number of operators is the number of new buses, and the default number of mechanics is 20% of the purchase number. The required training hours are presented in Table 2.5.

Vehicle Fuel Cost

Since fuel cost is one of largest operating costs for a transit agency, this cost category called for detailed study in formulating the model. As shown in the following equation, a bus life cycle fuel cost involves fuel price, bus fuel economy, bus life travel mileage, and fuel credits and taxes.

$$\text{Bus Life Cycle Fuel Cost} = \frac{\text{Life Travel Mileage}}{\text{FE} \times (\text{Fuel Price} + \text{Taxes} - \text{Credits})}$$

The bus life-cycle fuel cost is in dollar units. The unit of bus life travel mileage is the mile. FE is expressed in miles per DEG. Fuel price, tax, and credits use the same dollar per gallon unit. The following sections address how future fuel price and fuel economy are estimated. A brief description of fuel tax and credits is also included.

Fuel Price Forecast (2007–2030). Bus life fuel cost requires long-term fuel price estimation that extends 12 years or more. The model utilizes forecasts made by a number of fuel and energy studies.(*6–14*) The following two sections show how to approach the low, high, and default price values for diesel, gasoline, and CNG fuels.

Diesel and Gasoline Prices. The research team found few direct diesel and gasoline price predictions. Both fuel prices are tied closely to crude oil price. Imbalance in the gasoline/diesel demand ratio may affect fuel prices in the long term. Twelve different crude oil price studies conducted by different organizations were reviewed by the research team. The original prices (dollar per barrel) are presented in Table 2.6.

The research team made the following adjustments to obtain the gasoline and diesel price data:

- For discrete data (such as Studies 2 through 7 and 10), linear interpolation is used to create the intermediate year value between the available values.
- All prices are adjusted to 2007 dollars by using the domestic consumer price index (CPI) provided by the Department of Labor at the time of this research effort (Table 2.7).
- All pre-2006 prices are not considered.
- Year 2006 oil price (known value) is used as the baseline price. All projection prices in 2006 are aligned to the baseline price by shifting their price curves up or down. So, all prediction trends were preserved. The baseline 2006 oil price is the price recorded in the 2007 Annual Energy Outlook (AEO), prepared by EIA (a part of DOE).

These adjustments yielded 12 projections with the same start-year (2006) and start-price ($73.25 $/barrel). Table 2.8 shows the adjusted crude oil prices. The default value uses a weighted average of these 12 projections. The most recent and comprehensive 2007 AEO value has a weight of 50% in the averaging and the remaining 11 predictions are weighted evenly, at 4.55% each (50% total for eleven predictions). The low value for each year is selected as the minimum value from any of the 12 sources for that year. Similarly, the high value is the maximum possible price. Table 2.8 shows the three values in 2007 dollars from 2007 to 2030. Clearly, it is not possible to project the substantial swings in fuel price seen in 2008, and confidence in the model rests on the prediction accuracy averaged over the whole bus life.

Diesel and gasoline prices are obtained by applying a diesel-to-oil price factor and a gasoline-to-oil price factor to the crude oil price (low, default, and high). The two factors were again adopted from the 2007 AEO, which projected transportation diesel and gasoline price as well as the price of crude oil. As Table 2.9 shows, the two yearly factors are the ratio of year-by-year diesel and gasoline price ($/gallon) to crude oil price ($/barrel). The factors are about 4% and decrease in the future (i.e., the fuel production cost is projected to decrease). Using

Table 2.6. Crude oil price projections ($/barrel).

	Study 1 EIA 2007	Study 2 GII	Study 3 IEA	Study 4 EEA	Study 5 DB	Study 6 SEER	Study 7 EVA	Study 8 EU	Study 9 Texas	Study 10 GEM	Study 11 OPEC	Study 12 Delphi
1997												$19.77
1998												$19.57
1999												$19.49
2000										$28.00		$19.53
2001												$19.82
2002												$20.10
2003												$20.29
2004	$42.87											$20.50
2005	$56.76										$50.00	$20.72
2006	$69.11							$20.00	$51.88		$45.00	$20.86
2007	$66.71							$20.00	$47.25		$37.00	$21.05
2008	$64.09							$21.00	$44.13		$31.00	$21.24
2009	$60.91							$22.40	$43.69		$27.00	$21.45
2010	$57.47	$57.11	$51.50	$56.94	$39.66	$44.21	$42.28	$24.00	$43.25	$50.00	$25.00	$21.67
2011	$54.33							$24.40	$43.90		$25.00	$21.94
2012	$51.71							$24.80	$44.32		$25.00	$22.21
2013	$49.99							$25.20	$44.27		$25.00	$22.49
2014	$49.64							$25.60	$44.08		$25.00	$22.79
2015	$49.87	$46.54	$47.80	$49.80	$40.11	$45.27	$42.35	$26.00	$43.88		$25.00	$23.10
2016	$49.75							$26.50	$44.15		$25.00	$23.41
2017	$50.80							$27.00	$44.66		$25.00	$23.74
2018	$51.28							$27.70	$45.18		$25.00	$24.07
2019	$51.95							$28.20	$45.72		$25.00	
2020	$52.04	$45.06	$50.20	$47.42	$39.73	$45.87	$45.76	$29.00	$46.28	$47.00	$25.00	
2021	$52.73							$29.18	$48.50		$25.00	
2022	$53.43							$29.66	$50.13		$25.00	
2023	$54.90							$30.14	$52.19		$25.00	
2024	$55.64							$30.62	$53.50		$25.00	
2025	$56.37	$43.21	$52.60	$45.16	$39.95	$46.23	$49.45	$31.10	$55.56		$25.00	
2026	$57.11							$31.86	$57.09		$25.00	
2027	$57.63							$32.62	$58.67		$25.00	
2028	$58.12							$33.38	$60.14		$25.00	
2029	$58.61							$34.14	$61.55		$25.00	
2030	$59.12	$40.25	$55.00		$40.16	$46.60		$35.00	$63.30	$60.00	$25.00	

Notes: Projections are not adjusted to 2007 dollars, and each projection has its own baseline year; all price projections are in 2005 dollars except EU (1995 dollars), GEM (2000 dollars), and Delphi (1997 dollars); EIA = Energy Information Administration(*6*); GII = Global Insight, Inc.(*6*); IEA = International Energy Agency(*6*); EEA = Economic and Environmental Analysis, Inc.(*6*); DB = Deutsche Bank AG(*6*); SEER = Strategic Energy and Economic Research, Inc.(*6*); EVA = Energy Ventures Analysis, Inc.(*6*); EU = European Union (European Commission)(*7*); Texas = Texas Comptroller's Revenue Estimating Division(*8*); GEM = German Economy Ministry(*9*); OPEC = Organization of the Petroleum Exporting Countries(*10*); Delphi = 1997 Delphi IX Oil Price Survey(*11*).

Table 2.7. Consumer price index used to adjust crude oil and CNG price to 2007 dollars.

Years	Inflation Rate
1995 to 2007	1.36
1997 to 2007	1.29
2000 to 2007	1.20
2002 to 2007	1.15
2005 to 2007	1.06

Note: CPI calculated by Department of Labor inflation calculator at http://www.bls.gov/cpi/ accessed on May 21, 2007.

Table 2.8. Adjusted crude oil price projections and final oil price projection data (2007–2030 in $/barrel) in 2007 dollars.

	Study 1 EIA 2007	Study 2 GII	Study 3 IEA	Study 4 EEA	Study 5 DB	Study 6 SEER	Study 7 EVA	Study 8 EU	Study 9 Texas	Study 10 GEM	Study 11 OPEC	Study 12 Delphi	Min.	Weighted Average	Max.
2006	$73.25	$73.25	$73.25	$73.25	$73.25	$73.25	$73.25	$73.25	$73.25	$73.25	$73.25	$73.25	$73.25	$73.25	$73.25
2007	$70.71	$70.07	$68.59	$70.03	$65.45	$66.66	$66.14	$73.25	$65.51	$75.89	$62.55	$73.50	$62.55	$69.79	$75.89
2008	$67.94	$66.89	$63.92	$66.80	$57.65	$60.06	$59.03	$74.61	$62.39	$78.53	$56.55	$73.74	$56.55	$66.71	$78.53
2009	$64.56	$63.72	$59.26	$63.58	$49.84	$53.46	$51.93	$76.52	$61.95	$81.17	$52.55	$74.01	$49.84	$63.55	$81.17
2010	$60.92	$60.54	$54.59	$60.36	$42.04	$46.86	$44.82	$78.69	$61.51	$83.81	$50.55	$74.30	$42.04	$60.37	$83.81
2011	$57.59	$58.30	$53.81	$58.84	$42.14	$47.09	$44.83	$79.24	$62.16	$83.45	$50.55	$74.65	$42.14	$58.57	$83.45
2012	$54.82	$56.05	$53.02	$57.33	$42.23	$47.31	$44.85	$79.78	$62.58	$83.09	$50.55	$74.99	$42.23	$57.04	$83.09
2013	$52.99	$53.81	$52.24	$55.82	$42.33	$47.54	$44.86	$80.32	$62.53	$82.73	$50.55	$75.36	$42.33	$55.95	$82.73
2014	$52.61	$51.57	$51.45	$54.30	$42.42	$47.76	$44.88	$80.87	$62.34	$82.37	$50.55	$75.74	$42.42	$55.59	$82.37
2015	$52.86	$49.33	$50.67	$52.79	$42.52	$47.99	$44.89	$81.41	$62.14	$82.01	$50.55	$76.14	$42.52	$55.54	$82.01
2016	$52.73	$49.02	$51.18	$52.28	$42.44	$48.11	$45.61	$82.09	$62.41	$81.65	$50.55	$76.54	$42.44	$55.54	$82.09
2017	$53.85	$48.70	$51.69	$51.78	$42.36	$48.24	$46.34	$82.77	$62.92	$81.29	$50.55	$76.97	$42.36	$56.18	$82.77
2018	$54.35	$48.39	$52.19	$51.27	$42.27	$48.37	$47.06	$83.72	$63.44	$80.93	$50.55	$77.39	$42.27	$56.52	$83.72
2019	$55.07	$48.08	$52.70	$50.77	$42.19	$48.50	$47.78	$84.40	$63.98	$80.57	$50.55		$42.19	$56.01	$84.40
2020	$55.17	$47.76	$53.21	$50.27	$42.11	$48.62	$48.51	$85.49	$64.54	$80.21	$50.55		$42.11	$56.15	$85.49
2021	$55.90	$47.37	$53.72	$49.79	$42.16	$48.70	$49.29	$85.74	$66.76	$81.77	$50.55		$42.16	$56.74	$85.74
2022	$56.64	$46.98	$54.23	$49.31	$42.21	$48.77	$50.07	$86.39	$68.39	$83.33	$50.55		$42.21	$57.33	$86.39
2023	$58.20	$46.59	$54.74	$48.83	$42.25	$48.85	$50.85	$87.04	$70.45	$84.89	$50.55		$42.25	$58.35	$87.04
2024	$58.98	$46.19	$55.25	$48.35	$42.30	$48.93	$51.63	$87.70	$71.76	$86.45	$50.55		$42.30	$58.94	$87.70
2025	$59.76	$45.80	$55.76	$47.87	$42.35	$49.00	$52.42	$88.35	$73.82	$88.01	$50.55		$42.35	$59.57	$88.35
2026	$60.54	$45.18	$56.26		$42.39	$49.08		$89.38	$75.35	$89.57	$50.55		$42.39	$61.38	$89.57
2027	$61.08	$44.55	$56.77		$42.44	$49.16		$90.42	$76.93	$91.13	$50.55		$42.44	$61.91	$91.13
2028	$61.60	$43.92	$57.28		$42.48	$49.24		$91.45	$78.40	$92.69	$50.55		$42.48	$62.43	$92.69
2029	$62.13	$43.29	$57.79		$42.53	$49.32		$92.48	$79.81	$94.25	$50.55		$42.53	$62.94	$94.25
2030	$62.67	$42.67	$58.30		$42.57	$49.40		$93.65	$81.56	$95.81	$50.55		$42.57	$63.49	$95.81

Notes: All 2006 data use EIA 2006 data as the baseline; all price projections are in 2007 dollars.

Table 2.9. Factors used to convert crude oil price to untaxed diesel and gasoline prices.

	Diesel–Oil Price Factor	Gasoline–Oil Price Factor
2007	4.05%	3.86%
2008	3.90%	3.77%
2009	3.90%	3.73%
2010	4.01%	3.78%
2011	4.04%	3.85%
2012	4.08%	3.96%
2013	4.17%	4.02%
2014	4.09%	3.93%
2015	4.08%	3.91%
2016	4.17%	3.93%
2017	4.07%	3.88%
2018	4.05%	3.86%
2019	4.08%	3.89%
2020	4.06%	3.88%
2021	4.02%	3.86%
2022	4.05%	3.87%
2023	3.86%	3.74%
2024	3.85%	3.73%
2025	3.87%	3.73%
2026	3.80%	3.64%
2027	3.81%	3.64%
2028	3.85%	3.66%
2029	3.80%	3.63%
2030	3.82%	3.64%

Note: These factors convert $/barrel values for crude oil to $/gallon values for refined product.

these factors, final diesel and gasoline prices (low, default, and high) are calculated from the oil price (low, default, and high) and shown in Table 2.10 and Figure 2.1.

Compressed Natural Gas Price. Table 2.11 presents original CNG prices from 13 studies that predict the future price of different types of CNG, covering natural gas transportation price, commercial end user price, lower 48 (i.e., all U.S. states except Alaska and Hawaii) wellhead price, and Henry hub price. These data are then standardized to transportation natural gas price and appropriate year by applying the following adjustments:

- For discrete values, linear interpolation creates the intermediate values.
- Lawrence Berkeley National Laboratory (LBNL) and New York Mercantile Exchange, Inc. (NYMEX) present their CNG prices in terms of a nominal price. According to their description, the nominal prices are converted back to year 2000 dollars by using the EIA gross domestic product (GDP) chain-type price index. This methodology is applied to BPA data as well.
- All prices are adjusted into 2007 dollars using the domestic CPI provided by the Department of Labor at the time of this research (see Table 2.7).
- All price units are converted to dollars per diesel equivalent gallon ($/DEG). The conversion is based on energy equivalent content. A typical No. 2 diesel fuel has 129,800 BTU per gallon. One thousand cubic feet (or 1 mcf) of CNG has 1,028,000 BTU of energy. Hence 1 mcf of CNG is equal to 7.92 DEG, and 1 MMBTU (1 million BTU) equals 7.7 DEG (rounded).
- The 2006 average natural gas price (the price for transportation purposes) reported in the 2007 AEO report is selected as the baseline price. The other 12 prices are adjusted up or down to the same start price.

Table 2.10. Untaxed diesel and gasoline price forecast (2007–2030) in 2007 dollars.

	Diesel Price			Gasoline Price		
	Low	Default	High	Low	Default	High
2007	$2.54	$2.83	$3.08	$2.41	$2.69	$2.93
2008	$2.20	$2.60	$3.06	$2.13	$2.51	$2.96
2009	$1.94	$2.48	$3.16	$1.86	$2.37	$3.03
2010	$1.69	$2.42	$3.36	$1.59	$2.28	$3.17
2011	$1.70	$2.36	$3.37	$1.62	$2.26	$3.21
2012	$1.72	$2.33	$3.39	$1.67	$2.26	$3.29
2013	$1.77	$2.33	$3.45	$1.70	$2.25	$3.33
2014	$1.74	$2.27	$3.37	$1.67	$2.19	$3.24
2015	$1.74	$2.27	$3.35	$1.66	$2.17	$3.21
2016	$1.77	$2.31	$3.42	$1.67	$2.18	$3.23
2017	$1.72	$2.28	$3.37	$1.64	$2.18	$3.21
2018	$1.71	$2.29	$3.39	$1.63	$2.18	$3.23
2019	$1.72	$2.29	$3.45	$1.64	$2.18	$3.29
2020	$1.71	$2.28	$3.47	$1.63	$2.18	$3.32
2021	$1.70	$2.28	$3.45	$1.63	$2.19	$3.31
2022	$1.71	$2.32	$3.49	$1.63	$2.22	$3.35
2023	$1.63	$2.25	$3.36	$1.58	$2.18	$3.26
2024	$1.63	$2.27	$3.38	$1.58	$2.20	$3.27
2025	$1.64	$2.30	$3.42	$1.58	$2.22	$3.29
2026	$1.61	$2.33	$3.40	$1.54	$2.24	$3.26
2027	$1.62	$2.36	$3.47	$1.54	$2.25	$3.32
2028	$1.64	$2.40	$3.57	$1.55	$2.28	$3.39
2029	$1.62	$2.39	$3.58	$1.54	$2.28	$3.42
2030	$1.63	$2.42	$3.66	$1.55	$2.31	$3.49

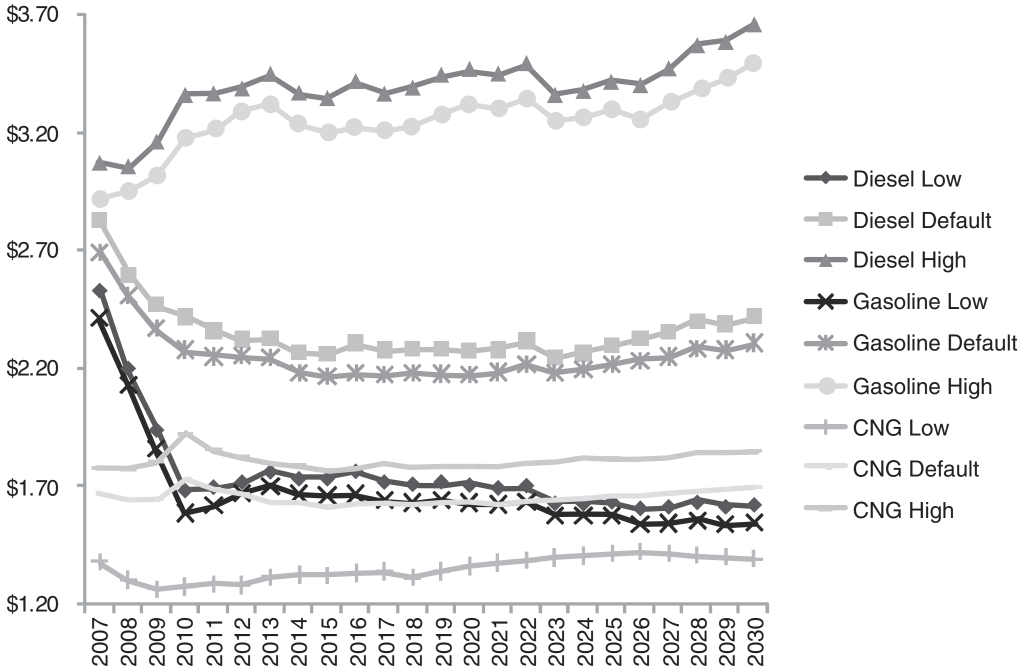


Figure 2.1. Future fuel price projection.

Table 2.12 shows the adjusted CNG prices from different studies. Similar to the crude oil price, natural gas default price uses the weighted average (50% to IEA price and 50% to the rest). The yearly minimum and maximum prices are for the low and high CNG price per year. Figure 2.1 presents the CNG projection prices from year 2007 to year 2030.

Fuel Taxes, Subsidies, and Incentives. The model provides tools for the user to compensate for fuel taxes and incentives. Since situations could vary widely for different agencies, the default values are presented as an average value for federal and states taxes (Table 2.13). The default local tax is set to zero in the model. The average value is chosen to allow a national LCC assessment by a user if no specific values are entered. The research team recognized that some transit operations may benefit from reduced taxes, but calculating this requires user entry.

Incentives are another issue for fuel pricing. Currently, CNG has a fuel tax credit from the SAFETEA-LU transportation legislation. This is equal to $0.50/GEG at the time of this writing and is planned to be in effect until 2009. Thus, the timespan for this credit, in addition to the amount of credit, is included in the model. The default fuel incentive in LCCM is zero.

Fuel Economy Model

The researchers used FE data from DOE (*15*) and U.S. DOT-funded chassis dynamometer testing of buses on various cycles over a wide range of average cycle speeds. In-use FE data show a lower FE (lower mpg) than the chassis data. This higher fuel consumption can be attributed in part to additional bus idling that is not reflected in the average speed of a bus route. In other words, for the chassis data, the average bus speed is for the cycle (mimicking a route) alone, but for the field data the average bus speed includes both revenue and non-revenue service, and the fuel consumed reflects use during idling or low-speed operation at the depot as well as on the route and during deadheading without passengers. Other causes contributing to the difference between fuel consumption in the field and on the chassis dynamometer include the possible use of air conditioning, heating (if the bus is equipped with auxiliary burners), cold starting, and fan loads that do not correspond to the chassis dynamometer fan loads. Also, chassis dynamometer data do not take into account the adverse effects of terrain that is not flat. Of course, bus technology would also cause the fuel consumed to vary. For example, chassis data collected from the New Flyer buses at WMATA, which are powered by a Cummins ISM diesel engine, may not be representative of all the diesel buses in the field study.

The in-use FE data from all four test sites (see site information and technologies in Section 1.3) are for 40-ft long buses except for the KC Metro buses. If the KC Metro data are to be of use in estimating 40-ft bus fuel economy, they would need to be adjusted for the difference in bus size. The bus size correction adopts the conclusion from Clark et al.(*16*) that the weight difference between the 60-ft bus and 40-ft bus could be used for the adjustment. The fuel consumption (gallon per

Table 2.11. Original CNG price projections from different studies.

	Study 1 EIA 2007	Study 2 GII	Study 3 EVA	Study 4 EEA	Study 5 DB	Study 6 SEER	Study 7 Altos	Study 8 EEA	Study 9 Texas	Study 10 NYMEX	Study 11 BPA	Study 12 LBNL 1	Study 13 LBNL 2
Type of CNG	**Transportation**	**Commercial End-User Prices**	**Lower 48 Wellhead Price**	**Commercial End-User Prices**	**Lower 48 Wellhead Price**	**Commercial End-User Prices**	**Lower 48 Wellhead Price**	**Henry Hub Price**	**NA**	**Henry Hub Price**	**Henry Hub Price**	**Henry Hub Price**	**Henry Hub Price**
$ Year	**2005**	**2005**	**2005**	**2005**	**2005**	**2005**	**2005**	**2002**	**2005**	**Nominal**	**Nominal**	**Nominal**	**Nominal**
Unit	**$/mcf**	**$/mcf**	**$/mcf**	**$/mcf**	**$/mcf**	**$/mcf**	**$/mcf**	**$/MMbtu**	**$/mcf**	**$/MMbtu**	**$/MMbtu**	**$/MMbtu**	**$/MMbtu**
2002								$3.36					
2003								$5.29					
2004	$12.28							$4.51					
2005	$15.20	$11.54	$7.51	$11.54	$7.51	$11.54	$7.51	$5.57					
2006	$12.34							$3.90	$7.92		$6.66		
2007	$12.65							$4.18	$5.91	$8.40	$7.06	$8.40	$8.40
2008	$12.50							$3.45	$5.33	$8.48	$6.76	$8.48	$8.48
2009	$12.69							$4.93	$5.06	$8.10	$5.65	$8.10	$8.10
2010	$14.38							$4.22	$5.14	$7.65	$5.24	$7.65	$7.65
2011	$13.91							$5.10	$5.21	$7.20	$5.20	$7.20	$7.20
2012	$13.69							$4.88	$5.19		$5.51	$6.90	$7.10
2013	$13.44							$3.30	$5.43		$5.77	$6.65	$7.00
2014	$13.33							$4.87	$5.49		$6.09	$6.55	$7.22
2015	$13.25	$10.05	$5.55	$9.98	$6.07	$8.83	$5.60	$4.43	$5.50		$6.56	$6.61	$7.28
2016	$13.28							$4.24	$5.56		$6.72	$6.82	$7.49
2017	$13.42							$4.20	$5.64			$7.25	$7.92
2018	$13.34							$4.33	$5.42			$7.25	$7.92
2019	$13.33							$4.40	$5.62			$7.30	$7.97
2020	$13.36							$4.64	$5.76			$7.52	$8.19
2021	$13.34								$5.94			$7.61	$8.28
2022	$13.47								$6.12			$8.00	$8.67
2023	$13.50								$6.31			$8.40	$9.07
2024	$13.59								$6.51			$8.70	$9.37
2025	$13.62	$10.02	$6.06	$10.08	$5.71	$9.51	$6.96		$6.71			$8.80	$9.47
2026	$13.57								$6.91			$9.15	$9.82
2027	$13.64								$7.13			$9.50	$10.17
2028	$13.76								$7.35			$9.95	$10.62
2029	$13.80								$7.58			$10.25	$10.92
2030	$13.86	$9.81			$5.45	$9.96	$7.55		$7.81			$10.50	$11.17

Notes: EIA = Energy Information Administration(*6*); GII = Global Insight, Inc.(*6*); EVA = Energy Ventures Analysis, Inc.(*6*); EEA = Economic and Environmental Analysis, Inc.(*6*); DB = Deutsche Bank AG(*6*); SEER = Strategic Energy and Economic Research, Inc.(*6*); Altos = Altos Management Partners, Inc.(*6*); EEA = Energy and Environmental Analysis(*12*); Texas = Texas Comptroller's Revenue Estimating Division(*8*); NYMEX = New York Mercantile Exchange, Inc.(*13*); BPA = Bonneville Power Administration(*14*); and LBNL = Lawrence Berkeley National Laboratory(*13*).

Table 2.12. Adjusted CNG price projections and final CNG price projection data (2007–2030) in $/DEG using 2007 dollars.

Year	EIA 2007	GII	EVA	EEA	DB	SEER	Altos	EEA	Texas	NYM EX	BPA	LBNL 1	LBNL 2	Min.	Weighted Average	Max.
2007	$1.69	$1.63	$1.63	$1.63	$1.63	$1.62	$1.63	$1.69	$1.38	$1.78	$1.68	$1.78	$1.78	$1.38	$1.67	$1.78
2008	$1.67	$1.61	$1.60	$1.61	$1.61	$1.58	$1.60	$1.58	$1.31	$1.77	$1.63	$1.77	$1.77	$1.31	$1.65	$1.77
2009	$1.70	$1.59	$1.57	$1.59	$1.59	$1.54	$1.58	$1.81	$1.27	$1.70	$1.47	$1.70	$1.70	$1.27	$1.65	$1.81
2010	$1.93	$1.57	$1.55	$1.57	$1.57	$1.51	$1.55	$1.70	$1.28	$1.63	$1.41	$1.63	$1.63	$1.28	$1.74	$1.93
2011	$1.86	$1.55	$1.52	$1.55	$1.56	$1.47	$1.52	$1.83	$1.29	$1.56	$1.39	$1.56	$1.56	$1.29	$1.70	$1.86
2012	$1.83	$1.53	$1.49	$1.53	$1.54	$1.43	$1.50	$1.80	$1.29		$1.42	$1.51	$1.53	$1.29	$1.67	$1.83
2013	$1.80	$1.51	$1.47	$1.51	$1.52	$1.40	$1.47	$1.56	$1.32		$1.44	$1.46	$1.50	$1.32	$1.63	$1.80
2014	$1.78	$1.49	$1.44	$1.48	$1.50	$1.36	$1.45	$1.80	$1.33		$1.47	$1.44	$1.52	$1.33	$1.63	$1.80
2015	$1.77	$1.47	$1.42	$1.46	$1.48	$1.33	$1.42	$1.73	$1.33		$1.51	$1.43	$1.51	$1.33	$1.62	$1.77
2016	$1.78	$1.47	$1.42	$1.47	$1.47	$1.33	$1.44	$1.70	$1.34		$1.51	$1.44	$1.52	$1.33	$1.62	$1.78
2017	$1.80	$1.47	$1.43	$1.47	$1.47	$1.34	$1.46	$1.70	$1.35			$1.48	$1.55	$1.34	$1.63	$1.80
2018	$1.79	$1.47	$1.44	$1.47	$1.46	$1.35	$1.48	$1.72	$1.32			$1.46	$1.54	$1.32	$1.63	$1.79
2019	$1.78	$1.47	$1.44	$1.47	$1.46	$1.36	$1.49	$1.73	$1.34			$1.45	$1.52	$1.34	$1.63	$1.78
2020	$1.79	$1.47	$1.45	$1.47	$1.45	$1.37	$1.51	$1.76	$1.36			$1.46	$1.53	$1.36	$1.64	$1.79
2021	$1.79	$1.47	$1.46	$1.47	$1.45	$1.38	$1.53		$1.39			$1.46	$1.53	$1.38	$1.62	$1.79
2022	$1.80	$1.47	$1.46	$1.47	$1.44	$1.39	$1.55		$1.41			$1.48	$1.55	$1.39	$1.64	$1.80
2023	$1.81	$1.47	$1.47	$1.47	$1.44	$1.40	$1.57		$1.44			$1.51	$1.57	$1.40	$1.64	$1.81
2024	$1.82	$1.47	$1.48	$1.48	$1.43	$1.41	$1.59		$1.46			$1.52	$1.58	$1.41	$1.65	$1.82
2025	$1.82	$1.47	$1.48	$1.48	$1.43	$1.42	$1.60		$1.49			$1.51	$1.57	$1.42	$1.66	$1.82
2026	$1.82	$1.46			$1.42	$1.43	$1.62		$1.52			$1.53	$1.59	$1.42	$1.66	$1.82
2027	$1.83	$1.46			$1.42	$1.44	$1.64		$1.55			$1.54	$1.60	$1.42	$1.67	$1.83
2028	$1.84	$1.45			$1.41	$1.45	$1.65		$1.58			$1.57	$1.63	$1.41	$1.69	$1.84
2029	$1.85	$1.45			$1.40	$1.46	$1.67		$1.61			$1.58	$1.63	$1.40	$1.69	$1.85
2030	$1.85	$1.44			$1.40	$1.48	$1.68		$1.64			$1.58	$1.64	$1.40	$1.70	$1.85

Notes: EIA = Energy Information Administration(*6*); GII = Global Insight, Inc.(*6*); EVA = Energy Ventures Analysis, Inc.(*6*); EEA = Economic and Environmental Analysis, Inc.(*6*); DB = Deutsche Bank AG(*6*); SEER = Strategic Energy and Economic Research, Inc.(*6*); Altos = Altos Management Partners, Inc.(*6*); EEA = Energy and Environmental Analysis(*12*); Texas = Texas Comptroller's Revenue Estimating Division(*8*); NYMEX = New York Mercantile Exchange, Inc.(*13*); BPA = Bonneville Power Administration(*14*); and LBNL = Lawrence Berkeley National Laboratory(*13*).

Table 2.13. Average federal and state fuel tax.

	Federal Tax	State Tax	Unit
Diesel	0.244	0.240	$/DEG
Gasoline	0.184	0.175	$/GEG
CNG	0.183	0.126	$/GEG

mile units) percent difference is close to half of the weight percent difference, calculated by assuming that both bus sizes are under half of their passenger load. *Half load* means that the bus weight includes the vehicle curb weight plus one driver and half of the seated passengers. Average passenger weight is assumed to be 150 lb. Table 2.14 shows the calculation formula and results (60-ft to 40-ft FE conversion factors) for KC Metro 60-ft diesel and diesel hybrid buses.

The limited number of test sites could not provide a complete range of FE data covering all operation speeds. However, recent WVU WMATA bus emissions and FE studies yield chassis dynamometer data from 16 different test cycles for diesel, CNG, and diesel hybrid buses. The average operation speed of the cycles ranges from 3.69 mph to 43.64 mph. The researchers determined that the LCC FE model, with a speed relationship generated from the chassis dynamometer data, would be adjusted to reflect in-field bus operation.

The model is not corrected for non-revenue fuel consumption. It is essential when considering average speed to know whether this speed is only for the route itself, or whether it includes idling, deadheading, or low-speed depot activity as well. It is the opinion of the research team that the average speed for all activity is close to the route speed, or that additional activity would generally lower the average speed slightly relative to the route speed. Idling detracts from speed, whereas deadheading would be expected to increase speed.

Weather effects (temperature and humidity) for FE are deduced from field data and studied and included in the FE model as a correction factor. These effects are addressed in a subsection below. Although the terrain effect could affect FE dramatically in very steep terrain, there is insufficient data available to be used to generate a reliable factor in the FE model. Clark et al.(*17*) concluded that terrain effects are small until grades are steep enough to require the use of brakes. It also would be a difficult task for a transit agency to find local geographic characteristics. Therefore, the terrain effects are omitted in the FE model and presented through the range of FE in the model.

Diesel Bus Fuel Economy. The four diesel bus sites do not yield a sufficiently high range of average speed for all LCC applications. WMATA yields different data for two routes, so a total of five pairs of speed and fuel economy data are available. These values are shown in Table 2.15, in which the KC Metro data have been adjusted to 40-ft bus equivalents.

Data on chassis dynamometer fuel economy for diesel buses (Cummins ISM engine) at WMATA are plotted against average cycle speed for 16 cycles. These data are fitted with a parabolic line to provide a trend against average operating speed. This line and the diesel chassis dynamometer data are shown in

Table 2.14. KC Metro FE conversion factor for 40- and 60-ft buses.

	40-ft Diesel	60-ft Diesel	40-ft Hybrid	60-ft Hybrid
Curb Weight	28,500 lb	41,500 lb	29,900 lb	43,700 lb
Number of Seats	40	64	39	62
Half Load [a]	31,650 lb	46,450 lb	33,050 lb	48,500 lb
FC_{60}/FC_{40} [b]	1 + 0.5 x (46,450-31,650) / 31,650 = 1.23		1 + 0.5 x (48,500-33,050) / 33,050 = 1.23	
FE_{60}/FE_{40} [c]	1 / 1.23 = 0.81		1 / 1.23 = 0.81	

Notes:

[a] Half Load = Curb Weight + (Half Number of Seats + 1 Driver) x 150; for calculation purposes, half load of the 39-passenger bus is rounded to 20 passengers.

[b] FC = Fuel consumption (gallons per mile).

[c] FE = Fuel economy (mpg).

Table 2.15. Comparison of field fuel economy and predicted fuel economy for diesel buses.

	Average Speed (mph)	Field FE (mpg)	Prediction FE (mpg)	Difference (%)
NYCT	6.35	2.33	2.20	-5.5%
KC Metro (40-ft equivalent)	12.25	3.15	3.11	-1.2%
LBT	13.80	3.45	3.31	-4.0%
WMATA-Montgomery route	17.10	3.53	3.69	4.5%
WMATA-Landover route	17.50	3.46	3.73	7.8%
			Average Difference %	0.3%

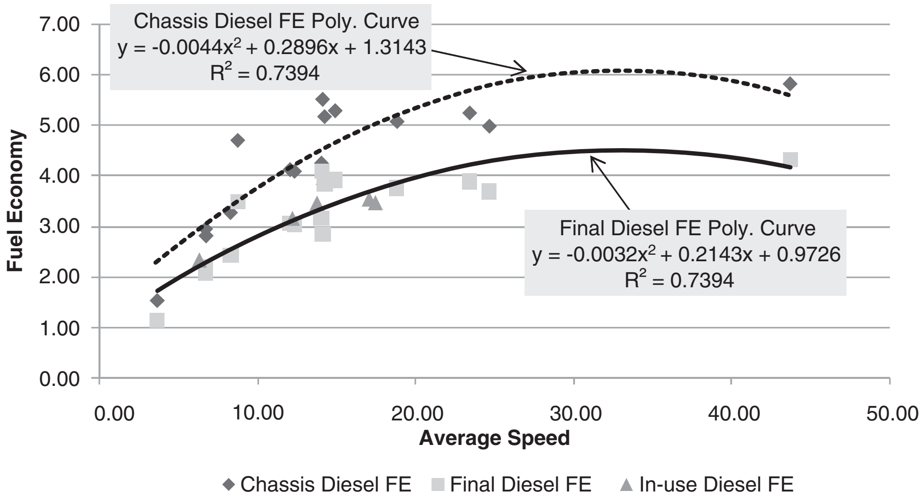


Figure 2.2. Diesel bus fuel economy data and parabolic trend lines.

Figure 2.2. The line was not forced through the origin, even though zero speed should imply zero mpg.

The study team assumed that a certain percentage of FE is lost due to air conditioner (A/C) or heating load, and that there also is a possible FE loss from terrain. An FE reduction ratio is used. In Figure 2.2, the solid line represents the final diesel bus in-use FE performance. It was created by reducing the overall FE curve by 26% from the chassis data (dotted line). A parabolic curve and equation shown in Figure 2.2 are used in the LCCM to predict diesel bus FE from the average speed.

The predicted in-field FE (calculated from the parabolic equation and operation speed) are compared to the real in-field FE, as shown in Table 2.15. The differences of five sites range from −5.5% to 7.8% with an average difference of 0.3%. The parabolic diesel FE equation is as follows:

$$\text{Diesel FE} = -0.003 \times \text{Speed}^2 + 0.214 \times \text{Speed} + 0.972$$

Diesel Hybrid Bus Fuel Economy. The same methodology is used for the diesel hybrid FE model. Three sites (NYCT, KC Metro, and WMATA) had diesel hybrid bus in-field FE data. KC Metro field FE data (60-ft diesel hybrid buses) are adjusted to relative 40-ft diesel bus FE by using a factor of 1.23 (found in Table 2.14). The WMATA site provided data for two distinct depots. Therefore, a total of four pairs of speed-FE data is available. Hybrid bus chassis dynamometer data were collected from WMATA diesel hybrid buses. For the hybrid bus case, a reduction percentage of 24.5% was found and applied to the chassis dynamometer data, as shown in Figure 2.3. In the figure, the dotted line represents a parabolic curve, created

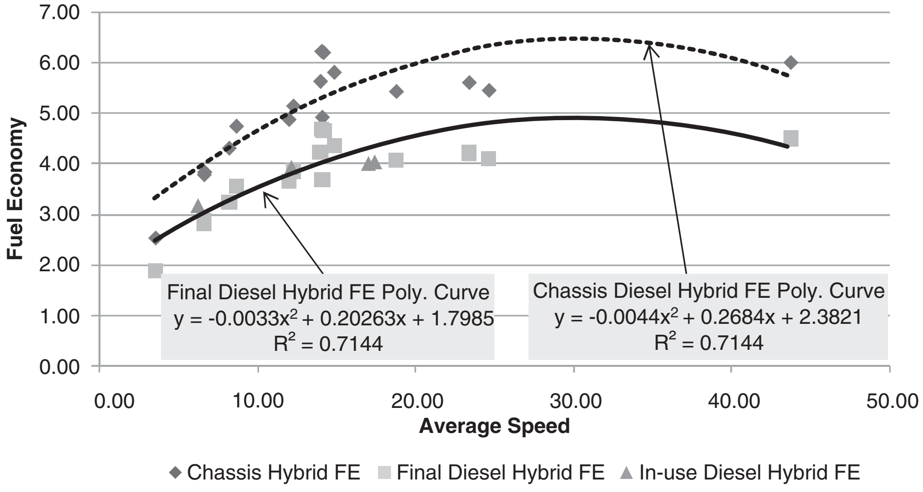


Figure 2.3. Diesel hybrid bus fuel economy data and parabolic trend lines.

Table 2.16. Comparison of field fuel economy and predicted fuel economy for diesel HEB.

	Average Speed (mph)	Field FE (mpg)	Prediction FE (mpg)	Difference (%)
NYCT	6.35	3.19	2.95	-7.5%
KC Metro	12.25	3.96	3.78	-4.5%
WMATA-Montgomery	17.10	4.04	4.29	6.3%
WMATA-Landover	17.50	4.07	4.33	6.4%
			Average Difference %	0.2%

from the adjusted data. The relative equation is the FE model for a hybrid bus, which is as follows:

$$FE = -0.003 \times Speed^2 + 0.202 \times Speed + 1.798$$

The ratio of differences between the chassis dynamometer data and field data is similar for conventional diesel and diesel hybrid buses (26% and 24.5%, respectively), which lends confidence to the process used for the LCC FE model.

The predicted FE values for diesel hybrid buses are compared to the real FE values for the sites in Table 2.16, which shows that the differences range from −7.5% to 6.4% and the average difference is 0.2%. In addition, the hybrid drive advantage for FE is compared for real and predicted cases in Table 2.17. The model represents the hybrid technology actual performance reasonably, but the NYCT FE ratio differs most from the prediction. The predicted 34% FE ratio is lower than the 48% found in practice in NYCT bus operation. This could reflect the effect of bus technology on FE and the problems associated with predicting FE at very low operating speeds.

CNG Bus Fuel Economy. All field and chassis CNG bus FE data are for lean-burn engines. It was difficult for the study team to construct the CNG bus FE model because of limited knowledge of the emerging stoichiometric CNG engine technology and inadequate field data. Since there were no published data on fuel economy benefit from stoichiometric technology, the model does not include any adjustment for this. The primary manufacturer of the stoichiometric technology has represented a small fuel economy improvement over lean-burn technology, but for throttled engines, the fuel economy ratio between the lean-burn and stoichiometric technology is likely to vary with engine load, and hence with average bus operating speed. As shown in Figure 2.4, the CNG final FE curve is adjusted using a pair of in-use FE operating points. The parabolic equation is as follows:

$$FE = -0.002 \times Speed^2 + 0.194 \times Speed + 0.552$$

The prediction equation matches the in-use data well, as shown in Table 2.18. For the two sites, the prediction differences are −0.8% and 1.2%. The model is tested further by using the 2006 NREL WMATA CNG bus study.(*18*) At the average speed of 11.6 mph, the prediction FE is 4% higher than the in-field FE. The CNG bus FE model is compared with the diesel FE model.

Table 2.19 presents the comparison results. At slow speeds, the FE of CNG buses is predicted to be 23% poorer than that of diesel buses, which compares to 27% poorer FE found in actual field operation. However, the field data were collected from old diesel and CNG buses. For the latest technology and at high speed, the field data suggest that CNG perform better than the model would predict—a 14% reduction is predicted and an 8% reduction is found in actual operation. However, the model represents a close match with the previous WMATA NREL study in which field data show a 17% reduction that corresponds to an 18% projection by the model. In the future, throttling losses, coupled with exhaust gas recirculation strategy, and influenced by bus gearing and operating speed, will continue to make CNG fuel economy more difficult to predict than diesel fuel economy.

Gasoline Hybrid Bus Fuel Economy. There is only one C-15 Program test site that operates gasoline hybrid buses, and there are no complete chassis dynamometer FE data available for gasoline hybrid buses. It is assumed that gasoline

Table 2.17. Comparison of diesel HEB FE advantage to diesel buses for field and prediction.

	Field FE: Hybrid to Diesel	Prediction FE: Hybrid to Diesel
NYCT	48%	34%
KC Metro	27%	22%
WMATA-Montgomery	14%	16%
WMATA-Landover	16%	16%

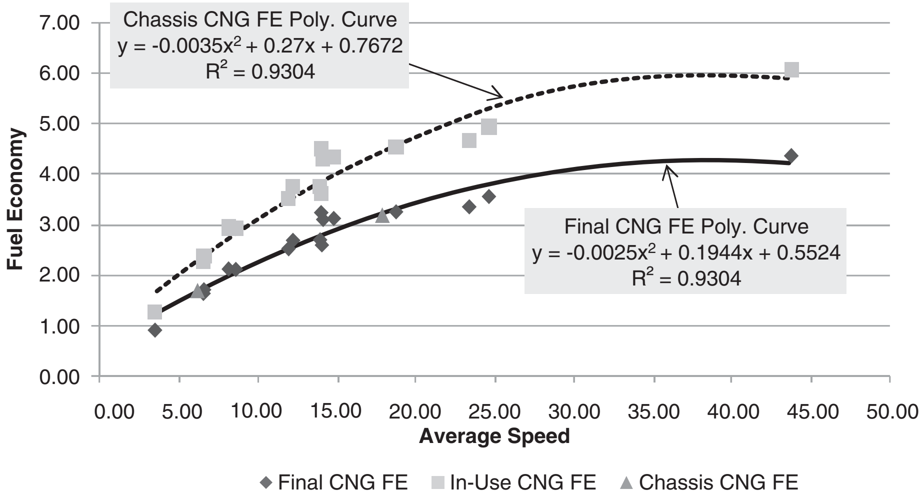


Figure 2.4. CNG bus fuel economy data and parabolic trend lines.

hybrid buses would exhibit similar behavior to diesel hybrid buses, although it is acknowledged that the gasoline engine might suffer lower FE at light loads due to throttling losses. The diesel hybrid final FE data (after adjustment) are adopted as baseline data to simulate gasoline field data. There is only one in-use gasoline HEB FE data point (3.71 mpg at 13.80 mph) available. If the diesel HEB curve is perfectly aligned to 3.71 mpg at 13.80 mph, the FE is 12% better than the diesel FE at that speed. The LBT gasoline HEB FE is found to be 7% better than diesel bus FE at LBT. The percentage was termed *the gasoline hybrid FE advantage.* Hence, the diesel HEB FE curve is reduced slightly more to 3.65 mpg, so that the gasoline FE advantage in the model becomes 10%, and moves closer to the field advantage (7%). The difference between estimated FE (3.65 mpg) and field FE (3.71 mpg) is 2%. As shown in Figure 2.5, the gasoline hybrid bus FE is created from a reduction of 8% from the diesel hybrid bus FE.

Hotel Load Effects on Fuel Economy. Hotel load effects (A/C and heat burner) are revealed by the bus FE performance at the test sites during all four seasons. Average monthly temperature is used as an indicator of how much the hotel load (particularly for air conditioning) is a factor. Although humidity is another important factor, humidity varies too widely within a season, and it is too complex for this model to predict FE using temperature and humidity together. The researchers adopted the following simple approach. The three coldest months and three hottest months were identified according to the historic city temperature record. The average FE values for cold and hot months are calculated separately and

Table 2.18. Comparison of field fuel economy and predicted fuel economy for CNG buses.

	Average Speed (mph)	Field FE (mpg)	Prediction FE (mpg)	Difference (%)
NYCT(*3*)	6.35	1.7	1.69	-0.8%
WMATA—Four Mile Run	17.90	3.19	3.23	1.2%
			Average Difference %	0.2%
WMATA(*18*)	11.60	2.37	2.47	4%

Note: The 2006 NREL study data (*18*) were not used in the FE model.

Table 2.19. Comparison of CNG buses FE penalty to diesel buses for field and prediction.

	Field FE: CNG to Diesel	Prediction FE: CNG to Diesel
NYCT(*3*)	-27%	-23%
WMATA—Four Mile Run*	-8%	-14%
WMATA(*18*)	-17%	-18%

Notes: *WMATA's Four Mile Run Depot did not operate diesel buses. The diesel FE was adopted from diesel buses operated at Landover Depot, which has an average operation speed of 17.50 mph. It is close to 17.90 mph at Four Mile Run.

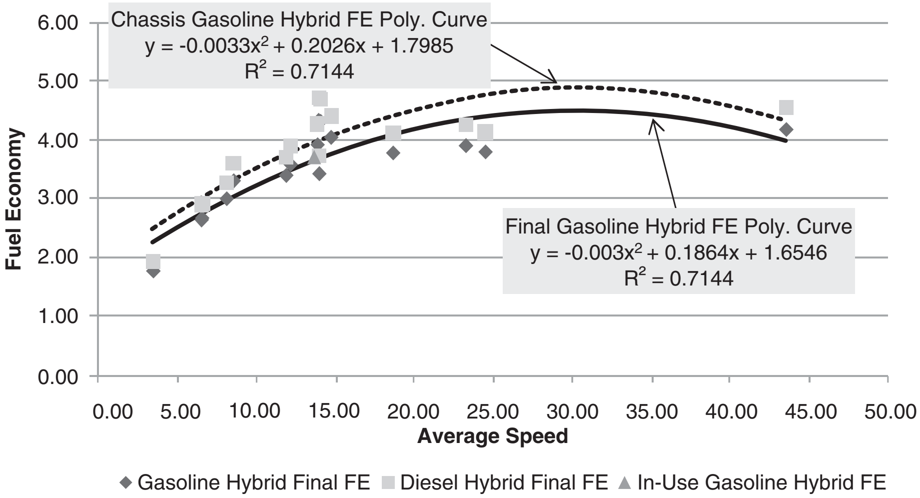


Figure 2.5. Gasoline hybrid bus fuel economy data and parabolic trend lines. The chassis curve was derived from diesel hybrid data.

compared to the yearly average FE. In most of the cases, transit buses were equipped with air conditioning systems. Generally, the coolest months had the highest FE (lowest fuel use), and the hottest months yielded the lowest FE. However, KC Metro buses presented opposing results. This was because although the KC Metro buses in Seattle spent extra fuel for burner heat during the cold season, mild summer temperatures did not make substantial use of air conditioning.

After the calculation, each site offers a low (3 months), default (12 months), and high (3 months) FE for four technologies. Low FE represents the maximum hotel load (A/C or heat burner) for the bus technology. Default represents bus usage in a temperate zone without extreme weather conditions and with modest A/C usage. High FE represents bus usage in a cold climate, where A/C is not used or perhaps not present on the bus. The heating burner is considered to be uncommon equipment for the U.S. bus fleet. Table 2.20 presents the performance for all four bus technologies (diesel, diesel hybrid, CNG, and gasoline hybrid) according to the climate at the four test sites. At the time that this LCC component was created, WMATA depots were not able to provide a complete one-year diesel FE data set. The FE data sets for the two hottest months were not available. However, the data set for the one remaining hot month is used for the low FE (high A/C use).

Unless the LCCM user is considering extreme climate conditions, or is using the model as a tool to predict FE performance for a specific hot or cold season, the default FE in the model reflects average yearly FE for most transit agencies. The four sites had no severe case, such as heavy use of both A/C and winter heat burner. The LCCM employs a scale for adjustment of FE by the user if atypical A/C or heater use are anticipated.

Major Component Replacement

Energy Storage System Rehabilitation. The cost of replacing the energy storage pack (for hybrid buses only) is calculated to include the labor to remove and replace (R&R) the major components at a rate of $50 per hour, along with miscellaneous supplies needed during the R&R process. Costs associated with replacing energy storage equipment are unique to hybrid buses and were obtained directly from the hybrid OEMs. Given the diverse mix of energy storage systems currently available on hybrid buses, costs range from those for lithium ion and nickel metal hydride batteries to ultra capacitors. Lead acid batteries, although currently used in some hybrid applications, are not considered in the model as a cost input because of the change to other energy storage devices being made for hybrids produced after 2007, thereby making lead acid batteries obsolete for current and future hybrid bus procurements. A difficult issue is raised by the probability that technological advances over the life of future buses are likely to be so great that advanced technology may be substituted at the time when rebuilding the original technology becomes necessary. However, there is no reasonable way to project the cost impacts of such events.

The average cost for energy storage equipment was determined to be $27,500, and the model bases high, low, and default cost on the expected life of the battery pack. The mid-cost value (default) assumes that each pack would last six years. The high cost value assumes a four-year battery life (more frequent replacements required during bus useful life), and the low cost value assumes an eight-year battery life.

In addition, the model does not simply assume that all battery packs would have to be replaced exactly at the projected end of their estimated life. Instead, the model assumes that a

Table 2.20. Hotel load effects on bus fuel economy.

Diesel Bus	Average (mpg)	High FE (mpg)	Low FE (mpg)	High to Average	Low to Average
NYCT—MCH	2.39	2.54	2.27	6%	-5%
NYCT—WF	2.28	2.35	2.17	3%	-5%
KC Metro-RB	2.95	3.02	2.79	2%	-5%
LBT	3.45	3.63	3.29	5%	-5%
WMATA—Montgomery	3.53	3.66	3.14	4%	-11%
WMATA—Landover	3.46	3.56	3.17	3%	-8%
			Average	4%	-7%
Diesel Hybrid Bus	**Average (mpg)**	**High FE (mpg)**	**Low FE (mpg)**	**High to Average**	**Low to Average**
NYCT—MCH	3.19	3.59	2.77	13%	-13%
KC Metro—AC Base	3.65	3.73	3.58	2%	-2%
WMATA—Montgomery	4.04	4.21	3.78	4%	-6%
WMATA-Landover	4.07	4.29	3.69	5%	-9%
			Average	6%	-8%
CNG Bus	**Average (mpg)**	**High FE (mpg)**	**Low FE (mpg)**	**High to Average**	**Low to Average**
NYCT—MCH	1.70	1.76	1.64	4%	-4%
WMATA—Old (Cummins)	2.36	2.5	2.23	6%	-6%
WMATA—Old (JD)	2.43	2.67	2.23	10%	-8%
WMATA—Four Mile Run	3.19	3.34	2.96	5%	-7%
			Average	6%	-6%
Gasoline Hybrid Bus	**Average (mpg)**	**High FE (mpg)**	**Low FE (mpg)**	**High to Average**	**Low to Average**
LBT	3.67	3.89	3.35	6%	-9%
			Average	6%	-9%

Notes: MCH = Mother Clara Hale (Depot); WF = West Farms (Depot); RB = Ryerson Base (Depot); and AC Base = Atlantic Base (Depot). JD = John Deere. Old refers to a previous study.(*18*)

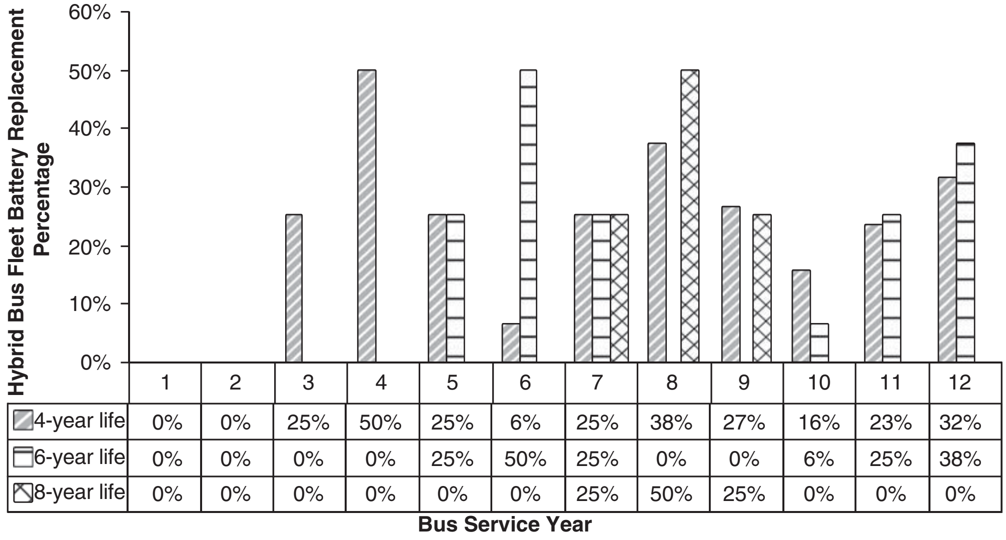
given battery pack (whether original or replaced) would have a 50% chance of failing during the year in which it was projected to fail, a 25% chance of failing one year earlier, and a 25% chance of failing one year later. Even if replacements were to be planned, a spread in the retrofit timespan might support this "25-50-25" assumption. The effect of compounding the assumption is shown in Figure 2.6.

For example, if a fleet were to have 80 new hybrid buses, and expected that their battery pack life is six years, Table 2.21 shows that 20 buses (25% of 80) would have their battery packs first replaced on the fifth year, 40 packs (50% of 80) would be replaced on the sixth year, and the remaining 20 packs (25% of 80) would need replacement on the seventh year. These replaced packs would follow the 25-50-25 rule. In the tenth year, 5 buses (25% of 20) would need their second replacement. In the eleventh year, 20 bus battery packs would be replaced. Ten of these would be from 50% of the fifth-year replacements and ten would be from 25% of the sixth-year replacements. Similarly, in the 12th year, 30 bus battery pack replacements would occur. The possibility of retrofits toward the end of bus useful life also provokes questions on early or late retirement of buses, but since policy would vary from site to site on bus retirement, no specific provisions are made in the LCC for adjusting bus retirement age. The bus life employed in the model is used regardless of the retrofit or replacement schedule.

The cost of a spare energy pack also is set at $27,500 for agencies that choose to keep one in inventory at all times. One spare energy pack per 20 hybrid buses is set as the default (middle-cost input), one spare pack per 30 buses represents the low-cost input, and one spare energy pack for every 10 hybrid buses represents the high-cost input.

Engine and Transmission Rehabilitation. Costs associated with rebuilding the ICE for all bus types, rebuilding automatic transmissions for diesel and CNG buses, and rebuilding the unique hybrid propulsion system are itemized separately. To achieve a level of consistency for all rebuilds, costing information was obtained from OEM-authorized rebuild vendors to ensure that overhead costs are fairly captured for all equipment.

In the case of hybrid propulsion system rebuilds, costs were obtained directly from the hybrid OEMs and are based on removing the original hybrid drive system and replacing



	1	2	3	4	5	6	7	8	9	10	11	12
▨4-year life	0%	0%	25%	50%	25%	6%	25%	38%	27%	16%	23%	32%
▤6-year life	0%	0%	0%	0%	25%	50%	25%	0%	0%	6%	25%	38%
☒8-year life	0%	0%	0%	0%	0%	0%	25%	50%	25%	0%	0%	0%

Figure 2.6. Battery replacement during 12-year bus life.

it with a factory remanufactured unit, at least until use of this equipment becomes more widespread and agencies gain the knowledge and tools needed to perform the rebuilding themselves. Likewise, costs associated with rebuilding the ICE for all bus types and the automatic transmissions for diesel and CNG buses are based on replacing the original units with rebuilt units from an OEM-authorized rebuilding facility. Because hybrid bus OEMs are expected to downsize ICEs used on these vehicles in the future, ICE rebuild costs for hybrid buses are projected to be lower than ICE rebuild costs for conventional diesel buses (see Table 2.22).

Engine and transmission rebuild follow a rebuild schedule for each propulsion system that defines when the original engine or transmission requires its first rebuild and when its subsequent rebuilds would occur. For example, a selection of (6,4,4,4. . . .) represents that the first rebuild takes place in year six and subsequent rebuilds occur every four years thereafter until the bus reaches the end of its useful life. The replacement uses the same 25-50-25 rule as used for the battery pack replacement schedule. It is expected that 25% of new or replacement components would fail (or be scheduled for replacement) one year prior to the expected life year, 50% would fail during the expected life year, and 25% would fail one year after the expected life year. The default replacement schedule for hybrid bus engines and transmissions is (7,6,6,6. . . .) and for CNG and diesel buses is (6,4,4,4. . . .). The model also provides (7,7,7,7. . . .) and (7,5,5,5. . . .) as possible alternative second replacement schedules for hybrid engines and transmissions. Similarly, the (6,6,6,6 . . .) and (6,3,3,3 . . .) schedules are offered as options for diesel and CNG buses.

Engine Rehabilitation Cost. Engine rehabilitation cost was decided by the cost of parts and labor, combined with the default replacement schedule. One-time replacement costs for diesel and CNG engines are based on the assumption that the engine would be rebuilt as a factory remanufactured unit (i.e., no in-chassis rebuilds) and include labor costs to remove and replace the engine. Costs are based on rebuilds conducted

Table 2.21. Battery replacement schedule for an 80-HEB fleet (6-year battery life).

	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Year 11	Year 12
1st Replacements	20	40	20					
2nd Replacements						5	10+10	5+20+5

Table 2.22. Internal combustion engine rebuild/replacement costs.

	Diesel	CNG	Hybrid
Low	$15,000	$15,000	$10,000
Medium	$20,000	$20,000	$15,000
High	$25,000	$25,000	$20,000

by an outside vendor to capture all overhead costs associated with the rebuilds or replacements. In the case of hybrid buses, where a variety of diesel engines can be used and rebuild/replacement data was sparse, costs are based on replacement engines (i.e., engines were replaced, not rebuilt). Replacement is common for engines that do not have cylinder liners and engines of this kind are commonplace in hybrid applications. In addition, the model assumes a longer interval between engine replacements. The costs for each of the three bus technologies are shown in Table 2.22.

In some cases, the bus purchaser might know of substantial future costs associated with a bus purchase. For example, a purchaser of 2008 diesel buses might have an internal obligation to meet 2010 EPA emissions standards around the time of the first engine rebuild. Because of this type of scenario, the model provides the option of adding in a miscellaneous one-time cost for future years in a separate model section. The engine rebuild cost does not include the additional costs associated with a possible engine technology update.

Transmission Rehabilitation Cost. Again, vendor rebuild costs are used to capture related overhead costs. In the case of the hybrid drive system it is expected that factory rebuilds done on an exchange basis would be the only available option, at least until use of this equipment becomes more widespread and agencies gain the knowledge and tools needed to perform the rebuilding themselves. In the case of diesel and CNG buses, agencies that rebuild their own automatic transmissions could insert their actual parts and labor cost (with or without accounting for overhead). Likewise, as more information becomes available on the rebuilding of hybrid drive systems, agencies could override the default setting by entering another, more appropriate, value. The costs for each of the three bus technologies are shown in Table 2.23.

Transmission rebuild cost assumptions for diesel and CNG buses are identical for low, medium, and high values. For diesel and CNG buses, the model makes the following assumptions:

- Transmissions would be rebuilt with factory remanufactured units and this includes labor costs to R&R the transmission, and
- Rebuilds would be conducted by an outside vendor to capture all associated overhead costs.

For hybrid buses, transmission rebuild cost assumptions are based on removal of the original hybrid propulsion system and replacement with a factory-remanufactured unit.

Scheduled and Unscheduled Vehicle Maintenance Costs

Maintenance costs (Table 2.24) for all three bus types are taken from the four test sites and categorized under scheduled and non-scheduled maintenance. In one case, however, projections had to be made where no actual field experience exists. That case consisted of unscheduled maintenance cost for 2007 diesel buses. It is estimated that these costs would be 5% more than similar costs for pre-2007 diesel buses. Scheduled and non-scheduled maintenance costs are then combined to represent total maintenance costs for each of the three bus types.

Propulsion- and brake-related maintenance costs are isolated as subsets of the total maintenance costs. Propulsion maintenance costs exclude those costs associated with rebuilding the ICE for all three bus types, transmission rebuilding costs for diesel and CNG buses, and unique hybrid equipment rebuild costs. Those costs are itemized separately elsewhere in the model. As shown in Table 2.24, the maintenance costs varied dramatically at different test sites, because each had unique management and operation situations, and test buses at each agency were of different model years. Simply mixing test data from four sites was not appropriate at this point. To avoid confounding factors that may exist between sites, the alternate technology maintenance costs were compared to the baseline fleet maintenance costs for each individual site. For that reason, pre-2007 diesel buses were selected as the baseline bus, and their maintenance data are assumed to be the average of the four test sites. The other four bus type maintenance costs are referenced to this baseline and presented in Table 2.25.

Warranty is a key factor that affects bus maintenance costs. It must be noted that for the relatively new hybrid buses, OEM repairs and adjustments made to buses at these sites are covered under warranty and these costs are not reflected in the maintenance costs. This also happened with other new bus technologies, where OEMs have an interest in monitoring equipment performance closely. In some cases, the nature of repairs is not known in detail. OEMs might affect repairs themselves as a way of obtaining firsthand feedback to further improve their product. In addition, new products typically encounter problems during the early stages of in-service field

Table 2.23. Transmission rebuild/replacement costs.

	Diesel	CNG	Hybrid
Low	$10,500	$10,500	$31,300
Medium	$11,750	$11,750	$35,850
High	$13,000	$13,000	$40,400

Table 2.24. Maintenance costs ($/mile).

	WMATA (*18*)			KC Metro (*4*)		NYCT (*3*)		NYCT Year 2 (*19*)		LBT		WMATA[1]		
	CNG-CWI	CNG-JD	Diesel	Diesel Hybrid	Diesel	Diesel Hybrid (125)[2]	CNG	Diesel Hybrid (125)[2]	Diesel Hybrid (200)[2]	Gasoline Hybrid	Diesel	CNG	Diesel Hybrid	Diesel
Scheduled	0.26	0.30	0.27	0.14	0.15	0.28	0.29	0.32	0.22	0.08	0.08	0.10	0.07	0.06
Unscheduled	0.26	0.27	0.32	0.30	0.31	0.95	1.01	1.10	0.53	0.14	0.40	0.18	0.06	0.08
Total	0.52	0.57	0.59	0.44	0.46	1.23	1.30	1.42	0.75	0.22	0.48	0.28	0.13	0.14
Propulsion	0.14	0.13	0.12	0.13	0.12	0.36	0.35	0.34	0.16	0.07	0.20	-	-	-
Brakes	0.03	0.07	0.07	0.01	0	0.04	0.18	0.16	0.07	0	0.03	-	-	-
Bus Age[3]	4	3	2	2	2	2-3	2-3	4	2-3	1-2	3-4	1-2	1	1
Bus MY	2001	2001	2000	2004	2004	2002	2002	2002	2004	2004-2005	2002	2005-2006	2006	2006

Notes:

[1] WMATA maintenance cost data were not used in the model mainly because of the warranty effects on WMATA data. Due to time constraints, the data collection was for a period of less than 18 months and buses were in their warranty period. Since neither warranty repairs nor actual warranty costs could be identified, the WMATA data were not used.

[2] Number of buses in purchase order.

[3] *Bus age* refers to the number of years the bus has been in revenue service.

CWI = Cummins Westport Inc.; JD = John Deere; MY = model year.

Table 2.25. Maintenance costs ($/mile).

	Pre-2007 Diesel			Diesel			Diesel Hybrid			Gasoline Hybrid			CNG		
	Low	Mid	High	Low	Mid	High	Low	Mid	High	Low	Mid	High	Low	Mid	High
Scheduled	0.08	0.17	0.27	0.15	0.21	0.27	0.08	0.18	0.28	0.08	0.18	0.28	0.14	0.28	0.3
Unscheduled	0.30	0.36	0.43	0.32	0.38	0.45	0.13	0.41	0.95	0.13	0.41	0.95	0.27	0.4	1.01
Total	0.38	0.53	0.70	0.47	0.59	0.72	0.21	0.59	1.23	0.21	0.59	1.23	0.41	0.68	1.31
Propulsion Portion	0.12	0.15	0.18	0.13	0.16	0.19	0.13	0.19	0.37	0.13	0.19	0.37	0.14	0.18	0.35
Brake Portion	0.04	0.07	0.16	0.04	0.07	0.16	0.02	0.05	0.12	0.02	0.05	0.12	0.04	0.07	0.16

use that diminish over time as the product becomes refined. There were no available data over a long enough timespan to capture the offset of costs by warranty. From some reviews of historical bus maintenance data performed by the study team, it is estimated that maintenance costs would be reduced by half during the warranty period (standard two-year warranty and possible extended warranty).

There is a concern that average speed might play a role in maintenance costs. The high NYCT maintenance costs are probably due to the slow operation (i.e., each mile represents more hours and fuel consumption than for similar buses operating at higher speeds). Arguments exist that engine life may be dictated by key-on hours, or even by cumulative fuel consumed. Key-on hours include all engine run time, and not just revenue service hours. The research team introduced a correction factor for per mile maintenance costs to account for higher per mile costs incurred with low-speed operation. Based on a review of the data, it was determined that cost is twice as high at 6 mph as it is at 15 mph. NYCT data supports this concept. This suggests a correction of the following kind:

$$\text{Correction Cost} = \text{Original Cost} \times \left(\frac{a+b}{\text{average speed}} \right)$$

In the absence of sufficient data, the researchers elected to use the values of a = 0.5 and b = 7.5 (shown as Weakened Function in Figure 2.7). These are in preference to values of $a = 0.333$ and $b = 10$ (shown as Original Function in Figure 2.7), which were also considered. The two functions are compared in Figure 2.7.

The following example shows how correction factors for warranty and operation speed are used to adjust vehicle maintenance costs. The example is for diesel hybrid bus operation for 12 years, at 12 mph average speed, with three years of extended warranty purchased.

- Original hybrid bus total maintenance cost = $0.59/mile,
- First two years' standard and three years' extended warranty maintenance cost = $0.30/mile,
- Remaining seven years' maintenance cost = $0.59/mile,
- Speed corrector factor = 0.5 + (7.5/12) = 1.125, and
- Corrected hybrid bus total maintenance cost = 1.125 × (5/12 × 0.30 + 7/12 × 0.59) = $0.53/mile.

The value of $0.53/mile represents an average over the life of the bus, in baseline year dollars.

2.2.3 Bus Life Cycle Cost Model Development

The bus Life Cycle Cost Model (LCCM) is implemented as an Excel spreadsheet that allows the user to evaluate and compare bus purchases (for buses utilizing varying propulsion technologies) in a convenient and flexible manner. The model is self-contained and includes data resulting from field measurements, modules that calculate fuel economy from user-input operating parameters, and various other information about maintenance and replacement schedules, training costs, and other factors. The user can accept default values or enter specific data into the worksheet, which then calculates and totals the various costs over the lifetime of the selected vehicles. Although detailed user instructions are provided in Appendix H, this section presents instructions for entering data and applying specific user inputs. It also focuses on how the model works.

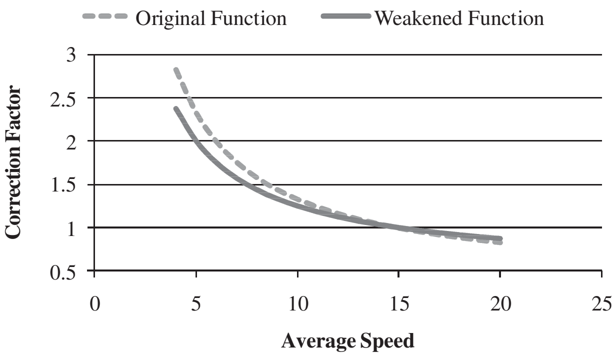


Figure 2.7. Comparison of speed correction factors for maintenance costs.

Table 2.26. Basic description of model worksheets.

Sheet	Description
User Inputs	Main interaction page where the user will enter data, view default values and be able to override them.
Output Chart (1)	Bar chart of main lifecycle cost subtotals and totals.
Output Chart (2)	Bar chart of life cycle capital, operational, and total cost associated with range bars.
Output Chart (3)	Bar chart of life cycle capital, operational, and total cost per bus associated with range bars.
Output Chart (4)	Bar chart of life cycle capital, operational, and total cost per bus mile associated with range bars.
Output Table	Table of results by cost item, subtotals, and totals.
Worksheet	Not editable. This page takes inputs from User Inputs page and performs all calculations.
Cost Data	Not editable. This page provides source cost data to the User Inputs Page.
Fuel Economy (1) to (6)	Not editable. Calculates fuel economy for each of the six purchase scenarios.
Fuel Economy Data	Not editable. Raw data for Fuel Economy pages.
Fuel Economy A/C Effects	Not editable. Model of A/C and heat load effects for Fuel Economy pages.
Battery Replacement Module	Not editable. Provides battery replacement schedule for different battery life expectancy.
Transmission Rehab Module	Not editable. Provides transmission rehab schedule for different transmission life expectancy.
Engine Rehab Module	Not editable. Provides engine rehab schedule for different engine life expectancy.

Overall Structure

The spreadsheet is made up of multiple sheets, each containing different parts of the model. Table 2.26 describes each sheet.

Green color-coded sheets in the LCCM are used to indicate user-editable fields. Only the User Inputs Sheet and the output sheets are editable. The User Inputs page is the main portal through which the user would enter parameters (in green or orange cells) and would view the model's projected costs (shown in white cells) based on those parameters. These projected costs are gathered from the various supporting sheets, which are color-coded red. From there, the user could edit these model costs in the pink cells. Costs (either the model-supplied costs or the user overrides) are passed to the Worksheet page for multiplication and summation. This overall flow among sheets is shown in Figure 2.8. The remainder of this section discusses the main sheets in greater detail.

User Inputs Sheet

The User Inputs sheet gathers data from supporting pages based on user entries, displays those data to the user, and then allows the user to override those data. Specific details relating to each of the data sections on the sheet are presented in the user instructions provided in Appendix H. The typical data section takes relevant user inputs, looks these inputs up in a table from a data sheet or module or performs the needed calculations directly, and then displays the results in the white cells. Low, medium, and high values are displayed so the model provides the user with a reasonable cost range for the item. Without a user input in the corresponding pink cell, the model would proceed with the medium (i.e., default) data value for further calculations. In the pink cells, the user could enter a new value, using better information from their specific agency, a high or low prediction provided by the model, or more current information than was available at the time this model was constructed. If a value is entered in a pink cell, that value—not the default—is passed along.

Treatment of Inflation in the Model

All costs on the User Inputs sheet are displayed and processed in base-year dollars. All of the data in the supporting data

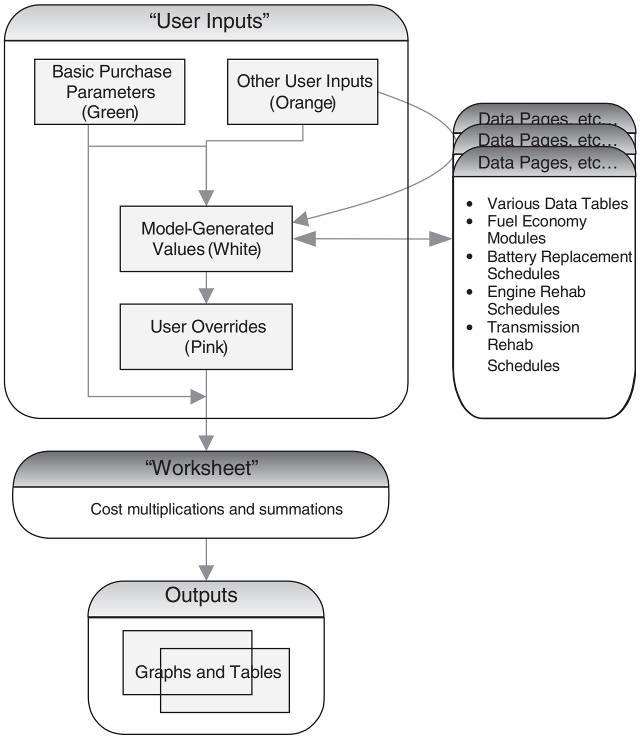


Figure 2.8. The overall flow of data among the LCCM's worksheets.

sheets are generated in 2007 dollars. The User Inputs sheet reads these data and then factors them by an inflation index equal to the compounded inflation of 2.918%. The determination of this rate is described in the following section entitled "Estimation of Inflation Factor." The user is unaware of this factoring for inflation except that the User Instructions clarify that it is used. Once the user inputs the base year or chooses a specific inflation index in the top section of the User Inputs sheet, the remaining inflation compensation is hidden. So, a purchase cost of $100 (in 2007 dollars) when the model is run in 2010 would be seen by the user as 109.14 (dollars), which is computed as $100*(1+2.918)^3$.

The model does not consider the opportunity costs of money as being different from inflation (i.e., the effective interest rate was zero), and therefore could treat future costs and present costs as being in present dollar terms. The differences between a purchase in year X and year Y would then only include differences in the technology costs, such as those associated with new emissions controls.

Estimation of Inflation Factor

An annual inflation factor of 2.918% used as the default in the model is estimated based on a composite of producer price indices from the Bureau of Labor Statistics. Seven commodity indices and one industry index were used. For each, an average (exponential) annual inflation rate was calculated, and ranged from between 1.96% and 4.13% per year. The rates were then averaged and weighted by the number of years in each index, to arrive at the composite of 2.918%. Table 2.27 summarizes the eight indices and the composite calculation. (For more information about the indices, see http://www.bls.gov/data/home.htm.) The indices are used only to convert dollar values between years. Actual changes in the cost of items such as buses and fuel are projected separately.

Data Sheets and Modules

These uneditable pages, which are color-coded red, contain both data tables and more active calculations based on entries taken from the User Inputs sheet. The Cost Data sheet contains tables for most of the costs. The six Fuel Economy pages receive inputs from the User Inputs sheet, including A/C and heater loads as well as in-use duty-level information, and then return estimated fuel economy ranges. The Battery Replacement Module contains battery replacement schedules for use in estimating replacement costs given bus and battery lifetime. Similar replacement schedules for engines and transmissions are included in pages for Engine Rehab Module and Transmission Rehab Module. Other sheets offer support data for these modules.

Worksheet

The Worksheet page reads the cost information (whether from the model's predictions in the white cells or the user's overrides in the pink cells) from the various data elements in the User Inputs sheet. Here, subtotals and totals for one-time costs, costs per bus, and operating costs per mile are calculated.

Output Charts and Table

Subtotals and totals from the Worksheet page are organized into a concise table and graphed using bar charts in these sheets.

Table 2.27. Summary of producer price indices used to estimate the annual inflation factor.

BLS Series	WPU149	WPU141302	WPU1413	WPU141106	WPU1411	WPU141	WPU14	PCU3361203361202
Industry	TE	TE	TE	TE	TE	TE	TE	Heavy-duty truck manufacturing
Product	TE	Completed vehicles on purchased chassis	Truck and bus bodies	Trucks	Motor vehicles	Motor vehicles and equip.	TE	Trucks, truck tractors, and bus chassis (chassis of own manufacture) 33,001 lb or more
Number of Years in Index	21	24	24	43	55	55	38	19
Ratio of Final Year to Initial Year Index Value	1.474	1.939	1.968	5.472	3.482	3.922	3.777	1.524
Average Growth Rate	1.96%	2.92%	2.99%	4.13%	2.34%	2.56%	3.66%	2.37%
Year-Weighted Average Growth Rate	2.918%							

Note: TE = Transportation equipment.

Source: Data from http://www.bls.gov/data/home.htm.

2.3 Abbreviated User Instructions for the LCCM

Although basic instructions are provided in this section, Appendix H provides a user guide, and Appendix I provides screenshots from the LCCM.

Before starting, remember to save the original file prior to making any inputs to it. The user should also remember to press the F9 key to register inputs and execute calculations before viewing the output tables and charts, and before exiting the model.

Begin in the Overall Parameters section by entering vital information including expected bus life in years, base year (all costs will be represented in the base year dollars), and bus length (40- or 60-ft). Click on the ⇓ symbol and scroll down to select the desired entry. The user may also change the inflation index, if needed, by manually typing in a new factor into the pink cell. For specific information, see the User Instructions by clicking the hyperlinked section title in the LCCM.

In the Purchase Scenarios section, click the Activate box in one or more of the six columns. This will allow up to six different bus-type comparisons to be made at one time. The LCCM's Purchase Scenarios subsections are described in the remainder of this section.

1—Technology Use the pull-down menu (⇓) to select the type of bus to be compared in each activated column (e.g., pre-2007 diesel, CNG, etc.). For specific information, see the User Instructions by clicking the hyperlinked section title in the LCCM.

2—Number of Vehicles in Purchase For each column activated, enter the number of buses to be purchased. For specific information, see the User Instructions by clicking the hyperlinked section title in the LCCM.

3—Purchase Year For each column activated, use the pull-down menu (⇓) to enter the bus purchase year. This can be the same as the base (current) year, or any year in the future. For specific information, see the User Instructions by clicking the hyperlinked section title in the LCCM.

4—Annual Mileage per Vehicle For each column activated, enter the expected mileage that each vehicle type will travel annually. For specific information, see the User Instructions by clicking the hyperlinked section title in the LCCM.

5—Fuel Economy Estimate The user should first click on "duty cycle" or "average speed" to highlight a selection for making fuel economy calculations. Depending on the selection made, the user should go to the appropriate subsection below and type in either the average bus speed in mph or the duty cycle percentage (where all must add up to 100%). The user should then proceed to Subsections 5B and 5C to select heating and air conditioning loadings. For specific information, see the User Instructions by clicking the hyperlinked section title in the LCCM.

5D—Review Resulting Fuel Economies Here the user is able to review the resulting fuel economy calculations based on the inputs made in Subsections 5A through 5C in the previous step. Results are expressed as low, medium, and high values; the model selects the medium input as the default unless the user manually types a different value into the pink cell. For specific information, see the User Instructions by clicking the hyperlinked section title in the LCCM.

6—Purchase Costs The model automatically selects the medium input as the default for the bus purchase cost unless the user types a different value into the pink cell. All costs are expressed in $1,000 multiples. For specific information, see the User Instructions by clicking the hyperlinked section title in the LCCM.

7—Extended Powertrain Warranty Costs Costs for an extended powertrain warranty are one-time costs accounted for at time of bus purchase. These costs do not include standard warranty and depend on the timespan of the warranty. Unless the user enters another value in the pink box, the model will select the medium value programmed into the model as the default. All costs are expressed in $1,000 multiples. For specific information on cost basis, see the User Instructions by clicking the hyperlinked section title in the LCCM.

8—Engine Rebuild/Replacement Costs for Bus Lifetime Use the pull-down menu (⇓) to select the engine rebuild schedule (e.g., 6,4,4,4 . . . means the first rebuild takes place at year six with subsequent rebuilds every four years thereafter). Each propulsion type has its own default rebuild schedule and unit rebuild costs based on the data collected. Unless the user enters a different value in the pink box, the model will select the medium value programmed into the model as the default based on the schedule selected. All costs are expressed in $1,000 multiples. For specific information on cost basis, see the User Instructions by clicking the hyperlinked section title in the LCCM.

9—Transmission Rebuild/Replacement Costs for Bus Lifetime Use the pull-down menu (⇓) to select the transmission rebuild schedule (e.g., 6,4,4,4 means the first rebuild takes place at year six with subsequent rebuilds every four years thereafter). Like engine rebuilds, each propulsion type has its own transmission rebuild schedule and unit rebuild cost based on the data collected. In a hybrid bus, the transmission is considered the overall hybrid drive system. Unless you enter a different value in the pink box, the model will select the medium value as the default based on the schedule selected. All costs are expressed in $1,000 multiples. For specific information on cost basis, see the User Instructions by clicking the hyperlinked section title in the LCCM.

10—Training Costs Enter the number of operators and mechanics that would require training based on the number of hybrid and CNG buses being compared. Then enter the respective hourly rate for each (default = $50 per hour). Training costs for hybrid and CNG buses are incremental to (above and beyond) training costs for diesel buses (which are assumed to be zero). All training costs are one-time only, except for CNG where the model automatically calculates 0.5 hours for each operator annually for safety training. The user also can use the pink cells to override model assumptions. All costs are expressed in $1,000 multiples. For specific information on cost basis, see the User Instructions by clicking the hyperlinked section title in the LCCM.

11—Unscheduled Maintenance Costs Unscheduled (not planned) maintenance costs are based on field experience and are listed in dollars per mile. The LCCM automatically selects the medium range as the default unless the user manually enters an amount from the high or low range for each bus type into the pink cell, or manually enters a per mile cost based on the user's own experience. For specific information, see the User Instructions by clicking the hyperlinked section title in the LCCM.

12—Scheduled Maintenance Costs Costs for scheduled (planned) maintenance are accounted for separately in the model in a way that is similar to the process for the cost of unscheduled maintenance. Again, the LCCM automatically selects the medium range as the default unless the user manually enters an amount into the pink cell from the high or low range for each bus type, or manually enters a per mile cost based on the user's own experience. For specific information, see the User Instructions by clicking the hyperlinked section title in the LCCM.

13A—Specific Infrastructure Costs This section accounts for infrastructure costs unique to CNG buses. Other fuel facility infrastructure costs are set as zero, unless specific costs are entered in the pink User Input cells. Enter the number of CNG buses that the new infrastructure (fueling, maintenance, and storage facilities) will need to service. Realize that in some cases existing CNG facilities may be large enough to handle planned CNG buses, while in other cases new CNG infrastructure will be needed. If CNG infrastructure is needed, the default calculated by the model is $1 million plus $15,000 for each CNG bus being purchased. Manually enter other values as appropriate. All costs are expressed in $1,000 multiples. For specific information and examples showing how CNG infrastructure costs are based, see the User Instructions by clicking the hyperlinked section title in the LCCM.

13B—Facilities' Operating and Maintenance Costs This section accounts for operations and maintenance (O&M) incremental costs for CNG infrastructure that are in addition to diesel and gasoline fuel facilities. Based on CNG infrastructure costs calculated in Section 13A, the model will calculate O&M costs based on 6% of CNG infrastructure costs. All costs are expressed in $1,000 multiples. For specific information and examples showing how O&M costs for CNG infrastructure are based, see the User Instructions by clicking the hyperlinked section title in the LCCM.

14A—Diagnostic Equipment This section accounts for diagnostic equipment costs unique to operating gasoline and diesel hybrid buses. Enter the number of hybrid buses to be serviced from a given workshop location (the model assumes that all hybrid buses will be serviced from one location). The model then selects the medium range value of $5,000 per 50 buses as the default unless the user manually enters the high or low value, or a different value into the pink cell. All costs are expressed in $1,000 multiples. For specific information, examples showing how hybrid diagnostic equipment costs are based, and how to account for hybrids serviced from multiple locations, see the User Instructions by clicking the hyperlinked section title in the LCCM.

14B—Energy Storage Replacement This subsection also applies only to hybrids and assumes an average energy storage pack replacement cost of $27,500 including R&R. Here, the equipment cost is constant at $27,500 per replacement. Based on the number of hybrid buses and expected lifespan entered earlier, the model selects the medium value (default) of a six-year life. The user also can manually enter the amount from the high-value cell (4-year battery life), the low-value cell (8-year battery life), or a different value into the pink cell. All costs are expressed in $1,000 multiples. For specific information and examples showing how energy storage replacement costs are based, see the User Instructions by clicking the hyperlinked section title in the LCCM.

14C—Spare Energy Storage Packs Using $27,500 as the fixed average cost for a spare energy pack, the model selects one spare energy pack per 20 hybrid buses as the default based on the number of hybrid buses the user entered earlier for purchase. The low-cost value is one spare energy pack per 30 buses, and one spare for every 10 hybrid buses represents the high-cost value. Unless you enter the high, low, or a different value manually, the model will select the default (medium) value. All costs are expressed in $1,000 multiples. For specific information, see the User Instructions by clicking the hyperlinked section title in the LCCM.

15—Projected Average Fuel Costs Prices for diesel, gasoline, and CNG are adopted from DOE and adjusted in future years by averaging several projections throughout the bus life for all buses being purchased. Taxes are not included. If applicable, account for taxes in Section 16. Cost units vary by fuel type (diesel equivalent gallons [DEGs] or gasoline equivalent gallons [GEGs]). If the user manually enters the base year crude oil and natural gas price, the model will adjust the default diesel, gasoline, and natural gas price projections based on base-year prices. Or the model will automatically select the medium-value default unless the user manually enters a different value in the pink cell. For specific information, see the User Instructions by clicking the hyperlinked section title in the LCCM.

16—Incentives, Credits, and Taxes The subsections below allow the user to account for various credits and costs for the different propulsion options being considered.

16A—Fuel Taxes Three taxes are listed: federal, state, and other. Unless the user makes a manual entry in the appropriate pink cell, the model will select predetermined values for state and federal taxes for each fuel type as defaults. A default is not supplied for “other tax.” *Note: the user must zero out federal or state tax amounts if your agency does not pay these taxes.* Based on the total taxes, the model will make tax calculations based on the fuel costs calculated in Section 15. Cost units vary by fuel type. For specific information, see the User Instructions by clicking the hyperlinked section title in the LCCM.

16B—Fuel Credits Here no fuel credits are taken as a default unless the user makes an entry. If applicable, begin by selecting fuel credits in four formats available from the pull-down menu (⇓). Then enter the value (in units appropriate to the pull-down menu selection) in the orange cell. The effective fuel credit (low, medium, high) is then calculated by the model in appropriate units (percent, cents per gallon, etc.). All credits will then be calculated and shown in cents/DEG. For specific information, see the User Instructions by clicking the hyperlinked section title in the LCCM.

16C—Purchase Credits No credits are given here as a default unless the user makes an entry. If applicable, this subsection allows the user to account for any bus purchase credits available to encourage advanced technologies. The difference between selected bus and default diesel bus purchase cost is shown first; adjust costs as needed. From the pull-down menu, select the type of purchase credit being applied. The program then calculates low, medium, and high values, and will select the medium as the default unless the user enters a different value in the pink cell. Note that the credit can be positive (for a cost reduction) or negative (for a tax or cost increase). For specific information, see the User Instructions by clicking the hyperlinked section title in the LCCM.

16D—Miscellaneous Credits and Grants In this subsection, the user manually enters any other credit or grant that has not already been accounted for in Section 16. Make an entry in the One-Time Credit cell if the credit is applied only once, or place an entry in the Yearly Operating Credit cell if applied annually over the life of the bus. Any cost should be in thousands of dollars. No credits are taken as a default unless the user enters them manually in the User Input cells.

16E—Miscellaneous Future Year One-Time Costs In this subsection, the user enters any one-time future cost for which the user wants the LCCM to account. An example would be a local requirement that forces the user to have older buses retrofitted to meet 2010 emissions standards at the time of the first engine rebuild. Enter any future cost in thousands of dollars on a per bus basis. The model will automatically adjust for inflation. No costs are applied as a default unless the user enters them manually in the User Input cells.

2.4 Testing and Execution of the LCCM

To illustrate LCCM application, various technology comparison scenarios were considered. The results are presented and discussed in the remainder of this section. The research team used the LCCM to evaluate and study the following cases:

- Comparison of different bus types using the default LCCM,
- Impact of bus purchase sizes on LCC,
- Impact of operation speed on LCC,
- Impact of fuel prices on LCC including a study of $5/g diesel and a study of the cost breakeven point,
- LCC comparison of four test sites and LCCM prediction,
- Impact of purchase year on LCC, and
- Impact of energy storage system price on hybrid bus LCC.

2.4.1 Default Model Case

The first scenario addresses the default model for general bus purchases. This case examines the 2007 purchase of 100 40-ft buses for use in operation at the national average bus speed (12.72 mph).(*5*) Annual mileage per bus is 37,000 miles.(*5*) Default values are used for fuel, maintenance, and capital costs, as described previously in Section 2.2.2. All four major technologies (conventional drive diesel, diesel hybrid-electric, gasoline hybrid-electric, and CNG) are considered in this scenario, as is pre-2007 diesel technology for comparative purposes. Therefore, after the five comparisons in this study, the sixth purchase scenario is left blank. For CNG buses, a 100-bus capacity new fueling facility is used in the LCC. The engine and transmission replacement schedule for diesel and CNG is at (6,4,4,4 . . .) (the replacement schedule was described in Section 2.2.2), whereas the hybrid bus replacement schedule for engine and hybrid drive system is (7,6,6,6. . . .). For a 100-bus purchase, it is assumed that 20 mechanics and 100 operators need training. Default maintenance costs are provided for all technologies. Complete fuel, vehicle, and infrastructure tax credits are not included in this analysis because of various incentives and laws established by federal, state, and local authorities. Therefore, to reflect commonly encountered incentives, the study team adjusted the LCCM to calculate an 80% federal subsidy toward bus purchase price.

Figures 2.9 through 2.12 present four output charts for a 100-bus purchase. These figures compare the totals for capital, variable, and life cycle costs of the technologies. Capital costs include bus purchase cost, extended warranty, engine repair and replacement, transmission repair and replacement, hybrid bus energy storage replacement, cost of training mechanics and operators, hybrid bus diagnostic equipment, fueling infrastructure, and one-time credit. Variable costs include unscheduled maintenance costs, scheduled maintenance costs, fuel costs, fueling facility operating costs, and yearly operating credit (i.e., a credit is considered as a negative cost). Life cycle costs are the sum of both capital and variable costs. Figure 2.9 and Figure 2.10 present total dollars for the 100-bus purchase. The bus life is set at 12 years, the full bus purchase cost is assumed to be borne by the bus operator, and LCC default values are used throughout. Figure 2.11 and Figure 2.12 present costs per bus and costs per bus mile for each purchase.

Of the four current technologies, conventional diesel buses are the least expensive to purchase and operate, at nearly $100 million for 100 buses, as shown in Figure 2.9 and Figure 2.10. Diesel HEB overall cost is about 20% higher than the same costs for the conventional drive diesel buses. CNG bus total cost is 4% higher than that of diesel buses. The gasoline hybrid buses are more expensive to run than the diesel hybrid buses, primarily due to fuel consumption differences, and are about 25% higher in overall cost than the conventional drive diesel buses. However, Figure 2.10 clearly shows that for default mode, the high and low cost limits of every technology comfortably bracket the average of the competing technologies. Although it is unlikely that any individual technology would be impacted adversely in every cost category, this scenario shows that any of the four technologies could prove to be optimal in real procurement and operation at national average conditions.

If the default scenario is revisited with the assumption that 80% of the bus purchase price for the fleet of 100 buses is subsidized, the CNG buses and diesel buses became similar and are the least expensive in overall cost, as shown in Figures 2.13

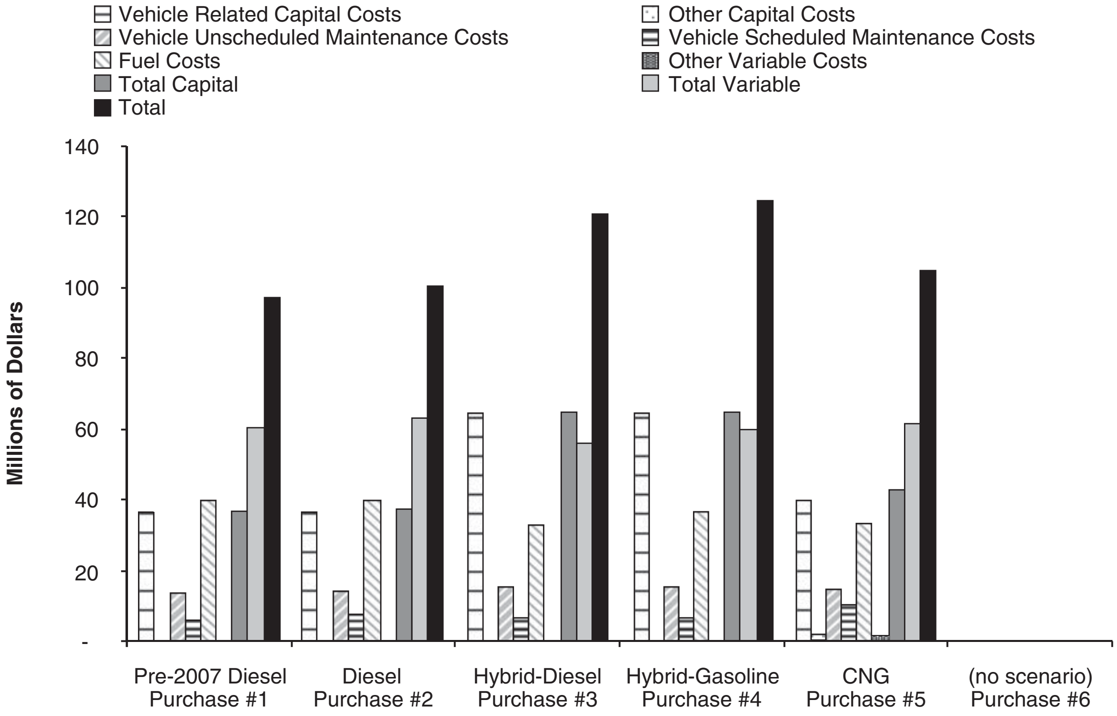


Figure 2.9. Detailed LCC outputs from the default model.

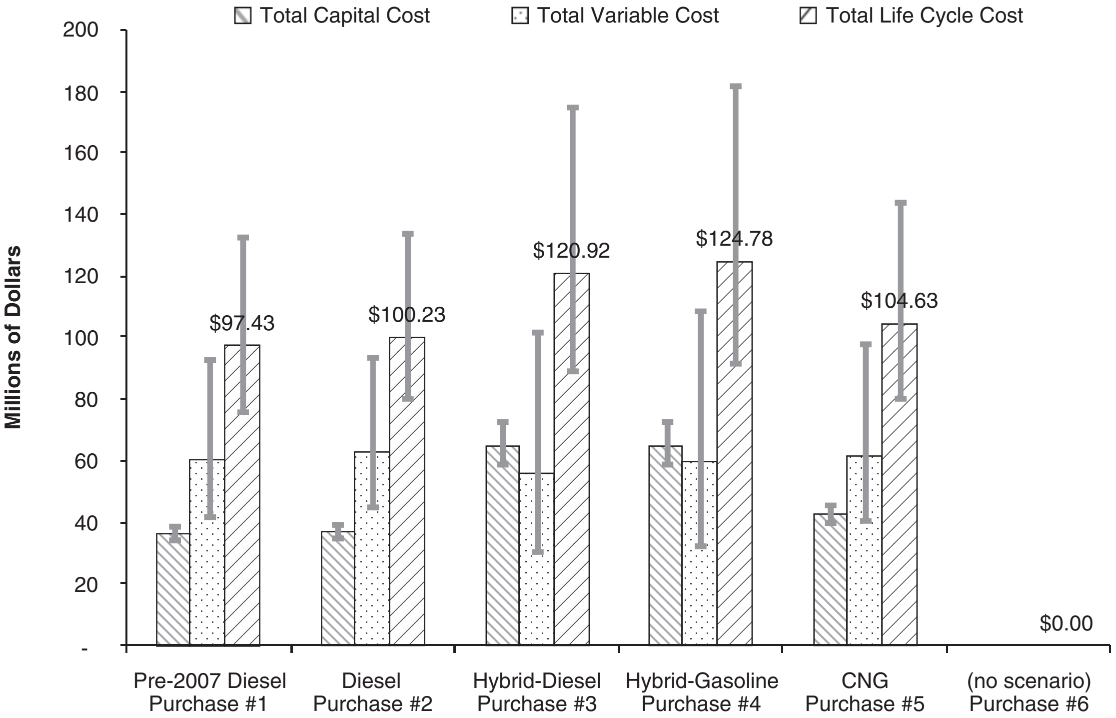


Figure 2.10. LCC outputs from the default model (with range bars).

through 2.15. The per bus scenario is omitted for this case. Diesel HEB and gasoline HEB were found to have the highest overall cost, although the subsidy closed the gap relative to the unsubsidized case. Diesel HEB and gasoline HEB are 6% and 11% higher than diesel buses in total cost. The 12.72 mph operation speed weakened the HEB fuel economy benefit, which is generally best during low-speed stop-and-go operation. Although the CNG fueling station cost must be borne by the transit agency, it accounted for less than 10% of the 100-bus purchase price. The subsidy for the purchase price of CNG buses would overcome CNG infrastructure cost. Again, gasoline price and poor fuel economy affected the cost performance of

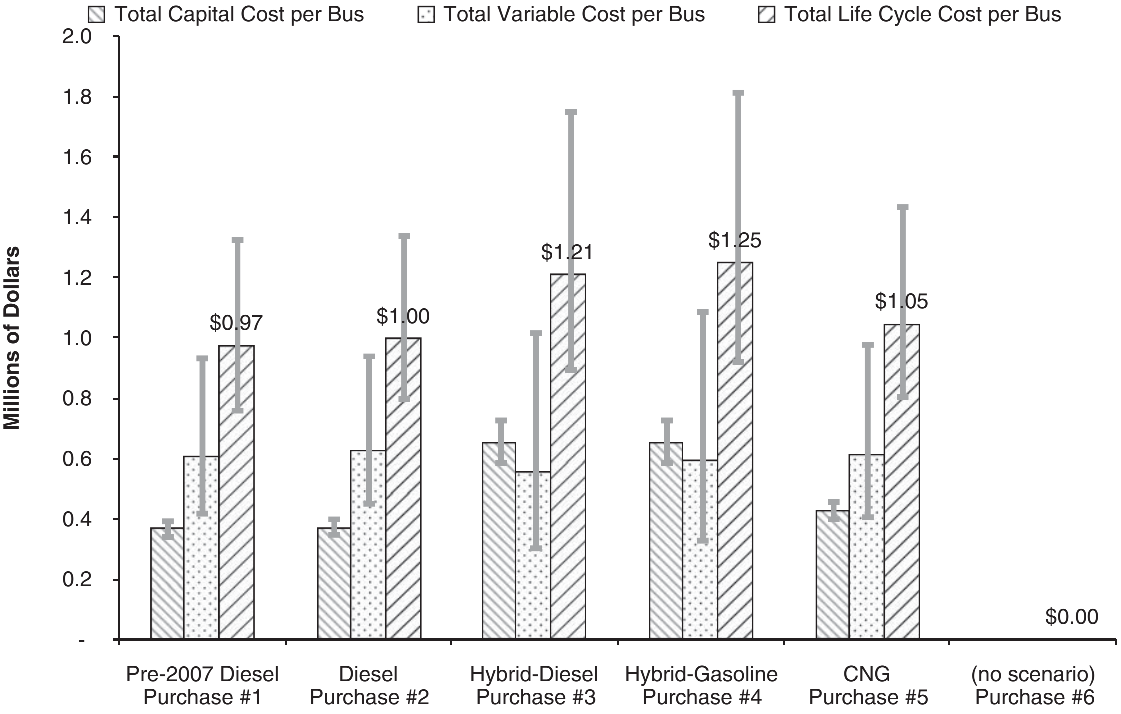


Figure 2.11. LCC outputs per bus from the default model (with range bars).

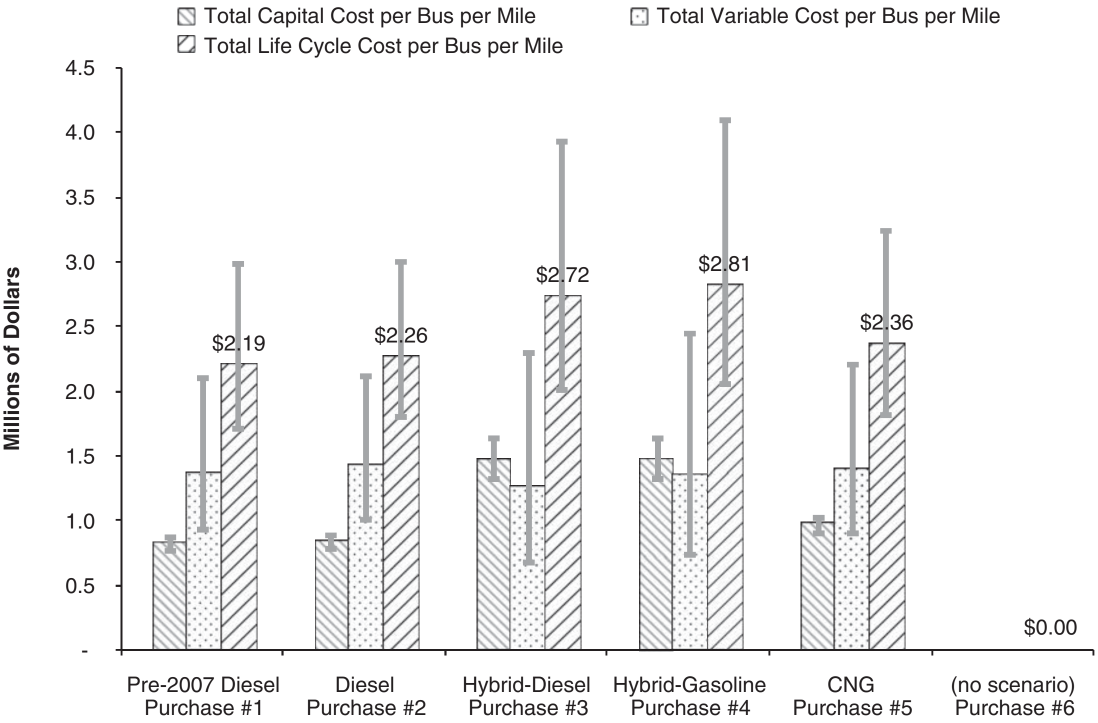


Figure 2.12. LCC outputs per bus mile from the default model (with range bars).

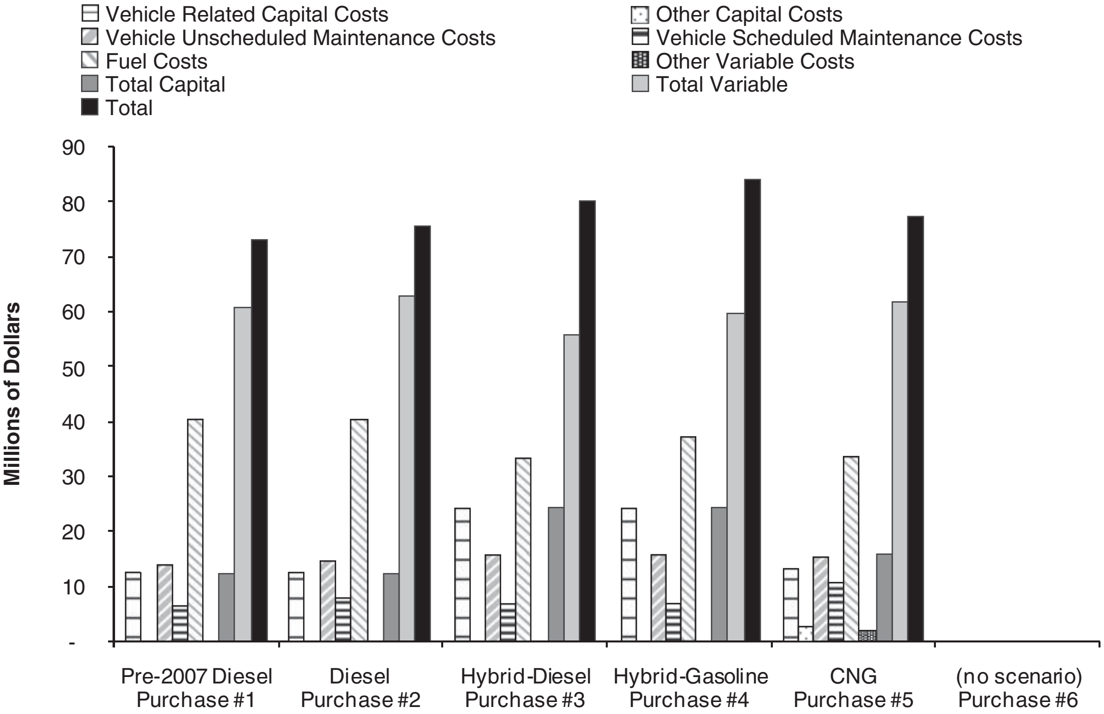


Figure 2.13. Detailed LCC outputs from the default model plus 80% purchase subsidy.

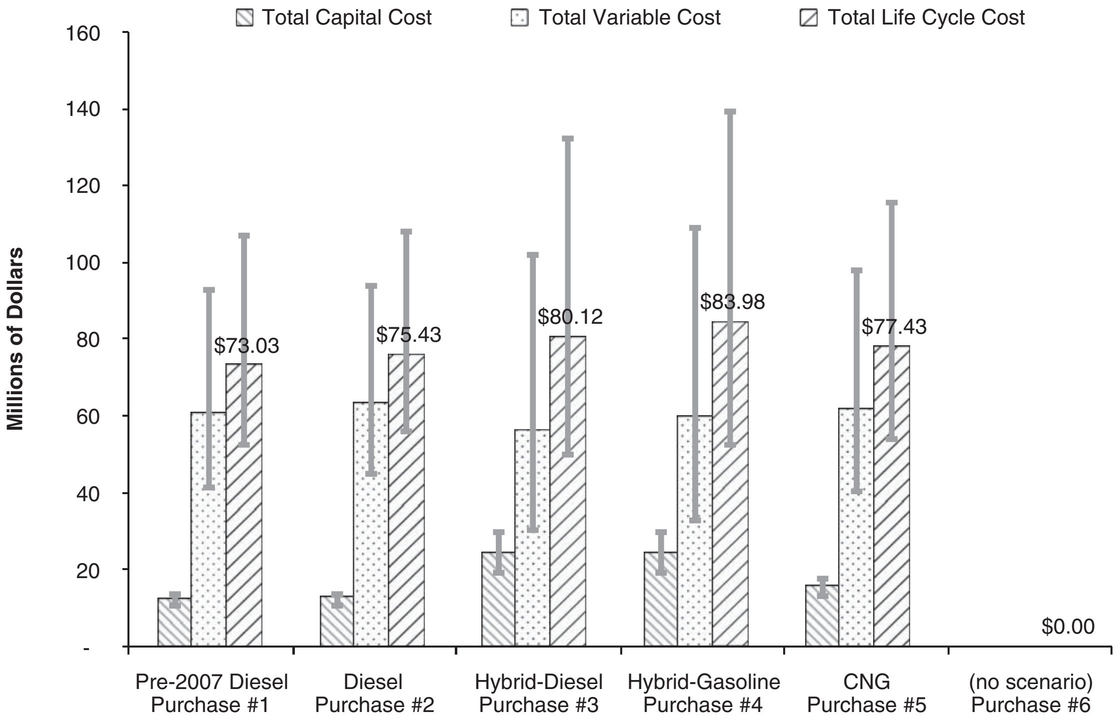


Figure 2.14. LCC outputs from the default model plus 80% purchase subsidy (with range bars).

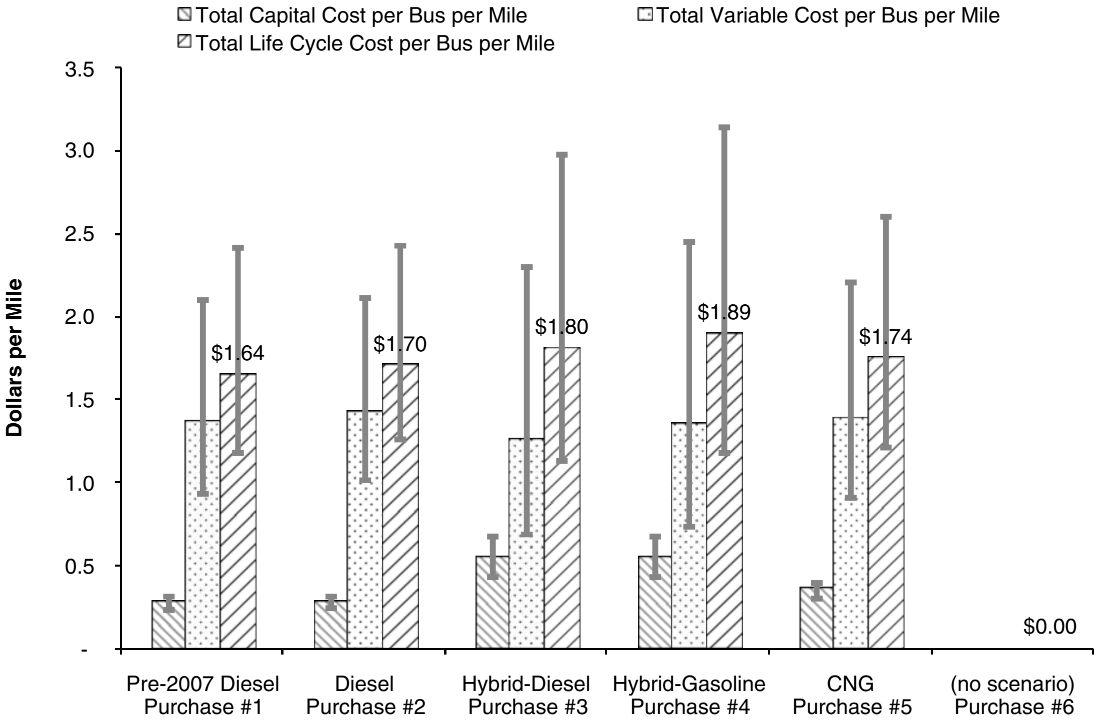


Figure 2.15. LCC outputs from the default model per bus mile plus 80% purchase subsidy (with range bars).

the gasoline hybrid bus. The case where CNG buses are procured and rely on an existing fueling station was not considered in this particular analysis; in situations where refueling facilities do not add to the cost burden, CNG buses become attractive. The impact of bus order size on LCC performance is addressed in the next section.

2.4.2 Influence of Bus Purchase Size

The LCC does not account for bus purchase price discounts when a large number of buses are purchased, because these benefits are typically specific to each purchase scenario. CNG buses are less affected by the cost of the fueling station when a larger number of buses is purchased. The purchase scale studied by the research team included purchase orders of 5, 10, 20, 50, 100, or 200 buses. Figures 2.16 through 2.18 show the LCC results predicted by the model for CNG buses. Clearly, a CNG order for a small number of buses (less than 50) is impacted more by infrastructure cost than is an order for a larger number of CNG buses. By running the model for diesel, diesel hybrid, and gasoline hybrid, it is evident that these three technologies would be virtually unaffected by the number of buses purchased in an order.

2.4.3 Operating Speed Case

The FE model research provided in Section 2.2.2 shows that hybrid buses offer attractive fuel economy advantages at low operating speeds. In this case, three average operating speeds are selected to investigate LCC performance at slow speed (6 mph), national average speed (12.72 mph), and high speed (20 mph). The 80% bus purchase price subsidy also is included, and the cost is calculated assuming a 100-bus purchase. The fuel prices used in this case are all default prices (gasoline at $2.88/DEG, diesel at $2.96/DEG, and CNG at $2.00/DEG).

At slow speed, HEB gain maximum FE advantage and become less expensive in overall cost relative to diesel buses, as shown in Figures 2.19 and 2.20. The LCCM finds that, at slow speeds, total costs for HEB are 4% lower than those for diesel buses. In medium- and high-speed operation, HEB overall costs are about 6% and 12% higher, respectively, than diesel bus costs. In addition, these figures show that bus overall costs are reduced at higher operating speed. This is due to the ultimate per mile fuel savings and low maintenance cost per mile in the high-speed operation situation. For 37,000 miles of annual use and default costs for fuel and maintenance, the results suggest that conventional and hybrid diesel buses have similar life cycle costs if they are operated in the range of 8 to 10 mph.

Although these figures assume the default annual mileage of 37,000 miles per bus, if buses' operating speeds are very low, annual mileage also is likely to be lower. In that case, the HEB FE advantage would be reduced relative to overall cost. The opposite is also true: if buses are operating at very high speeds, the HEB FE advantage would increase due to the extra amount of bus mileage. Total maintenance costs would be affected in the same way.

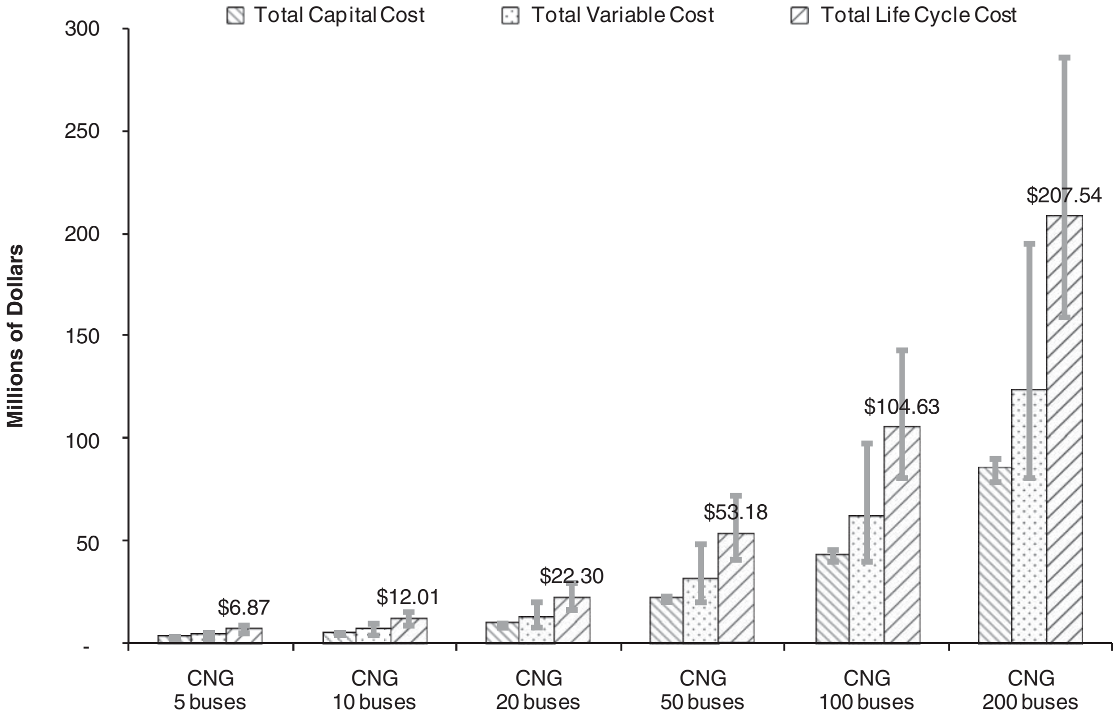


Figure 2.16. LCC by scaled purchase for orders from 5 to 200 CNG buses (with range bars).

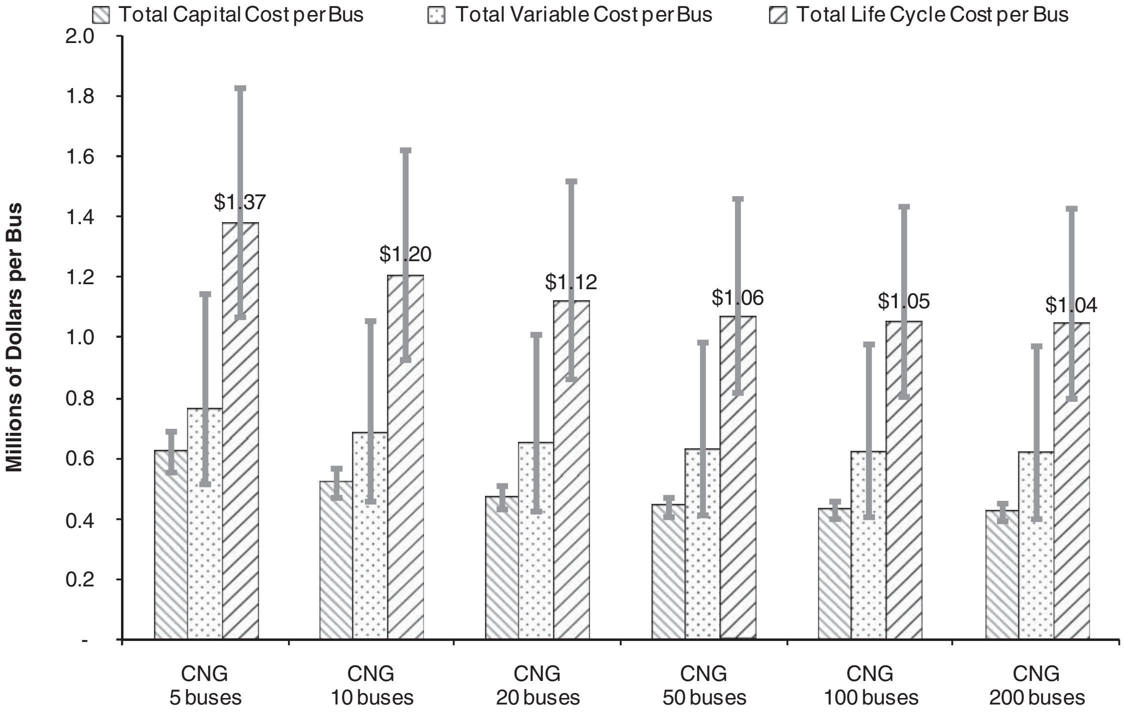


Figure 2.17. LCC per bus by scaled purchase for orders from 5 to 200 CNG buses (with range bars).

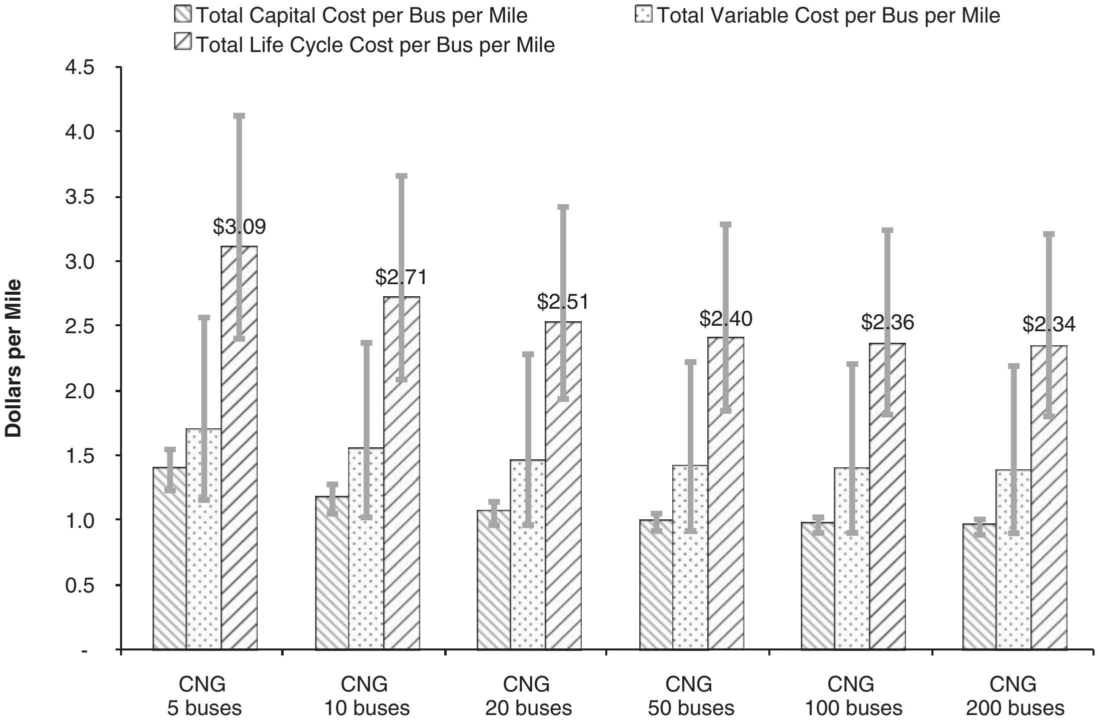


Figure 2.18. LCC per bus mile by scaled purchase for orders from 5 to 200 CNG buses (with range bars).

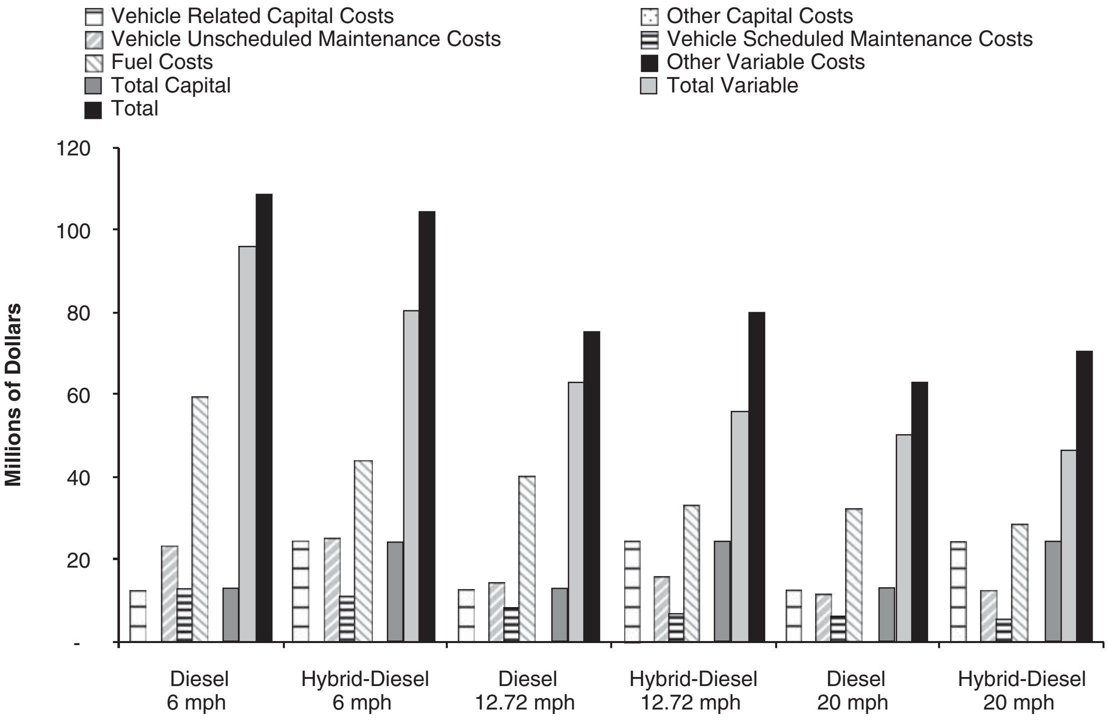


Figure 2.19. Speed effects on detailed LCC comparison of diesel and diesel hybrid buses. An 80% purchase subsidy is included.

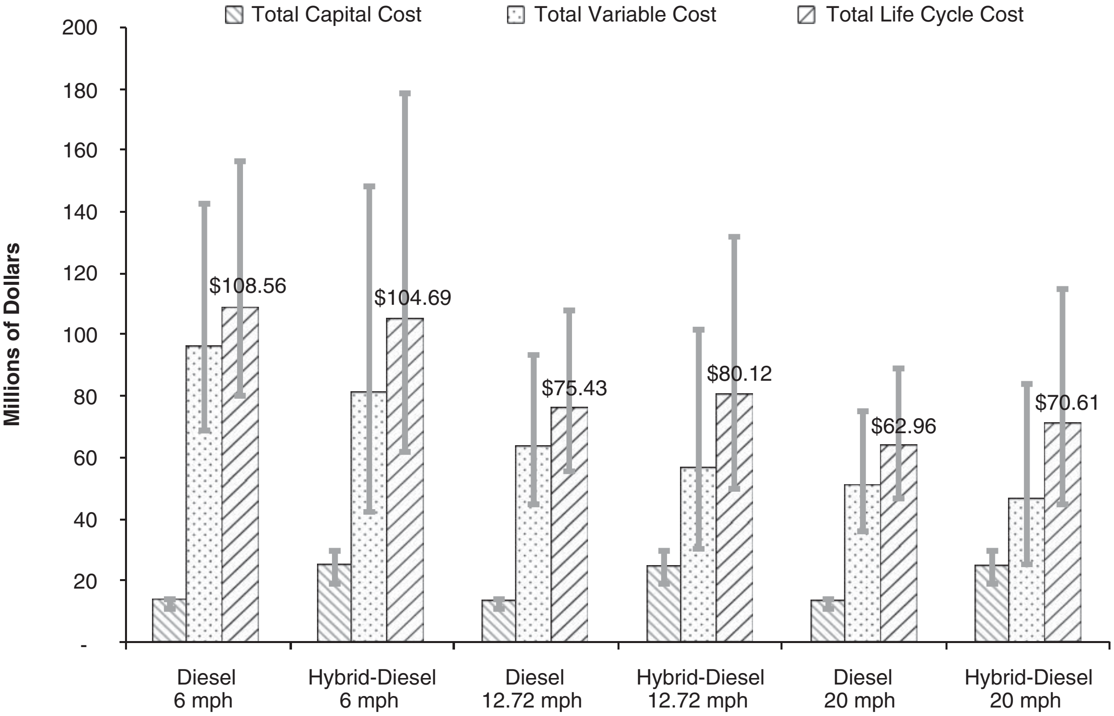


Figure 2.20. Speed effects on LCC comparison of diesel and diesel hybrid buses (with range bars). An 80% purchase subsidy is included.

For a 100-bus purchase with an 80% subsidy, operating speeds affect gasoline and diesel HEB in similar ways. As shown in Figures 2.21 and 2.22, at different operation speeds, diesel HEB are consistently about 5% lower in overall cost than gasoline HEB. Again, gasoline price and lower FE affected the gasoline HEB performance against diesel HEB.

Similar to diesel versus diesel HEB in slow-speed operation, CNG buses cost more than HEB. As shown in Figures 2.23 through 2.26, the difference in costs between diesel HEB and CNG buses is −8% (at 6 mph), 3% (at 12.72 mph), and 11% (at 20 mph) for a 100-bus purchase with 80% subsidy. Compared to −4%, 6%, and 12% between diesel HEB and diesel buses at the three studied speeds, the CNG bus is disadvantaged at low speed. CNG engines, being throttled, are disadvantaged by lower thermal efficiency at light loads associated with low-speed operation.

2.4.4 High-Priced Diesel Case

In 2008, diesel fuel prices rose substantially and exhibited volatility. To simulate an "alarmist" case, the research team considered a scenario in which diesel and gasoline prices increase to an average of $5/g and $4.5/g, respectively, for the 12-year bus life. These prices are substantially above the default values in the model. The gasoline price is 90% of the regular diesel price. The subsidy of 80% for a 100-bus purchase is reflected in this case. CNG price is not changed and uses the default prediction (average $2/DEG), although fuels do tend to track one another when prices fluctuate severely. Hence, this scenario is unlikely to be sustained over many years. With this fuel price change, the diesel HEB and diesel buses became similar in overall cost, as shown in Figures 2.27 through 2.30. If the CNG price is stable and stays low, CNG buses are the least expensive in overall cost at nearly 25% lower than diesel and diesel HEB. This case uses the national average speed of 12.72 mph. It is evident that HEB would perform much better at lower speed in this high-fuel-price scenario, but not all variable combinations could be examined within this report. It is evident that fuel price plays a strong role in determining the most cost-effective technology choice. Fuel price volatility is therefore a confounding factor that affects the model's ability to provide accurate predictions.

If 100% of the bus purchase price were borne by the transit agency, the low CNG price still made CNG bus operation lowest in total cost when liquid fuel prices were elevated to $5/g for diesel and $4.5/g for gasoline, as shown in Figures 2.31 through 2.34. However, the difference in cost between diesel HEB and diesel is reduced to 12%, compared to the 20% described in the default model case in Section 2.4.1 where the diesel price is $2.88/g. Similarly for the gasoline HEB, the difference is reduced from 25% for the default model case where the gasoline price is $2.96/gallon to 16% in the current case. When the cost differential between gasoline and diesel fuels is greater, gasoline HEB can become economically attractive.

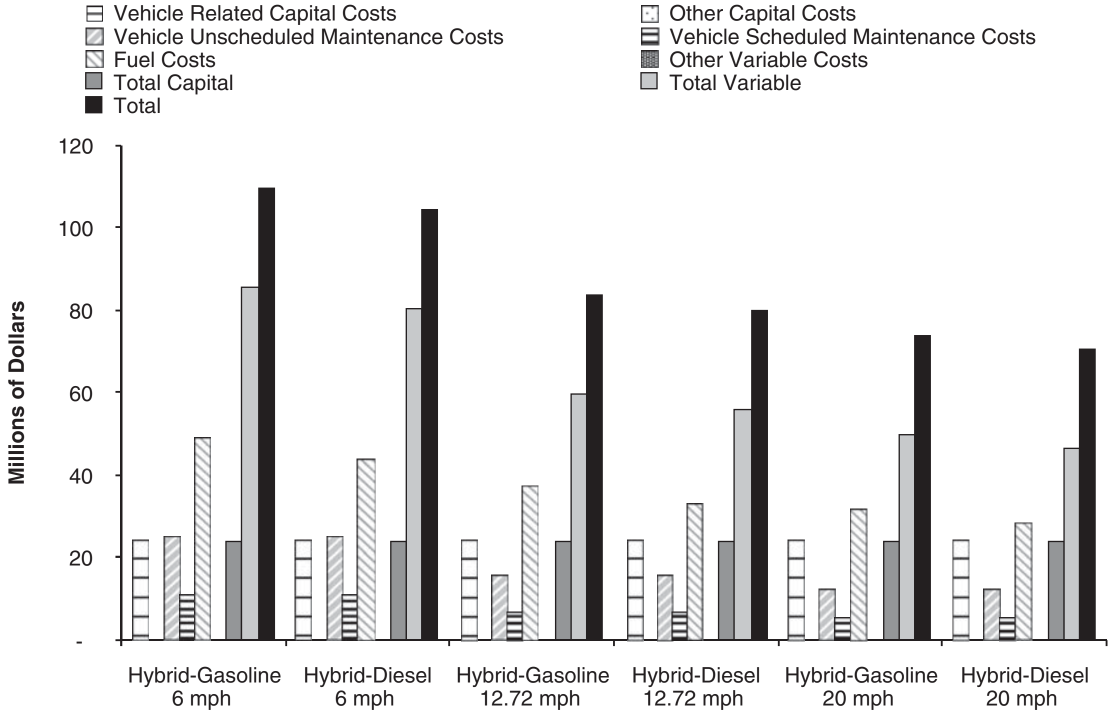


Figure 2.21. Speed effects on detailed LCC comparison of gasoline hybrid and diesel hybrid buses. An 80% purchase subsidy is included.

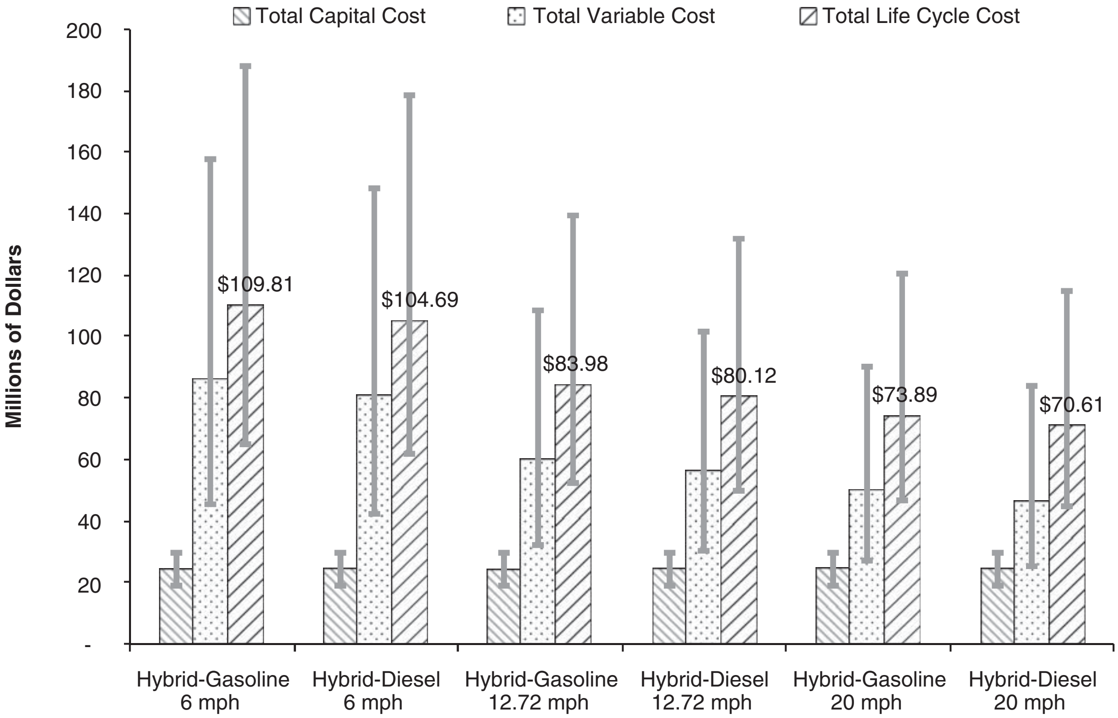


Figure 2.22. Speed effects on LCC comparison of gasoline hybrid and diesel hybrid buses (with range bars). An 80% purchase subsidy is included.

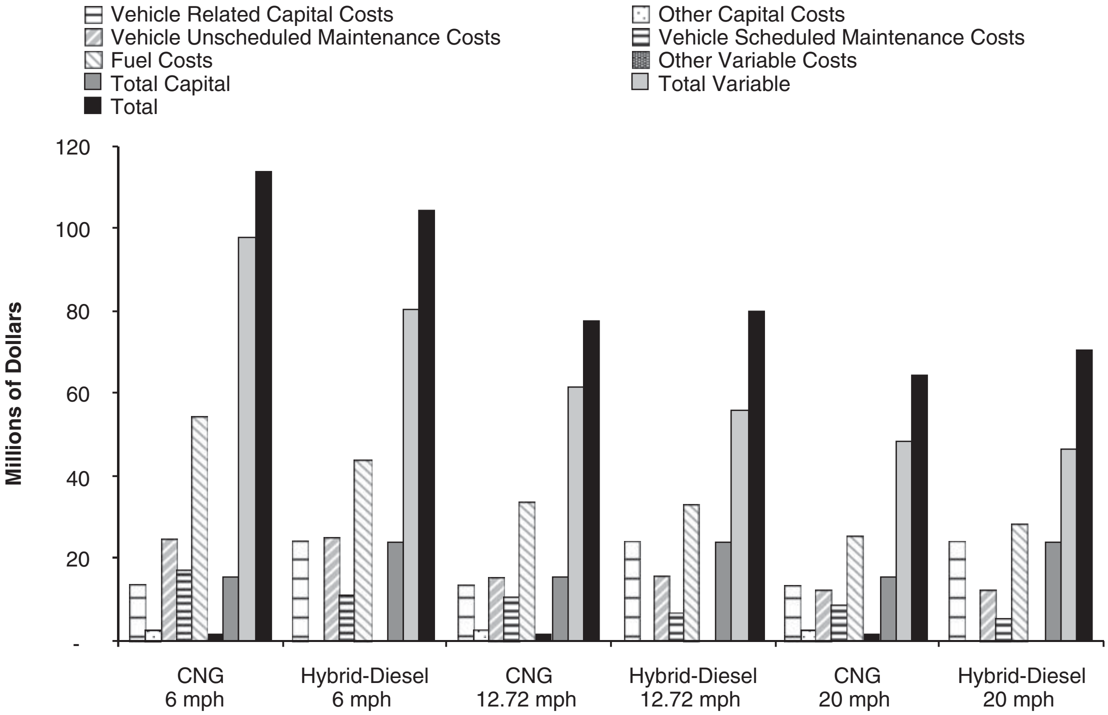


Figure 2.23. Speed effects on detailed LCC comparison of CNG and diesel hybrid buses. An 80% purchase subsidy is included.

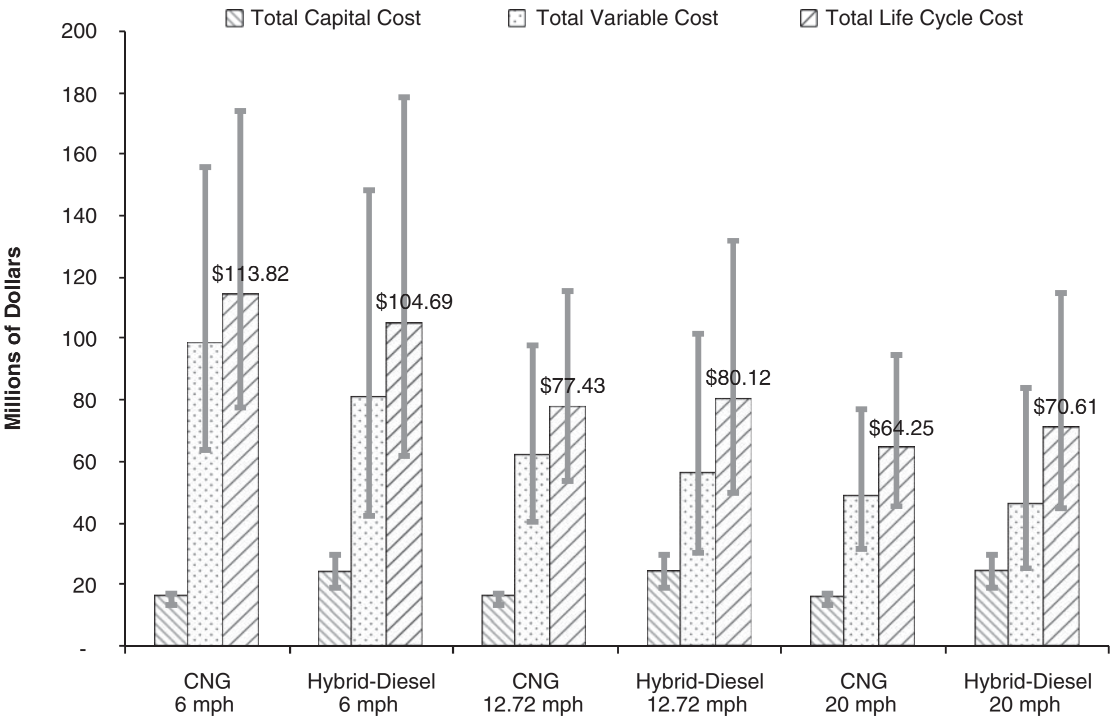


Figure 2.24. Speed effects on LCC comparison of CNG and diesel hybrid buses (with range bars). An 80% purchase subsidy is included.

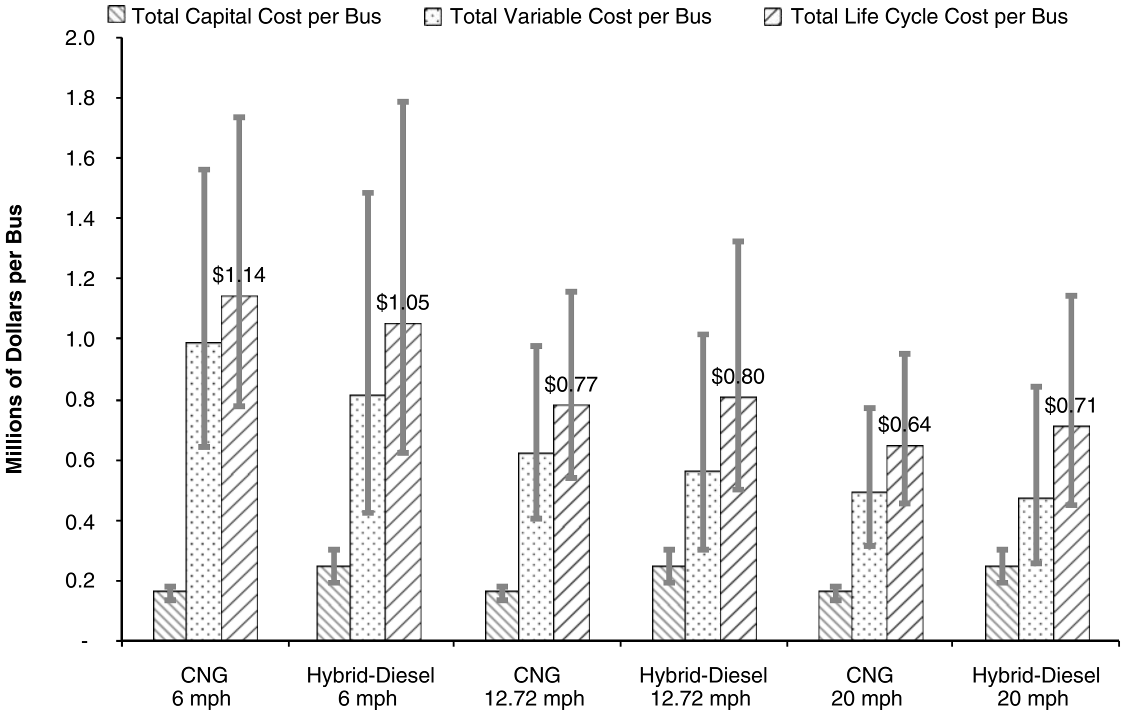


Figure 2.25. Speed effects per bus on LCC comparison of CNG and diesel hybrid buses. An 80% purchase subsidy is included.

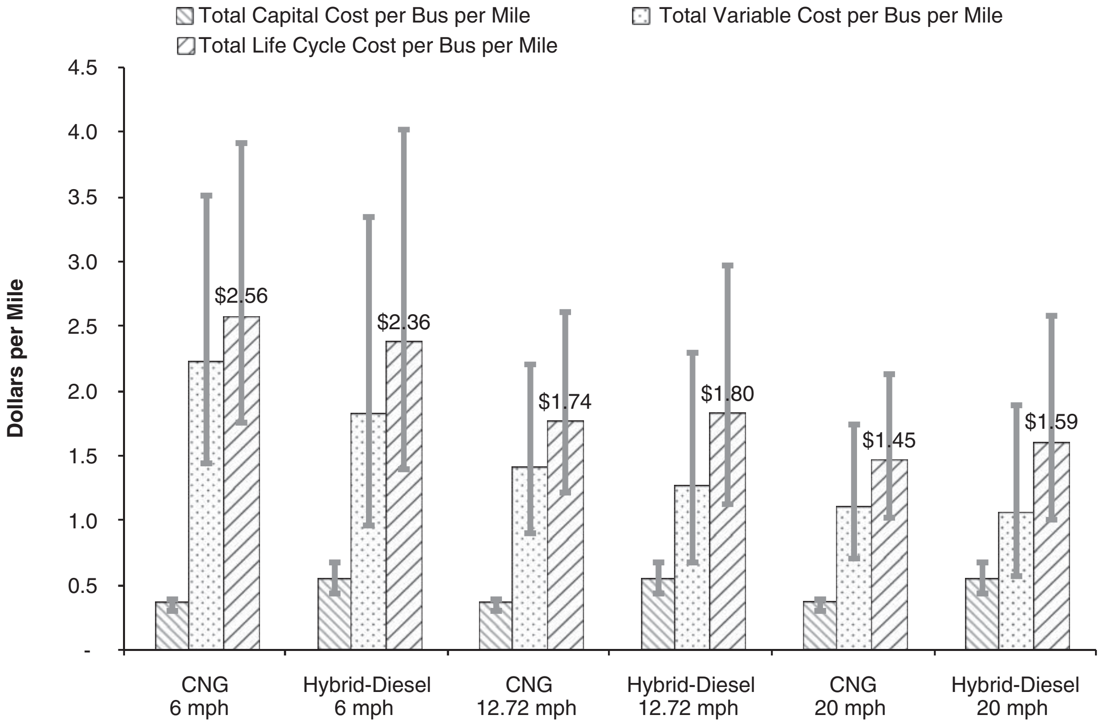


Figure 2.26. Speed effects per bus mile on LCC comparison of CNG and diesel hybrid buses. An 80% purchase subsidy is included.

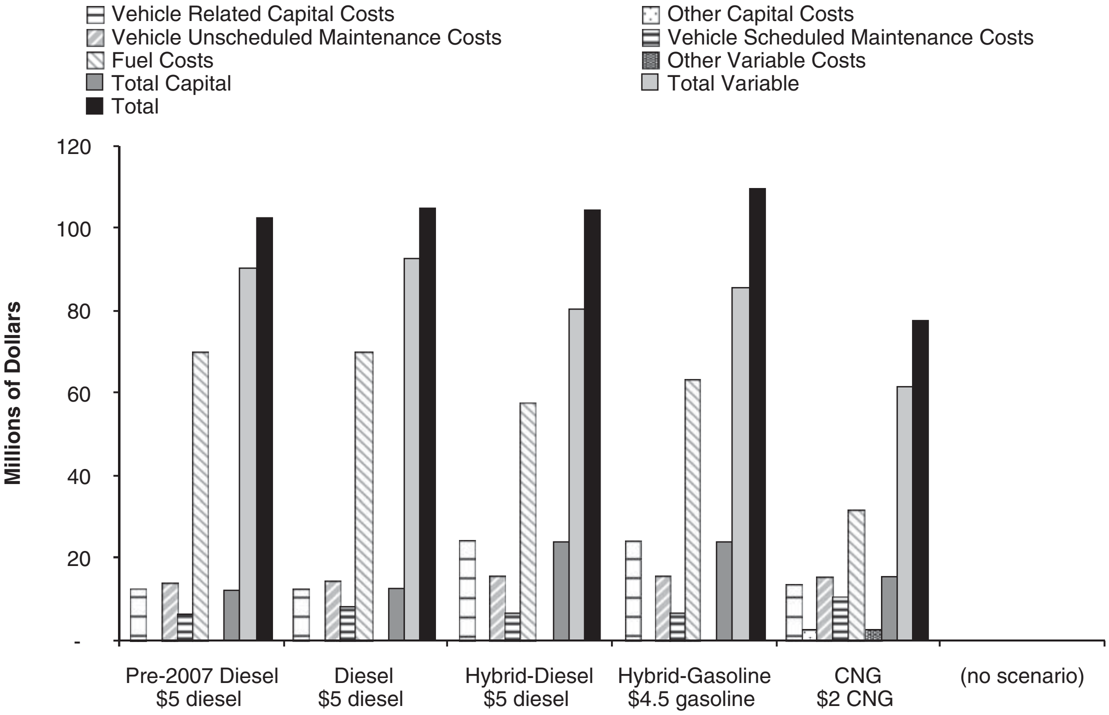


Figure 2.27. Detailed LCC comparison with diesel price at $5/g and 80% purchase subsidy.

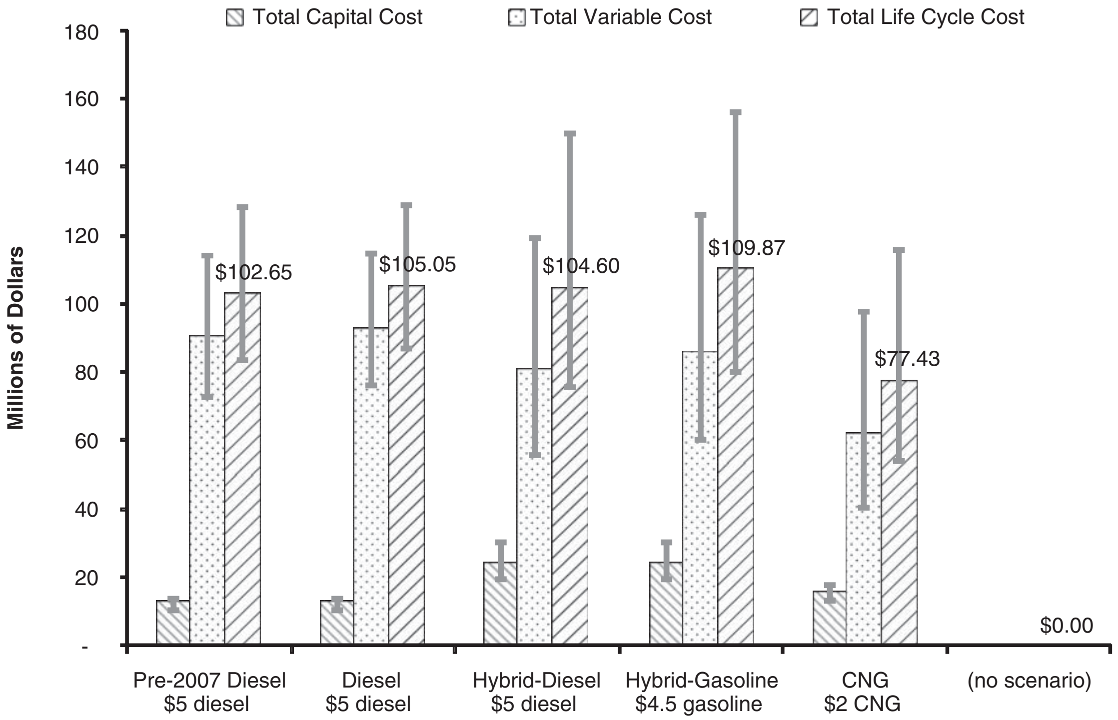


Figure 2.28. LCC comparison with diesel price at $5/g and 80% purchase subsidy (with range bars).

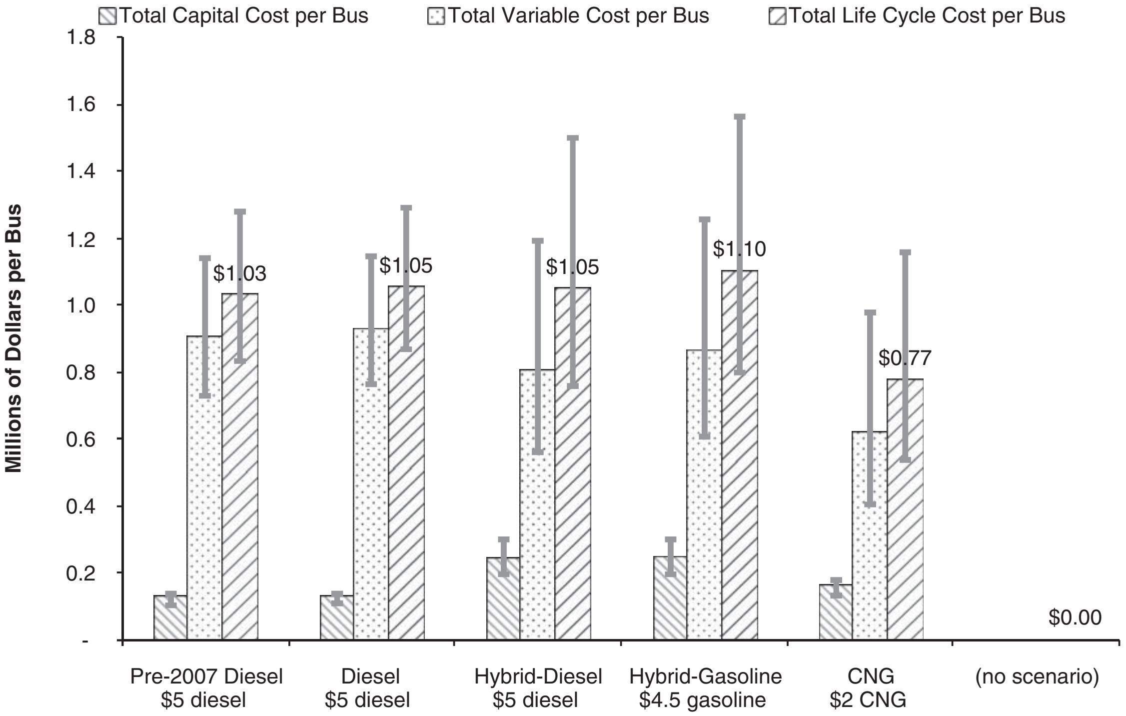


Figure 2.29. LCC comparison per bus with diesel price at $5/g and 80% purchase subsidy (with range bars).

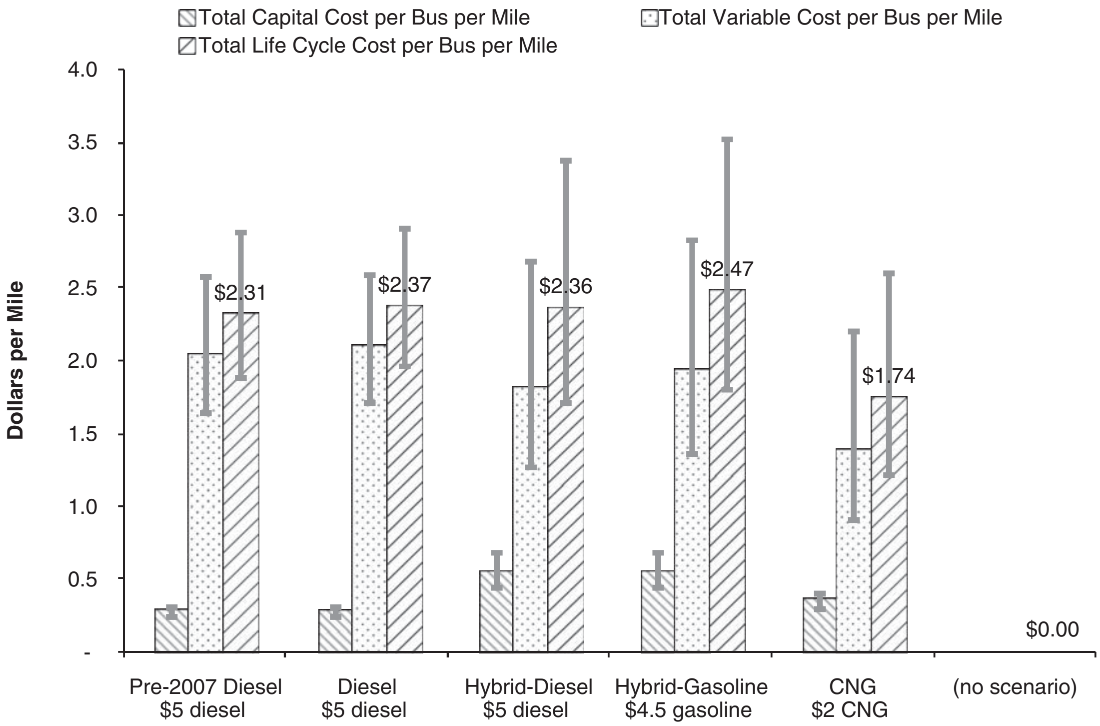


Figure 2.30. LCC comparison per bus mile with diesel price at $5/g and 80% purchase subsidy (with range bars).

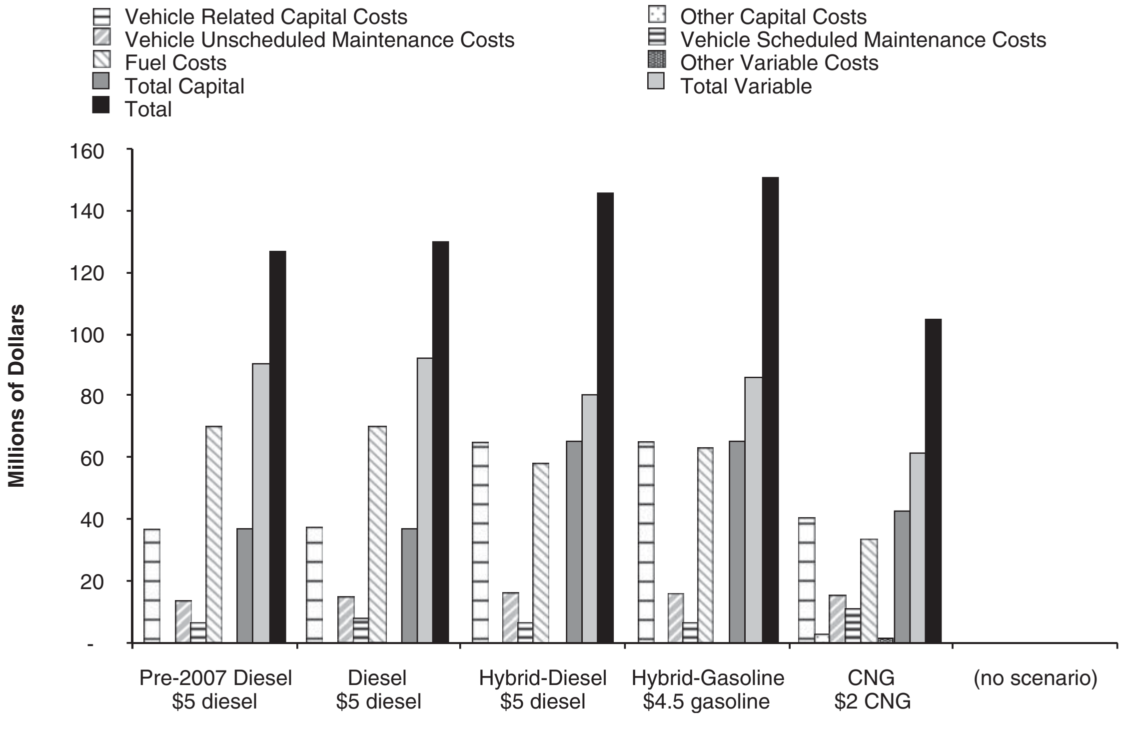


Figure 2.31. Detailed LCC comparison with diesel price at $5/g and no purchase subsidy.

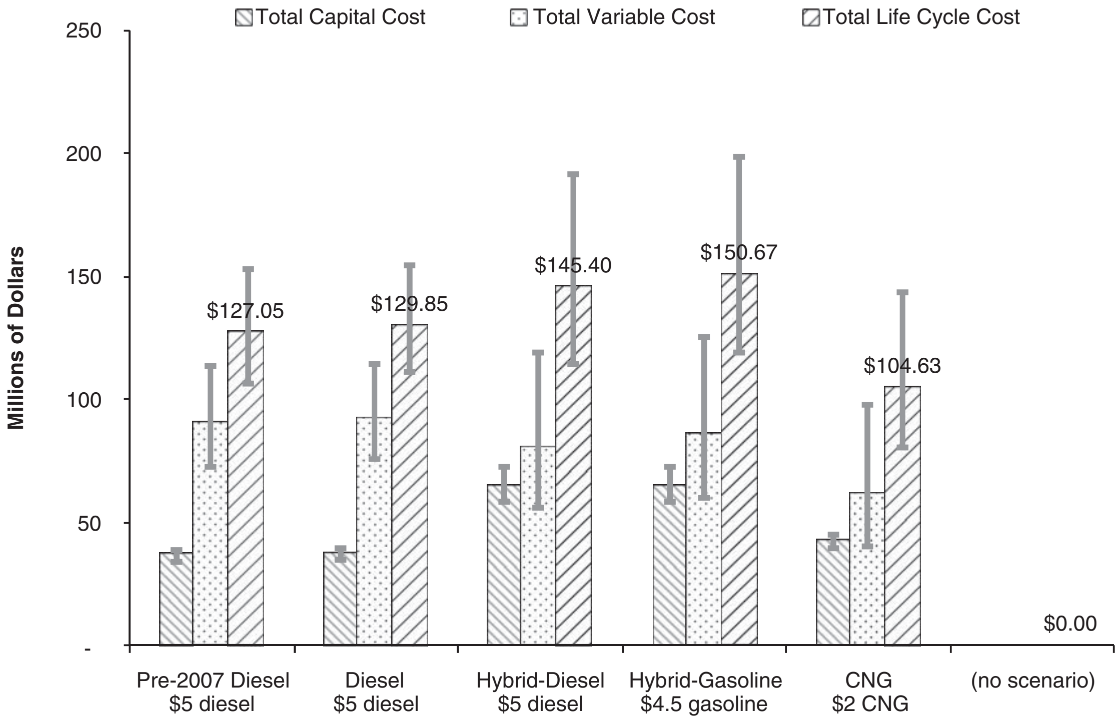


Figure 2.32. LCC comparison with diesel price at $5/g and no purchase subsidy (with range bars).

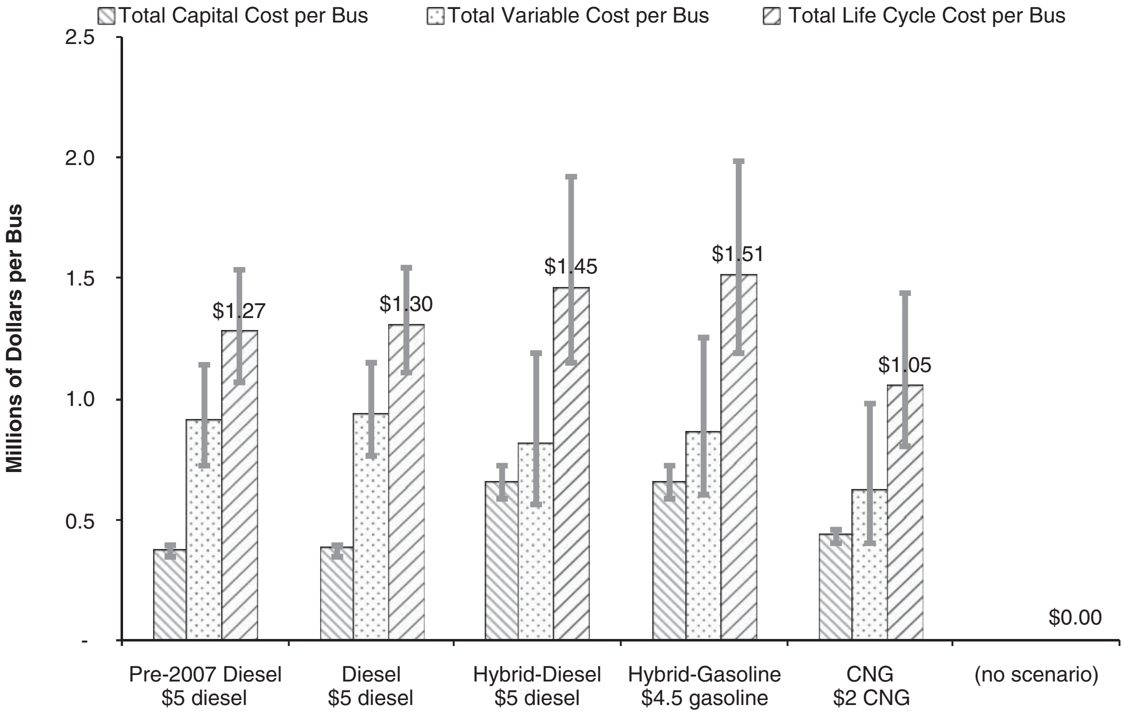


Figure 2.33. LCC comparison per bus with diesel price at $5/g and no purchase subsidy (with range bars).

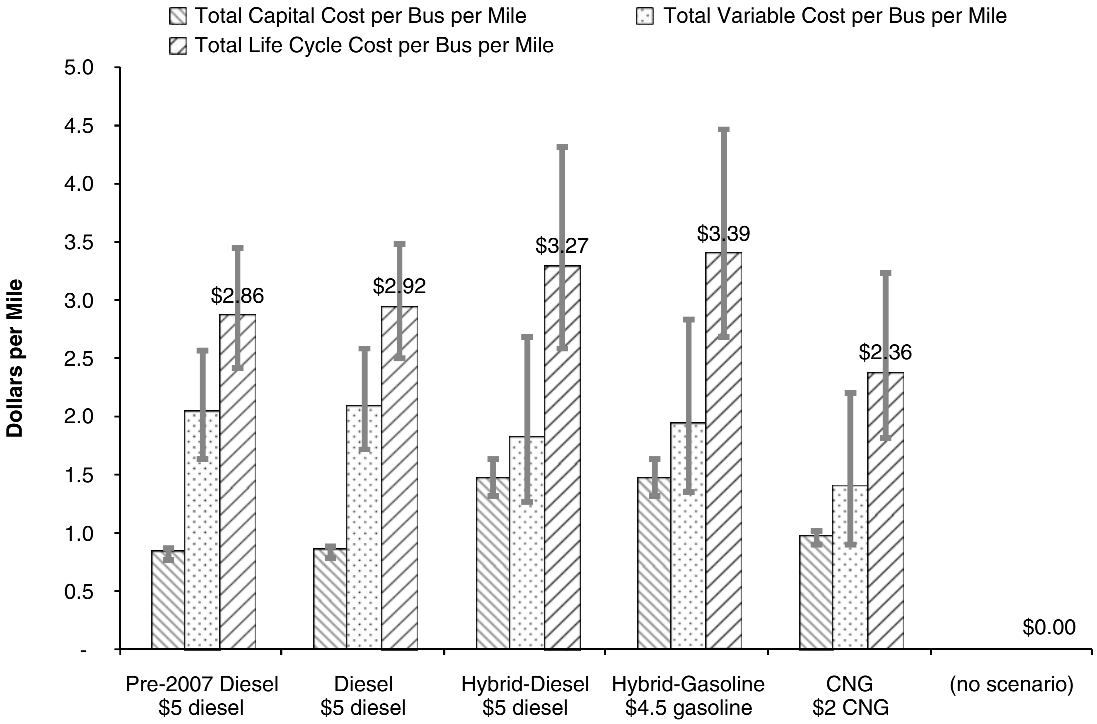


Figure 2.34. LCC comparison per bus mile with diesel price at $5/g and no purchase subsidy (with range bars).

This circumstance could arise if the imbalance between supply and demand for the gasoline/diesel split ratio increases due to global growth in the future.

2.4.5 Cost Breakeven Point Case

As discussed above, if an 80% bus purchase subsidy is considered, HEB and diesel costs are similar, even for a 12-year bus life at medium operating speed of 12.72 mph. In the case of no subsidy, the research team found that fuel prices had to become very high (average diesel price at $11.50/DEG and gasoline price at $10.35/DEG) to reach the point at which diesel HEB and diesel bus overall cost were the same for the 12.72 mph default speed. See Figures 2.35 through 2.38. Operating gasoline HEB is slightly more expensive than either the diesel or the diesel HEB, unless the differential in prices of gasoline and diesel increases. The gasoline HEB is about 5% higher in overall cost than the diesel HEB. Previous analysis provided in Section 2.4.3 shows that HEB cost less to operate than diesel buses at 6 mph operating speed with the 80% purchase subsidy included. It is evident that operation speeds and purchase credits play a major role in HEB LCC performance at a fixed diesel fuel price.

2.4.6 WMATA Test Site Case

To build confidence in the model, the research team compared model prediction to real-world transit operation at the four test sites. This section presents WMATA test site data from new bus purchases against model calculations. Table 2.28 presents the inputs used for the LCCM. It shows that maintenance costs were the least predictable values. This was due to limited data and unclear warranty issues.

Figures 2.39 through 2.42 present the three bus technologies' two-year performance at WMATA. It is not possible to compare a 12-year bus life accurately, since no site has a long-term technology experience. These charts are created without the 80% purchase subsidy. The differences between real and predicted were acceptable (10% or less) for the three technologies shown in Table 2.29. When no incentives are considered, WMATA site data shows that diesel HEB are 40% higher than conventional diesel buses in total cost, which is predicted as 53% higher by the model. In-field CNG buses cost about 5% higher than diesel buses, and the model shows 13% instead. The differences between real and predicted mainly could be attributed to maintenance and CNG infrastructure cost.

A 12-year test run also is presented for comparison purposes, as shown in Figures 2.43 and 2.44. In this run, the differences between the predicted and real data are much greater than for the 2-year test run. As shown in Table 2.29, differences for two-year real and predicted data ranged from 8% to 19%. Again, maintenance and CNG infrastructure cost are key factors in the prediction. Especially the site maintenance data, which are collected for the initial two years of bus operation, are

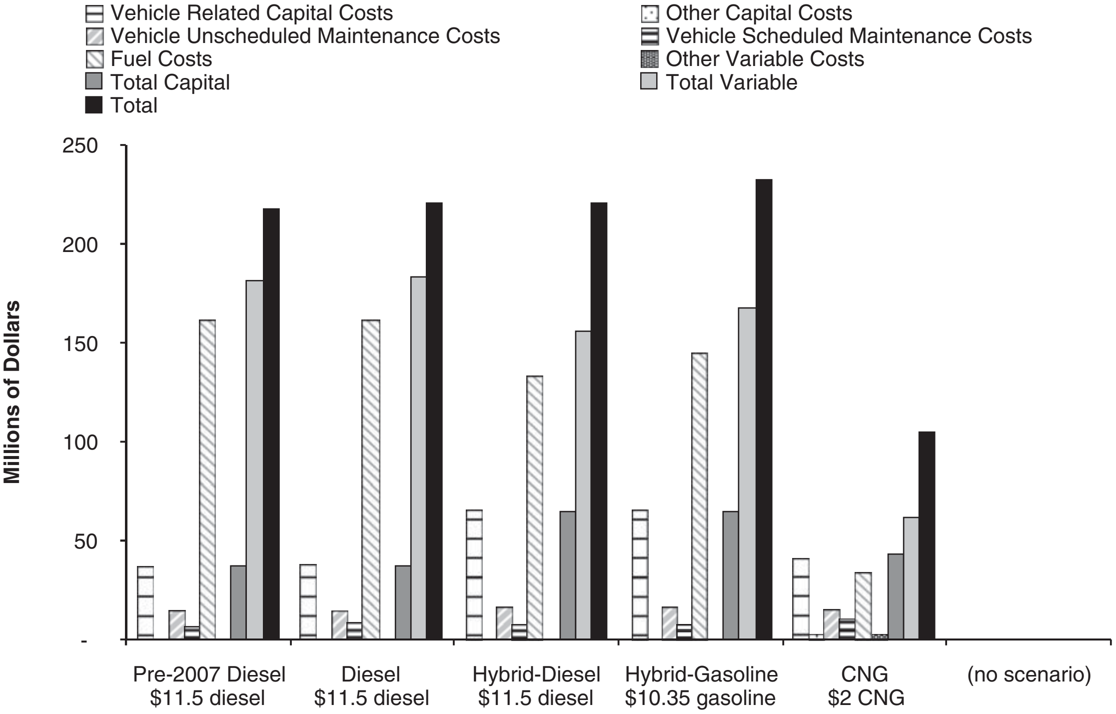


Figure 2.35. Detailed LCC breakeven point for diesel and diesel hybrid with diesel price at $11.50/g and no purchase subsidy.

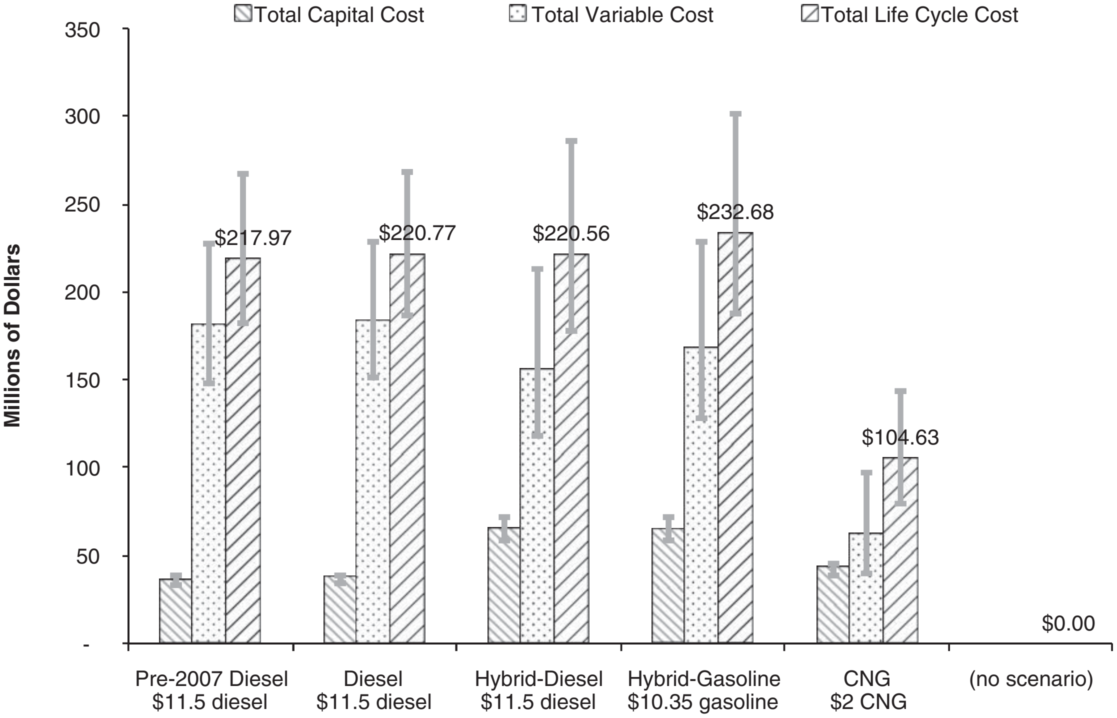


Figure 2.36. LCC breakeven point for diesel and diesel hybrid with diesel price at $11.50/g and no purchase subsidy (with range bars).

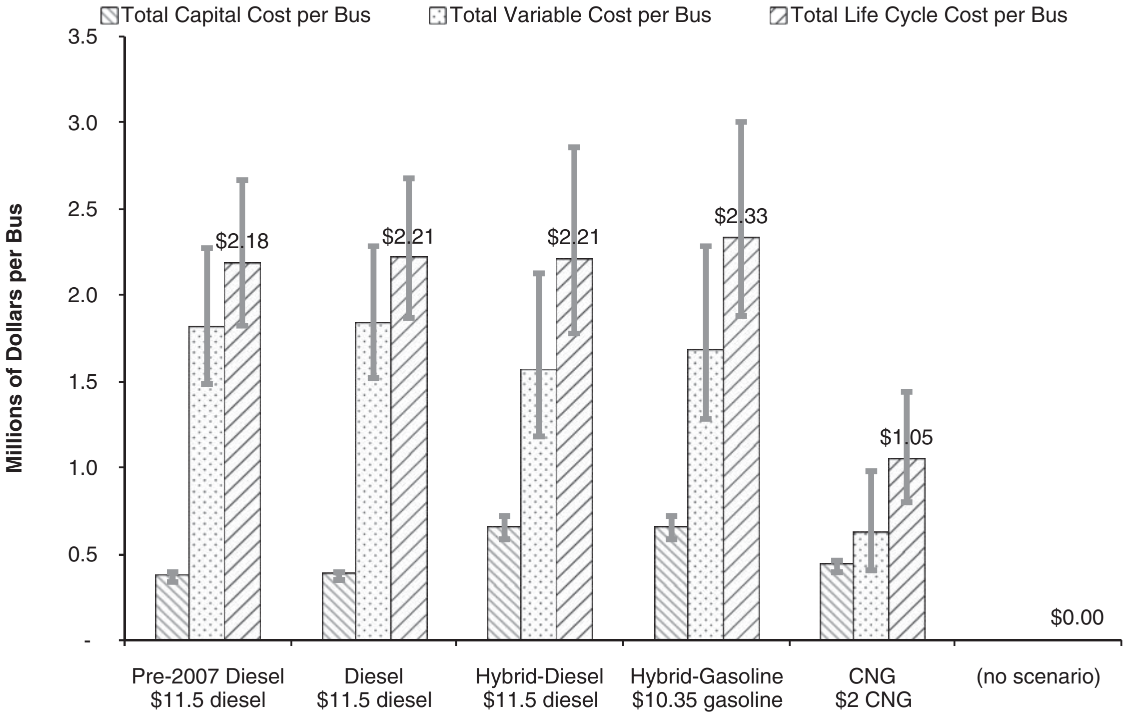


Figure 2.37. LCC breakeven point per bus for diesel and diesel hybrid with diesel price at $11.50/g and no purchase subsidy (with range bars).

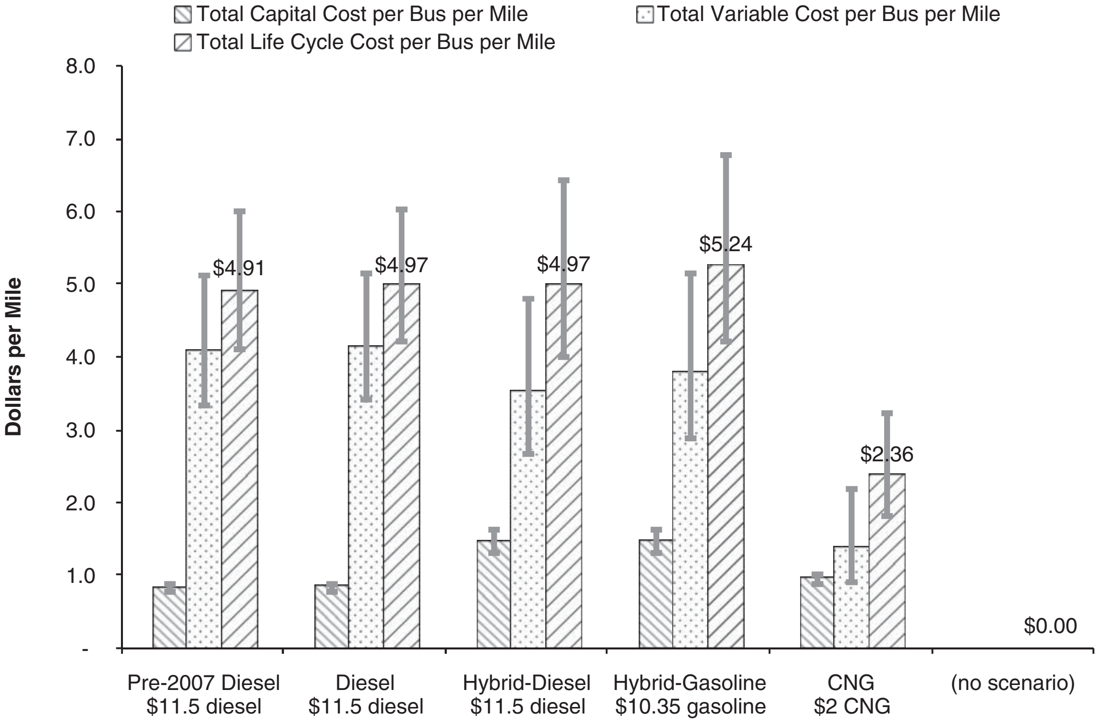


Figure 2.38. LCC breakeven point per bus mile for diesel and diesel hybrid with diesel price at $11.50/g and no purchase subsidy (with range bars).

Table 2.28. Model inputs for WMATA site and default model inputs.

	Pre-2007 Diesel		Diesel Hybrid		CNG	
	Site	Default	Site	Default	Site	Default
Purchase Order	117	117	50	50	250	250
Average Speed (mph)	17.3[1]	17.3[1]	17.3[1]	17.3[1]	17.9	17.9
Fuel Economy (mpg)	3.48[2]	3.71	3.96[3]	4.31	3.21[4]	3.23
Purchase Cost ($)	349,000	305,000	521,980	510,000	274,000	340,000
Extended Warranty ($)	0	0	0	0	0	0
Unscheduled Maintenance for 2 Years ($/Mile)	0.08	0.17	0.06	0.19	0.18	0.18
Scheduled Maintenance for 2 Years ($/Mile)	0.06	0.08	0.07	0.08	0.10	0.13
Unscheduled Maintenance for 12 Years($/Mile)	0.08	0.31	0.06	0.35	0.18	0.34
Scheduled Maintenance for 12 Years ($/Mile)	0.06	0.15	0.07	0.15	0.10	0.24
CNG Infrastructure ($)					15,000,000[5]	4,750,000
Purchase Scenario	1	2	3	4	5	6

Notes:

1 Average speed of 17.1 and 17.5 mph at two depots.

2 Average fuel economy of 3.45 and 3.50 mpg at two depots.

3 Average fuel economy of 3.94 and 3.98 mpg at two depots.

4 Average fuel economy of 3.11 and 3.31 mpg of two different CNG engine technologies.

5 This cost is for recent refurbishment of the Four Mile Run CNG facility. It is reported that $1.3 million was for the fueling station.

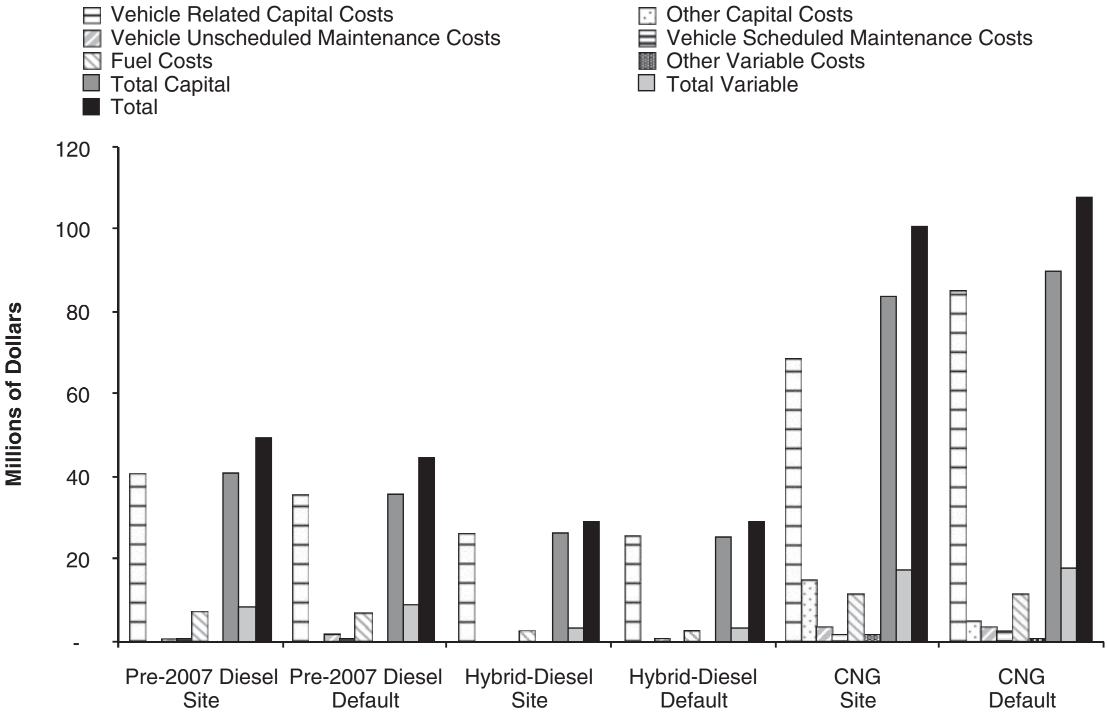


Figure 2.39. Detailed LCC comparison of model and 2 years of WMATA real-world data.

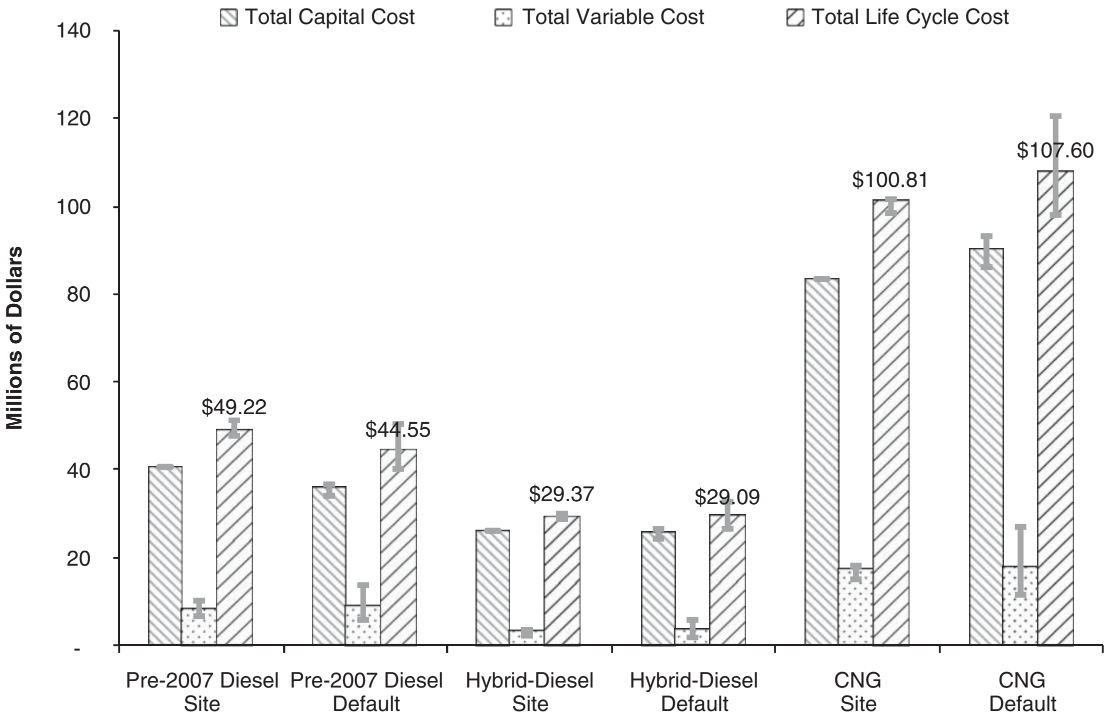


Figure 2.40. LCC comparison of model and 2 years of WMATA real-world data (with range bars).

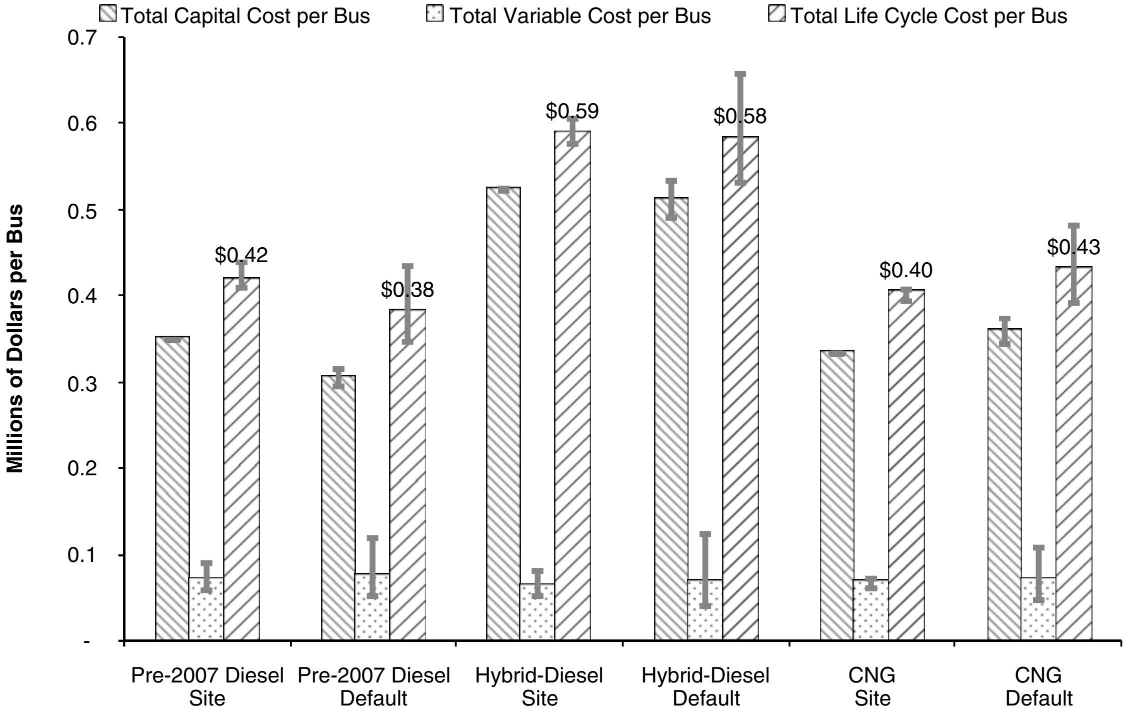


Figure 2.41. LCC comparison of model and 2 years of WMATA real-world data, per bus (with range bars).

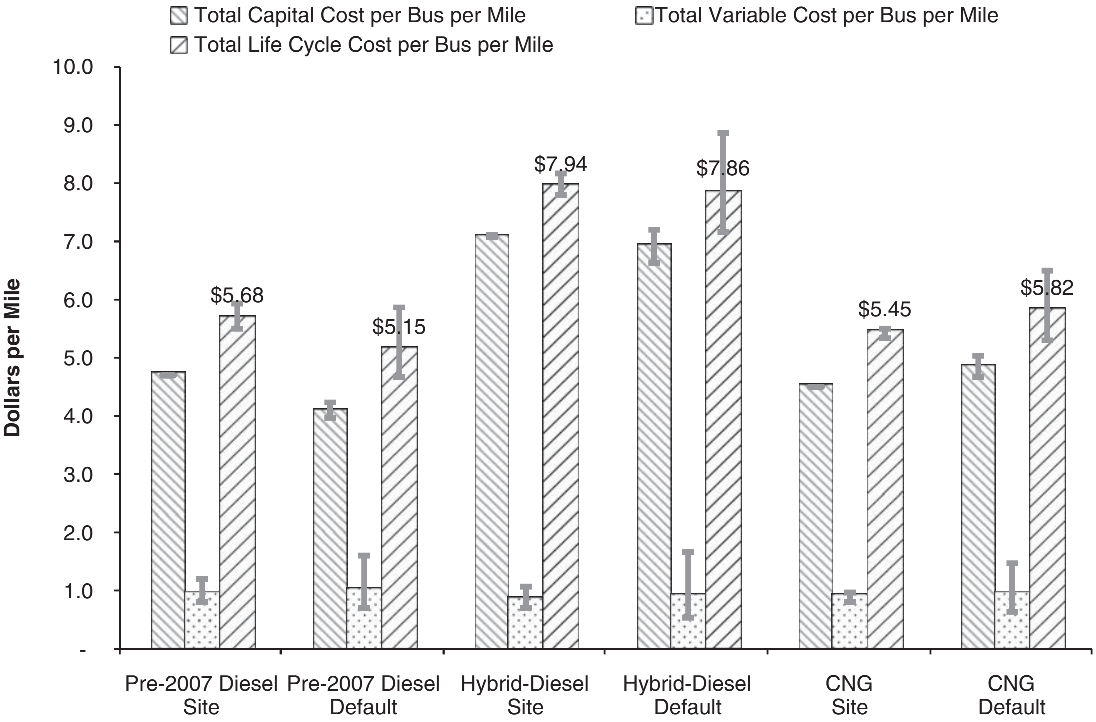


Figure 2.42. LCC comparison of model and 2 years of WMATA real-world data, per bus mile (with range bars).

smaller than predicted due to the influence of warranty coverage. For long-term operation, the fuel cost benefit reduced HEB total cost to 21% higher than the amount of diesel buses from field data or 26% higher by the model. CNG buses are 4% lower in cost from field data and 5% higher in cost for the model, suggesting that CNG and diesel operating costs are about even.

If 80% of purchase credit is used in the model, the LCC differences between HEB and diesel are reduced to 12% by the model prediction and 7% by the field data (see Figure 2.45). For CNG buses, they become –7% by the model prediction and –2% by the field data.

2.4.7 WMATA NREL CNG Study Case

This section reproduces NREL's comparison study on WMATA diesel technology and two CNG bus technologies (CNG engines were made by Cummins Westport/CWI and John Deere).(*18*) The cost data are not used in the development of the LCCM. The case was used for a demonstration test. Table 2.30 presents the inputs to the LCCM.(*18*)

Figures 2.46 and 2.47 present three bus technologies' two-year performance at WMATA.(*18*) These charts do not include the 80% purchase subsidy. The model matches the field data well—partially because CNG infrastructure costs are not considered. The infrastructure costs were unknown, and the study is for the defined number of buses. The two-year performance differences between real and predicted cost are within the 5% range for the three technologies as shown in Table 2.31.(*18*) WMATA site data show that CNG CWI buses were 12% higher than diesel buses in total cost, which is predicted as 13% by the model. CNG Deere buses are also 12% higher in cost than diesel buses, and the model again shows the same

Table 2.29. WMATA site and model comparisons (no purchase subsidy).

	2-Year Site	2-Year Model	Difference	12-Year Site	12-Year Model	Difference
Diesel LCC per Bus (Millions of $)	0.42	0.38	10%	0.84	0.91	8%
Diesel HEB LCC per Bus (Millions of $)	0.59	0.58	2%	1.02	1.15	13%
CNG LCC per Bus (Millions of $)	0.40	0.43	8%	0.81	0.96	19%
Diesel HEB vs. Diesel	40%	53%	-	21%	26%	-
CNG vs. Diesel	4.8%	13%	-	-4%	5%	-

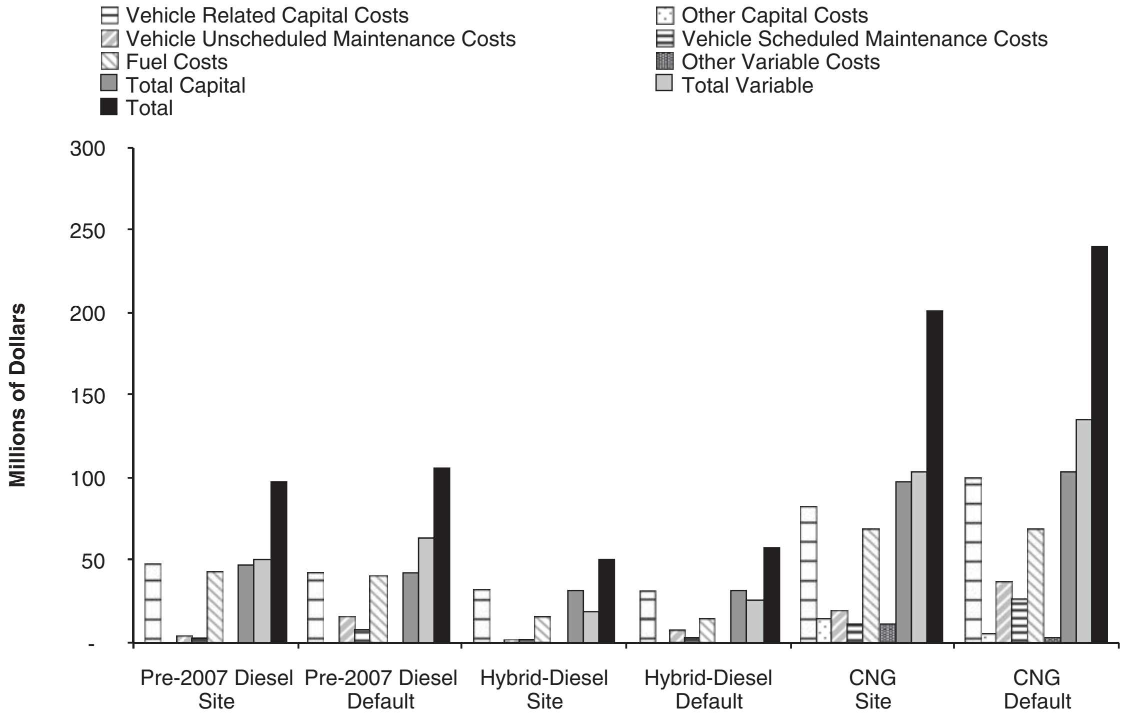


Figure 2.43. Detailed LCC comparison of model and 12 years of WMATA real-world data.

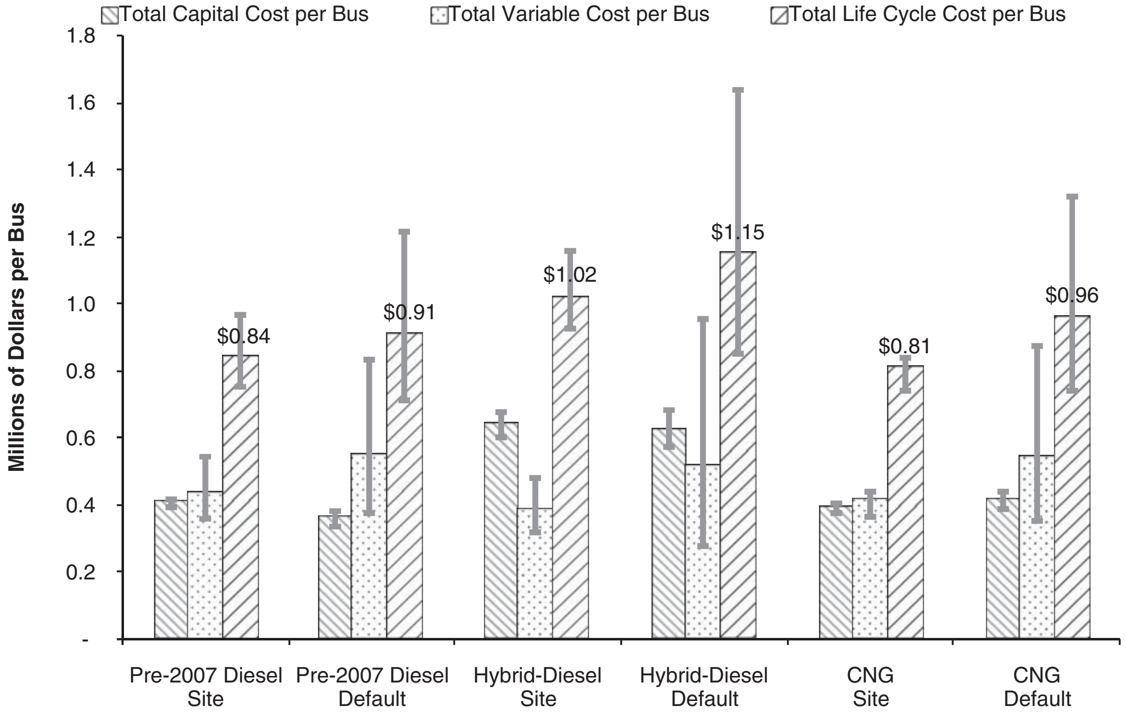


Figure 2.44. LCC comparison of model and 12 years of WMATA real-world data, per bus (with range bars).

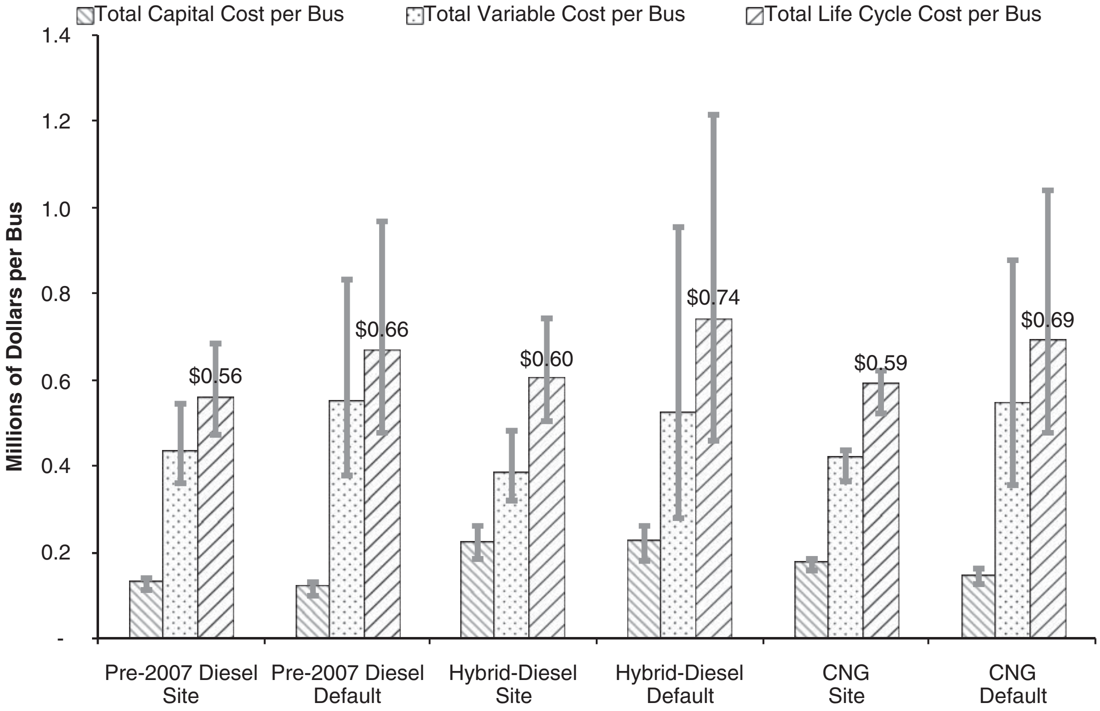


Figure 2.45. LCC comparison of model and 12 years of WMATA real-world data, per bus (with range bars). An 80% purchase subsidy is included.

13% difference. A 12-year test run is shown in Figure 2.48.(*18*) The differences between the predicted and the real data are greater in the 12-year test run than in the 2-year test run. As shown in Table 2.31, the 12-year performance differences between real and predicted costs ranged from –4% to 6%. For long-term operation, the model finds that CNG buses are 19% higher in LCC than diesel buses. The field data show LCC at 8% higher for CNG CWI and 10% higher for CNG Deere. The zero infrastructure costs benefit CNG LCC cost in this study. Still, the field maintenance cost data are based on a one-year evaluation and warranty issues cloud the real costs.

2.4.8 LBT Test Site Case

This section presents the LBT test site gasoline HEB LCC performance. Table 2.32 presents the inputs to the LCCM. LBT purchased 5-year extended warranties for 27 of their 47 gasoline HEB. This case studies gasoline HEB LCC performance

Table 2.30. Model inputs for WMATA site and default model inputs.

	Pre-2007 Diesel		Cummins CNG		Deere CNG	
	Site	Default	Site	Default	Site	Default
Purchase Order	5	5	5	5	5	5
Average Speed (mph)	11.6	11.6	11.6	11.6	11.6	11.6
Fuel Economy (mpg)	2.84	3.02	2.32	2.47	2.39	2.47
Purchase Cost ($)	300,000	305,000	340,000	340,000	340,000	340,000
Extended Warranty ($)	0	0	0	0	0	0
Unscheduled Maintenance for 2 Years ($/Mile)	0.32	0.21	0.26	0.23	0.27	0.23
Scheduled Maintenance for 2 Years ($/Mile)	0.27	0.10	0.26	0.16	0.3	0.16
Unscheduled Maintenance for 12 Years ($/Mile)	0.32	0.38	0.26	0.42	0.27	0.42
Scheduled Maintenance for 12 Years ($/Mile)	0.27	0.18	0.26	0.29	0.3	0.29
Infrastructure*	0	0	0	0	0	0
Purchase Scenarios	1	2	3	4	5	6

Note: *The actual infrastructure cost was not considered, since the study was restricted to a certain number of buses.

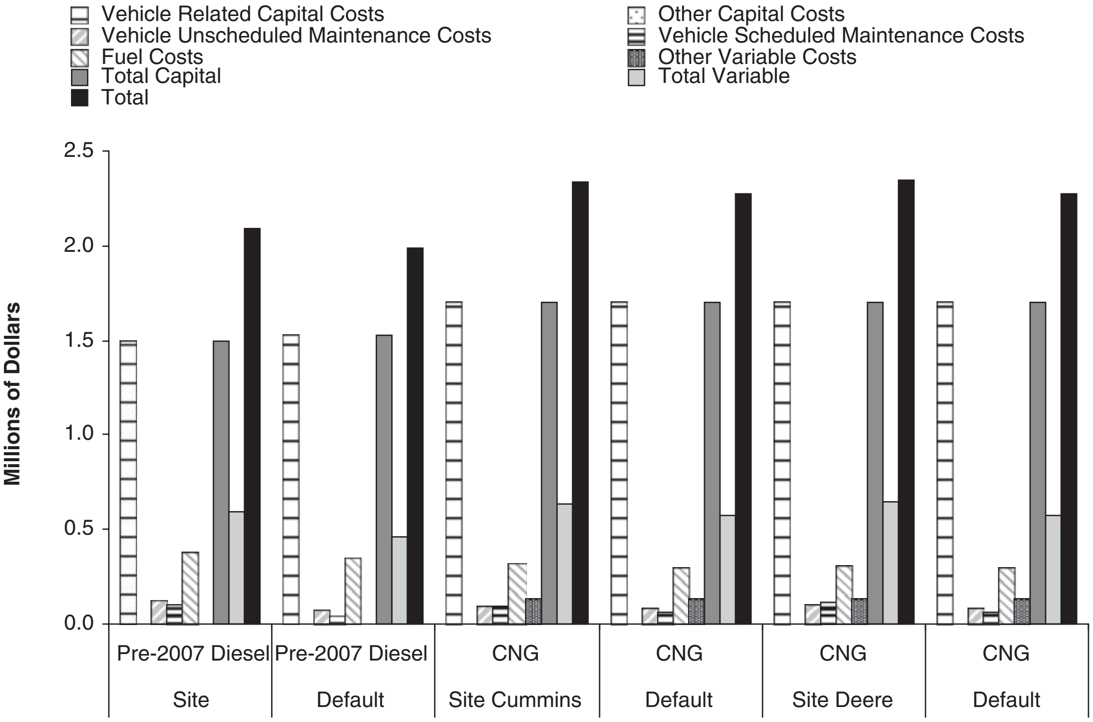


Figure 2.46. Detailed LCC comparison of model and 2 years of WMATA real-world data.

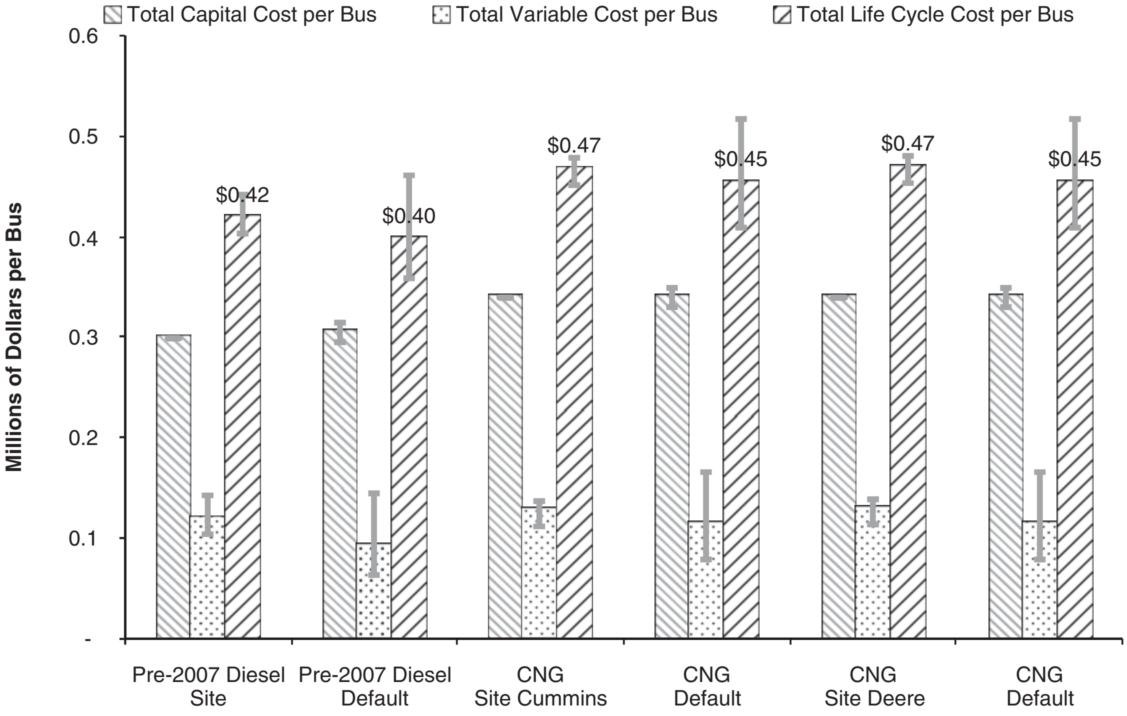


Figure 2.47. LCC comparison of model and 2 years of WMATA real-world data, per bus (with range bars).

Table 2.31. WMATA site and model comparisons (no purchase subsidy).

	2-Year Site	2-Year Model	Difference	12-Year Site	12-Year Model	Difference
Diesel LCC per Bus (Millions of $)	0.42	0.40	-5%	1.07	1.03	-4%
CNG CWI LCC per Bus (Millions of $)	0.47	0.45	-4%	1.16	1.23	6%
CNG Deere LCC per Bus (Millions of $)	0.47	0.45	-4%	1.18	1.23	4%
CNG CWI vs. Diesel	12%	13%	-	8%	19%	-
CNG Deere vs. Diesel	12%	13%	-	10%	19%	-

by separating them into two groups: one with the extended warranty and the other without the extended warranty. The model's warranty cost is very close to the real cost, as shown in Table 2.32. It also presents the reduced overall 12-year maintenance costs caused by the extended warranty. LBT spent $1.49 million to build a gasoline fueling station. Since the gasoline HEB are studied in two groups, the infrastructure cost is distributed between the two groups proportionately.

Figures 2.49 and 2.50 present the three bus study groups' two-year performance at LBT without an 80% purchase subsidy. The groups with and without extended warranty are referred to as Gasoline HEB-1 and Gasoline HEB-2, respectively. The differences between two years of real data and the data predicted by the LCCM are within the 5% range for all three technologies as shown in Table 2.33. When no incentives are included, LBT site data shows that gasoline HEB-1 buses are an average 56% higher than diesel buses in total cost, which is predicted as 64% by the model. Both field data and the model found that gasoline HEB-2 bus costs reduce to 51% higher than diesel buses. Apparently, extended warranty costs were the extra expense for the two-year run.

A 12-year test run also is presented for comparison, as shown in Figures 2.51 and 2.52. The difference between the predicted and real data is higher due to uncorrected field maintenance costs, as shown in Table 2.33. Twelve-year differences ranged from 4% to 15%. For long-term operation, total HEB cost reduces to an average of 17% higher than that reported for diesel buses from field data or an average of 27% higher as determined by the model. See Table 2.33. In this case, the two HEB groups are close to each other. Therefore, for the 12-year

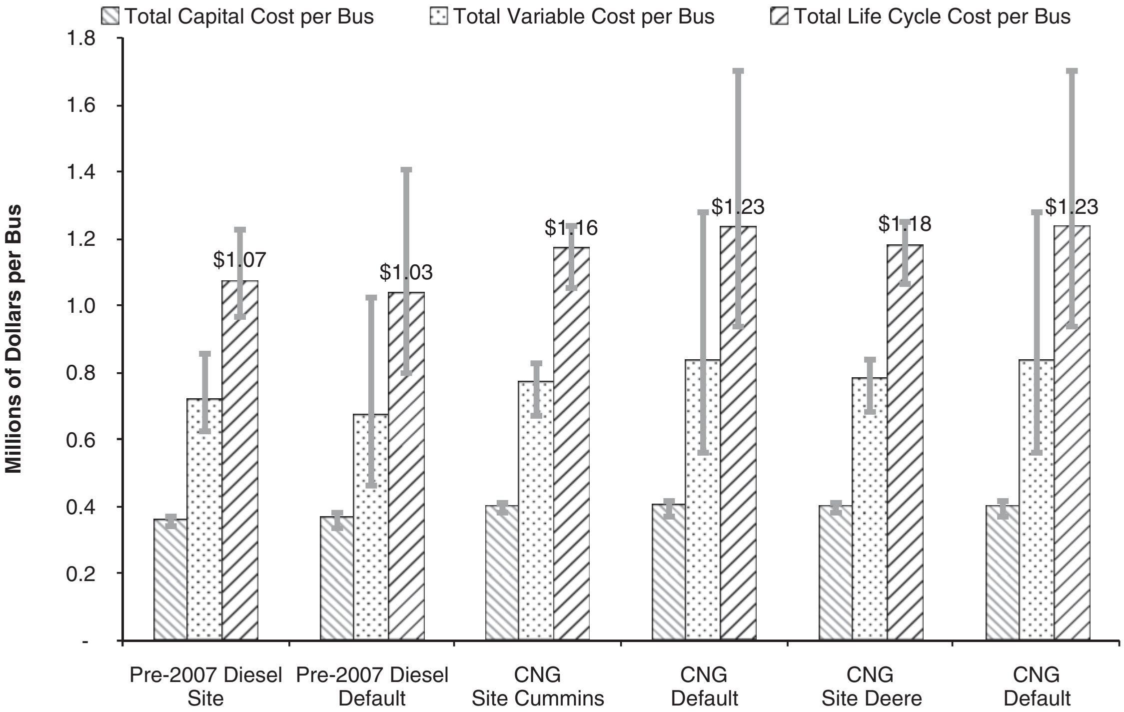


Figure 2.48. LCC comparison of model and 12 years of WMATA real-world data, per bus (with range bars).

Table 2.32. Model inputs for LBT site and default model inputs.

	Diesel		Gasoline Hybrid		Gasoline Hybrid	
	Site	Default	Site	Default	Site	Default
Purchase Order	39	39	27	27	20	20
Average Speed (mph)	13.8[a]	13.8[a]	13.8[a]	13.8[a]	13.8[a]	13.8[a]
Fuel Economy (mpg)	3.49	3.31	3.75	3.65	3.75	3.65
Purchase Cost ($)	290,000	305,000	463,000	510,000	463,000	510,000
Extended 5-Year Warranty ($)	0	0	42,000	41,670	0	0
Unscheduled Maintenance for 2 Years ($/Mile)	0.40	0.19	0.14	0.21	0.14	0.21
Scheduled Maintenance for 2 Years ($/Mile)	0.08	0.09	0.08	0.09	0.08	0.09
Unscheduled Maintenance for 12 Years ($/Mile)	0.40	0.34	0.14	0.30[b]	0.14	0.39
Scheduled Maintenance for 12 Years ($/Mile)	0.08	0.16	0.08	0.13[b]	0.08	0.17
Infrastructure ($)	0	0	1,490,000 x 27/47[c]	0	1,490,000 x 20/47[c]	0
Purchase Scenarios	1	2	3	4	5	6

Notes:

[a] Average speed of LBT's two depots.

[b] Extended warranty reduced vehicle default maintenance cost; 27 of 40 buses ordered had 5-year extended warranty. The remainder did not.

[c] The cost is for investment in a new gasoline fuel station. The total cost was distributed to 27 and 20 bus orders proportionately.

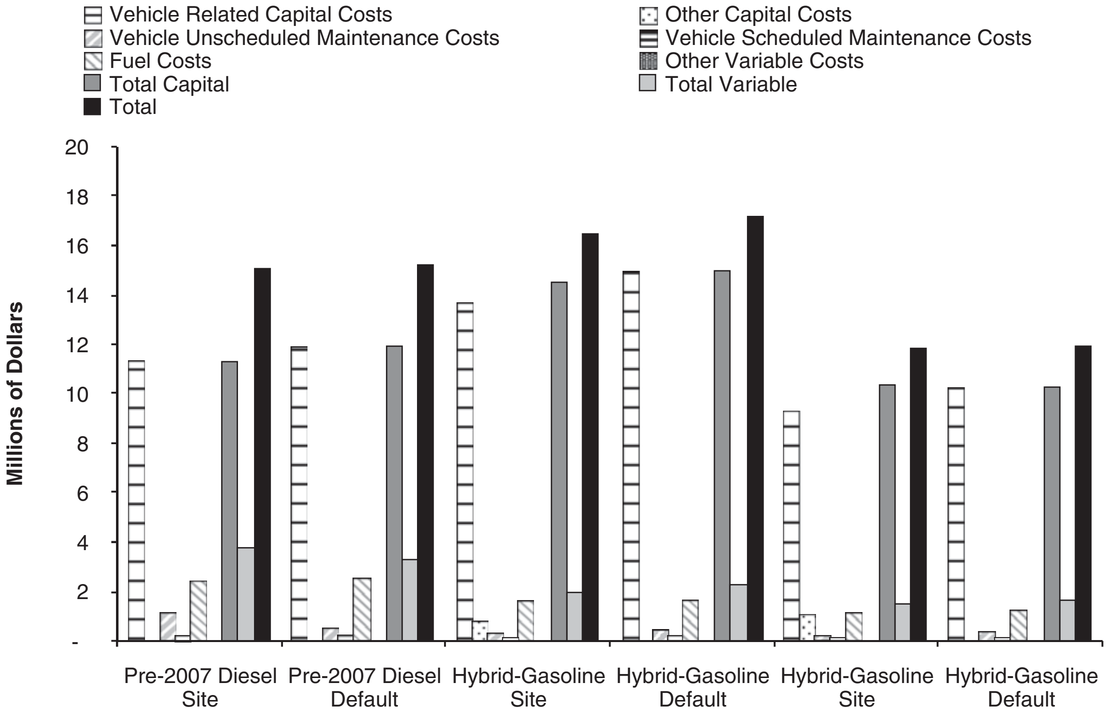


Figure 2.49. Detailed LCC comparison of model and 2 years of LBT real-world data.

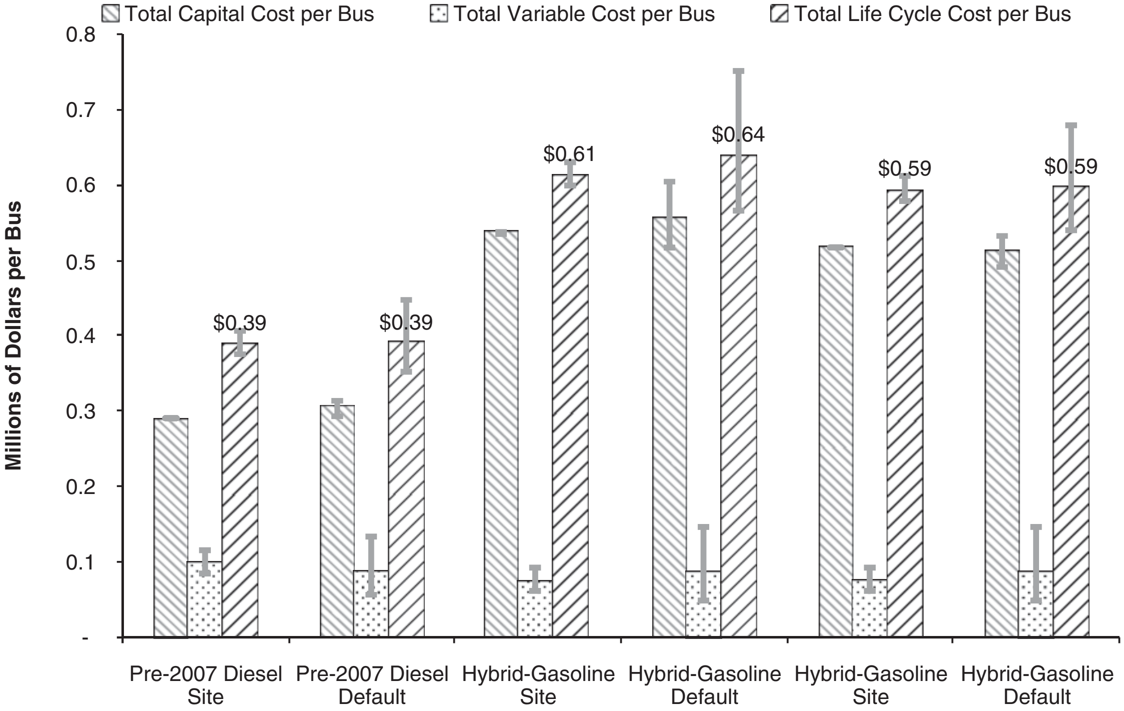


Figure 2.50. LCC comparison of model and 2 years of LBT real-world data, per bus (with range bars).

bus life, additional costs for 5-year warranty cost were basically equal to the savings on maintenance costs.

If an 80% purchase subsidy is used in the model, the LCC differences between HEB and diesel are reduced to an average of 12% by model prediction and 4% by field data (see Figure 2.53).

2.4.9 NYCT Test Site Case

The NYCT test site is a special case due to its buses' slow speed of operation. Diesel HEB and CNG buses are compared using real-world data and model default data. Table 2.34 (*3*) presents these inputs in the LCCM, and shows that HEB and CNG bus purchase prices for NYCT were much lower than the average HEB price in the model. HEB FE was underestimated by 8% in the model. The real-world HEB fuel economy was higher than the predicted values suggest, even though they take the low operation speed into consideration (for detail, see Section 2.2.2).

Figures 2.54 and 2.55 present CNG and diesel HEB two-year performance for NYCT without an 80% purchase subsidy. The differences between real and predicted are 13% for HEB and −8% for CNG buses, as shown in Table 2.35. The opposite directions of these differences emphasize that the model may mispredict the actual differential cost between two technologies with a higher percentage difference than a single technology evaluation might suggest. However, it is mainly HEB purchase price that makes the model predict high for HEB, and an unusual $7.4 million for CNG infrastructure that causes the model to predict low for CNG in this case. When

Table 2.33. LBT site and model comparison (no purchase subsidy).

	2-Year Site	2-Year Model	Difference	12-Year Site	12-Year Model	Difference
Diesel LCC per Bus (Millions of $)	0.39	0.39	0%	0.93	0.97	4%
Gasoline HEB-1 per Bus (Millions of $)	0.61	0.64	5%	1.1	1.22	11%
Gasoline HEB-2 per Bus (Millions of $)	0.59	0.59	0%	1.08	1.24	15%
Gasoline HEB-1 vs. Diesel	56%	64%	-	18%	26%	-
Gasoline HEB-2 vs. Diesel	51%	51%	-	16%	28%	-

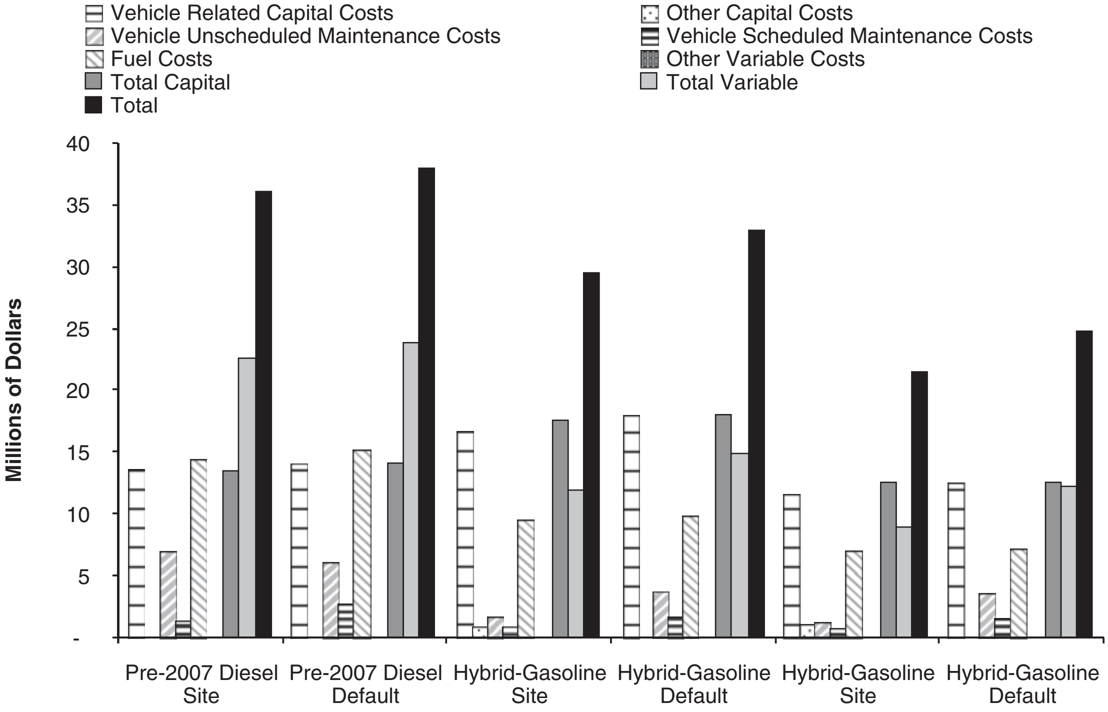


Figure 2.51. Detailed LCC comparison of model and 12 years of LBT real-world data.

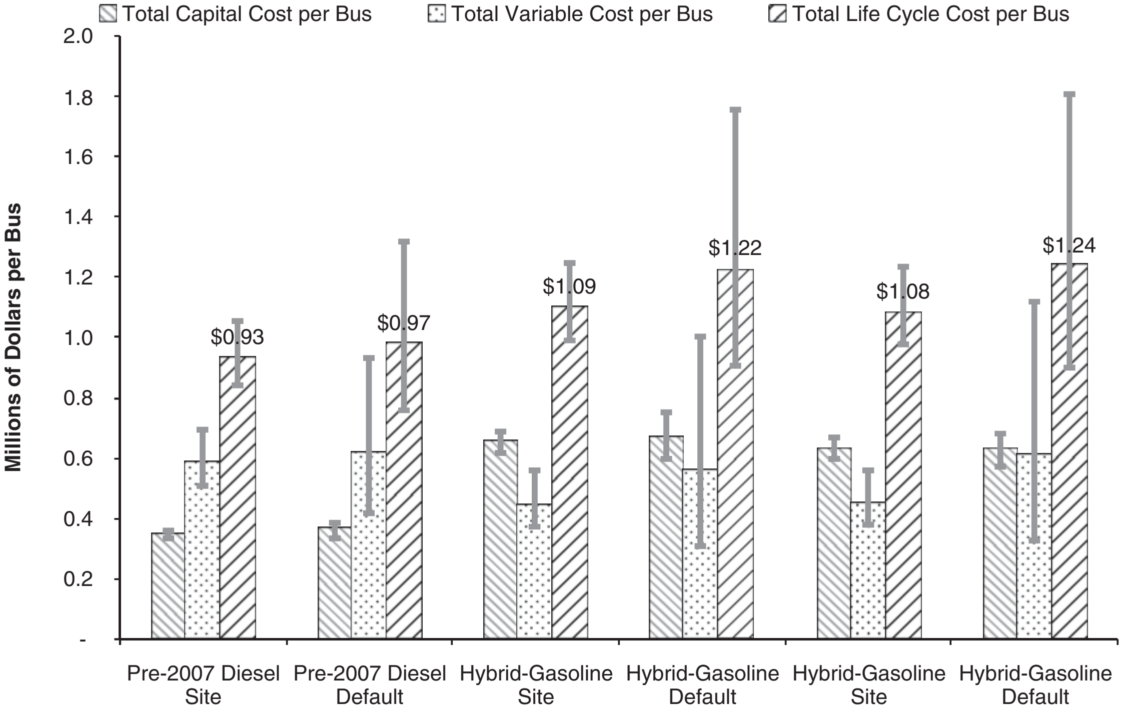


Figure 2.52. LCC comparison of model and 12 years of LBT real-world data, per bus (with range bars).

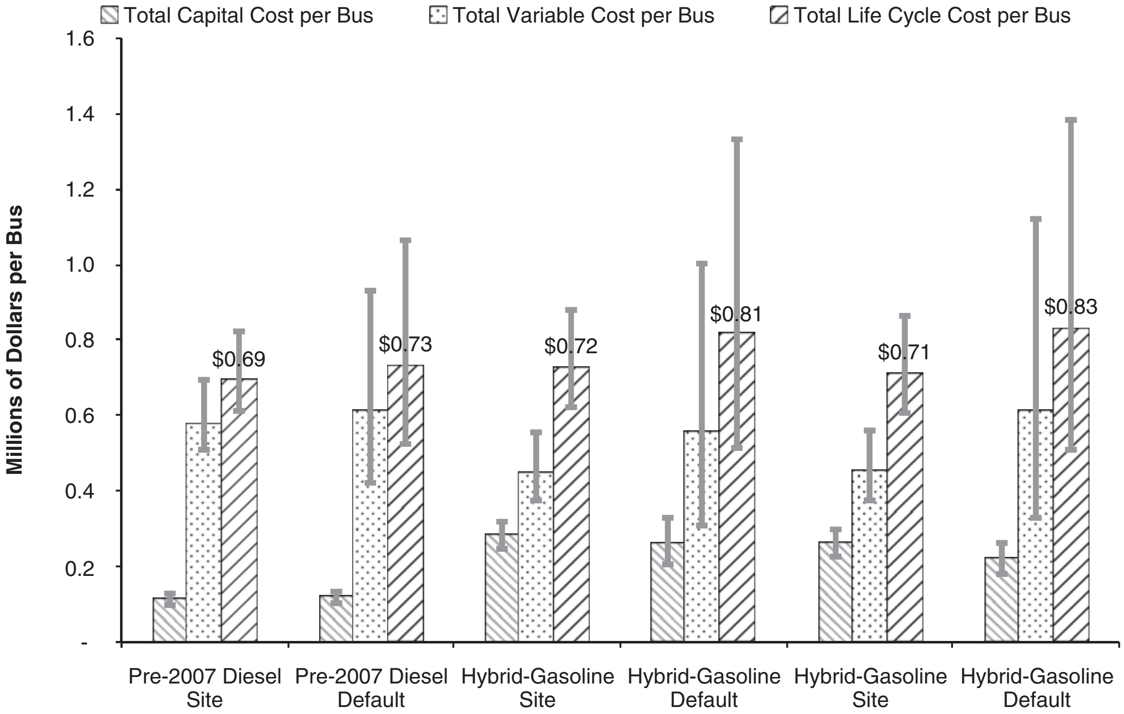


Figure 2.53. LCC comparison of model and 12 years of LBT real-world data, per bus (with range bars). An 80% purchase subsidy is included.

no incentives are considered, NYCT site data shows that diesel HEB are 4% higher than CNG buses in total cost, which is predicted as 27% by the model. An informed user, with knowledge of the actual bus purchase price, would produce more accurate results from the spreadsheet.

A 12-year test run also is presented for comparison purposes, as shown in Figures 2.56 and 2.57.(*3*) The differences between the predicted and real data for the 12-year data are much smaller than those presented for the 2-year test run. As shown in Table 2.35, they are 1% and –6% for HEB and CNG, respectively. The impact of maintenance costs is greater for the 12-year period of operation. Although the model adjusts maintenance costs higher for New York's slow bus speed, this adjustment is not as high as needed to match NYCT performance. Hence, the reduced maintenance costs offset the overestimated bus purchase price and infrastructure cost in the model. CNG and HEB perform similarly in LCC for the 12-year test run. Table 2.35 site data show that HEB save 4% when compared to CNG buses. Model predictions show that HEB cost 4% more than CNG buses.

Table 2.34. Model inputs for NYCT site and default model inputs.

	Diesel Hybrid		CNG	
	Site	Default	Site	Default
Purchase Order	125	125	260	260
Average Speed (mph)	6.3[a]	6.3[a]	6.4[a]	6.4[a]
Fuel Economy (mpg)	3.19	2.94	1.70	1.69
Purchase Cost ($)	385,000	510,000	313,000	340,000
Extended Warranty ($)	0	0	0	0
Unscheduled Maintenance for 2 Years ($/Mile)	0.95	0.35	1.01	0.33
Scheduled Maintenance for 2 Years ($/Mile)	0.28	0.15	0.29	0.23
Unscheduled Maintenance for 12 Years ($/Mile)	0.95	0.64	1.01	0.61
Scheduled Maintenance for 12 Years ($/Mile)	0.28	0.28	0.29	0.43
Infrastructure ($)	140,000[b]	0	7,400,000[c]	4,900,000
Purchase Scenario	1	2	3	4

Notes:

[a] Average speed of NYCT's two depots.

[b] For two battery conditioning stations.

[c] For CNG fueling infrastructure.

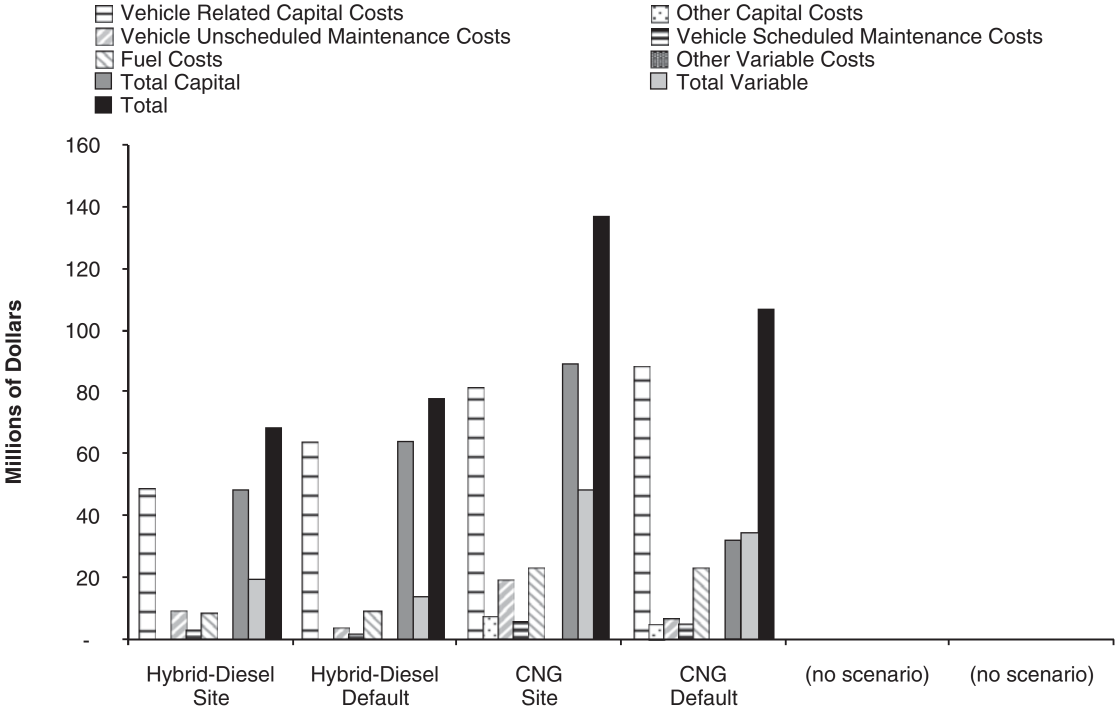


Figure 2.54. Detailed LCC comparison of model and 2 years of NYCT real-world data.

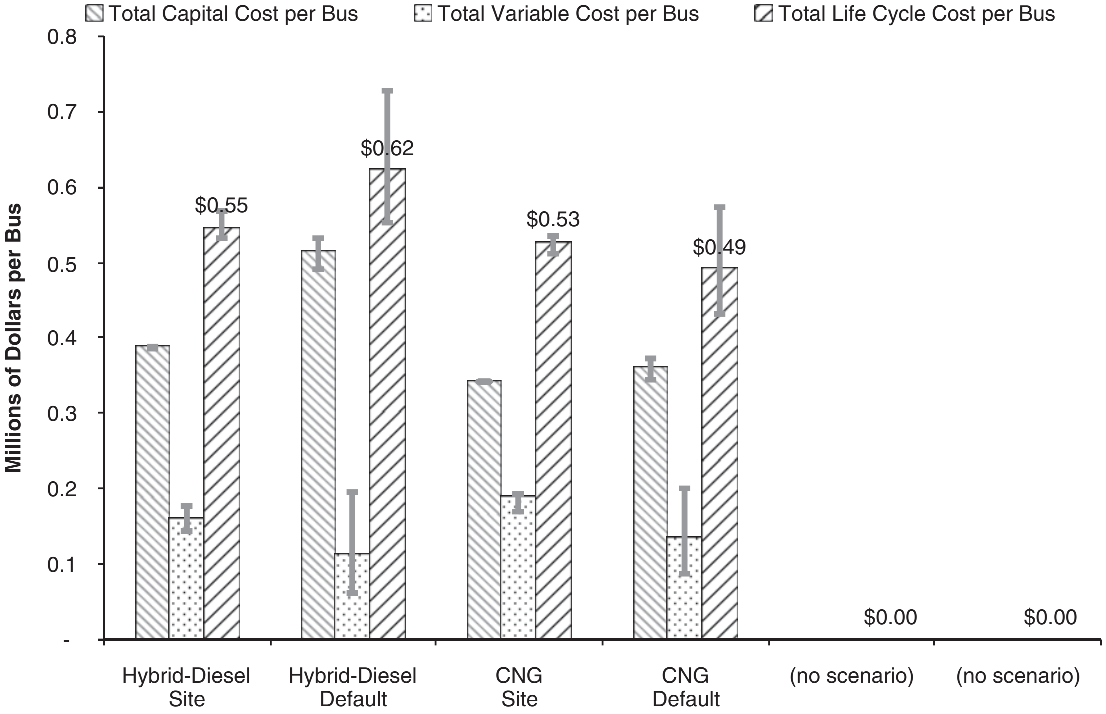


Figure 2.55. LCC comparison of model and 2 years of NYCT real-world data, per bus (with range bars).

Table 2.35. NYCT site and model comparisons (no purchase subsidy).

	2-Year Site	2-Year Model	Difference	12-Year Site	12-Year Model	Difference
Diesel HEB LCC per Bus (Millions of $)	0.55	0.62	13%	1.45	1.47	1%
CNG LCC per Bus (Millions of $)	0.53	0.49	-8%	1.51	1.42	-6%
Diesel HEB vs. CNG	4%	27%	-	-4%	4%	-

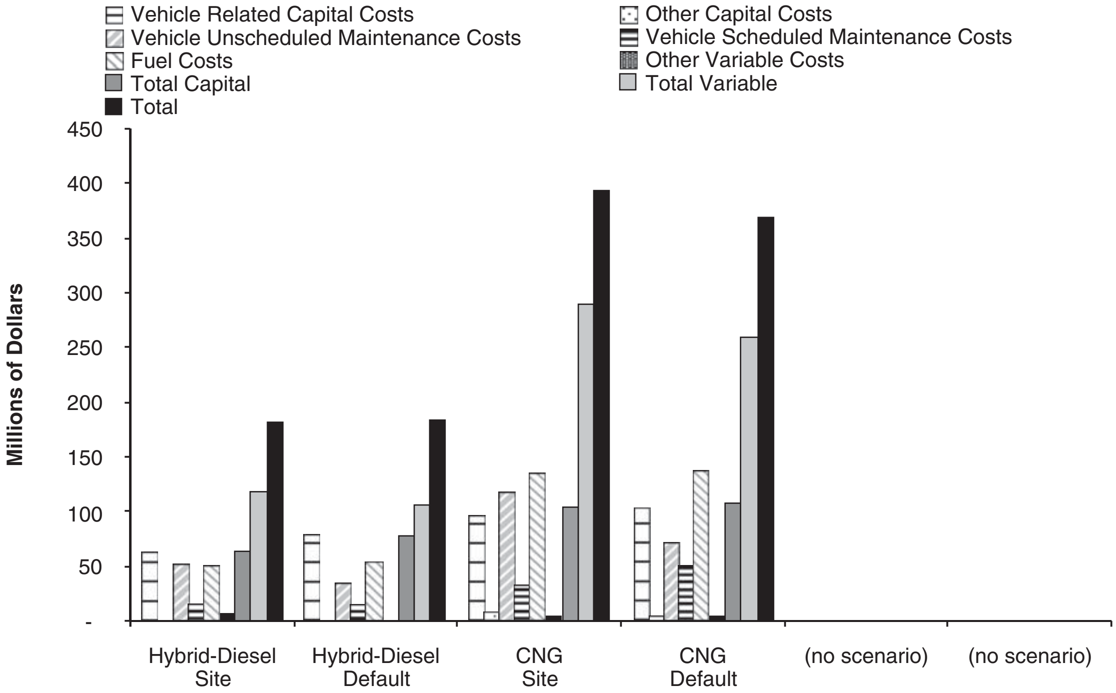


Figure 2.56. Detailed LCC comparison of model and 12 years of NYCT real-world data.

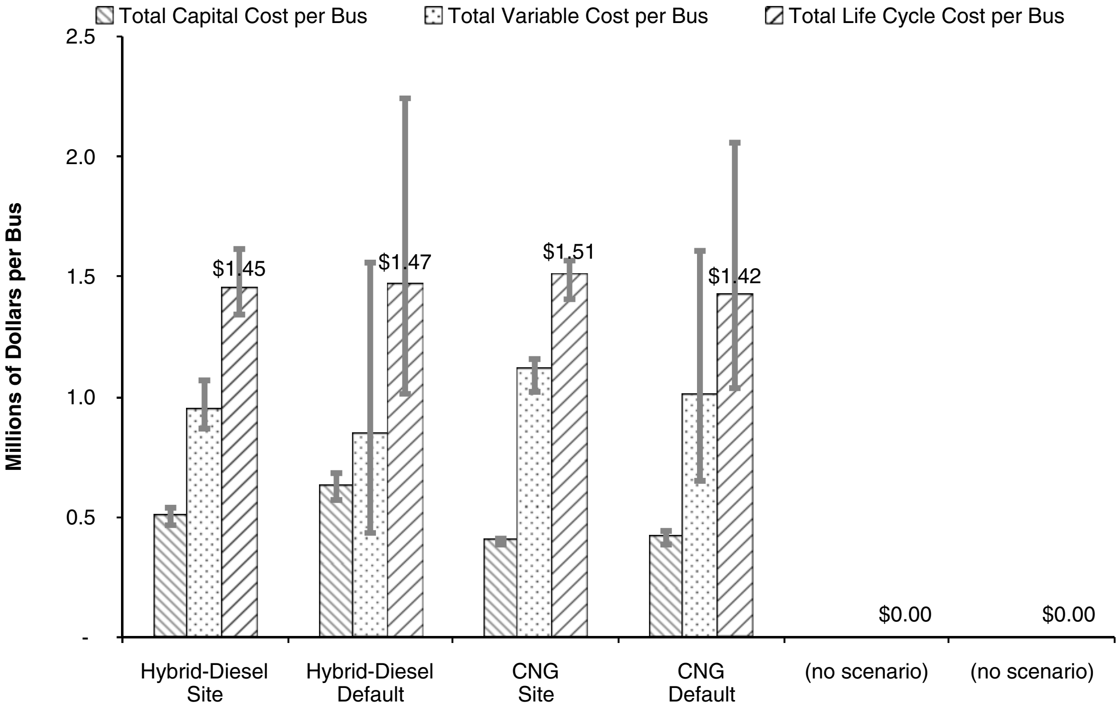


Figure 2.57. LCC comparison of model and 12 years of NYCT real-world data, per bus (with range bars).

Table 2.36. Model inputs for KC Metro site and default model inputs.

	60-ft Diesel		60-ft Diesel Hybrid	
	Site	Default	Site	Default
Purchase Order	30	30	235	235
Average Speed (mph)	12.4	12.4	11.6	11.6
Fuel Economy (mpg)	2.50	2.54	3.17	3.00
Purchase Cost ($)	445,000	403,000	645,000	663,000
Unscheduled Maintenance for 2 Years ($/Mile)	0.31	0.21	0.30	0.24
Scheduled Maintenance for 2 Years ($/Mile)	0.15	0.14	0.14	0.12
Unscheduled Maintenance for 12 Years ($/Mile)	0.31	0.38	0.30	0.43
Scheduled Maintenance for 12 Years ($/mile)	0.15	0.25	0.14	0.22
Purchase Scenarios	1	2	3	4

2.4.10 KC Metro Test Site Case

This section presents KC Metro test site performance for 60-ft diesel and diesel HEB as compared against the model calculation. Table 2.36 shows the inputs to the LCCM.(*4*) Figures 2.58 and 2.59 present two bus technologies' two-year performance at KC Metro without an 80% purchase subsidy.(*4*) The differences between real and predicted two-year data are −11% and −3% for diesel and diesel hybrid technologies respectively, as shown in Table 2.37. When no incentives are considered, KC Metro site data shows that diesel HEB are 37% higher than diesel buses in total two-year cost, which is predicted as 49% by the model. The bulk of this cost difference is due to a difference in actual versus predicted purchase price.

A 12-year test run is also presented for comparison, as shown in Figures 2.60 and 2.61. The predictions are as good as those found in the two-year test run. As shown in Table 2.37, the differences are 2% and 7% for 60-ft diesel and diesel HEB, respectively. Again, fuel savings make HEB incremental costs reduce to 14% above diesel bus costs for site data and 20% above diesel bus costs in the model.

2.4.11 Purchase Year 2008 Versus Purchase Year 2012

This section compares the 12-year LCC performance of different purchases for 2008 and 2012. All costs are in 2007 dollars. The three technologies compared are diesel, diesel HEB,

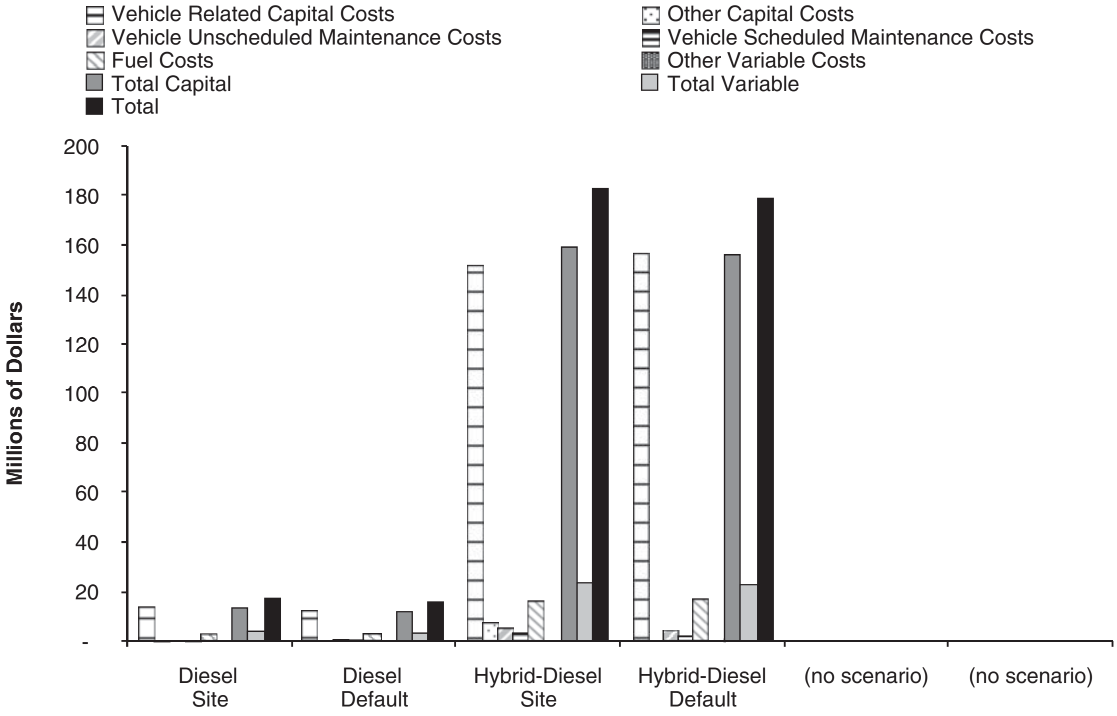


Figure 2.58. Detailed LCC comparison of model and 2 years of KC Metro real-world data.

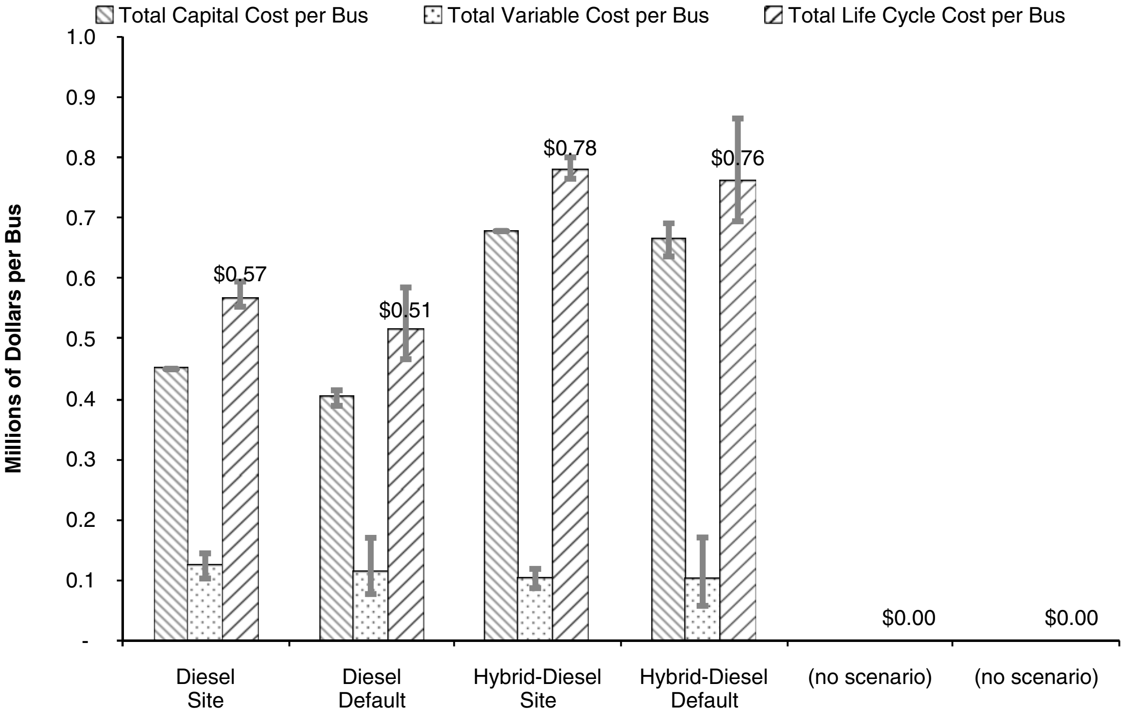


Figure 2.59. LCC comparison of model and 2 years of KC Metro real-world data, per bus (with range bars).

and CNG. As shown in Figures 2.62 and 2.63, purchasing in the future is associated with less impact of technology choice on bus LCC. Diesel bus price is projected to increase after 2010 because of stringent emissions standards requiring complex engine design and the possible addition of an after-treatment device. However, the projected 2012 diesel fuel price in 2007 dollars is slightly lower than the 2007 diesel price. This offsets the incremental cost. The 2012 diesel hybrid bus price would be reduced by 15% of the 2007 price.

2.4.12 Battery Pack Price Case

This case studies the impact of battery pack price on diesel hybrid buses. It illustrates how the model could be used for different purposes and compares the LCC for four scenarios as shown. Included are a 100-bus purchase and 12-year life-long comparison test run. The following scenarios are compared:

- Energy storage system (ESS) high is estimated for 4-year battery life = $73,150 per bus for 12 years.
- ESS default is estimated for 6-year battery life = $46,410 per bus for 12 years.
- ESS low is estimated for 8-year battery life = $27,500 per bus for 12 years.
- ESS zero is estimated for bus life-long battery life (such as an ultracapacitor pack) = $0 per bus for 12 years.

The model becomes a tool for the battery designer to demonstrate how much the battery price and life can benefit bus LCC. Figures 2.64 and 2.65 show that ESS costs are a small portion of capital cost. Compared to the 4-year life ESS LCC, the zero-maintenance ESS could reduce 6% of LCC.

Table 2.37. KC Metro site and model comparisons (no purchase subsidy).

	2-Year Site	2-Year Model	Difference	12-Year Site	12-Year Model	Difference
Diesel LCC per Bus (Millions of $)	0.57	0.51	-11%	1.22	1.24	2%
Diesel HEB LCC per Bus (Millions of $)	0.78	0.76	-3%	1.39	1.49	7%
Diesel HEB vs. Diesel	37%	49%	-	14%	20%	-

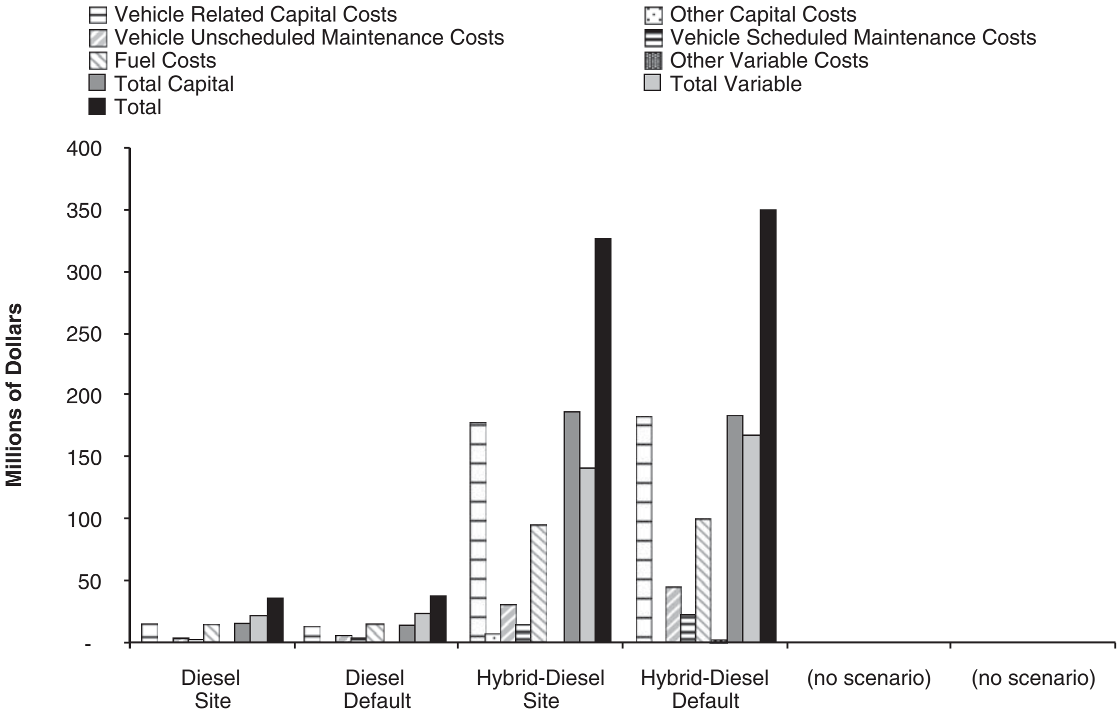


Figure 2.60. Detailed LCC comparison of model and 12 years of KC Metro real-world data.

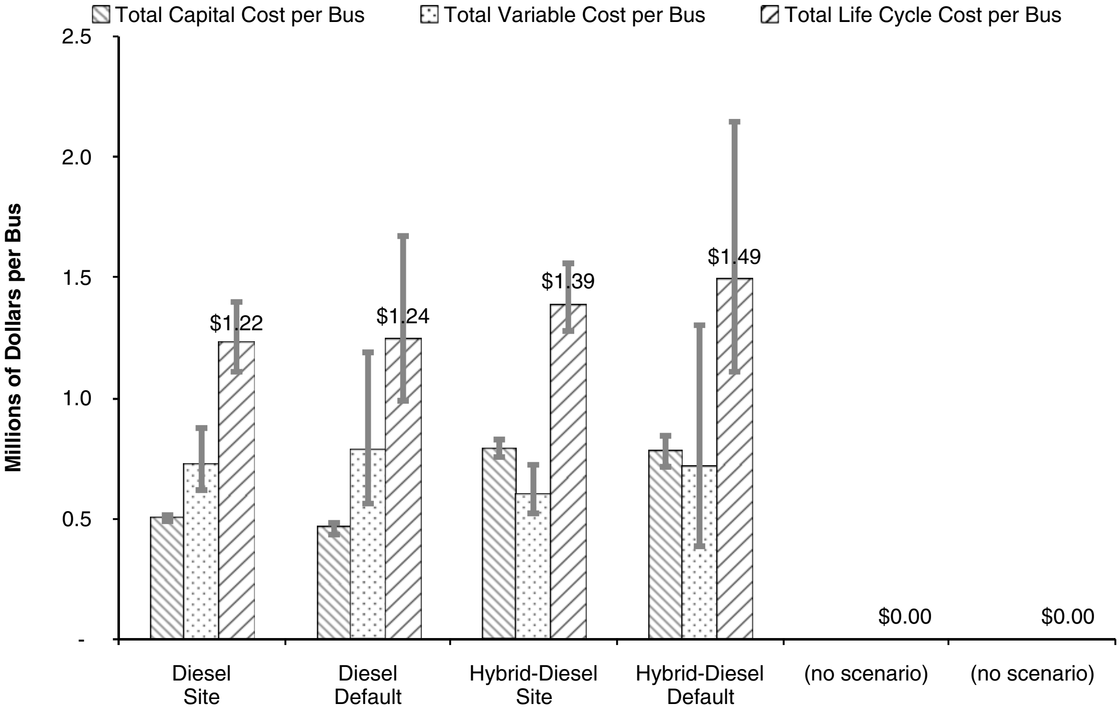


Figure 2.61. LCC comparison of model and 12 years of KC Metro real-world data, per bus (with range bars).

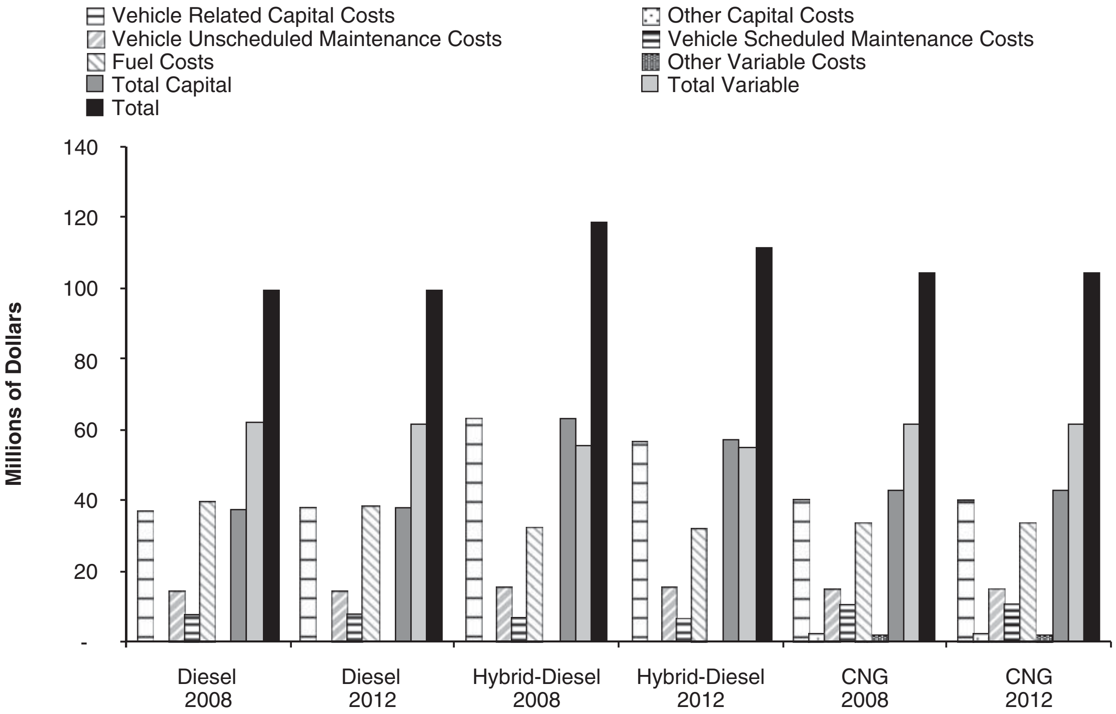


Figure 2.62. Detailed LCC comparison of 2008 and 2012 purchase.

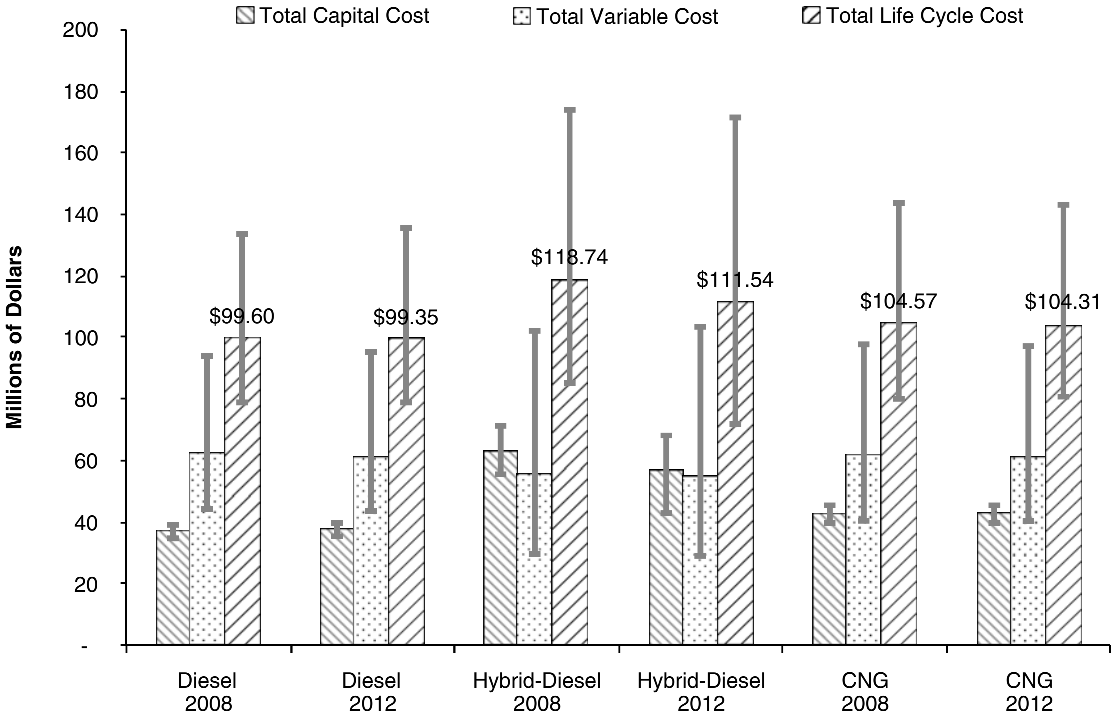


Figure 2.63. LCC comparison of 2008 and 2012 purchase (with range bars).

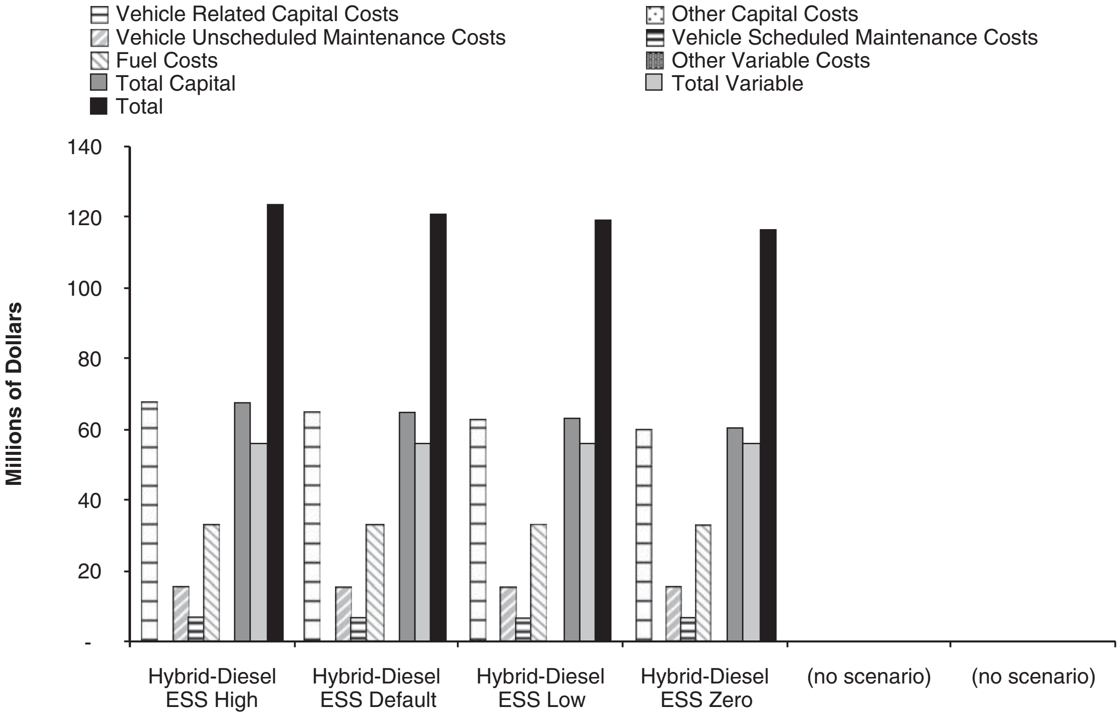


Figure 2.64. Effects of energy storage price on hybrid bus LCC.

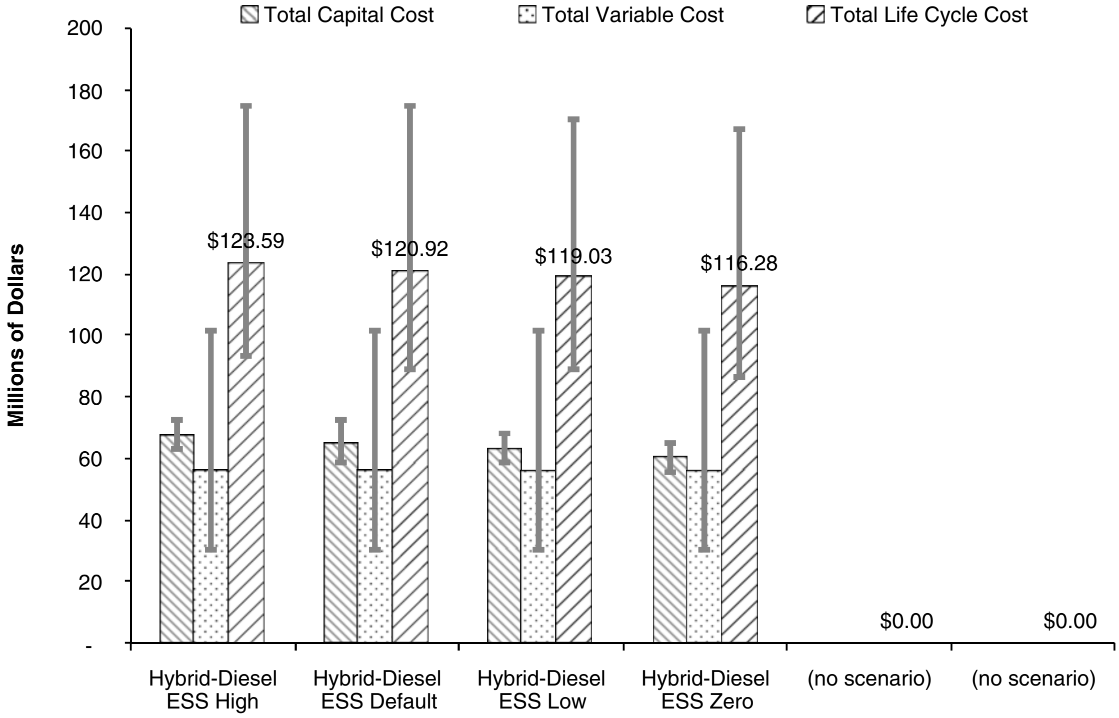


Figure 2.65. Effects of energy storage price on hybrid bus LCC (with range bars).

CHAPTER 3

Conclusions and Suggested Research

3.1 Conclusions

Published studies have shown that HEB offer cleaner and more fuel-efficient performance than conventional diesel buses. Concurrently, new stoichiometric CNG buses being deployed are likely to represent a substantial emissions advance over legacy lean-burn CNG buses in real-world operation, and all CNG buses have traditionally offered very low PM emissions. Advanced engine after-treatment devices and engine technologies will enhance emissions from both diesel and diesel HEB in the future. However, it is expected that a 14% to 48% HEB FE advantage would remain in real-world operation depending on different operation situations, primarily related to the average route speed, or degree of stop-and-go operation.

Bus capital and operation cost data were acquired for this study from four transit fleets (NYCT, KC Metro, LBT, and WMATA) with additional information gathered from literature reviews. Data from NYCT and KC Metro were obtained from a DOE/NREL study.(*3, 4*) Additional cost data were collected through a survey of bus and hybrid drive OEMs, and from the fuel industry. The study team gathered future fuel pricing data from various agencies and government sources. Based on these data and projections from the research team, the LCCM was built in spreadsheet format to calculate costs including vehicle purchase, insurance, warranty, personnel training, infrastructure, facility maintenance, fuel, major component replacement, and vehicle maintenance. A detailed model for FE was constructed, using field and chassis dynamometer data, for inclusion in the LCC. This FE model was essential, because route speed impacts the FE of all bus types substantially. The LCC also considered the FE impact of climate control, including air conditioning and fuel burner heating. These auxiliary loads can account for FE changes of fuel consumption at 4% to 9% from season to season.

The model provides users with default values and with upper and lower limits for all cost items. Users are permitted and encouraged to input their individual assumptions and known data for a specific transit operation. In particular, the user may have a bus purchase cost that reflects additional equipment, or is reduced through volume-purchase negotiation. Several test runs were performed to investigate typical operations and some special cases. LCCM predictions are summarized as follows:

- The LCCM demonstrates that conventional drive diesel buses are nearly always least expensive to operate, with or without subsidy.
- Transient behavior of buses increases as bus average speed decreases, and average speed has a substantial impact on fuel economy, in general, and the difference in fuel economy between technologies, in particular. HEB regenerative braking benefits HEB relative to diesel at low speeds. Hotel loads (particularly climate control) impact fuel consumption measurably.
- For low-speed operation (tested at 6 mph average speed) with a subsidy of 80% of bus purchase price, diesel HEB excels in terms of low overall cost.
- Gasoline HEB usually cost 5% to 10% higher than diesel HEB in 12-year overall expense.
- CNG proved to be the next-best cost option after conventional drive diesel for mid- and high-speed operation (12.7 and 20 mph each) without subsidy; with an 80% subsidy, the diesel HEB offers similar, or slightly higher, cost benefit to CNG.
- The C-15 researchers considered the important scenario of high liquid fuel prices ($5/g diesel fuel price), which benefits HEB in comparative LCC performance against conventional diesel buses.
- CNG buses would gain advantages from a low and stable CNG price. For an extreme case with diesel at $5/g and

CNG at $2/DEG, the low CNG price makes CNG bus operation lowest in total cost with or without subsidy. However, fuel costs tend to track one another in the U.S. economy.

- The study also found that CNG buses are most suited to mid-size or large bus fleets (operating over 50 CNG buses) because of the costs of CNG infrastructure (primarily the compressor station), unless infrastructure costs are not borne by the transit agency. Lack of existing CNG fueling infrastructure would adversely impact a decision to purchase CNG buses.
- The model was demonstrated on data from four transit agencies. The projected results are close to real operation data, and the model reasonably reflects comparative differences among technologies in real-world operation.
- Uncertainties in future fuel prices, and the relationship between HEB capital cost and market penetration, add uncertainty to the model conclusions.

3.2 Suggested Future Research

Extended data collection is suggested to study the impact of after-warranty bus operation in greater detail, and to understand the reliability and longevity of advanced engines and propulsion systems. Data are lacking on stoichiometric CNG buses, which are entering service only at the time of this writing. The lack of complete data merits further study of FE, emissions, and maintenance cost. Other advanced propulsion technologies such as fuel cells or electric buses could be considered in the model, and the model could be extended to include other bus sizes, particularly 30- or 35-ft 12-year-life buses. In addition, the present LCCM has not considered the possibility of improved technology rebuilds for middle-aged 12-year or extended-life buses, or the effect of operating terrain (gradient) on bus FE. Climate change concerns may spawn carbon trading in the future, and this would require future examination as a cost impact.

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Appendices and Toolkit

The LCCM tool and Appendices A through I for this report are provided with the accompanying software (CRP-CD-71) and are also available as an ISO image at www.TRB.org. Titles of Appendices A through I are as follows:

Appendix A:	Technology Review
Appendix B:	Test Site/Evaluation Description
Appendix C:	Transit Fleet Information
Appendix D:	International Hybrid-Electric Bus Programs
Appendix E:	North American Hybrid Systems and Bus Manufacturers
Appendix F:	Transit Bus Emissions Survey Overview
Appendix G:	Driver Cycles and Schedules
Appendix H:	Detailed Bus Life Cycle Cost Model User Instructions
Appendix I:	C-15 Life Cycle Model Tabs Screenshots

Acronyms and Abbreviations

AC	Alternating current
A/C	Air conditioner
AC Base	Atlantic Base (Depot)
ADB	Transit coach duty cycle
ADVISOR	ADvanced VehIcle SimulatOR
AEO	Annual Energy Outlook
AFC	Alkaline fuel cells
AFV	Alternative fueled vehicles
ANL	Argonne National Laboratory
APC	Automatic passenger counter
APU	Auxiliary power unit
AQIRP	Auto/Oil Air Quality Improvement Research Program
AVL	Automotive vehicle location
AVTA	Advanced Vehicle Testing Activity
BAE Systems	British Aerospace (BAe) and Marconi Electronic Systems (MES)
BDL	Below detective limits
BMS	Battery management system
BP	British Petroleum
BPA	Bonneville Power Administration
CAA	Clean Air Act
CARB	California Air Resources Board
CAT	Caterpillar Inc.
CBD	Central business district
CHP	Combined heat and power
CI	Compression ignition
CNG	Compressed natural gas
CO	Carbon monoxide
CO_2	Carbon dioxide
CPI	Consumer Price Index
CRDPF	Continuously regenerating diesel particulate filter
CSHVC	City suburban heavy vehicle cycle
CWI	Cummins Westport Inc.
DARPA	Defense Advanced Research Projects Agency
DART	Dallas Area Rapid Transit
DB	Deutsche Bank AG
DC	Direct current
DDC	Detroit Diesel Corporation

DEC	Department of Environmental Conservation
DEG	Diesel equivalent gallon
DMFC	Direct methanol fuel cells
DPF	Diesel Particulate Filter
DPIM	Dual power inverter module
DUBDC	Dutch urban bus driving cycle
EC	Environment Canada
EEA	Economic and Environmental Analysis, Inc.
EGR	Exhaust gas recirculation
EIA	Energy Information Administration
ESS	Energy storage system
ETC	European transient cycle
EVA	Energy Ventures Analysis, Inc.
EU	European Union
FC	Fuel cells
FE	Fuel economy
GDP	Gross domestic product
GEG	Gasoline equivalent gallon
GEM	German Economy Ministry
GII	Global Insight Inc.
GPS	Global positioning system
HC	Hydrocarbons
HEB	Hybrid-electric bus(es)
HED	Hybrid-electric drive
HEV	Hybrid-electric vehicle
HHICE	Hybrid hydrogen internal combustion engine
HLA	Hydraulic launch assist
HIL	Hardware in the loop
HSC	Hybrid system controller
ICE	Internal combustion engine
IEA	International Energy Agency
IM	Induction machine
IPM	Interior permanent magnet
ITS	Intelligent Transportation System
JD	John Deere
KC Metro	King County Metro
LBT	Long Beach Transit
LBNL	Lawrence Berkeley National Laboratory
LCC	Life cycle cost
LCCM	Life Cycle Cost Model
Li-Ion	Lithium ion
Li-Poly	Lithium polymer
LNG	Liquefied natural gas
LP	Liquefied petroleum
MBRC	Miles between roadcalls
MCFC	Molten carbonate fuel cells
MCH	Mother Clara Hale (Depot)
MCDS	Mexico City Driving Schedule
MOBILE	MOBILE6 Vehicle Emissions Modeling Software
MTA/NYC	New York City Metropolitan Transit Authority
MTBE	Methyl tertiary butyl ether
MTV	Manhattanville

MY	Model year
NAAQS	National Ambient Air Quality Standards
NAVC	Northeast Advanced Vehicle Consortium
NEC	Net energy change
Ni-Cd	Nickel cadmium
Ni-MH	Nickel metal hydride
$Ni/NaCl_2$	Nickel/sodium chloride
NMHC	Non-methane hydrocarbons
NO_2	Nitrogen dioxide
NOx	Nitrogen oxides
NREL	National Renewable Energy Laboratory
NTE	Not to exceed
NYCT	New York City Transit
NYMEX	New York Mercantile Exchange, Inc.
O_3	Ground-level ozone
OAQPS	Office of Air Quality Planning and Standards
OCTA	Orange County Transit Authority
OECD	Organisation for Economic Co-operation and Development
OEM	Original equipment manufacturer
OPEC	Organization of the Petroleum Exporting Countries
PAFC	Phosphoric acid fuel cells
Pb	Lead
PEMFC	Proton exchange membrane fuel cells
PM	Particulate matter
PMI	Preventive maintenance inspection
PSAT	Powertrain System Analysis Toolkit
PTI	Pennsylvania Transportation Institute
RB	Ryerson Base (Depot)
RESS	Rechargeable energy storage system
RVP	Reid Vapor Pressure
SAE	Society of Automotive Engineers
SEER	Strategic Energy and Economic Research, Inc.
SI	Spark ignition
SO_2	Sulfur dioxide
SOC	State of charge
SOFC	Solid oxide fuel cells
SOx	Sulfur oxides
SPM	Surface permanent magnet
TDC	Transit Development Corporation
THC	Total hydrocarbons
TransLab	Transportable Heavy-Duty Vehicle Emissions Testing Laboratory
TRC	Transit Resource Center
TWC	Three-way catalyst
UDDS	Urban dynamometer driving schedule
ULSD	Ultra-low sulfur diesel
USABC	United States Advanced Battery Consortium
VRM	Variable reluctance machine
WF	West Farms (Depot)
WMATA	Washington Metropolitan Area Transit Authority
WVU	West Virginia University

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
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
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