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FEDERAL TRANSIT ADMINISTRATION

Transit Vehicle Emissions Program

Final Report

AUGUST 2013

FTA Report No. 0048
Federal Transit Administration

PREPARED BY

W. Scott Wayne
West Virginia University

U.S. Department of Transportation
Federal Transit Administration

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Metric Conversion Table

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
LENGTH				
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
VOLUME				
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
NOTE: volumes greater than 1000 L shall be shown in m^3				
MASS				
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
TEMPERATURE (exact degrees)				
^{o}F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^{o}C

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13. ABSTRACT

The evaluation, selection, and implementation of fuel and powertrain technology choices are critically important to accomplishing the mission of providing safe, efficient, reliable, environmentally-conscious, and cost-effective public transportation. Vehicle procurement decisions evolve to be a difficult compromise between economic, environmental, and operability requirements. West Virginia University conducted a research program to provide the transit industry with resources to assist transit agency managers to evaluate a low-emissions, fuel-efficient option in vehicle procurement and planning activities to encourage the design, production, and use of environmentally-friendly transit buses. This report summarizes technical assistance provided to the Federal Transit Administration (FTA) and the Larsen Pennsylvania Transportation Institute to establish an emissions testing program as part of the Altoona Bus Testing Center. The report also summarizes the development of a searchable database of transit bus emissions data, a transit fleet emissions model, and a transit vehicle live cycle cost model.

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ABSTRACT

The evaluation, selection, and implementation of fuel and powertrain technology choices are critically important to accomplishing the mission of providing safe, efficient, reliable, environmentally-conscious, and cost-effective public transportation. Vehicle procurement decisions evolve to be a difficult compromise between economic, environmental, and operability requirements. West Virginia University (WVU) conducted a research program to provide the transit industry with resources to assist transit agency managers to evaluate a low-emissions, fuel-efficient option in vehicle procurement and planning activities to encourage the design, production, and use of environmentally-friendly transit buses. This report summarizes technical assistance provided to the Federal Transit Administration (FTA) and the Larsen Pennsylvania Transportation Institute to establish an emissions testing program as part of the Altoona Bus Testing Center. The report also summarizes the development of a searchable database of transit bus emissions data, a transit fleet emissions model, and a transit vehicle life cycle cost model.

Introduction

The evaluation, selection, and implementation of fuel and powertrain technology choices are critically important to accomplishing this mission of providing safe, efficient, reliable, environmentally-conscious, and cost-effective public transportation. Each technology offers a different mix of advantages and disadvantages, making the selection of technology complex. Vehicle procurement decisions evolve to be a difficult compromise between economic, environmental, and operability requirements. West Virginia University (WVU) conducted a research program to provide the transit industry with resources to assist transit agency managers to evaluate a low emissions, fuel-efficient option in vehicle procurement and planning activities to will encourage the design, production, and use of environmentally-friendly transit buses. The program has three major objectives:

- Task 1: Provide technical assistance to the Federal Transit Administration (FTA) and the Larsen Pennsylvania Transportation Institute (PTI) to establish a legislatively-mandated emissions testing program for all new-model transit vehicles.
- Task 2: Evaluate the efficiency and emissions benefits of alternative-fueled and advanced-technology transit vehicles.
- Task 3: Develop online tools and resources to assist transit agency managers in determining the most appropriate and advantageous bus propulsion technologies for their transit applications considering emissions, fuel type, fuel economy, and life cycle cost.

Task 1 Summary

In Task 1, WVU provided technical assistance to FTA and the Larsen Pennsylvania Transportation Institute at Penn State University to develop and implement a transit vehicle emissions testing program as part of the Altoona Bus Testing Program. WVU evaluated potential test methodologies and recommended that the emissions testing be performed using a chassis dynamometer and 40 CFR Part 1065 dilution tunnel and emissions sampling system, following as closely as possible the test procedures mandated by the U.S. Environmental Protection Agency for heavy-duty engine emissions testing. WVU provided technical assistance to select and define emissions sampling system specifications. Finally, the WVU Transportable Emissions Laboratory conducted a side-by-side comparison study to validate the test procedures and results of the PTI laboratory. The new emissions laboratory is operational at PTI. The audit of the dynamometer and emissions equipment did not reveal any problems or deficiencies in the equipment, with the exception of the particulate matter filter conditioning and weighing facilities. PTI should invest in an environmentally-controlled clean room and upgrade its microbalance. Results from side-by-side emissions testing yielded satisfactory agreement. The emissions testing revealed the challenges associated with measuring emissions from modern (2010 and newer) transit buses equipped with active diesel particulate filters (DPF) and selective catalytic reduction (SCR). These active after-treatment systems introduce test-to-test substantial variability as a result of thermal management and active regeneration events. Although this variability cannot be completely eliminated through testing procedures, it can be mitigated, to some extent, through very consistent vehicle warm-up practices, consistent soak times between subsequent tests, and rigorous test procedures. Recommendations to improve the test procedures at PTI are summarized in a detailed technical report and in a later section of this report.

Task 2 Summary

In Task 2, WVU used its Transportable Vehicle Emissions Laboratory (TransLab) to measure the fuel consumption and exhaust emissions from a wide variety of transit buses, including buses powered by conventional petroleum-derived diesel fuel, compressed natural gas (CNG), Fischer-Tropsch synthetically-derived diesel fuel, biodiesel fuel blends, and buses equipped with diesel-hybrid electric powertrains. The intent of the emissions and fuel consumption characterization of transit buses was to provide data to feed into an online transit bus emissions database and the transit fleet emissions inventory that was developed under Task 3 of this project. Results of the individual emissions measurement campaigns were also published in the technical literature. A complete list of publications originating from this project can be found in Section 5 of this report.

Task 3 Summary

The objective of Task 3 was to develop online accessible tools to estimate the emissions profile of existing transit fleets and evaluate how integration of new clean diesel, alternative fuel, and hybrid-electric into the fleet will alter the emissions footprint. WVU developed a set of tools for evaluating the pollutant emissions and fuel economy of transit bus fleets. The tools include a searchable database of transit vehicle emissions test data and a transit fleet emissions inventory model. In addition, WVU, Battelle, and the Transit Resource Center have developed a transit vehicle life cycle cost model under contract with the Transit Cooperative Research Program in Project C-15 [34]. The tools can be accessed on a publicly-available website called the Integrated Bus Information System (IBIS). IBIS is accessible at http://ibis.wvu.edu.

Benefits

The objective of this research program was to provide the transit industry with resources to assist transit agency managers to evaluate low-emissions, fuel-efficient options in vehicle procurement and planning activities. As a result of this research program and in conjunction with a program funded at PTI, FTA has established a standardized emissions testing component of the Altoona

Bus Testing Program. This PTI laboratory was validated against the WVU Transportable Emissions Laboratory, which has more than 20 years of experience measuring emissions from heavy-duty vehicles. The program will provide standardized tailpipe emissions test results for all new transit buses that can be used by transit agencies for vehicle procurement and strategic environmental planning. This research program also developed three online tools that assist transit agencies to evaluate alternative fuel and propulsion system options when making vehicle procurement decisions. These tools include a searchable database of transit bus emissions data, a transit bus fleet emissions inventory modeling tool, and a transit bus life cycle cost (LCC) model. Future research will update the LCC model and continue to add new bus technologies to the transit fleet emissions inventory model.

SECTION

1

Introduction

The evaluation, selection, and implementation of fuel and powertrain technology choices are critically important to accomplishing the mission of providing safe, efficient, reliable, environmentally-conscious, and cost-effective public transportation. Each technology offers a different mix of advantages and disadvantages, making the selection of technology complex.

Hybrid electric buses offer the potential for fuel savings for transit operators and are expected to become important components of bus fleets around the world in the coming decade. An advantage of hybrid buses is the ability to recover and reuse energy lost during braking. Hybrid buses may also benefit from engine downsizing, reduction of engine transient operation, idle engine-stop, and flexible engine control. Hybrid-electric buses also offer reduced exhaust emissions compared to non-hybrid diesel buses. The fuel efficiency and emissions advantages may be countered by higher capital costs, battery system replacement costs, additional maintenance costs, and mechanic and training costs. Additionally, the fuel efficiency benefit of hybrid buses is dependent on the driving cycle, with the greatest advantage arising in low-speed stop-and-go inner-city operation.

Natural-gas-powered buses have become an increasingly popular choice for transit, particularly in some areas where conventional diesel-powered fleets are prohibited or discouraged through regional air quality regulations. The South Coast Air Quality Management District in California prohibits purchase of new diesel-powered fleet vehicles. Natural-gas-powered buses, primarily compressed natural gas (CNG) with some liquefied natural gas (LNG), offer extremely low particulate matter (PM) mass emissions and oxides of nitrogen (NOx) emissions. The current generation of stoichiometric combustion natural gas buses boasts improved fuel efficiency compared to legacy lean-burn natural gas buses. Low natural gas fuel prices, which are expected to remain low for the foreseeable future due to newly-discovered large domestic reserves of natural gas, make CNG and LNG attractive options. Natural gas may also offer greenhouse gas (GHG) emissions benefits due to the lower carbon content in the fuel. The natural gas option suffers from high refueling and maintenance infrastructure installation costs, increased vehicle weight resulting from onboard CNG storage tanks, and throttling losses that reduce engine efficiency.

Non-hybrid diesel-fueled buses remain the predominant technology in the transit fleet. Diesel buses offer the lowest capital vehicle costs and have been regarded as a very reliable technology. Diesel buses offer superior fuel efficiency compared to CNG buses. However, conventional diesel buses are not without their drawbacks. To meet stringent emissions regulations, diesel engine manufacturers have implemented actively-regenerating diesel particulate filters and selective catalytic reduction with urea injection as well as other engine technologies. As a result, diesel engines have become significantly more complex and maintenance-intensive. Emissions control technologies have also eroded diesel engine fuel efficiency and increased capital and operating costs for diesel bus fleets.

Rarely does an obvious technology choice emerge, and the vehicle procurement decisions evolve to be a difficult compromise between economic, environmental, and operability requirements. In addition, there is often inherent conservatism in decision-making because the reliability of novel technologies is not proven and is difficult to assess. Compounding the difficulty of fleet planning and procurement is the dearth of information, resources, and tools to enable the evaluation of environmental, economic, and operational implications of the various fuel and technology choices for transit vehicles.

West Virginia University (WVU) conducted a research program to provide the transit industry with resources to assist transit agency managers to evaluate and consider low emissions in the vehicle procurement and planning activities to encourage the design, production, and use of environmentally-friendly transit buses. The intent of the research program was to provide public transit agencies, engine and vehicle manufacturers, transit industry associations, government regulatory agencies, and other transit industry constituents with information concerning the exhaust emissions of existing and new technology transit vehicles. The program has three major objectives:

- Task 1: Provide technical assistance to the Federal Transit Administration (FTA) and Larsen Pennsylvania Transportation Institute (PTI) to establish a legislatively-mandated emissions testing program for all new model transit vehicles.
- Task 2: Evaluate the efficiency and emissions benefits of alternative-fueled and advanced-technology transit vehicles.
- Task 3: Develop online tools and resources to assist transit agency managers in determining the most appropriate and advantageous bus propulsion technologies for their transit applications considering, emissions, fuel type, fuel economy, and life cycle cost.

This report and the addenda summarize the work done and accomplishment achieved during the course of the project to develop resources and tools to assist transit fleets managers evaluate available technology and fuel options from the perspectives of emissions implications, efficiency, and life cycle cost.

SECTION

2

Task 1 – Provide Technical Assistance to FTA and PTI

FTA's New Model Bus Testing Program tests new transit bus models for safety, structural integrity and durability, reliability, performance, maintainability, noise, and fuel economy. The data from all the tests are compiled into a test report that is made available to the manufacturer and transit agencies to provide information during the procurement process. These are not pass-or-fail tests. The Bus Testing Program applies to recipients of FTA capital assistance for the procurement of transit buses. To be eligible for FTA capital assistance funds, a grantee must certify that it has received a copy of the FTA New Model Bus Testing Program Report for the model of bus being purchased. The program was established 1987 by Section 317 of the Surface Transportation and Uniform Relocation Assistance Act (STURAA), mandating that any new model of vehicle (ranging from large articulated buses to small vans) purchased in part with federal funds for use in mass transportation revenue service must undergo testing [1]. The testing program is administered by the Altoona Bus Research and Testing Center housed in the Thomas D. Larsen Pennsylvania Transportation Institute (PTI) at Penn State University.

On September 30, 2008, FTA published a notice of proposed rulemaking in the Federal Register [2] that discussed proposals to incorporate brake performance and emissions tests into FTA's testing program, as required by 49 U.S.C. Section 5318 [3], as amended by the Safe, Accountable, Flexible, Equitable Transportation Efficiency Act: A Legacy for Users (SAFETEA-LU) [4]. The final rule was adopted in October 2009 requiring by statute that an emissions test procedure be performed on all new model transit buses as part of the FTA New Model Bus Testing Program beginning on January 1, 2010. The emissions test was to be conducted at a newly-constructed Vehicle Research and Testing Laboratory (Figure 2-1) at the Larson Institute Test Track (Figure 2-2) located in Bellefonte, Pennsylvania, by staff of the Altoona Bus Testing and Research Center.

As of 2003, the Altoona Bus Research and Testing Center did not have a heavy-duty vehicle emissions testing facility and had no prior experience measuring the exhaust emissions of heavy-duty vehicles or engines. Moreover, FTA had not established the formal regulations mandating exhaust emissions testing as part of the New Model Bus Testing Program and had not established a formal emissions testing protocol specifying the methodology by which transit vehicle emissions would be measured and reported. WVU provided technical assistance and expertise to FTA and the Altoona Bus Research and Testing Center to establish and promulgate rules formally establishing the emissions testing program;

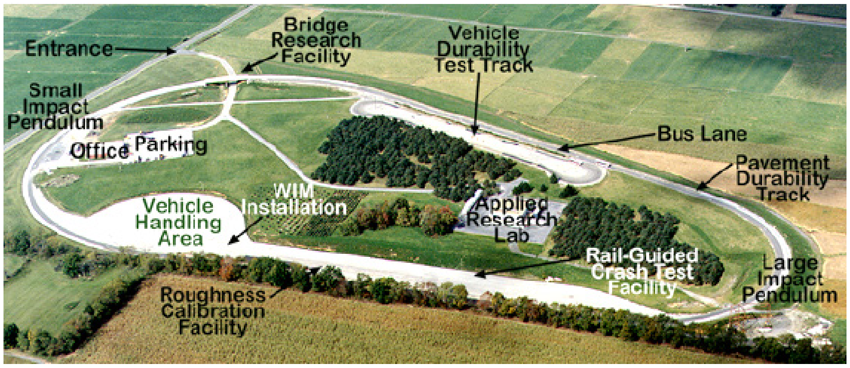
determine the methodology to be used to conduct the emissions testing; design, install, and commission an emissions testing facility; and develop formal testing procedures.

Figure 2-1

Larsen Institute Vehicle Research and Testing Laboratory

Figure 2-2

Larsen Institute Test Track



The goal of Task 1 was to provide technical assistant FTA and Larsen Institute to establish a transit vehicle emissions testing program that met the needs of the transit industry. The following activities were undertaken as part of this task:

1. Evaluate emissions testing methodologies.
2. Solicit input from transit industry constituents to establish the industry's needs, concerns, and feedback on the format of the emissions testing program.
3. Assist the engineering staff at the Larsen Institute to design and procure emissions testing equipment for the Vehicle Research and Testing Laboratory.
4. Develop emissions testing procedures.
5. Conduct a side-by-side laboratory comparison between the Bus Research and Testing Center Laboratory and the WVU Transportable Vehicle Emissions Testing Laboratory.

Evaluate Emissions Testing Methodologies

The purpose of the Altoona emissions testing is to provide transit agencies with a reliable and accurate comparison of the emissions performance of various transit vehicle fuel and propulsion technologies and transit vehicle models for use in vehicle procurement activities. The emissions test are not pass-or-fail and are not a component of any regulatory or compliance program. The goal was to develop an emissions testing methodology that provided accurate, reliable, and repeatable emissions results that could be used to compare vehicle technologies.

At the onset of this activity, the Larsen Institute had just begun construction of a facility to house the emissions testing laboratory and had initiated the procurement of a 350 hp, large-roll chassis dynamometer. The Institute also processed a Horiba gaseous emissions bench capable of analyzing bag samples of vehicle exhaust and a prototype partial-flow gravimetric PM sampling system developed at the Southwest Research Institute.

Figure 2-3

Chassis dynamometer at Larsen Institute Vehicle Research and Testing Laboratory

Several emissions testing methodologies were considered including 1) using a portable emissions measurement system (PEMS) to measure emissions while the bus was operated on the Larsen Institute test track or on the chassis dynamometer, 2) using the existing gaseous and PM measurement equipment to sample emissions during dynamometer testing, and 3) using a U.S. Environmental Protection Agency (EPA) compliant gaseous and particulate sampling system.

Portable Emissions Measurement Systems (PEMS)

Portable emissions measurement systems are emissions sampling systems that can be installed on-board a vehicle to sample emissions while the vehicle is driven on a road or test track. Portable instruments are often less accurate than laboratory-grade instruments due to the limitations on size, cost, and selection of detectors that are tolerant to on-road conditions such as vibration and temperature fluctuations. Moreover, emissions tests conducted on a road or track are less repeatable than a test conducted on a chassis dynamometer due to uncontrollable variations in traffic pattern and environmental conditions. WVU completed an in-depth survey and evaluation of on-board emissions measurement technologies in August 2006 to determine whether on-board PEMS testing could produce accurate, repeatable and reliable results that met the objectives of the New Model Bus Testing Program. The results of this survey were published in a detailed report submitted to FTA and PTI [5]. Commercial PEMS systems include the Semtech On-Board Emissions Analyzers manufactured by Sensors, Inc., and the Horiba OBS-2000 On-Board Emissions Measurement System.

Figure 2-4

Sensors' Semtech-DS Portable Emissions Measurement System

This study reviewed the currently-available methods for measuring emissions gas concentrations, particulate matter, exhaust flow rate, engine torque, engine speed, and ambient conditions. Also, data acquisition systems and factors affecting overall system operation were reviewed. This review was intended to provide information to allow an informed selection of an available on-board emissions measurement system or selection of components to design an on-board system for specific needs. On-board systems offer a relatively inexpensive alternative to an emissions laboratory. However, data collected with on-board systems will likely be of lower quality than that collected in a laboratory with stationary, laboratory-grade equipment. The lower data quality is due, in part, to the limited analyzer technologies capable of operating under the relatively harsh conditions encountered in the on-board testing environment.

WVU recommended that PTI make use of stationary laboratory-grade emissions measurement equipment rather than on-board emissions measurement systems. This recommendation was based on several factors. First, PTI was planning to have a new heavy-duty chassis dynamometer operational by February 2004. Second, the intent of the emissions test was to provide data suitable for comparing emissions from vehicles by different manufacturers and providing the information to prospective customers. Stationary laboratory dynamometer emissions testing results in less test-to-test variation than on-board emissions testing and produces more accurate and repeatable results. Furthermore, on-board measurement of particulate emissions is extremely challenging. At the time the survey was completed, no commercially-available and industry-accepted portable PM measurement system was available. Accurate and repeatable on-board PM measurement remains a difficult challenge.

Existing Gaseous and Particulate Measurement Equipment at PTI

Existing emissions measurement equipment was available at PTI consisting of Horiba gaseous emissions sampling bench and a partial exhaust PM sampling system. WVU evaluated the existing equipment available at PTI as a cost effective approach to developing and emissions measurement capability. WVU compiled an interim report addressing modification that could be done to the gaseous sampling bench [6] that could be implemented for use with the PTI chassis dynamometer. In this case, the gaseous sampling bench would be used to sample undiluted exhaust. The existing PM sampling system was deemed unusable. Modifications to the existing gaseous emissions sampling bench were considered as cost-effective emissions measurement capability. However, it would have been difficult to make this existing gaseous sampling system compliant with the industry-accepted EPA 1065 heavy-duty engine emissions measurement methodology [7]. Moreover, a PM sampling system would have to be developed or procured. Accurate sampling of PM during a transient test cycle using a partial-flow sampling system is extremely difficult to accomplish. Ultimately, this option was not pursued by PTI.

EPA 1065 Compliant Emissions Laboratory

Heavy-duty engine emissions certification testing procedures are governed by the Code of Federal Regulations (CFR) Part 1065 [7]. The CFR prescribes in detail the specifications of the measurement equipment, calibration procedures, testing procedures, and documentation and reporting requirements for engine certification testing for heavy-duty vehicles. Although chassis dynamometer testing is not officially used for heavy-duty engine emissions certification, most heavy-duty chassis dynamometer emissions laboratories in the United States follow the emissions sampling procedures prescribed by CFR Part 1065. The transit vehicle emissions test conducted at Altoona Bus Research and Testing Center is not for emissions certification or regulatory purposes. However, the results produced will ultimately be compared by end users to data from other chassis dynamometer facilities. For this reason, WVU believed that the test methods used at PTI must produce test results that are of equal quality to those of other recognized chassis dynamometer facilities. WVU recommended that PTI invest in a CFR Part 1065-compliant emissions sampling system as the best option for implementing the New Model Bus Emissions Testing Program. Although a 1065-compliant system was the most expensive option, it was regarded as the only option that could produce accurate, reliable, and repeatable emissions data suitable for comparing different transit vehicle, engine, and fuel technologies. Based on the evaluation of emissions measurement methods and feedback from the transit industry, the CFR 1065-compliant emissions laboratory option was selected by FTA and PTI. PTI purchased a turn-key CFR 1065-compliant emissions sampling system from Horiba. The emissions laboratory was installed and commissioned by Horiba and became operational in January 2010.

Solicit Input from Transit Industry

WVU and PTI jointly conducted two sessions at American Public Transportation Association (APTA) conferences in October 2007 and May 2008 to solicit transit industry input on the proposed New Model Bus Emissions Testing Program. FTA, PTI, and WVU gave joint presentations at the APTA Bus Technical Maintenance & Procurement Workshop in October 2007 [8]. The workshop session was intended to provide notice of the impending Notice of Proposed Rulemaking (NPRM) by FTA to add emissions and brake testing to the Altoona Bus Testing Program and to solicit comments and feedback from the transit industry. The presentations, along with an account of the question and answers sessions, are provided as an addendum to this final report. Feedback from these APTA workshop sessions were incorporated into the NPRM a draft emissions testing protocol for the New Model Bus Emissions Testing Program.

Assist PTI with Emissions Equipment Procurement

Following consideration of several emissions testing methods including on-board portable emissions measurement systems, retrofitting of an existing gaseous emissions sampling bench and installation of a fully 1065-compliant emissions sampling system, PTI made the decision to pursue funding from FTA to purchase a complete CFR 1065-compliant emissions sampling system from Horiba. The system would include a full exhaust dilution tunnel, a dilute gaseous emissions sampling system, a raw gaseous emissions sampling system, a PM sampling system, and a dilution air conditioning system.

WVU had extensive experience with the design of dilution tunnels, gaseous emissions, and PM sampling systems. WVU designed and fabricated two CFR Part 1065 dilution tunnels and PM sampling systems for the WVU Engine Dynamometer Laboratory and the Transportable Chassis Dynamometer Laboratory. WVU also had extensive experience with gaseous emissions analyzers manufactured by Rosemount, Horiba, and California Analytical.

WVU provided technical assistance to PTI in the selection and specification of the dilution tunnel and emissions sampling system. WVU advised PTI regarding the features and capabilities that the emissions sampling system should include and reviewed bid specifications provided by Horiba to PTI, and WVU engineering staff accompanied PTI during meetings with Horiba.

Develop Emissions Testing Protocol

WVU developed a draft emissions testing protocol for the Altoona New Model Bus Emissions Testing Program [9]. This harmonized CFR 1065 emissions sampling procedures, coast down procedures, road load coefficient determination procedures, and SAE J2711 conventional and hybrid vehicle test procedures [10] into a single test protocol. The testing protocol covered equipment specifications and equipment calibration intervals and procedures. The draft protocol was included with the NPRM published by FTA that established an emissions testing component of the New Model Bus Testing Program. The protocol was also provided to PTI to guide the development of standard operating procedures for the Vehicle Research and Testing Center emissions dynamometer laboratory. The emissions testing protocol is an addendum to this final report.

Side-by-Side Emissions Laboratory Comparison

In preparation for the implementation of the new emissions testing procedure, the Altoona Bus Research and Testing Center, housed in the Larsen Institute at Penn State, designed, constructed and commissioned a chassis dynamometer emissions test facility. The Center for Alternative Fuels, Engines and Emissions (CAFEE) at WVU provided technical assistance and expertise to the Institute on the design and specifications of the emissions testing equipment. In May 2011, the WVU Transportable Emissions Testing Laboratory, which has more than 20 years of experience measuring emissions from heavy-duty vehicles, conducted a side-by-side emissions laboratory correlation study with PTI emissions testing facility. The objectives of this side-by-side comparison were to:

- Measure the tailpipe exhaust emission of a 2010 EPA-compliant diesel transit bus using the WVU Transportable Emissions Laboratory and the PTI Vehicle Research and Testing Laboratory.
- Present and compare emissions test results measured by the WVU and PTI emissions laboratories.
- Evaluate and compare emissions testing procedures used by the WVU and PTI emissions laboratories and make recommendations for improving test procedures at each facility.

- Evaluate the difficulties associated with accurately measuring the emissions levels of 2010 and newer heavy-duty vehicles equipped with active exhaust after-treatment technologies and make recommendations for improving codified emissions testing procedures, protocols, and regulations.

WVU designed and built the first transportable heavy-duty chassis dynamometer vehicle emissions laboratory in the early 1990s [11]. A second heavy-duty transportable laboratory was completed in 1996, and a medium duty chassis dynamometer was added in 2001. Over the last two decades, the WVU transportable laboratories have collectively measured the emissions from more than 1,000 different heavy-duty vehicles, including transit buses, over-the-road tractor trailers, refuse trucks, construction vehicles, delivery vehicles, and other vocational vehicles. A wide spectrum of conventional and alternative fuels has been studied, including conventional petroleum-derived diesel fuels, ultra-low sulfur diesel (ULSD) fuels, gas-to-liquid distillates (GTL), biodiesel fuels, CNG, LNG, gasolines, methanol blends, and ethanol blends. The heavy-duty vehicle propulsion technologies tested include conventional diesel vehicles as well as a wide array of hybrid electric buses and trucks, all-electric vehicles, plug-in hybrids, hydraulic hybrids, and fuel-cell powered buses. The tests also span a wide variety of exhaust emissions after-treatment configurations from engines without emissions control to vehicles fitted with diesel oxidation catalysts, lean NOx catalysts, diesel particulate filters, and selective catalytic reduction (SCR) devices. The research activities of the WVU Translab over the last two decades have also provided the largest national repository of vehicle field emissions data [12]. The WVU Transportable Emissions Laboratory has a widely-established reputation in the field of heavy-duty vehicle emissions characterization.

The primary intent of this side-by-side laboratory comparison was to demonstrate that the PTI emissions testing laboratory and testing procedures produced emissions results that were in agreement with an emissions laboratory that has a long history of heavy-duty emissions testing. Detailed results of the side-by-side emissions laboratory comparison was published in a detailed technical report [13]. A brief summary of the results and conclusions are presented below.

Test Vehicle

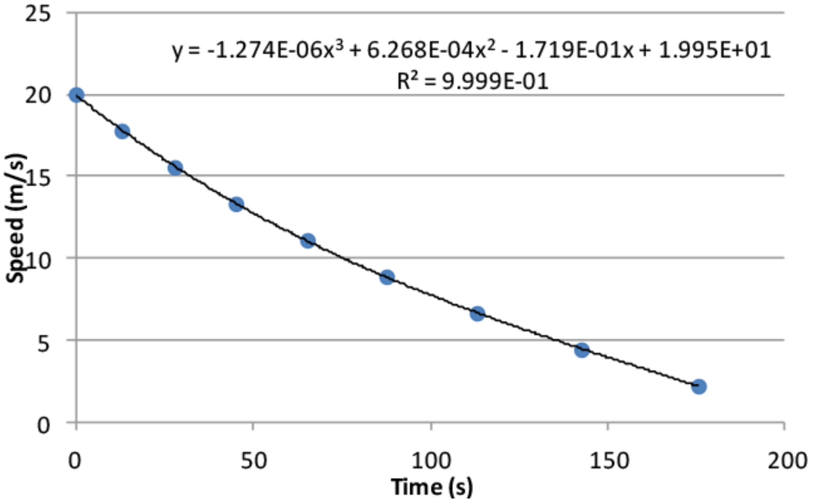
The vehicle used during correlation testing was a Model Year 2010 Gillig 29-ft transit bus (Model G27E102N2). The bus was powered by a Cummins ISL9-280 diesel engine (SN# 73095474) and equipped with a diesel particulate filter (DPF) and Urea Selective Catalytic Reduction (u-SCR) exhaust after-treatment (ACEXH0540LAR, 0.29 g/bhp-hr NOx FEL, 0.21 g/bhp-hr NOx CEL). The bus capacity was 30 seated and 12 standing passengers with a curb weight of 23,490 lbf and gross vehicle weight rating of 30,000 lbf. The vehicle was provided by the New Castle Area Transit Authority and had an accumulated mileage of 27,133 on receipt. The bus was tested on the chassis dynamometer at a simulated weight of 25,880 lbf.

Dynamometer Loading Comparison

The purpose of the chassis dynamometer is to provide accurate simulation of the road load (aerodynamic drag and tire rolling resistance) that the vehicle would experience if driven on the road over the entire speed range through which the vehicle is tested. Precise calibration of the chassis dynamometer road load coefficients is critical to ensuring that the test vehicle is properly loaded by the dynamometer during testing. To determine the aerodynamic and rolling resistance, the test vehicle is coasted with the transmission in neutral from 50 mph to a stop on a straight level roadway while vehicle speed is recorded. Figure 2-5 shows the on-road coast down profile for the Gillig bus.

Figure 2-5

Composite coast down profile of test bus



Data from the coast down profile are processed to determine the load that the dynamometer must apply at each speed to simulate the aerodynamic and rolling resistance loads the bus would experience during normal driving. Details on the determination of the dynamometer load profile from the vehicle coast down profile and be found in reference [13]. Figure 2-6 shows the road load power demand determined from the coast down profile using WVU's and PTI's road load methodology. To verify that the dynamometers were loading the vehicle properly, the bus was coasted down on both WVU's and PTI's dynamometers. Figure 2-7 shows the results of the on-dynamometer coast down. The intent of coast down and road load determination portion of the test program was to demonstrate that experimental coast down and road load coefficient methodologies yielded sufficiently similar loading of the vehicle on the dynamometer. Based on the analysis and comparison of road load coefficients the discrepancy between the PTI and WVU results were within the expected range of agreement.

Figure 2-6

Road load power demand as a function of vehicle speed using road load coefficients derived by PTI and WVU

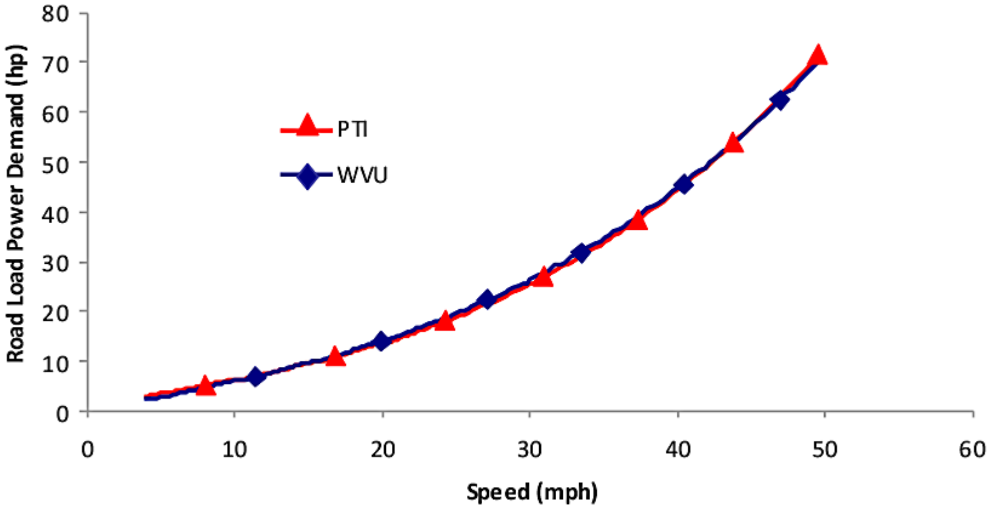
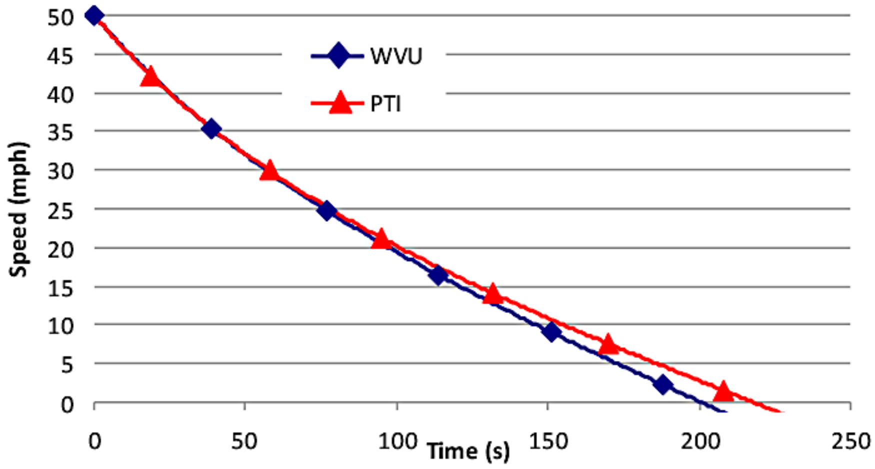


Figure 2-7

Coast down profiles determined from road load coefficients for both WVU and PTI road load determination methods



As further confirmation that the two dynamometers were loading the test bus in a similar fashion, fuel consumption was measured while the bus was operated at several steady-state speeds on the WVU and PTI dynamometers. Table 2-1 and Figure 2-8 show the results of this comparison. Agreement between average fuel economy based on gravimetric fuel measurements on the two dynamometers was relatively good at 20, 30 and 40 mph, but fuel economy at 5 mph was significantly lower (35.1%) on the WVU dynamometer. Agreement in average fuel economy between the PTI and WVU at 10 mph was coincidental, as there was significant test-to-test variation on the PTI dynamometer with fuel economy of 9.65, 6.06 and 5.93 mpg (7.09 mpg average), whereas fuel economy from the WVU laboratory was 7.7 mpg.

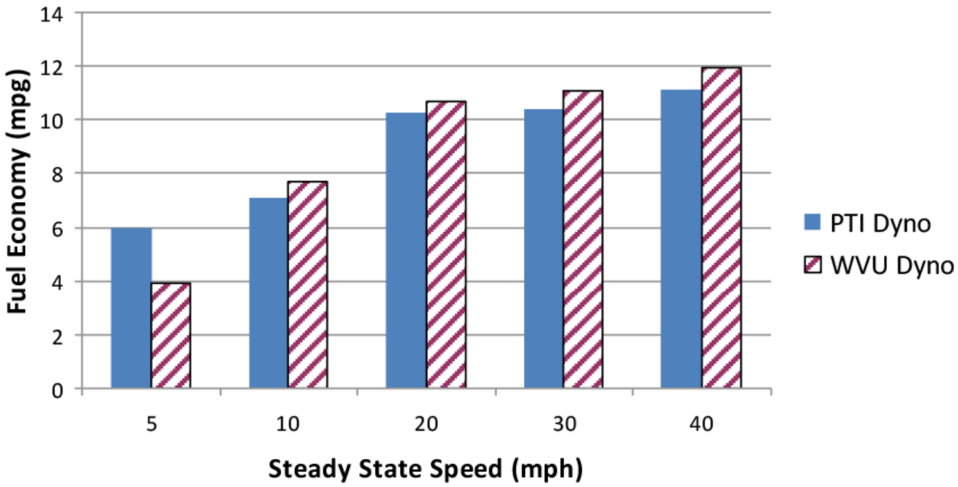
Table 2-1

Gravimetric Fuel Economy Comparison

Speed	PTI Fuel Economy (mpg)	WVU Fuel Economy (mpg)	Difference (%)
5 mph	6.06	3.93	35.1%
10 mph	7.21	7.70	-6.7%
20 mph	10.46	10.70	-2.3%
30 mph	10.64	11.14	-4.7%
40 mph	11.32	11.97	-5.7%

Figure 2-8

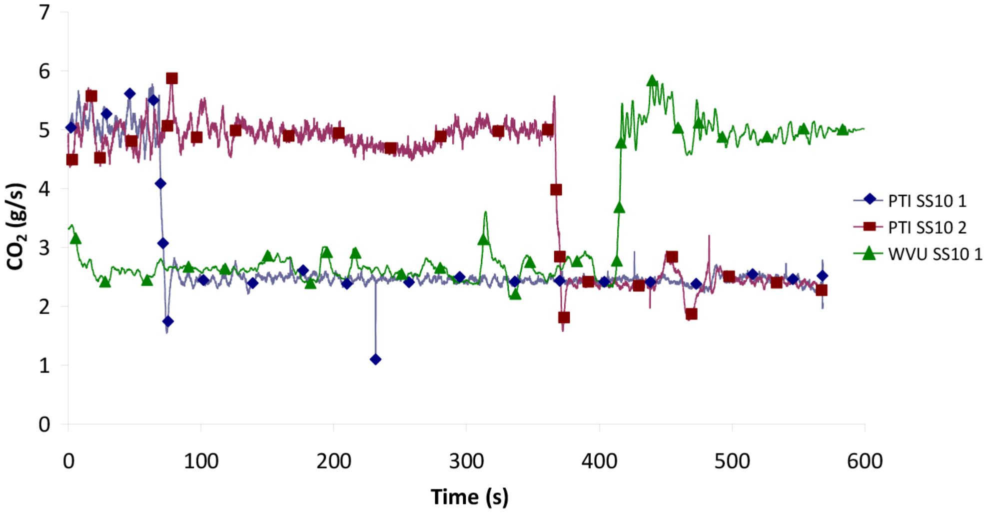
Gravimetric fuel economy from steady-state tests on PTI and WVU chassis dynamometers



The 2010 Gillig bus was equipped with a u-SCR system to meet regulated NOx limits. Proper operation of the vehicle u-SCR required that it be sufficiently hot to achieve NOx conversion. The vehicle employed engine control strategies to increase exhaust gas temperature to maintain u-SCR temperature when the vehicle power level was low. In the case of steady-state tests, the loading on the engine was low as the only loads were from aerodynamic drag and rolling resistance. Fuel consumption as a result of u-SCR thermal management was highly variable during low-speed steady state operation. Figure 2-9 shows variation in measured CO_2 emissions, which can be used as a surrogate for fuel consumption, as a result of active u-SCR thermal management. Steady-state fuel consumption between the PTI and WVU dynamometer compared well when excluding tests where u-SCR thermal management was active.

Figure 2-9

CO_2 emissions rates during 10 mph steady-state testing on PTI and WVU chassis dynamometers



As a final confirmation that the PTI and WVU dynamometers were providing equivalent load to the bus during the tests, the engine percent torque reported by the engine control unit (ECU) was examined. Table 2-2 shows average ECU broadcast engine percent torque values recorded during steady-state testing on both the PTI and WVU dynamometers. Broadcast engine torque at all speeds excepting 5 mph compare well, which indicated that the dynamometers were both applying similar loads to the vehicle. The broadcast engine torque during 5 mph stead-state testing on the WVU dynamometer was significantly higher than that observed from the PTI dynamometer. This discrepancy arose as a result of u-SCR thermal management in the second half of the test on the WVU dynamometer.

Table 2-2

Average ECU Broadcast Engine Percent Torque During Steady-State Testing

	5 mph	10 mph	20 mph	30 mph	40 mph
PTI Dynamometer	13.1%	17.6%	19.9%	27.8%	33.4%
WVU Dynamometer	16.6%	17.8%	20.0%	27.0%	33.7%

The results of the dynamometer loading comparison indicate that the PTI and WVU dynamometers provided load on the test vehicle that accurately simulated the loads that the bus would encounter when driven on the road. These tests also confirmed that methods employed by PTI to determine the road load coefficients and the dynamometer load profile provided accurate results.

Gaseous Sampling System Comparison

During testing on the PTI chassis dynamometer, both PTI and WVU measured emissions concentrations by sampling from the PTI dilution tunnel. The objective of the parallel sampling was to compare how well the emissions gaseous emissions analyzers and procedures employed by the laboratories compared and, if differences were observed, to investigate the effect of the differences and recommend changes to equipment and procedures to improve system accuracy. The exhaust from the test vehicle was routed to PTI's dilution tunnel where it was mixed with conditioned ambient air. The PTI emissions laboratory drew gaseous and particulate emissions samples from the dilution tunnel sample plane. In parallel, the WVU emissions laboratory drew samples from a spare sample port in the PTI dilution tunnel.

Figure 2-10 shows time aligned carbon dioxide concentration measured by the PTI and WVU gas analysis systems while both sampling simultaneously from the PTI dilution tunnel. Figure 2-10 shows that peak CO_2 concentrations reported by the WVU laboratory exceed those from the PTI laboratory for the entirety of the parallel test over the OCTA driving schedule. Figure 2-11 shows a simple linear regression with PTI concentration as the dependent variable and WVU concentrations as the independent variable. A simple interpretation of the regression analysis would indicate that the PTI measurements, on average, were approximately 4 percent lower than the WVU measurements since the intercept (91.828 ppm) represents less than 0.2 percent of the maximum value (50,000 ppm).

Figure 2-10

Dilute exhaust CO_2 concentrations measured by PTI and WVU over a test using OCTA speed-time driving schedule

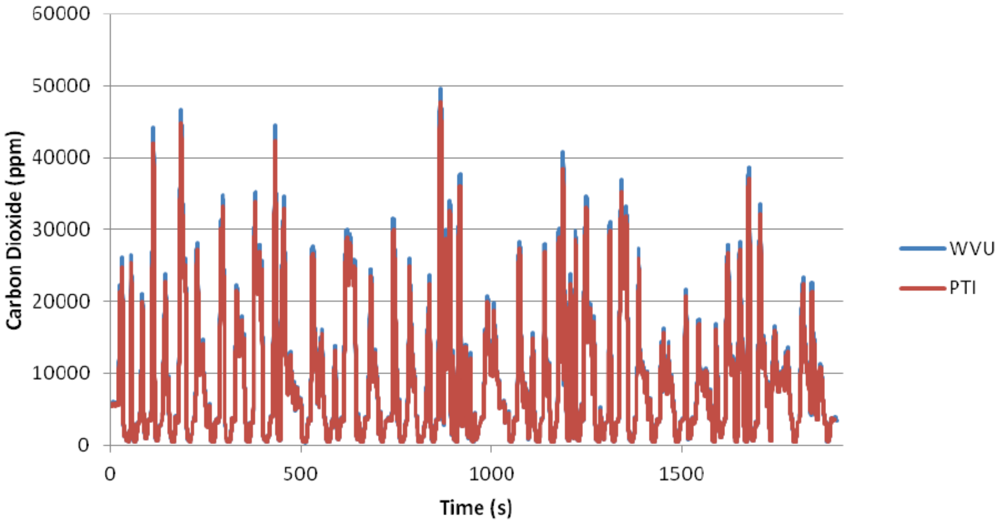


Figure 2-11

Simple linear regression analysis of parallel CO_2 measurements over OCTA driving schedule

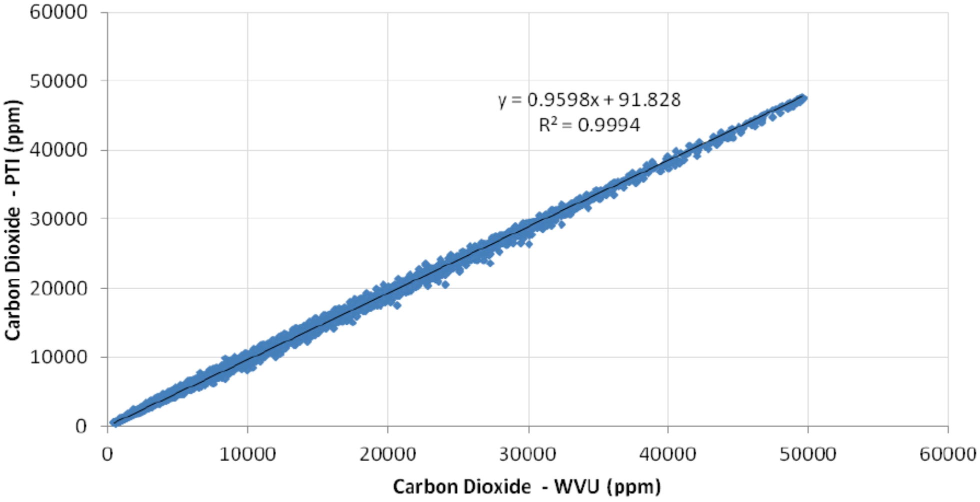


Figure 2-12 and Figure 2-13 show the comparison of measured NOx emissions. The average NOx concentration measured by the WVU laboratory during the test was 0.395 ppm, whereas the average measured by the PTI laboratory was 0.374, a difference of 5.3 percent.

Figure 2-12

Dilute exhaust NOx concentrations measured by PTI and WVU over test using OCTA speed-time driving schedule

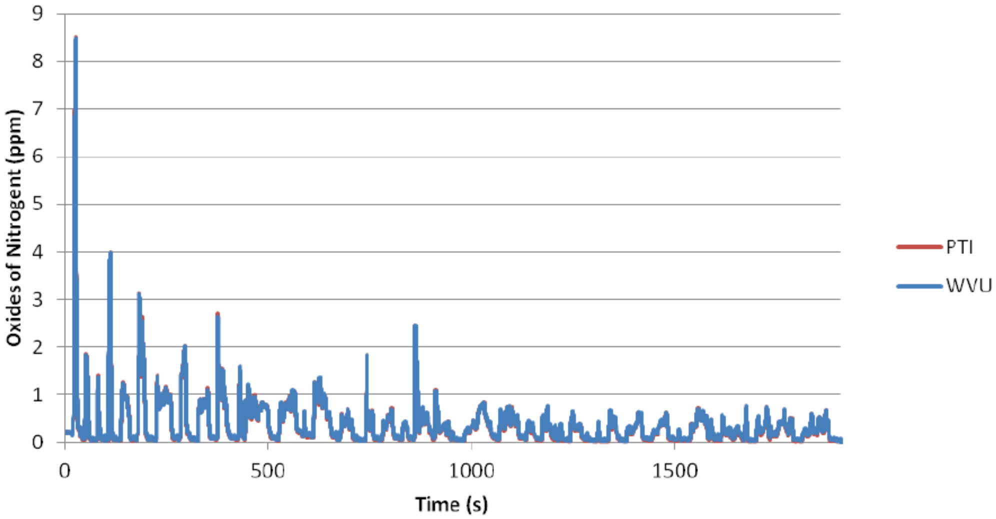
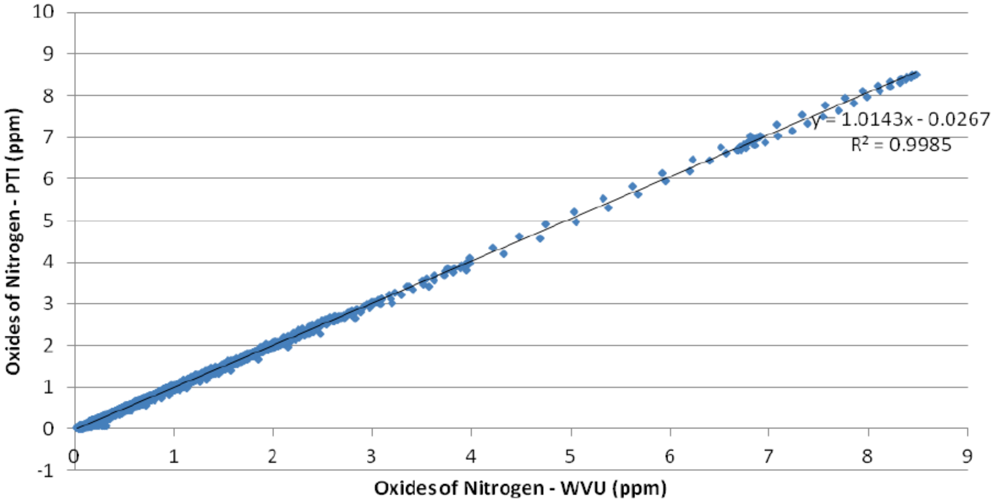


Figure 2-13

Simple linear regression analysis of parallel NOx measurements over OCTA driving schedule



Measurement of hydrocarbon emissions and carbon monoxide emissions proved to be more challenging due to the vanishingly low levels of these constituents in the vehicle's exhaust gases. As shown in Figure 2-14 and Figure 2-15, offsets were observed in the measured hydrocarbon (HC) and carbon monoxide (CO) concentrations between PTI and WVU. Linear regressions resulted in coefficients of regression of $R^2 = 0.86$ for HC concentration and $R^2 = 0.40$ for CO concentration. Note that both laboratories used calibration gas concentrations that were orders of magnitude higher than the maximum hydrocarbon and carbon monoxide concentrations observed during the test. Calibrating the HC and CO analyzers on a lower range may improve the accuracy of the measurements.

Figure 2-14

Dilute exhaust total HC concentrations measured by PTI and WVU over test using OCTA speed-time driving schedule

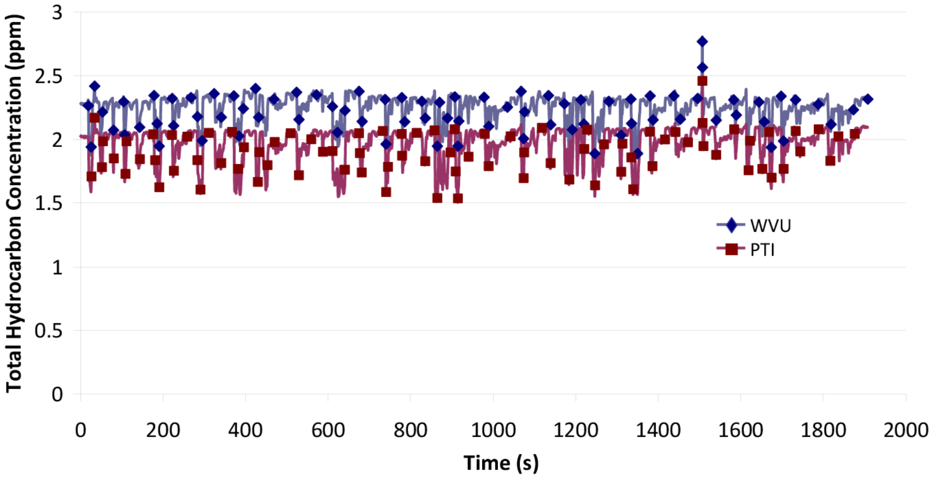
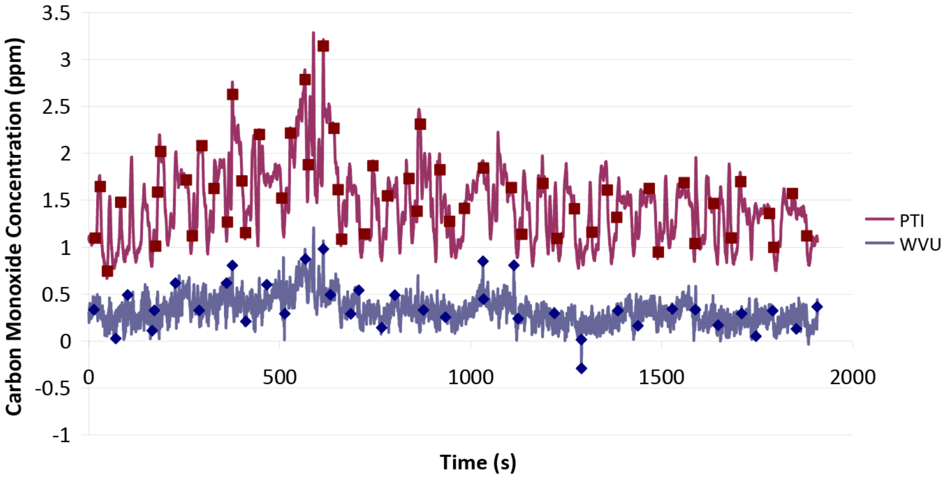


Figure 2-15

Dilute exhaust CO concentrations measured by PTI and WVU over test using OCTA speed-time driving schedule



In conclusion, parallel measurements by the WVU and PTI laboratories showed that, while the instrumentation used by both laboratories to measure gaseous dilute exhaust emissions sufficient to accurately characterize vehicle performance, quality of the measurements are assured only through rigorous procedures such as post-test drift correction, selection of calibration gases which are representative of dilute exhaust concentrations, and improved secondary fuel measurement.

Driver Performance

During chassis dynamometer testing, a skilled driver operated the vehicle by following the driving cycle presented on a driver's interface screen. The PTI and WVU chassis dynamometer laboratories use slightly different driver's interface methods. The PTI laboratory presented a speed "window" where the driver was instructed to keep vehicle speed within a ±2 mph tolerance of the target speed, and the WVU laboratory presented a speed "trace" where the driver was instructed to operate the bus to follow a trace speed line as closely as possible. The manner in which the driving cycle is presented to the driver on the driver's interface could potentially elicit different driving behavior and, therefore, affect the measured emissions. To investigate the impact of the different driver's interface styles could have on emissions test results, both interface styles were evaluated. There was no significant difference in distance traveled with either laboratory or method.

Regression analyses of the tests performed by the PTI laboratory using the "window" driver's interface had the lowest slopes and the lowest coefficients of regression. Tests performed using the PTI chassis dynamometer using speed traces in lieu of windows resulted in vehicle speed more closely matching schedule speed, as indicated by regression slopes closer to unity, coefficients of regression closer to unity, and standard error being reduced by approximately 40 percent (window SEE: 1.12 mph, trace SEE: 0.65) . This improvement is visually represented by Figure 2-16 and Figure 2-17, which show plots of actual speed vs. target speed from tests over the OCTA schedule using, respectively, "window" and "trace" driver's interfaces with the PTI chassis dynamometer.

Figure 2-16

Simple least squares regression analysis of actual vehicle speed on target speed from OCTA tests on PTI chassis dynamometer using "window" driver's interface method

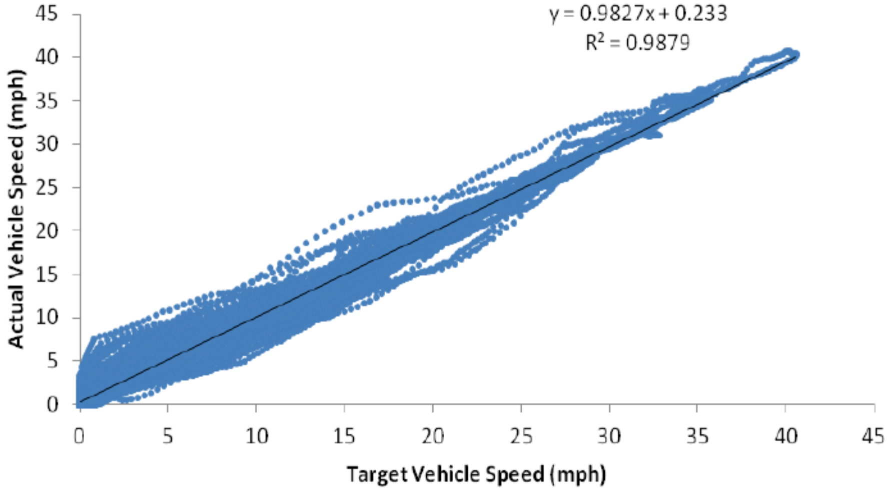
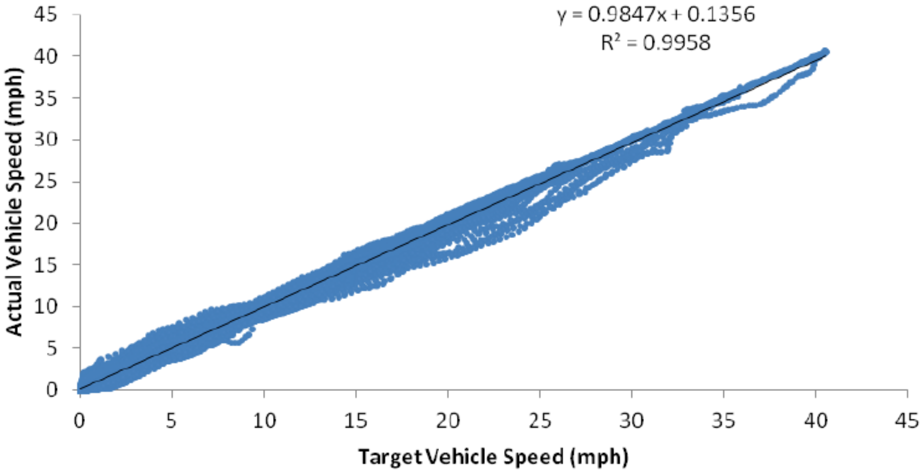


Figure 2-17

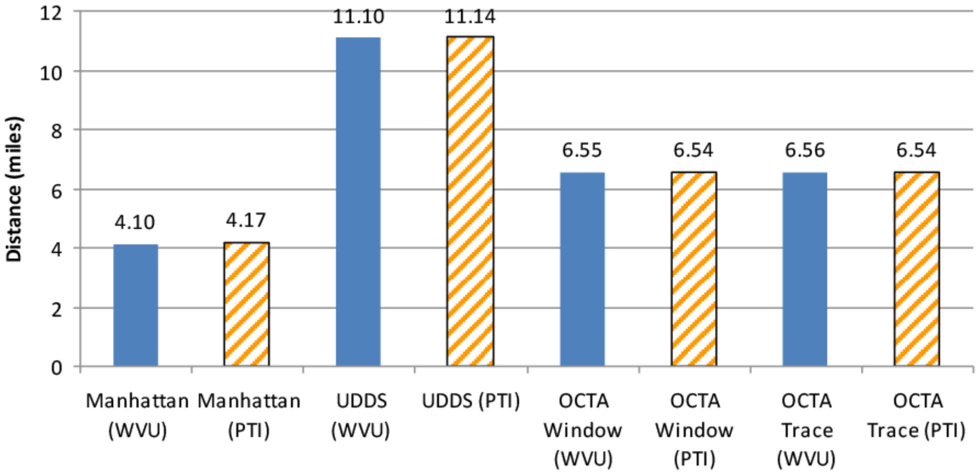
Simple least squares regression analysis of actual vehicle speed on target speed from OCTA tests on PTI chassis dynamometer using "trace" driver's interface method



The most straightforward comparison between the laboratories is to compare how well the distance traveled by the bus over each driving schedule. Figure 2-18 shows a comparison of the average distance covered by the bus on the WVU and PTI chassis dynamometers. All tests fell within 1 percent of the schedule distance of 6.55 miles. Simple least squares regression analysis of actual vehicle speed against target speed was performed for each test and showed that actual vehicle speed was generally slightly lower than schedule speed based on regression slopes less than unity. Previous experience has shown that this occurs because, while the driver might try to anticipate acceleration events, the vehicle may not have enough power to achieve the acceleration rate demanded by the driving cycle. Conversely, the vehicle brakes can decelerate at a high enough rates to follow portions of the speed-time trace where deceleration is taking place. The slight differences in distance traveled would not significantly affect fuel economy or emissions.

Figure 2-18

Distance traveled by bus on PTI and WVU chassis dynamometers over individual speed-time driving schedules



Comparison of Results for Side-by-Side Comparison

The final phase of the study was to compare the results of emissions test performed by the PTI emissions laboratory with tests performed by the WVU emissions laboratory. Independent testing using transient driving schedules was performed by the WVU and PTI laboratories to compare their overall performance. Both laboratories evaluated emissions and fuel economy while the bus was exercised over a variety of speed-time driving schedules. The results of these tests are presented in the sections that follow. Data were collected by both laboratories over a total of 12 tests. Three speed-time driving schedules were examined, including the Manhattan bus schedule (Figure 2-19) to represent low-speed urban transit bus operation, the Orange County Transit Authority (OCTA) driving schedule (Figure 20) to represent a mix of urban and suburban transit bus operation, and heavy-duty Urban Dynamometer Driving Schedule (UDDS) to represent higher speed operation (Figure 2-21).

Figure 2-19

Target speed for Manhattan driving schedule

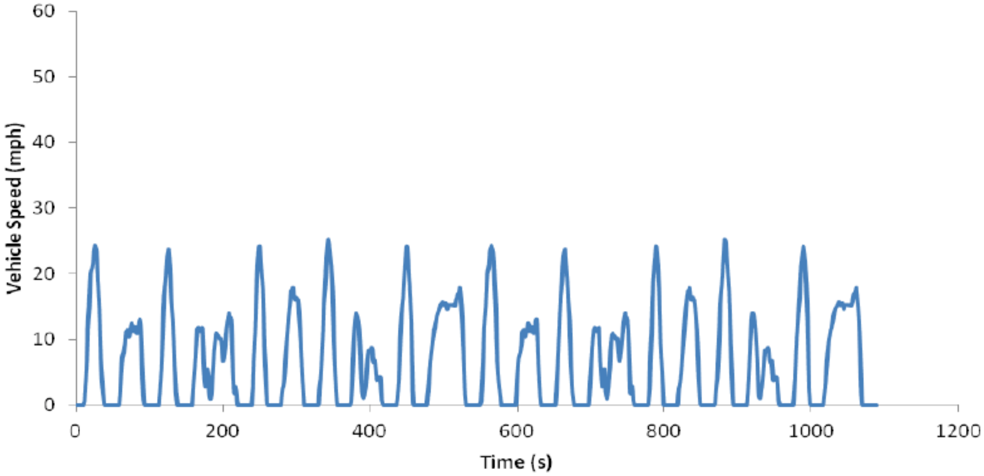


Figure 2-20

Target speed for OCTA driving schedule

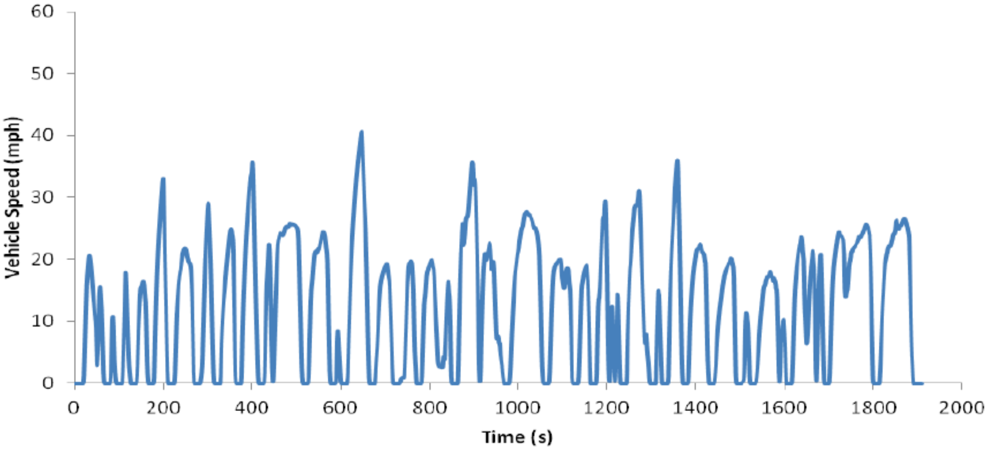
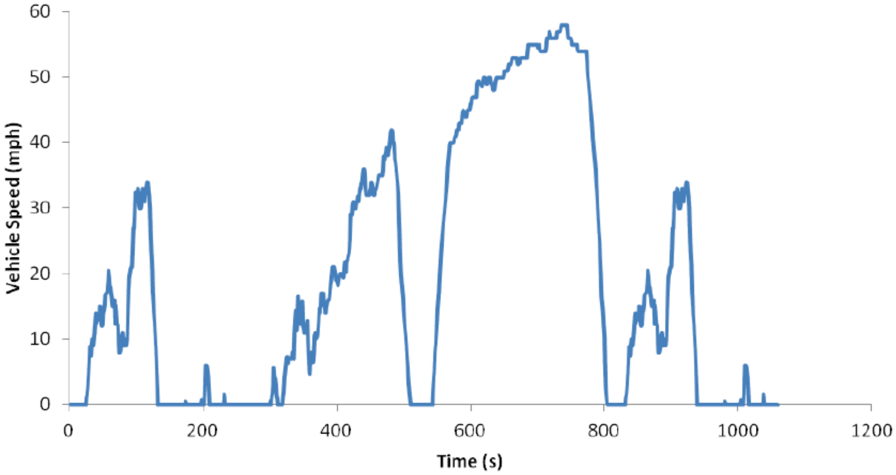


Figure 2-21

Target speed for UDDS

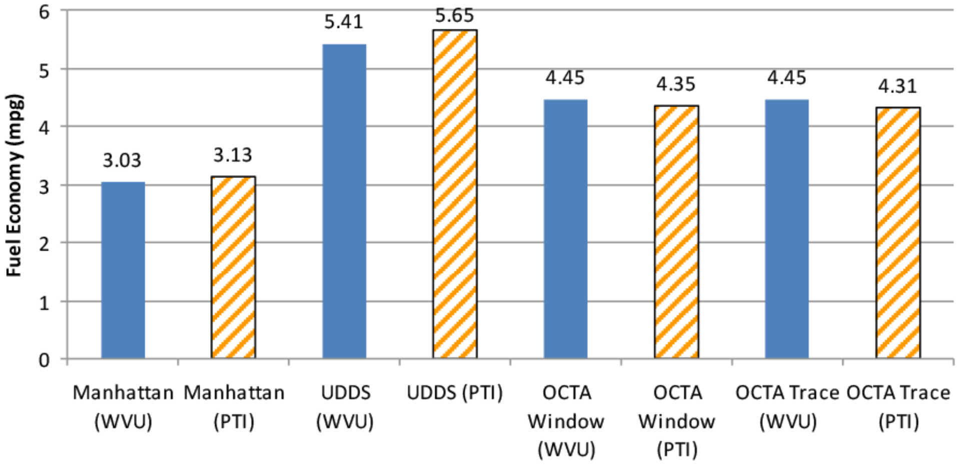


Fuel Economy

Figure 2-22 shows the average fuel economy measure by each laboratory. Measured fuel economy showed relatively good agreement between the laboratories, with average fuel economy measured by the PTI laboratory 3.3 percent higher than that measured by the WVU laboratory over the Manhattan, 2.3 percent lower over the OCTA "window," 3.2 percent lower over the OCTA "trace," and 4.4 percent higher over the UDDS.

Figure 2-22

Average fuel economy measured by WVU and PTI laboratories over each driving schedule



NOx Emissions

Table 2-3 and Figure 2-23 show distance-specific NOx results. Achieving good comparative results and low test-to-test variability for NOx emissions from the bus was difficult as a consequence of its urea-SCR after-treatment. Variability in operation of the urea-SCR after-treatment arises due to the need to keep exhaust gas temperature at a sufficiently high temperature for the NOx reduction reaction to occur and due to storage and subsequent release of ammonia in the SCR catalyst substrate. The best test-to-test repeatability in NOx emissions was achieved by the WVU laboratory over the OCTA driving schedule, where the observed coefficient of variation for three tests was 7.4 percent. Test-to-test variability's for the PTI laboratory over OCTA tests were 73.6 percent and 70.1 percent, respectively, and the largest difference between two tests over the same driving schedule was observed by the PTI laboratory over the trace OCTA, where the highest NOx measurement (0.623 grams per mile) was seven time higher than the lowest (0.084 grams per mile).

Continuous second-by second emissions data were examined in an attempt to understand the observed variability in the NOx emissions. Figure 2-24 shows integrated NOx emissions over the double UDDS as measured by the WVU laboratory. In the figure, the integrated value has been reset to zero after the first speed-time transient and at the start of the second complete UDDS. The integration was reset to zero after the first transient to negate the effects of cooler exhaust temperatures entering the SCR immediately after the start of the test. Integrated NOx during the period between 150 and 1060 seconds was relatively comparable between the three individual tests once the SCR reached normal operating temperature. Since the exhaust temperatures during the period between 1060 and 2120 seconds (second complete UDDS) for the tests were similar, as shown in Figure 2-25, one might expect NOx emissions to be consistent. However, NOx integrated during the third segment (second complete UDDS) for test C0032-005-07 (3.67 grams) was more than four times higher than over the same period for test C0032-005-05 (0.85 grams). Figure 2-25 illustrates that thermal management of the SCR system is not the only factor contributing to NOx variability.

Table 2-3

Distance-Specific NOx Emissions Measured by WVU and PTI Laboratories over Manhattan, UDDS and OCTA Cycles

	Test #1 (g/mi)	Test #2 (g/mi)	Test #3 (g/mi)	Average (g/mi)	COV (%)
Manhattan Driving Cycle					
WVU	0.1907	0.2430	0.1982	0.2106	13.4
PTI	0.6934	0.3206	0.4783	0.4974	39.8
Urban Dynamometer Driving Schedule					
WVU	0.2205	0.1914	0.1994	0.2038	25.9
PTI	0.0911	0.4710	0.2241	0.2621	37.3
OCTA Driving Cycle (Window Interface)					
WVU	0.7095	0.7697	0.5604	0.6799	7.4
PTI	0.0844	0.4999	0.6230	0.4024	73.6
OCTA Driving Cycle (Trace Interface)					
WVU	0.4484	0.4255	0.6660	0.5133	15.8
PTI	0.2097	0.2002	0.3733	0.2611	70.1

Figure 2-23

Distance-specific NOx emissions measured by WVU and PTI laboratories over Manhattan, UDDS, and OCTA cycles

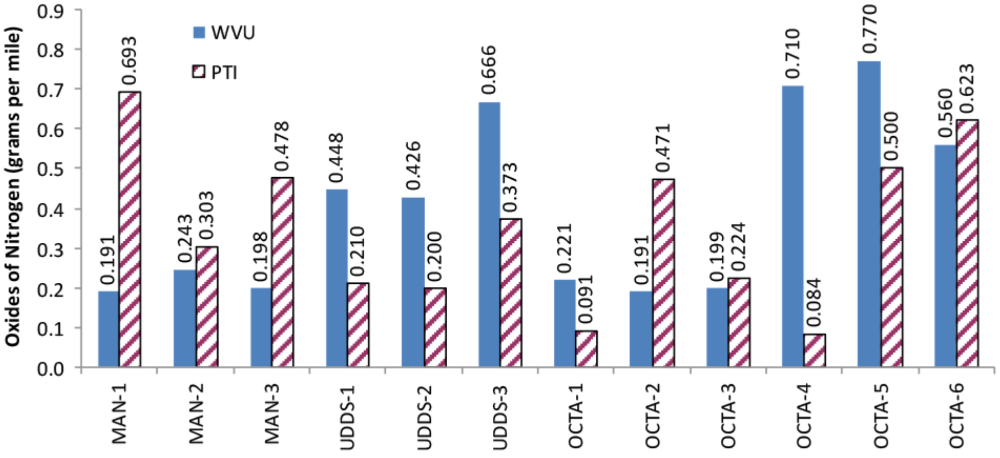
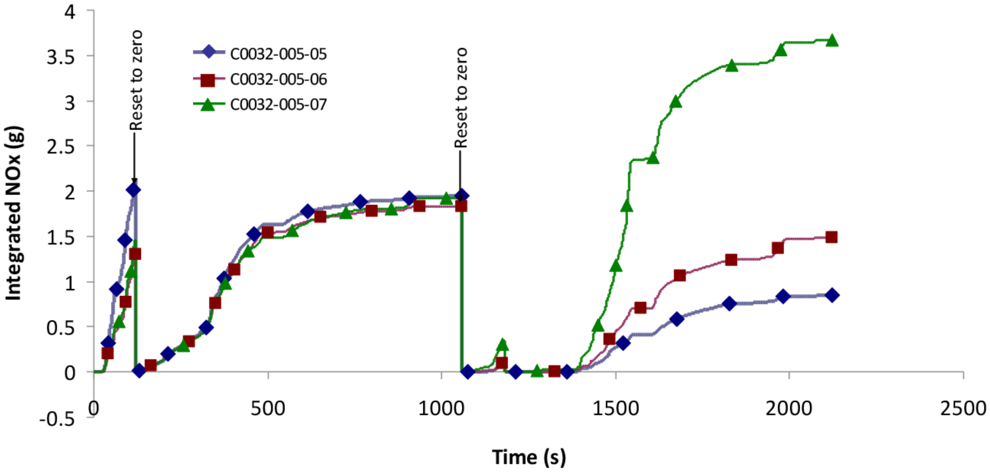


Figure 2-24

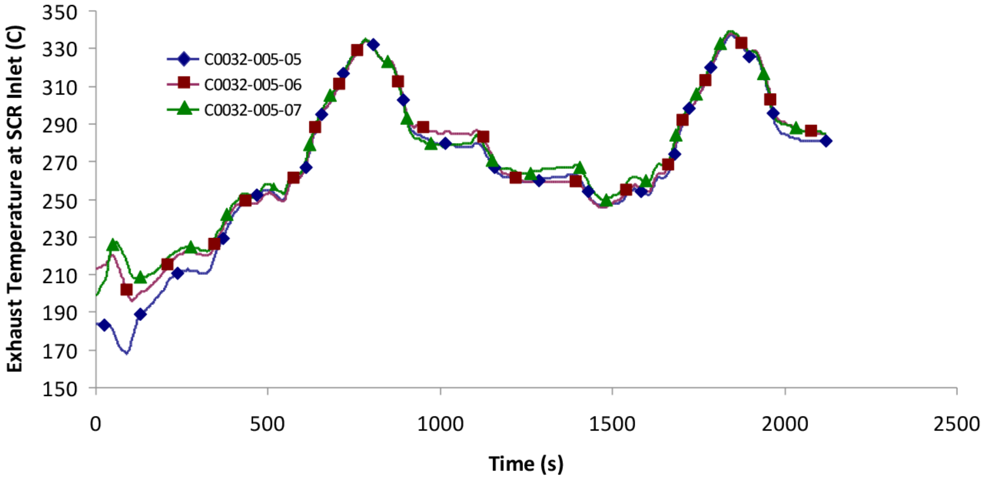
Integrated NOx emissions measured over UDDS by WVU laboratory



Although the test results exhibited substantial test-to-test and laboratory-to-laboratory variation, the variability was attributed to the active after-treatment systems on the transit bus and was not related to the measurement equipment or laboratory operating procedures. The model year 2010 bus that was used in the inter-laboratory comparison is representative of current technology transit buses with active after-treatment systems. It is clear from the result of this study that achieving consistent test-to-test emissions results from these advanced low emissions vehicles is substantially more challenging. In fact, it may be impossible to achieve the level of test-to-test consistency that was possible with the legacy vehicles with passive after-treatment technologies. The best recommendation that can be offered in this regard is to maintain highly-consistent testing procedures particularly related to vehicle preconditioning and soak times between subsequent test runs in order to minimize to the greatest extent variation in engine and after-treatment system temperatures.

Figure 2-25

Exhaust temperature at SCR over UDDS for WVU laboratory



HC Emissions

Table 2-4 and Figure 2-26 shows distance specific HC results. Accurate quantification of HC emissions is challenging because the HC concentrations in the exhaust approach the minimum detection limits of the instrumentation. Further, diesel particulate filter technologies which are required, beginning in 2007 to meet particulate matter emissions standards, substantially reduce HC emissions in the tail pipe. It is now common for hydrocarbon emissions from modern diesel engines equipped with diesel particulate filters to be negative. This occurs as a result of methane present in the ambient air being consumed by the engine during the combustion process, resulting in dilute exhaust HC concentrations being lower than ambient concentrations. It is concluded that the PTI and WVU emissions laboratories were capable of accurately measuring HC emissions within the limitations of the current 40 CFR Part 1065 [7] methodologies and available instrumentation.

Table 2-4

Distance-Specific HC Emissions Measured by WVU and PTI Laboratories over Manhattan, UDDS, and OCTA Cycles

	Test #1 (g/mi)	Test #2 (g/mi)	Test #3 (g/mi)	Average (g/mi)	COV (%)
Manhattan Driving Cycle					
WVU	-0.0157	-0.0478	-0.1383	-0.0673	94.5
PTI	0.0132	0.0115	0.0249	0.0165	44.3
Urban Dynamometer Driving Schedule					
WVU	-0.0496	-0.0580	-0.0606	-0.0561	10.3
PTI	0.0049	0.0051	0.0064	0.0164	14.8
OCTA Driving Cycle (Window Interface)					
WVU	-0.1070	-0.0647	-0.0478	-0.0732	41.7
PTI	0.0079	0.0124	0.0079	0.0282	27.5
OCTA Driving Cycle (Trace Interface)					
WVU	0.0103	-0.0295	-0.0106	0.0099	27.5
PTI	0.0038	0.0105	0.0151	0.0098	199.8

Figure 2-26

Distance-specific HC emissions measured by WVU and PTI laboratories over Manhattan, UDDS and OCTA cycles

CO Emissions

Diesel particulate filters are also highly effective in reducing carbon monoxide emissions to very low levels. Table 2-5 and Figure 2-27 shows CO emissions measured and reported by the PTI and WVU laboratories. As was the case with HC emissions, measuring CO emissions at such low levels is challenging. The PTI laboratory consistently reported higher CO emissions than the WVU laboratory. This may be a result of differences in CO analyzer calibration. Selecting an appropriate calibration range for CO is challenging because during much of the test cycle, CO levels are near zero, but during certain transient operation, higher CO spikes can occur. Carbon monoxide emissions from 2007 and later transit buses equipped with diesel particulate filters are well below the EPA certification limits and are not a significant environmental concern at the levels that are emitted. The only guidance that can be offered with regard to CO emissions measurement is to select the lowest possible calibration range that captures the majority of short-term CO spikes.

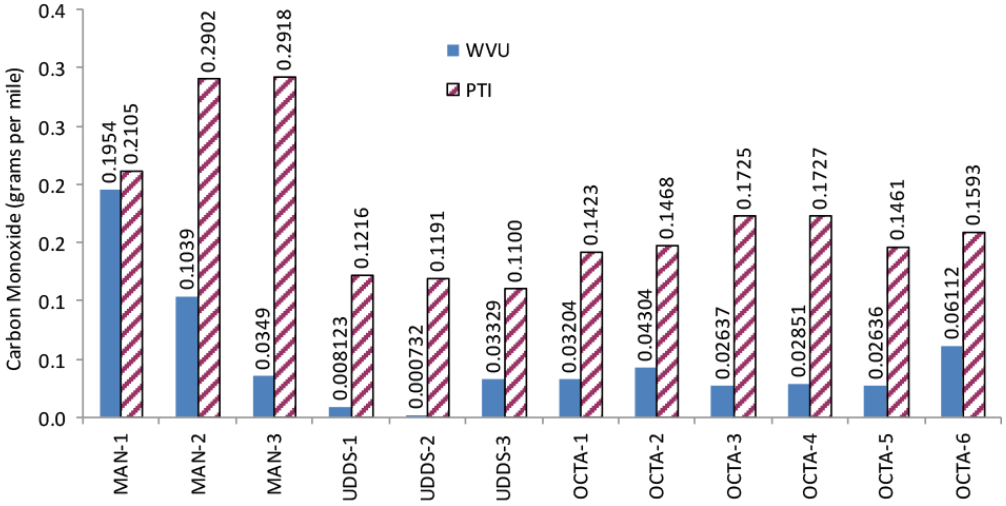
Table 2-5

Distance-specific HC emissions measured by WVU and PTI laboratories over Manhattan, UDDS and OCTA cycles

	Test #1 (g/mi)	Test #2 (g/mi)	Test #3 (g/mi)	Average (g/mi)	COV (%)
Manhattan Driving Cycle					
WVU	0.1954	0.1039	0.0349	0.1114	72.3
PTI	0.2105	0.2902	0.2918	0.2642	17.6
Urban Dynamometer Driving Schedule					
WVU	0.0081	0.0007	0.0333	0.0140	121.5
PTI	0.1216	0.1191	0.1200	0.1202	5.2
OCTA Driving Cycle (Window Interface)					
WVU	0.0320	0.0430	0.0264	0.0338	25.1
PTI	0.1423	0.1468	0.1727	0.1539	10.6
OCTA Driving Cycle (Trace Interface)					
WVU	0.0281	0.0264	0.0611	0.0385	50.4
PTI	0.1727	0.1461	0.1593	0.1594	8.3

Figure 2-27

Distance-specific CO emissions measured by WVU and PTI laboratories over Manhattan, UDDS, and OCTA cycles



Inter-Laboratory Comparison Study Conclusions

The WVU Transportable Emissions Laboratory conducted a side-by-side inter-laboratory comparison study alongside the PTI Vehicle Research and Testing Center. A key objective was to validate the equipment, test procedures, and results of the PTI laboratory.

- The PTI emissions laboratory includes a Schenck Pegasus large roll dynamometer and a Horiba Instruments full-scale exhaust dilution tunnel with Horiba MEXA dilute and raw exhaust gaseous emissions analyzers. All equipment complies with 40 CFR part 1065 requirements for heavy-duty engine and vehicle emissions testing. The equipment is state-of-the-art. No issues were observed with the quality and capabilities of the dynamometer, dilution tunnel system, or MEXA emissions sampling equipment.
- The intent of coast down and road load determination portion of the test program was to demonstrate that experimental coast down and road load coefficient methodologies yielded sufficiently similar loading of the vehicle on the dynamometer. It was concluded that the PTI chassis dynamometer accurately simulated the loads that a bus would encounter during normal on-road operation and that the coast down and road load simulation methods being employed by PTI are appropriate and accurate.
- The objective of the parallel sampling was to compare how well the emissions measurement equipment and procedures employed by the laboratories compared. This phase of the study addressed only the gaseous emissions analyzers. Parallel measurements by the WVU and PTI laboratories showed that while the instrumentation used by both laboratories to measure gaseous dilute exhaust emissions sufficient to accurately characterize vehicle performance, quality of the measurements are assured only through rigorous procedures such as post-test drift correction, selection of calibration gases which are representative of dilute exhaust concentrations, and improved secondary fuel measurement.
- The final phase of the study was to compare the results of emissions test performed by the PTI emissions laboratory with tests performed by the WVU emissions laboratory. Independent testing using transient driving schedules was performed by the WVU and PTI laboratories to compare their overall performance. Fuel economy results between the two laboratories compared relatively well, with percent differences of between -0.33 and 5.6 percent for the Manhattan Cycle, between -4.02 and -2.70 percent for the OCTA cycle and between 3.70 and 5.36 percent for the UDDS. NOx results for both laboratories showed substantial variability and illustrated no discernible trends. The variability was attributed to the unpredictable influence of the u-SCR after-treatment system on the test vehicle and was

not linked to laboratory equipment or testing procedures. As expected, CO and total HC emissions were extremely low due to the presence of the diesel particulate filter on the test vehicle, which practically eliminated these emissions constituents in addition to substantially reducing particulate emissions. Measured HC emissions were at or below ambient levels.

- Direct comparison of measured emissions results was confounded by the variability caused by the thermal management of the u-SCR system on the vehicle. Despite variability induced by the u-SCR system, the side-by-side emissions testing did not reveal any major concerns regarding the measurement accuracy and procedures employed by PTI. When planning the study, the goal was to challenge the two laboratories to measure emissions from a transit bus that represented a present-day (2010) technology. The very low emissions levels and active after-treatment equipment characteristic of 2010 and newer vehicles presented significant challenged in terms of test-to-test repeatability.

Inter-Laboratory Comparison Recommendations

During the correlation study, WVU observed the practices and equipment used by the PTI laboratory in performing chassis emissions evaluations. Based on these observations, WVU believes that by following these recommendations, the PTI laboratory would conform to regulations for emissions testing promulgated by the EPA (40 CFR Part 1065), improve the accuracy of the data collected, allow for more comprehensive understanding of the data collected, and enhance the ability of PTI to troubleshoot issues that inevitably arise during testing due to vehicle, dynamometer, and emissions analysis equipment problems.

- As part of the coast down procedures PTI employed on its chassis dynamometer, it was observed that the dynamometer was used to bring the vehicle up to speed prior to allowing it to coast down. During that time, the vehicle engine was not operating. WVU recommends that PTI operate the vehicle engine with the transmission in neutral during dynamometer coast downs. When the vehicle is in neutral and the engine is shut down, the transmission will not operate as it would during normal operation and will affect the coast down characteristics of the vehicle, especially since the transmission oil pump is driven through the input shaft from the engine.
- More comprehensive inventory practices for calibration gas standards should be developed. During the correlation program, WVU noted that some of the gas standards used to calibrate the PTI emissions analyzers had passed their expiration date. While the expired gas standard concentration is likely unchanged and is still useable, EPA certification regulations require the test facility receive prior approval from an EPA administrator to use expired gas standards for certification testing. Procedures for verifying the standard's

concentration against an unexpired standard or reference gas should be developed and followed if expired standards are to be used (see 40 CFR 1065.750(b)(2)(i)).

The zero and span response of emissions analyzers should be verified prior to and following each emissions test. The response of emissions analyzers varies with time, especially when ambient conditions are variable or when the analyzer is warming up. Additionally, the analyzer response might be affected by inadvertent instrument adjustments, especially pressure and changes in sample temperature (failed heated line). As a result of these variations, EPA regulations have incorporated analyzer drift check/correction into their certification procedures. These procedures require that analyzer response to zero and span gases be checked and, if required, adjusted prior to each test and rechecked at the conclusion of each test. As stated in 40 CFR 1065.530(b)(10), zero and span all continuous analyzers using NIST-traceable gases that meet the specifications of §1065.750. Span FID analyzers on a carbon number basis of one (1), C1. For example, if you use a C3H8 span gas of concentration 200 µmol/mol, span the FID to respond with a value of 600 µmol/mol. Span FID analyzers consistent with the determination of their respective response factors, RF, and penetration fractions, PF, according to §1065.365. As stated in 40 CFR 1065.530(g)(3)(i), zero and span all batch gas analyzers no later than 30 minutes after the duty cycle is complete or during the soak period if practical.

- EPA engine certification regulations require that final emissions results be corrected to account for analyzer drift during the test. Application of this procedure requires that the analyzers be zeroed and spanned immediately prior to and following each test and that the specified equation be used to correct both continuous and integrated bag measurements prior to calculating final results. PTI should incorporate pre- and post-test zero and span procedures and ensure that its data processing software applies drift correction, as per 40 CFR Part 1065.550(b). As stated in 40 CFR 1065.550(b), gas analyzer drift validation is required for all gaseous exhaust constituents for which an emission standard applies
- PTI should establish standard operating procedures specific to its laboratory equipment for the relevant calibration and verification procedures required under 40 CFR Part 1065, Subpart D. The standard operating procedures should address the following required equipment verifications and calibrations:
  - §1065.307 Linearity verification
  - §1065.310 Torque calibration
  - §1065.315 Pressure, temperature, and dewpoint calibration
  - §1065.320 Fuel-flow calibration

- §1065.330 Exhaust-flow calibration
- §1065.340 Diluted exhaust flow (CVS) calibration
- §1065.341 CVS and batch sampler verification (propane check)
- §1065.342 Sample dryer verification
- §1065.345 Vacuum-side leak verification.
- §1065.350 H_2O interference verification for CO_2 NDIR analyzers
- §1065.355 H_2O and CO_2 interference verification for CO NDIR analyzers
- §1065.360 HC FID optimization and verification
- §1065.365 Non-methane cutter penetration fractions
- §1065.370 NOx CLD CO_2 and H_2O quench verification
- §1065.376 Chiller NO_2 penetration
- §1065.378 NO_2-to-NO converter conversion verification
- §1065.390 PM balance verifications and weighing process verification
- §1065.395 Inertial PM balance verifications

Of particular concern are periodic propane injection tests (40 CFR Part 1065.340). During this procedure, a known volume of propane is injected into the dilution tunnel and compared to the volume recovered calculated using the flow rate of dilution air and the concentration reported by the hydrocarbon analyzer. This procedure serves as verification that there are no errors in flow calculation and that there are not significant leaks in the dilution tunnel.

- Fuel (hydrogen) supply line from hydrocarbon analyzer should be replaced with armored line.
- PTI should improve its particulate filter weighing equipment and filter conditioning environment. EPA regulations for particulate filter weighing and filter conditioning are very restrictive since the mass of particulate collected on the filter has become extremely small with the advent of advanced after-treatment. Requirements include preconditioning filters in a temperature- and humidity-controlled environment such that the effect on weight of moisture adsorbed by the filter is consistent. The small mass of PM also requires the use of extremely sensitive weighing equipment with resolution below 1 microgram, typically 0.1 microgram. Regulations require that the weighing equipment undergo frequent calibration using NIST traceable calibration standards. An additional regulatory requirement includes using reference filters to periodically verify weighing equipment and the conditioning environment.

- PTI should explore logging broadcast data from the test vehicle ECU. These data can prove valuable, as they allow for verification of laboratory equipment, diagnosing vehicle-related issues, verifying normal vehicle operation, and serving to supplement emissions-related research performed using emissions test data. Horiba, which provided much of the PTI laboratory equipment and software, support some ECU data logging, but PTI could also investigate third-party or in-house solutions.
- PTI should establish consistent test practices with respect to vehicle engine and after-treatment conditioning. While advanced after-treatment systems have made it difficult to get repeatable results from one emissions test to another, it remains important to establish a set conditioning period prior to each test. WVU has a long-established practice of reporting results only from "hot-start" tests. "Hot-start" tests are defined as tests that are performed after a prior test followed by a 20-minute period during which the vehicle is shut down. For example, WVU will typically operate the vehicle in some fashion (steady-speed unloaded) to warm up the vehicle engine, after-treatment system, and chassis dynamometer components. Once the warm-up is complete, WVU performs a full emissions test, considered to be a "warm-start" test, followed by a 20-minute soak, then a hot-start test. This practice is based on EPA engine certification testing procedures, which require 20-minute soaks with the engine shut off between valid engine emissions tests. Allowing extended periods of time with the vehicle shut down or idling between tests can cause unintended variability due to different after-treatment system temperatures at the start of subsequent tests.
- At least three repeatable emissions tests should be performed when reporting results. The average result and a coefficient of variation should be reported to give an indication of the test-to-test variability in the results.

SECTION

3

Task 2 – Evaluate Advanced Transit Vehicles

The goal of Task 2 was to evaluate the emissions, fuel efficiency, and lifecycle costs of new clean technology transit vehicle to provide information that can be used by transit agencies for vehicle procurement, by engine and vehicle manufacturers to assess the effectiveness of new technologies, and by state and local governments to meet environmental targets and regulations. Major activities included the following:

1. Measure emissions and fuel consumption from alternative fuel and clean technology transit vehicles at various transit agencies in the United States using the WVU Transportable Emissions Laboratory.
2. Evaluate the impact of the increased use of alternative fuels on the emissions and fuel consumption of the United States transit fleet.
3. Evaluate the life cycle costs associated with conventional diesel, alternative fuel, and hybrid electric transit buses.

Measure Fuel Efficiency and Emissions of Advanced Transit Vehicles

Greater use of alternative fuels in public transportation vehicles would yield environmental benefits in comparison to continued reliance upon diesel fuel, primarily in reduced tailpipe emissions of air pollutants harmful to public health and quieter operation. Engines operated with most alternative fuels emit lower levels of non-methane hydrocarbons (NMHC), NOx, and PM than current diesel engines in all kinds of transit vehicles. Moreover, substituting domestically-produced alternative fuels for diesel would yield energy-security benefits through reduced reliance on imported petroleum and reduced risks of price volatility and supply interruptions.

Many public transit agencies throughout the nation have adopted alternative fuel, hybrid-electric vehicle, and advanced retrofit exhaust after-treatment technologies since the mid-1990s. Some reasons for choosing alternative fuels and hybrid-electric technologies include:

- Complying with air quality regulations in non-attainment areas
- Complying with local or regional air quality regulations and targets

- Recent price advantages of alternative fuels such as natural gas compared to diesel fuel prices
- Reducing dependence on foreign oil by substitution with domestically-produced fossil and renewable fuels
- Federal state and local incentive programs that provide financial assistance for purchase of clean fuel buses
- Promotion by industry and environmental groups advocating renewable, domestic and clean fuels.

Quantifying these external benefits at local, regional, and national levels requires accurate data regarding the fuel efficiencies and emissions associated with the various alternative fuels and technology options.

The WVU Transportable Emissions Laboratory, shown in Figure 2-28, has measured the emissions and fuel consumption of more than 850 transit buses ranging in model year from 1967 to 2011, including buses fueled on type 1 and type 2 low-sulfur diesel fuel, type 1 and type 2 ULSD fuel, synthetic Fischer-Tropsch diesel fuel, biodiesel fuel blends, CNG, LNG, gasoline, and gasoline-ethanol blends. WVU has also characterized the fuel consumption and emissions of both series and parallel architecture diesel hybrid-electric transit buses and series architecture gasoline hybrid electric transit buses.

The fuel consumption and emissions results obtained by the WVU Transportable Emissions Laboratory have been made available to the transit industry and public through reports, publications, and presentations at professional conferences, including the Society of Automotive Engineers (SAE), the American Public Transportation Association (APTA), the Transportation Research Board (TRB), the Coordinating Research Council (CRC), and Directions in Engine-Efficiency and Emissions Research (DEER) conferences and in technical journals such as the *Journal of the Air and Waste Management Association, Transportation Research Record, Journal of the Transportation Research Forum,* and others.

The fuel consumption and emissions data from the WVU Transportable Lab studies are also available through a searchable database on the WVU Integrated Bus Information System (IBIS) web page at www.ibis.wvu.edu. These data were also used to develop a Transit Fleet Emissions Inventory model that is also accessible on the IBIS web page. More detail about the IBIS database, emission model, and other resources is presented in Section 4 of this report. Specific emissions testing campaigns conducted in part or in full using funding from this program are described briefly in the sections that follow.

Figure 3-1

WVU Transportable Emissions Laboratory

Washington Metropolitan Transit Authority – 2004

A major task of this project was to develop a transit fleet emissions inventory model that could be used to evaluate alternative fuel and hybrid electric buses for procurement planning. The fuel consumption and emissions of heavy-duty vehicles are strongly influenced by the driving patterns of the vehicle vocation. To predict the emissions of a given transit bus in its anticipated service application, the emissions must be characterized throughout the operational speed envelop. The intent of this emissions testing campaign was to collect data to support the development of the IBIS fleet emissions inventory model. A 2000 model year Orion diesel bus was tested by the WVU Transportable Emissions Laboratory over 14 driving cycles to characterize emissions and to investigate possible correlations between cycle emissions. The bus was powered by a 2000 MY Detroit Diesel Corporation (DDC) Series 50, 8.5 liter, 275 hp engine fuel with ULSD type 1 diesel fuel. The bus was tested on 13 different test schedules plus idle. The test cycles included the Central Business District (CBD) cycle, the Beeline cycle, the Braunschweig cycle, the European Transient cycle (ETC), the UDDS, the City Suburban Heavy-Duty Vehicle Route (CSHVR), the NYBus cycle, the New York Composite (NYComp) cycle, the Manhattan cycle, the OCTA cycle, the Washington Metropolitan Transit Authority (WMATA) cycle, the Arterial cycle, and the Commuter cycle. Table 3-1 compares the actual characteristics of common transit bus driving cycles. For each cycle, the actual duration, distance, average speed, maximum speed, average acceleration (Accln.) and deceleration (Decln.), maximum acceleration and deceleration, and percentage of idle are tabulated.

Table 3-1

Transit Bus Driving Cycle Statistics

	Duration (secs)	Distance (mi)	Avg. Speed (mph)	Max. Speed (mph)	Avg. Accln. (ft/sec^2)	Avg. Decln. (ft/sec^2)	Max. Accln. (ft/sec^2)	Max. Decln. (ft/sec^2)	% of Idle
Idle	1798	n/a	0	0	0	0	0	0	100
NYBus	598	0.58	3.47	29.78	1.67	1.53	4.65	5.65	62.37
Manhattan	1088	2.12	7.00	25.31	1.51	1.61	4.42	4.42	33.09
WMATA	1837	4.29	8.40	45.35	1.27	1.41	4.59	5.15	38.70
NYComp	1027	2.48	8.71	35.24	1.09	1.18	4.14	4.09	30.09
OCTA	1948	6.73	12.44	40.23	1.37	1.67	4.42	5.09	20.60
CBD	560	1.95	12.54	20.00	1.55	1.86	4.25	5.15	7.23
Braunschweig	1748	6.85	14.11	36.49	1.50	1.73	4.42	4.76	20.77
Beeline	1722	6.91	14.45	50.31	1.58	1.83	4.25	4.81	25.61
CSHVR	1592	6.68	15.10	43.84	1.20	1.19	4.48	4.14	23.56
UDDS	1059	5.53	18.80	58.02	0.92	1.16	4.14	4.65	31.54
Arterial	290	2.14	26.51	41.15	1.46	2.35	4.42	5.43	6.50
ETC	1181	9.23	28.13	49.35	0.75	0.94	3.75	4.42	4.57
Commuter	328	4.13	45.30	56.42	0.63	1.12	3.86	3.86	7.01
Paris	1909	3.55	6.74	29.7	1.75	1.85	6.75	13.49	12.1
KCM	1964	12.78	23.42	60.0	1.61	2.31	14.18	11.94	17.6
Transient	688	2.85	14.92	47.5	1.02	1.37	4.25	1.89	15.6

Distance-specific and time-specific NOx emissions with average vehicle speed are presented in Figure 2-29. Distance-specific NOx emissions decreased with increasing vehicle speed while the time-specific NOx increased with increasing vehicle speed. Distance-specific and time-specific PM emissions with respect to average vehicle speed are presented in Figure 2-30. Distance-specific PM emissions showed a decreasing trend with average vehicle speed, but the time-specific PM emissions showed a weak increasing trend with vehicle speed. However, if the idle PM emissions were excluded from the data set, then the time-specific PM emissions did not follow any pattern with respect to average vehicle speed. Distance-specific and time-specific CO_2 emissions with average vehicle speed are presented in Figure 31. Distance-specific CO_2 decreased with average vehicle speed while the time-specific CO_2 increased with increasing vehicle speed. It has been found that operating the bus between 10 and 30 mph yielded lower distance-specific and time-specific CO_2 emissions, although the bus had better fuel economy at higher vehicle speeds. A detailed account of this study can be found in Wayne et al. [14].

Figure 3-2

Effect of vehicle speed on distance-specific and time-specific NOx emissions

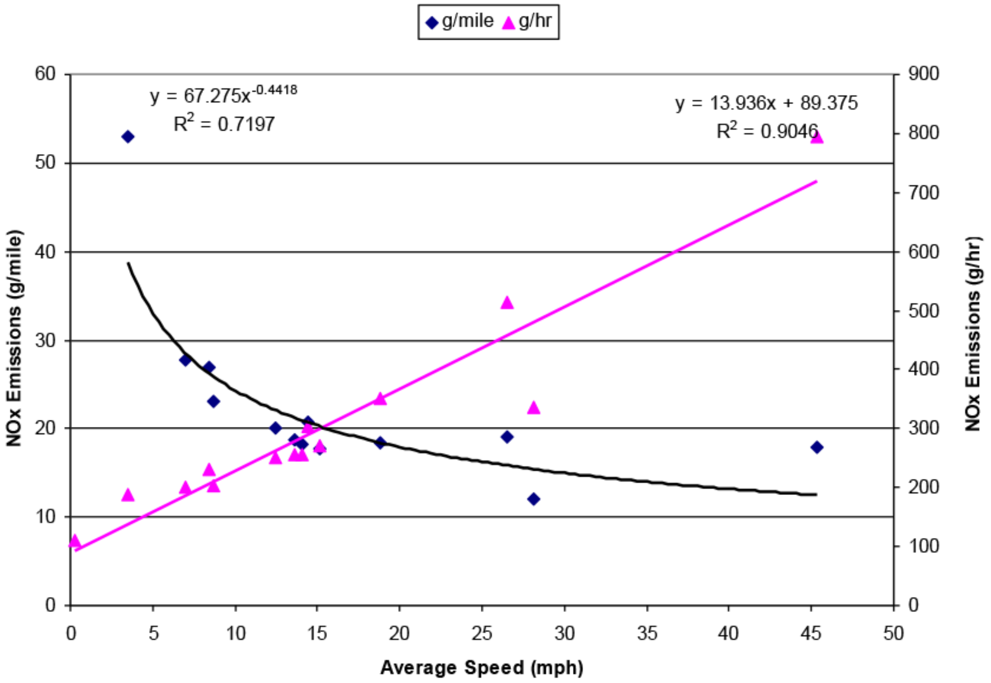


Figure 3-3

Effect of vehicle speed on distance-specific and time-specific PM emissions

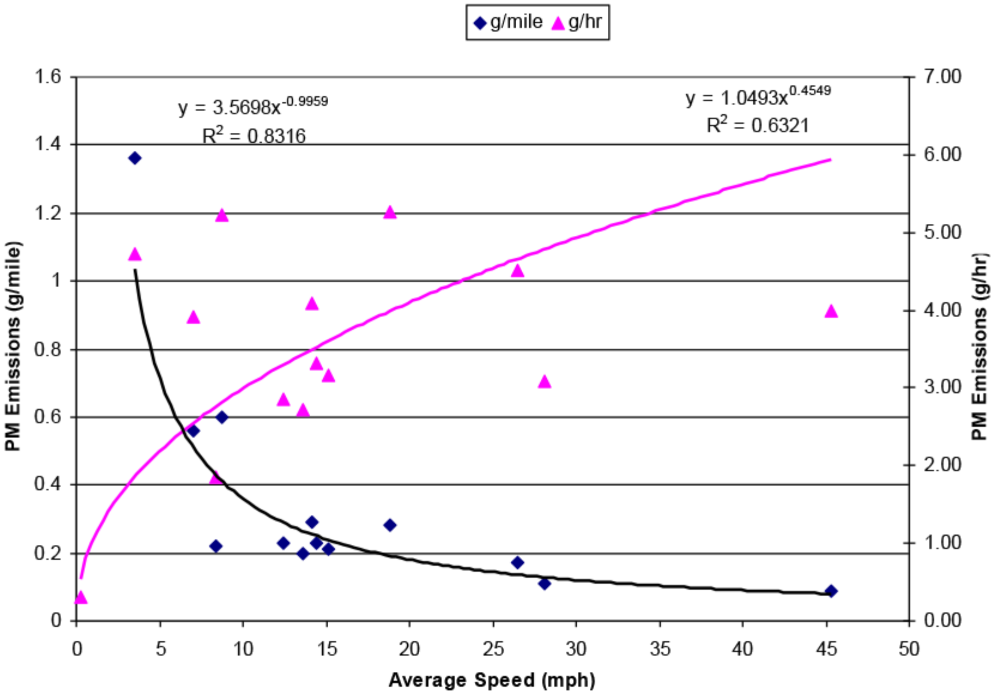
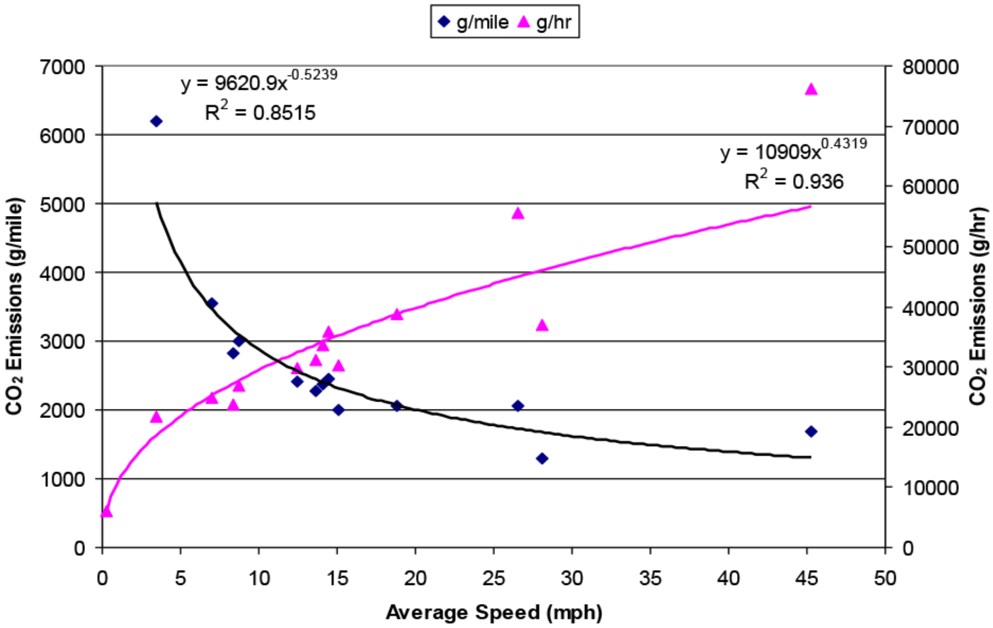


Figure 3-4

Effect of vehicle speed on distance-specific and time-specific CO_2 emissions



Washington Metropolitan Transit Authority – 2006

Although diesel engines still power most of the heavy-duty transit buses in the United States, many major cities are also operating fleets in which a significant percentage of buses are powered by lean-burn natural gas engines. Emissions from these buses are often expressed in distance-specific units of grams per mile (g/mile) or grams per kilometer (g/km), but the driving cycle or route employed during emissions measurement has a strong influence on the reported results. A driving cycle that demands less energy per unit distance than others results in higher fuel economy and lower distance-specific oxides of nitrogen emissions. In addition to energy per unit distance, the degree to which the driving cycle is transient in nature can also affect emissions. This emissions study included 2005–2006 model year parallel architecture diesel hybrid-electric buses, lean-burn CNG buses, non-DPF-equipped diesel buses, and 2002 model year DPF-retrofit diesel buses. Bus specifications are listed in Table 3-2.

Table 3-2

WMATA 2006 Test Vehicle Specifications

WMATA Bus No.	Bus Type	Bus Model	Engine Model	Transmission	After-treatment	GVW (lbf)	Odometer Mileage
6001	Diesel-Hybrid	2006 New Flyer DE40LF	2006 Cummins ISL 280	Allison E^P 40 parallel hybrid	Engelhard DPX Diesel Particulate Filter	40,600	18,551
6002	Diesel-Hybrid	2005 New Flyer DE40LF	2005 Cummins ISL 280				15,460
6003	Diesel-Hybrid						20,373
6146	Diesel	2006 New Flyer DE40LFR	2006 Cummins ISM 280	Voith D864.3E	Catalytic Converter	40,600	5,635
6150	Diesel						7,171
2639	CNG	2005 Orion 07.501	2005 John Deere RG6081 280 hp	Allison B400R	Catalytic Converters	42,540	4,225
2621	CNG						3,148
2640	CNG						7,717
2501	CNG	2005 Orion 07.501	2004 Cummins CG- 280	Voith D864.3E	Catalytic Converters	42,540	18,593
2502	CNG						26,858
2503	CNG		2005 Cummins CG- 280				4,719
9643	Diesel	1992 Orion 05.501	2003 DDC S50 275 hp	Not Available	Engelhard DPX	39,375	509,065
9654	Diesel				Johnson-Matthey CCRT		586,458

In this program, one bus each from three technologies was tested on 17 chassis cycles used in North America and Europe, and the other buses were tested on a subset of these cycles. The first two John Deere and Cummins buses and the first diesel bus were tested at half load on six different drive cycles: the New York Bus Cycle (NYBus), the ADEME-RATP Paris Cycle (Paris), the Manhattan Cycle (Man), the WMATA Cycle, the Orange County Transit Authority Cycle (OCTA), and the Braunschweig Cycle (Braun). The third John Deere and Cummins buses and the second diesel bus were tested at three different load conditions involving the Paris, the OCTA, and the Braunschweig cycles. These buses then were tested at half-loaded state on the 17 drive cycles listed in Table 3-1. The primary goal of this emissions testing was to gather data for the IBIS transit fleet emissions inventory model.

Distance-specific emissions of NOx and PM from all three buses are plotted with average cycle speed and presented in Figure 3-32 and Figure 3-33, respectively. It can be observed that NOx in g/mile from the third bus decreased with increasing average cycle speed. The highest NOx was obtained from the slowest cycle (the NYBus cycle, 3.69 mph average speed), whereas the high speed Commuter cycle (43.64 mph) resulted in the lowest NOx emissions. This correlation resulted in a R^2 value of 0.82 in power regression analysis. NOx emissions from the first two buses also followed a similar trend. CO_2 and HC emissions also followed the similar trend, with average cycle speed for all these buses. The NYBus cycle on each occasion exhibited the highest emissions while the Commuter cycle exhibited the lowest emissions. PM and CO emissions, however, were not observed to follow any trend with average cycle speed. This is primarily due to the fact that both CO and PM emissions from these buses were very low and, in some tests, they were below the detectable limit of the laboratory.

Fuel economy (FE) from these three buses has been inferred by carbon balance and was expressed in miles per energy equivalent diesel gallon (mi/gal). For all three buses, FE improved with average cycle speed, as shown in Figure 3-34. The lowest FE was observed on the NYBus cycle, and the highest FE was exhibited on the Commuter cycle. FE has a downward trend once the average cycle speed exceeds approximately 35 mph, but this could be an artifact of the parabolic fit to the data. Lack of FE data after this speed (only one) has been a limiting factor in establishing this trend. It would be interesting to see how FE from these vehicles would be affected once the average speed exceeded 50 mph. The relationship of FE with average cycle speed on a polynomial fit induced an R^2 value of 0.93.

Figure 3-5

Effect of average cycle speed on distance-specific NOx emissions

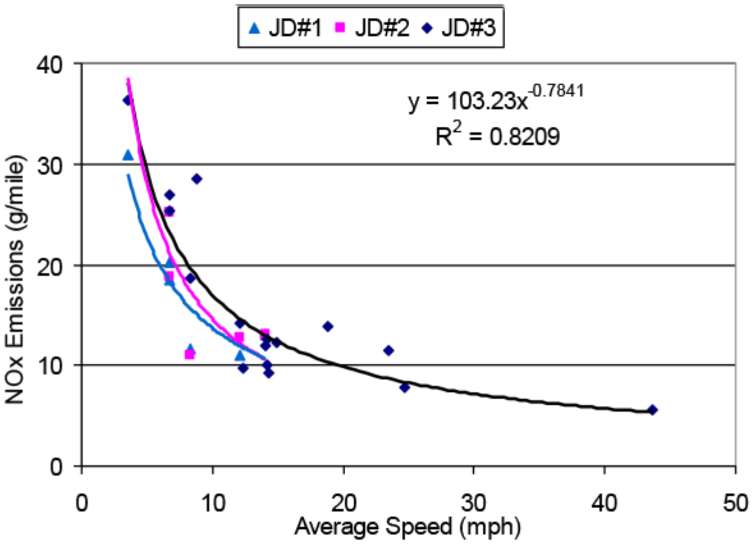


Figure 3-6

Effect of average cycle speed on distance-specific PM emissions

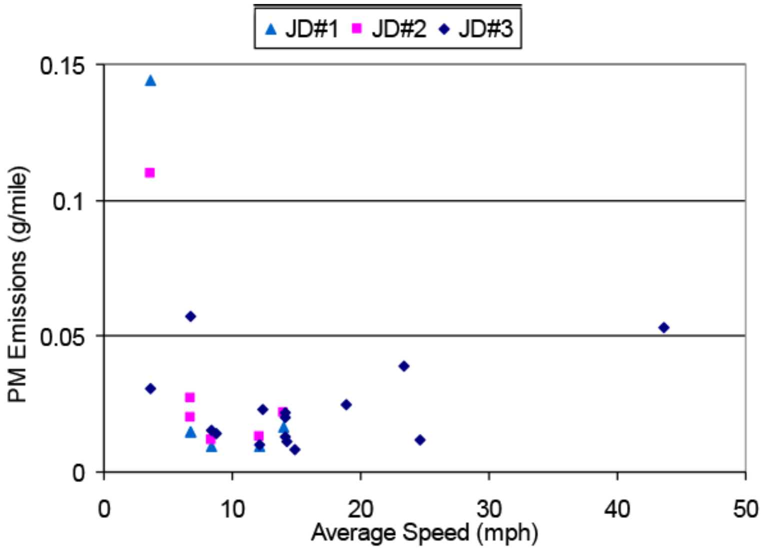
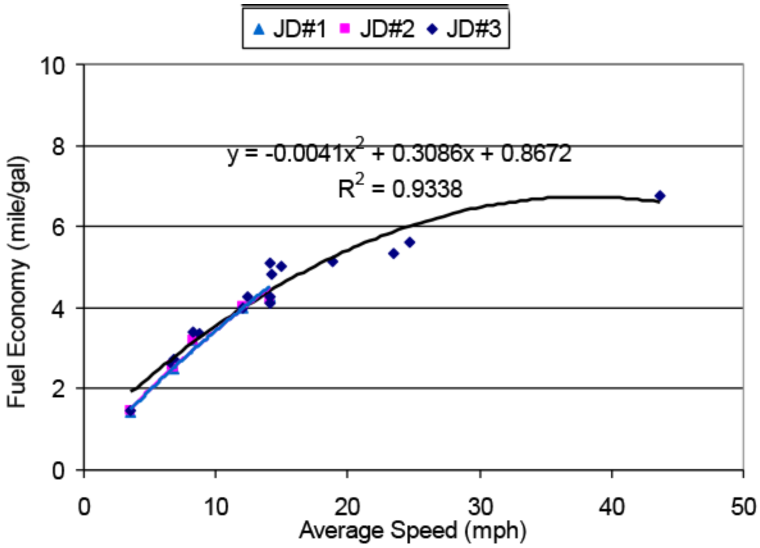


Figure 3-7

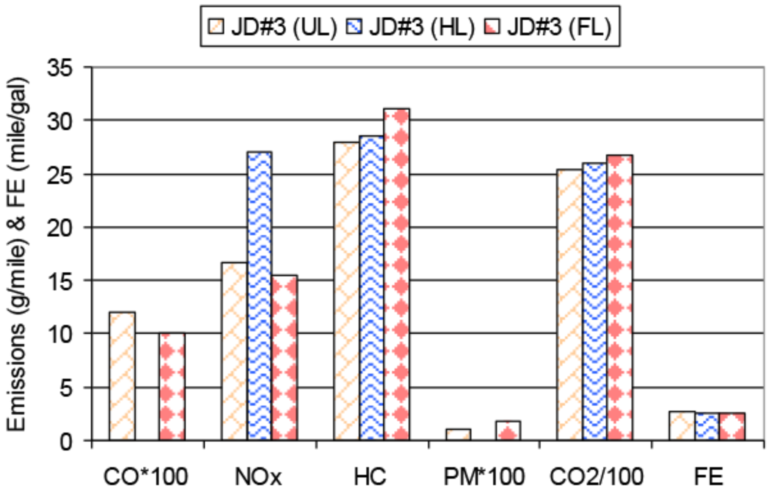
Effect of average cycle speed on fuel economy



In this study, the effect of passenger load on the fuel efficiency and emissions was also investigated to develop weight correction factors for the IBIS transit vehicle emissions inventory model. The third John Deere-powered bus was tested at three load conditions: no-load condition with 32,470 lbf, full-loaded state with 41,470 lbf, and half-loaded state with 36,970 lbf of test weight. Three common cycles—the Braunschweig cycle, the Paris cycle, and the OCTA cycle—were employed to observe the effects of test weight on emissions and fuel economy. Effect of these three test weights on emissions and fuel economy on the Paris cycle is shown in Figure 3-35. No clear trend of the effect of test weights on HC and PM emissions was observed on these three cycles. CO_2 emissions increased with increasing test weight on the Paris cycle, and, consequently, fuel economy decreased with increasing weight. CO_2 emissions at full load were higher those that at no load and half load on the OCTA and the Braunschweig cycles. The lowest FE was also observed when the bus was tested at the fully-loaded state on the OCTA and Braunschweig cycles. CO emissions varied a little on the Paris cycle but substantially varied on the OCTA cycle, and the Braunschweig cycle. NOx emissions varied considerably on all cycles but did not follow a trend of increment between no-load, half-load, and full-load test weights. NOx was substantially higher at half load than that at the other two test weights. NOx emissions from the third bus were also higher than that of the first bus on six common cycles except the Braunschweig cycle, and they were also higher than those of the second bus on the Paris, Manhattan, WMATA, and OCTA cycles. The highest NOx was observed from the second bus on the NYBus cycle (44.2 g/mile). For transit buses, the full-load weight was only 27 percent higher than the no-load weight, so it is not surprising that emissions effects might be hard to detect. Therefore, it could be concluded that emissions and FE from natural gas buses are more affected by the drive cycles than by their test weights.

Figure 3-8

Effect of test weight on emissions and FE on Paris cycle



Detailed accounts of this study were published in two interim technical reports [15, 16] and two technical conference papers [17, 18]. The data were primarily employed in the development of the IBIS transit fleet emissions inventory model, which is discussed in Section 4 of this report.

Westchester County NY Department of Transportation – 2006

This emissions testing campaign characterized the emissions of a series architecture diesel hybrid-electric bus (Table 3-3). The hybrid-electric buses tested at WMATA were equipped with Allison's 2-mode parallel hybrid drive system. In a parallel hybrid, both the electric motors and engine are used to drive the vehicle. In a series hybrid, the engine runs a generator to generate electricity. The vehicle is propelled solely by electric motors, and there is no direct coupling of the engine to the drive wheels. The intent of this work was to determine how series and parallel propulsion system architecture influenced the emissions and fuel consumption of the bus. The data collected were used to further the development of the IBIS transit fleet emissions inventory model. The bus was tested using the Beeline, OCTA, NYBus, UDDS, Manhattan, and WMATA driving cycles to characterize the influence of duty cycle on emissions and fuel consumption.

Table 3-3

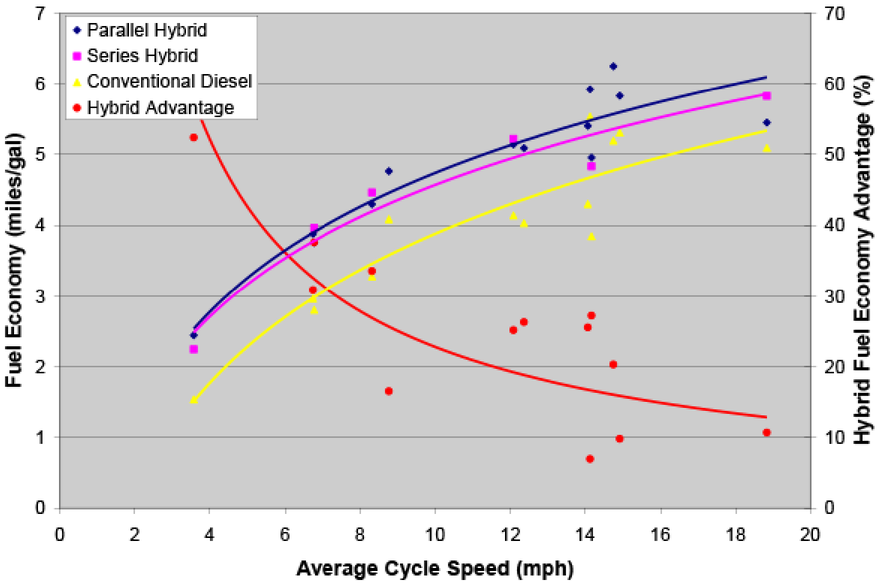
WCDOT Diesel Series Hybrid-Electric Transit Bus Specifications

WCDOT Bus No.	Bus Type	Bus Model	Engine Model	Transmission	After-treatment	GVW (lbf)	Odometer Mileage
204	Diesel-Hybrid	2006 Orion 07.501	2006 Cummins ISB 206H	BAE Systems HybriDrive series hybrid	Diesel Particulate Filter	42,540	5,074

Figure 3-9 shows a comparison of fuel economy between an Allison EP40 2-mode parallel hybrid bus, a BAE Systems HybriDrive series hybrid bus, and a non-hybrid diesel bus. The parallel architecture hybrid bus achieved slightly better fuel efficiency than the series architecture hybrid bus. However, the two are reasonably similar such that an average model could be used to represent both series and parallel hybrid buses in the IBIS transit fleet emissions model. Also shown the hybrid fuel economy advantage compared to a conventional non-hybrid diesel bus.

Figure 3-9

Fuel economy comparison between parallel hybrid, series hybrid, and conventional diesel transit buses



The Westchester County series hybrid bus testing was conducted jointly with testing funded directly by the Westchester County Department of Transportation. The complete results of the study including the series hybrid bus results were published by Sandoval et al. [19].

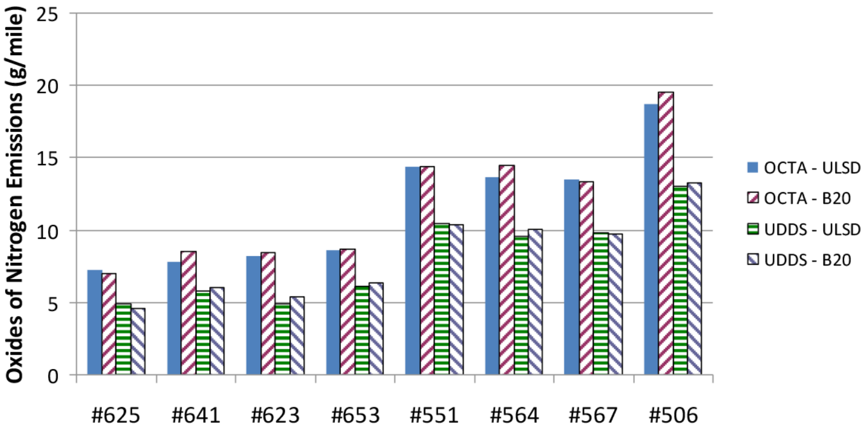
Central Florida Regional Transportation Authority – 2010

These emissions testing campaign was funded jointly by the Central Florida Regional Transportation Authority and FTA funding from this program. The goal of the FTA component of the program was to characterize the effects of biodiesel fuel in transit bus emissions and fuel consumption. Fuel economy and regulated emissions were measured from eight 40-ft transit buses operated on petroleum diesel and a “B20” blend of 80 percent diesel fuel and 20 percent biodiesel by volume. Model years of the vehicles evaluated were newer 2007-08 Gillig low-floor buses, 2005 Gillig Phantom buses, and a 2002 Gillig Phantom bus. Each bus was evaluated using two transient speed-time schedules—the OCTA driving schedule, which represents moderate speed urban/suburban operation, and the UDDS, which represents a mix of suburban and higher-speed on-highway operation. Use of biodiesel is attractive to displace petroleum fuel and reduce an operation’s carbon footprint, particularly when the biodiesel may be produced regionally from non-edible or non-feed stock products. Usually, it is assumed that biodiesel will also reduce PM emissions relative to those of petroleum diesel.

A comparison between tests performed with diesel fuel and those performed with B20 fuels showed no discernible difference in fuel economy. Figure 3-10 shows NOx emissions. The use of B20 biodiesel resulted in inconsistent but slightly higher NOx emissions. The use of B20 also resulted in significant reductions in distance-specific PM emissions as compared to the use of conventional diesel fuel, with a 26 percent reduction over the OCTA and a 32 percent reduction over the UDDS for non-DPF-equipped buses. For the non-DPF-equipped 2005 model year buses, average reductions in distance-specific PM emissions from the use of B20 were 0.182 grams per mile over the OCTA driving schedule and 0.236 grams per mile over the UDDS. These reductions were significantly higher than the reductions observed for the DPF-equipped buses (0.006 g/mile over the OCTA and 0.005 g/mile over the UDDS).

Figure 3-10

3-10 Comparison of NOx emissions between buses fueled with a B20 biodiesel blend and straight petroleum diesel



The emissions data collected were included in the IBIS searchable emissions database and will be used to develop biodiesel correction factors for the IBIS transit fleet emission model. A more detailed analysis of the data can be found in Clark et al. [20].

Washington Metropolitan Transit Authority – 2010

New heavy-duty vehicle emissions limits went into effect beginning with the 2007 model year. To meet these new emissions standards, diesel engine manufacturers implemented engine design changes and actively control diesel particulate filters. Natural gas engine manufacturer Cummins-Westport converted from lean-burn combustion technology to stoichiometric combustion technology. Therefore, the 2007 model year represented a major change in transit bus engine technology. An emissions testing campaign was conducted to characterize the emissions of 2007+ stoichiometric CNG transit buses and diesel hybrid-electric buses with 2007 and newer engines. Table 3-4 lists the specifications of the buses tested. The vehicles were tested using the 17 driving cycles listed in Table 3-2.

Table 3-4

WMATA 2010 Test Vehicle Specifications

WMATA Bus No.	Bus Type	Bus Model	Engine Model	Transmission	After-treatment	GVW (lbf)	Odometer Mileage
5452	60-ft Articulated Diesel-Hybrid	2009 New Flyer DE60LFA	2009 Cummins ISL 330H	Allison EV 50 parallel hybrid	Diesel Particulate Filter	66,790	7,235
5451							13,481
6315	40-ft Diesel-Hybrid	2008 New Flyer DE40LFR	2008 Cummins ISM 280	Allison EP 40 parallel hybrid	Diesel Particulate Filter	42,540	28,743
5420	60-ft Articulated CNG	2008 NABI 60BRT.08	2008 Cummins ISL-G320	Allison B500 WTEC	Catalytic Converter	68,540	28,924
5410							347,553

Figure 3-11 show a summary of the diesel- energy-equivalent fuel economy and CO_2 emission of the buses. Comparison of CNG (60-ft stoichiometric and 40-ft lean burn) and equivalent size hybrid buses reveals that fuel consumption for CNG is approximately 45–50 percent higher than for the hybrids. CNG contains less carbon per unit of fuel energy (LHV) than petroleum fuels and, therefore, produces less CO_2 for a given required energy input. When compared with diesel, CNG-fueled transit buses produced up to 12 percent less CO_2 emissions. Hybrid vehicles take advantage of regenerative braking and improved engine operation to reduce fuel consumption. This advantage over diesel is shown to be approximately 20 percent for MY 2003–2006 buses, whereas the hybrid advantage of the new MY buses was measured as only approximately 5 percent. The reduced fuel consumption of the 2007 and newer hybrid buses is a combined result of additional emissions control technology required to meet the tighter emissions regulations and increased weight compared to the earlier model hybrid buses.

Figure 3-11

CO_2 and fuel economy comparison of WMATA buses using OCTA cycle

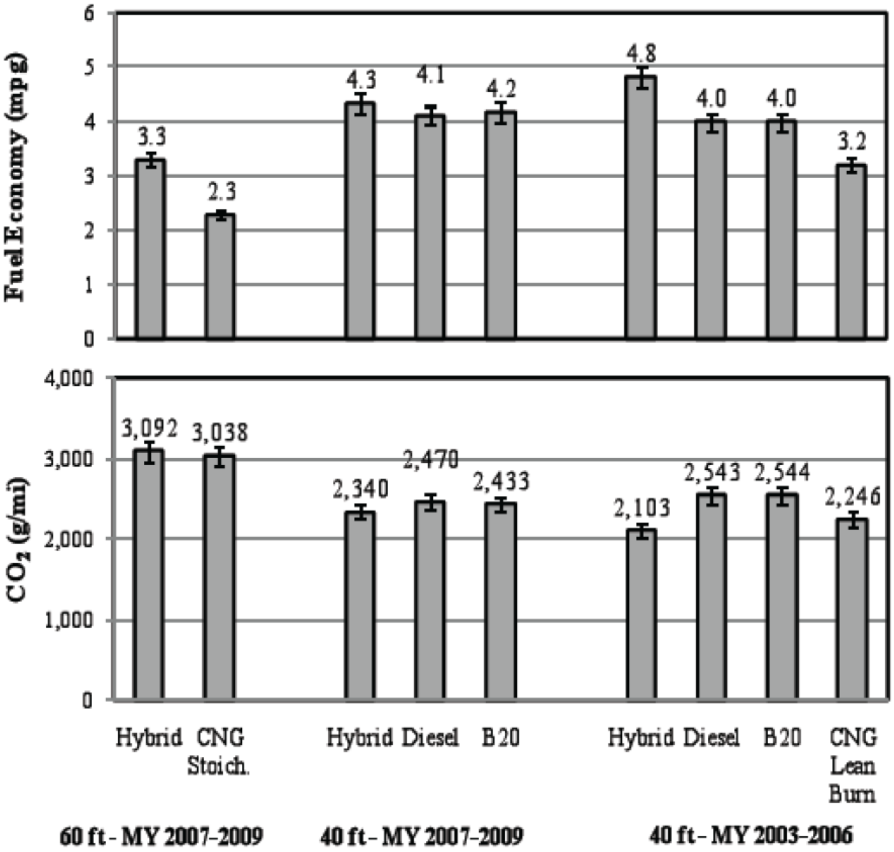
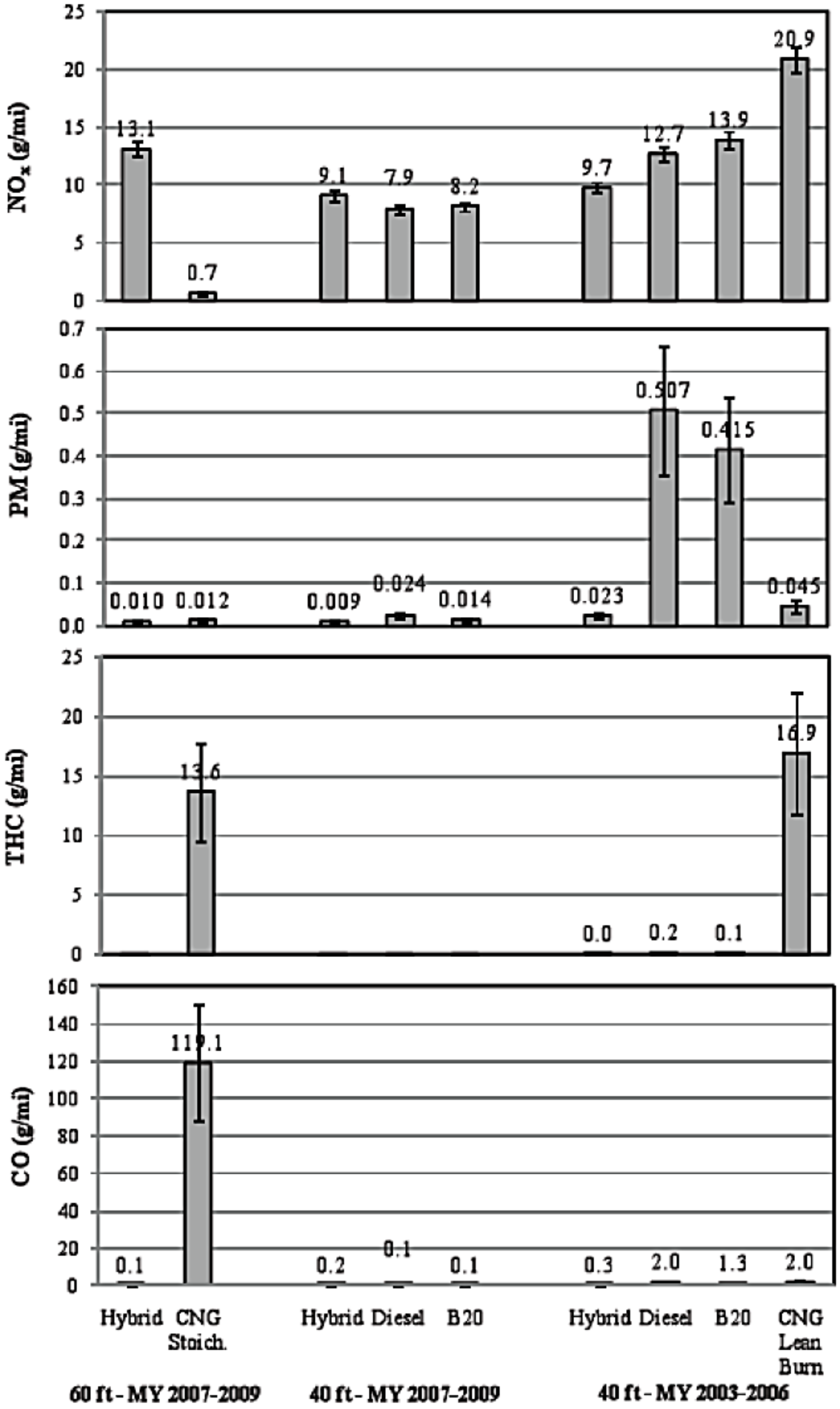


Figure 3-12 presents regulated emissions (NOx, PM, HC, and CO) for the test vehicles. The stoichiometric CNG bus exhibited lower NOx and PM emissions than the older lean-burn technology bus. Total HC emissions were relatively high for the CNG buses, but these comprise primarily unburned methane, which does not contribute to ground-level ozone- and smog-producing reactions. The 2007 and newer diesel hybrid buses, which were equipped with actively-managed diesel particulate filters, exhibited vanishingly low PM emissions.

Figure 3-12

OCTA cycle distance-specific emissions



The results of this study were published in a technical conference paper by Nix et al. [21] and two technical reports submitted to WMATA, which supplied the test vehicles for the study [22, 23]. The data from this study were used to develop emissions models for 2007 and newer CNG and diesel hybrid buses in the IBIS transit fleet emissions model.

Pennsylvania Transportation Institute – 2011

Beginning with the 2007 model year, the U.S. EPA reduced NOx emissions limits from 2.5 g/bhp-hr to 0.2 g/bhp-hr for heavy-duty truck and bus engines. These reductions were phased in on a percent-of-sales basis. Most manufacturers opted to meet the family emissions limit of 1.2 g/bhp-hr between 2007 and 2010. By 2010, all engines were required to meet the 0.2 g/bhp-hr standard. Engine design modifications alone were not capable of achieving the necessary reductions in NOx. Therefore, engine manufacturers had to implement u-SCR exhaust after-treatment. U-SCR is a method of converting NOx to nitrogen and water using a base metal or precious metal catalyst and urea as a reductant. The urea solution is injected into the exhaust stream where it is converted to ammonia through thermal decomposition. SCR catalysts also require thermal management to keep the exhaust stream at a sufficiently high temperature to achieve NOx reduction.

In May 2011, the WVU Transportable Laboratory conducted side-by-side emission testing with the PTI Vehicle Research Laboratory. The primary intent of the testing was to compare the two emissions laboratories and verify that they produced reasonably-comparable results. The testing was performed using a model year 2010 30-ft Gillig transit bus powered by a 2010 model year Cummins ISL9-280 diesel engine equipped with u- SCR and a diesel particulate filter. The advertised NOx certification level for the engine was at or below 0.29 g/bhp-hr. The u-SCR and DPF are both actively managed after-treatment systems. The u-SCR required addition of urea to the exhaust stream to promote the reaction that reduce NOx to N_2 and H_2O as well as injection of additional diesel fuel into the exhaust for thermal management when exhaust temperature drop below that needed for proper SCR system operation. The DPF requires additional diesel fuel for periodic regeneration of the particulate filter. The active nature of these after-treatment systems present challenges in emissions measurement due to substantially more test-to-test variability and the sensitivity of the systems to environmental temperature and duty cycle. In addition to providing a comparison and vetting of the PTI emissions testing laboratory, this study provided valuable data on the emissions and fuel efficiency performance of 2010 and newer transit buses with u-SCR after-treatment and shed light on the added challenges that these active after-treatment technologies impose on the measurement of bus emissions.

Figure 3-13 shows the progression of measured distance specific NOx emissions from 2002 to 2010 based on data from buses tested by the WVU Transportable Emissions Laboratory. The NOx emissions of this 2010 transit bus represent a substantial reduction over buses manufactured between 2007 and 2010. The effectiveness of the u-SCR system in reducing NOx emissions is emphasized when compared to performance of non u-SCR equipped transit buses.

Figure 3-13

Progression of transit bus NOx emissions

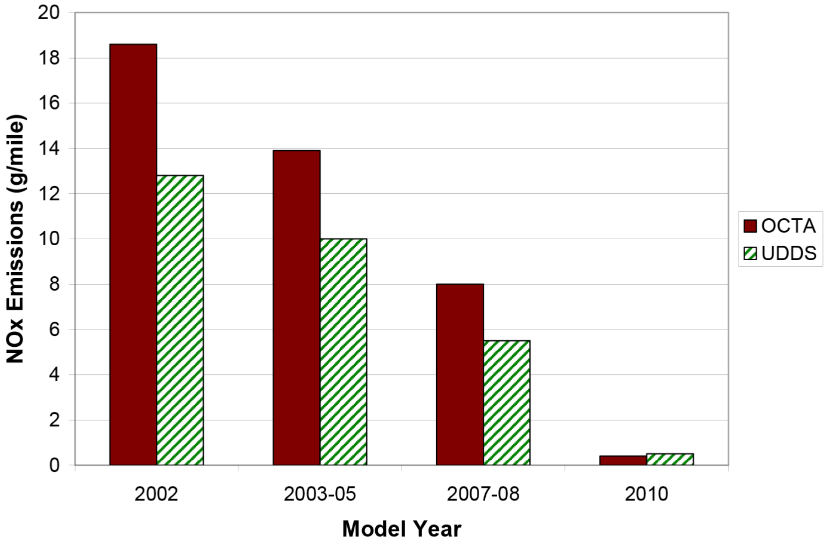


Table 3-5 show emissions measured over successive Paris and Cruise driving cycles beginning with a cold-start test. A 20-minute engine-off soak period was observed between successive tests. A monotonically decreasing trend in NOx emissions was observed indicating the sensitivity of SCR performance to exhaust temperature. During the cold-start tests, the effect of the SCR thermal management is clearly apparent as additional diesel fuel was injected into the exhaust stream to increase the SCR temperature.

Table 3-5

Emissions of 2010 Transit Bus with u-SCR over Successive Test Cycles

		Paris Driving Cycle			Cruise Driving Cycle		
		Fuel Economy (mpg)	*Oxides of Nitrogen (g/mi)*	*Particulate Emissions (g/mi)*	*Fuel Economy (mpg)*	*Oxides of Nitrogen (g/mi)*	*Particulate Emissions (g/mi)*
Loaded (25,880 lbf)	Cold	2.75	4.091	0.026	6.30	0.685	0.013
	Hot	3.13	0.915	0.020	7.11	0.280	0.04
	Hot	3.12	0.486	0.013	6.90	0.274	0.04
	Hot	3.09	0.362	0.021	7.07	0.266	0.03
	Hot Avg.	3.11	0.588	0.018	7.03	0.273	0.03

The presence of u-SCR exhaust after-treatment had a significant effect on fuel economy and exhaust emissions, especially during cold-start operation. Based on observed carbon-balance fuel consumption data, the engine/after-treatment control introduced additional fuel to provide additional heating of the u-SCR based on the exhaust temperature entering the catalyst. This introduction of additional fuel reduced the duration of the period immediately following the start of each driving schedule where NOx emissions were high as a result of reduced u-SCR efficiency at lower operating temperatures. Figure 3-14 show SCR catalyst exit temperature and integrated NOx emissions for cold and hot start tests. The NOx emissions rate declined as the catalyst temperature increased.

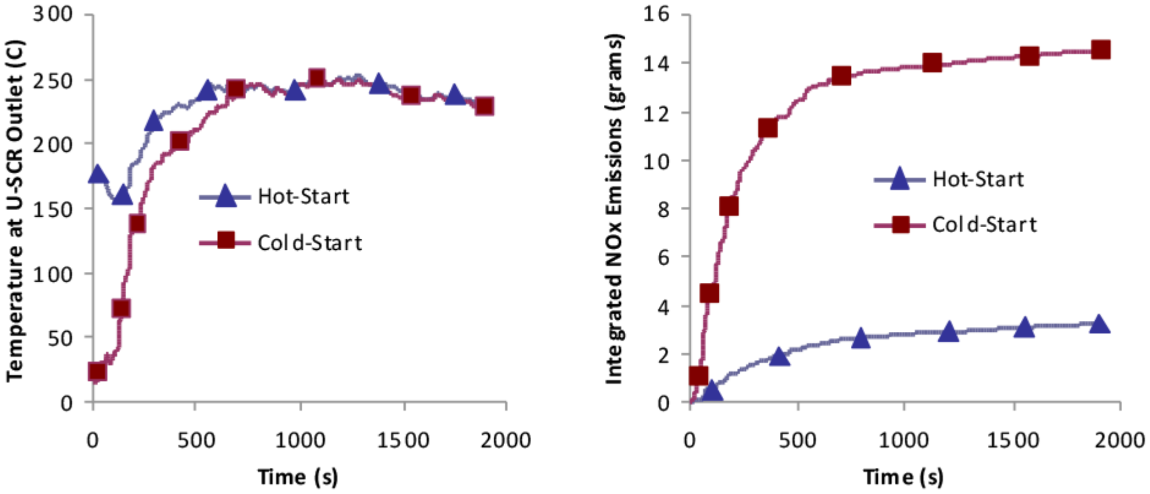


Figure 3-14

Exhaust temperature and integrated NOx emissions for cold- and hot-start tests

The presence of u-SCR exhaust after-treatment made the goal of minimizing run-to-run variability difficult. Traditionally, run-to-run variability was minimized through careful laboratory practice and consistent testing procedures, including observation of consistent soak times between tests. Factors that might affect run-to-run variability prior to the introduction of advanced after-treatment such as u-SCR or DPFs would arise from driver behavior and cooling fan activity. The combination of additional fuel required during u-SCR catalyst, the temperature dependence NOx reduction efficiency of the catalyst, and the lack of a means to control or measure the amount of ammonia stored in the catalyst have introduced variability that is difficult to control. Figure 3-15 shows exhaust temperature and integrated NOx emissions for three successive hot start tests. Each of the runs was preceded by a chassis test run followed by a 20-minute engine off (ignition off) soak period. The integrated NOx emissions from the first evaluation run (C0032-006-03) were more than 2.5 times those observed during the third evaluation run (C0032-006-05). One might conclude that the higher NOx emissions during the first evaluation run were partly the result of a colder u-SCR catalyst. Figure 3-15 shows that the exhaust temperature at the catalyst outlet for the first test in the sequence was lower than that for the subsequent tests. However, one might expect that integrated NOx emissions from the second and third evaluation runs in the sequence would have closer agreement as there was little difference in exhaust temperature at the catalyst outlet for those runs.

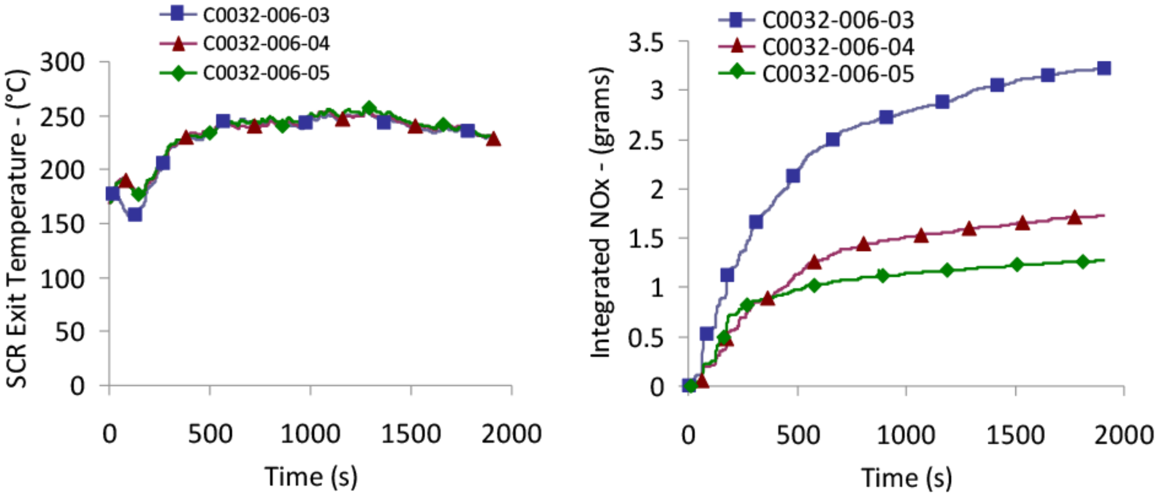


Figure 3-15

Exhaust temperature and integrated NOx emissions for three successive hot-start test runs

The presence of u-SCR after-treatment introduced significant challenges as it resulted in significant run-to-run variability. This run-to-run variability resulted from variability in the u-SCR catalyst temperature at the beginning of each test that was influenced the preceding test run. Variation in catalyst ammonia loading at the start of each test run may also have been a cause of variability in post u-SCR NOx levels even when run-to-run exhaust temperature profiles were consistent. There was also variability resulting from the control algorithm employed by the after-treatment system to maintain u-SCR temperature. A significant conclusion from this study is that the run-to-run variability and the complexity introduced by u-SCR system temperature dependence and control must be taken into consideration when performing emissions testing and when interpreting emissions test results. Additional results and analysis can be found in Clark et al. [24].

Evaluating Alternative Fuels in the U.S. Transit Fleet

WVU performed an analysis of the level of pollutant emissions produced by the U.S. transit fleet and evaluated potential reductions that could be achieved by greater adoption of alternative fuels including CNG, LNG, and biodiesel and advanced vehicle technologies such as hybrid electric drive systems. This report was prepared as part of an alternative fuels study required by Section 3016(C) of the Safe, Accountable, Flexible, and Efficient Transportation Act: A Legacy for Users (SAFETEA-LU). That section directed the Secretary of Transportation to conduct a study of the actions necessary to increase the use of alternative fuels in public transportation vehicles. The study considered potential environmental and other benefits expected from increased use of alternative fuels as well as incentives and opportunities to encourage greater implementation of alternative fuels and technologies within the transit industry. The results of the analysis were published in an interim report titled "Environmental Benefits of Alternative Fuels and Advanced Technology in Transit" [25] and a technical paper in Energy and Environment [26]. The information contained in the report developed by WVU was used by FTA to prepare a report for the U.S. Congress on the benefits of alternative fuels an policy options to encourage wider adoption of alternative fuels in public transit [27].

Cumulative tailpipe emissions from the existing transit bus fleet were estimated by considering the emissions from conventional diesel buses, CNG buses, LNG buses, and diesel-electric hybrid buses using 2003 fleet statistics data reported by APTA and measured transit bus emissions data from transit buses tested by WVU and other organizations (Table 3-6). Emissions and fuel consumption by transit bus technology were estimated and reported. To assess the potential environmental impact of greater use of alternative fuels and hybrid-electric buses, hypothetical scenarios in which new "clean-diesel" (post-2007 model year), CNG, diesel-electric hybrid, gasoline electric hybrid, and biodiesel fuel use were each individually increased to 15 percent of the U.S. fleet. Table 3-7 shows the changes in annual emissions and fuel consumption that could be achieved based on the 2003 U.S. transit fleet demographics as a baseline.

Table 3-6

Estimated Total Emissions from Existing National Transit Bus Fleet in 2003

	#of Buses	CO (tons)	NMHC (tons)	CH_4 (tons)	NOx (tons)	PM (tons)	CO_2 (tons)	Fuel Consumed (gal)
Total Emissions								
Diesel	49,938	15,886	2,611		65,669	1,494	6,497,649	589,135
CNG/LNG	7,609	1,194	308	5,879	6,318	7	796,630	100,393
Diesel Hybrid	489	5	0.6		220	0.5	35,865	3,361
Total	58,036	17,085	2,920	5,879	72,207	1,502	7,330,143	692,889
Average Emissions Levels per Bus								
		CO (g/mi)	**NMHC (g/mi)**	**CH_4 (g/mi)**	**NOx (g/mi)**	**PM (g/mi)**	**CO_2 (g/mi)**	**Fuel Economy (mi/gal)**
Diesel		6.98	1.15		28.84	0.66	2,853	3.51
CNG/LNG		3.44	0.89	16.94	18.21	0.02	2,296	3.14
Diesel Hybrid		0.22	0.03		9.87	0.02	1,608	6.02

Table 3-7

Impact of Increasing Alternative Fuels to 15% of Transit Bus Fleet

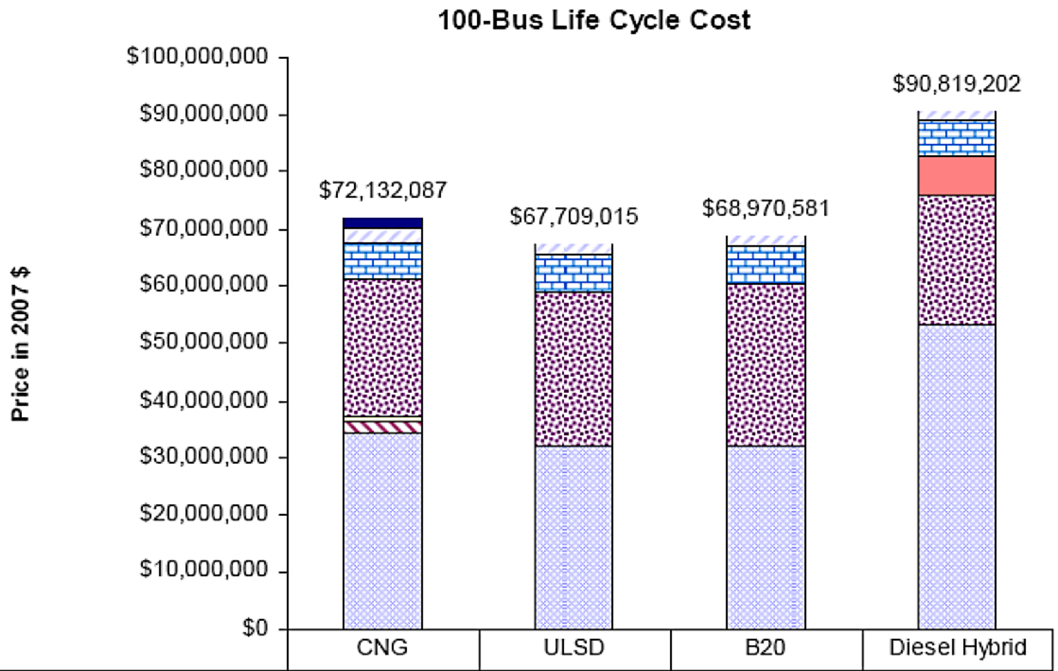
	CO (tons)	NMHC (tons)	CH_4 (tons)	NOx (tons)	PM (tons)	CO_2 (tons)	Fuel Consumed (gal)
Incremental Change Relative to Anticipated 2009 Fleet Levels							
Clean Diesel	↓ 1,723	↓ 377	-	↓ 3,291	↓ 201	↑ 35,251	↑ 2,664
CNG	↓689	↓ 341	↓ 422	↓ 4,239	↓ 205	↓ 220,758	↑ 2,154
Diesel Hybrid	↓ 1,776	↓ 366	-	↓ 4,418	↓ 202	↓ 491,352	↓ 50,658
Gasoline Hybrid	↑ 6,178	↓ 211	-	↓ 5,963	↓ 199	↓ 74,114	↑ 2,833
Biodiesel (B20) (a)	↓ 384	↓ 166	-	↑ 369	↓ 38	↑ 25,087	↑ 3,876

It was concluded that accelerated implementation of all of the technologies considered offered some benefits over current procurement trends. New technology conventional diesel and diesel-electric hybrid buses offered similar reductions in CO, NMHC, NOx, and PM emissions because both benefit from the most recent clean-diesel technology engines. Increased implementation of lean-burn CNG buses offered similar reductions in NMHC, NOx, and PM compared to diesel and diesel-electric hybrids. CNG buses appeared superior to conventional clean-diesel buses in terms of CO_2 emissions. In terms of emissions, the technologies considered are closely grouped due to fuel neutral EPA emissions regulations of 2007.

Evaluate Transit Vehicle Life Cycle Costs

WVU performed a LCC analysis comparing CNG, diesel hybrid electric, non-hybrid clean diesel, and B20 biodiesel (20% biodiesel and 80% ULSD) fuel bus technologies. The report employed published cost and performance data as well as emissions measurement data from the WVU database. The results of this analysis were published as FTA Report FTA-WV-26-7004.2007.1 [28]. This LCC analysis and report were intended to provide interim life cycle cost data prior to the completion and public distribution of the Transit Cooperative Research Program (TCRP) C-15 Life Cycle Cost Study and Model, which WVU, TRC, and Battelle were developing under contract TCRP.

The report considered a 100-bus purchase of new transit buses made in the year 2007 and assumed a bus useful life of 12 years. The report presented information on the capital vehicle cost, fueling and infrastructure costs, emissions equipment costs, fuel costs, propulsion system-related maintenance costs, facility maintenance costs, and battery replacement costs (hybrid buses only) for the competing technologies. Figure 3-16 shows a comparison of life cycle costs for the technologies with a breakdown of those costs by category. The results were also presented on per-bus-mile and per-seat-mile basis (Figure 3-17).



	CNG	ULSD	B20	Diesel Hybrid
Total: CC+OC	$72,132,087	$67,709,015	$68,970,581	$90,819,202
■ Compression Electricity	$1,900,323	$0	$0	$0
☐ Facility Maintenance	$2,443,272	$2,072,295	$2,103,853	$1,746,986
⊞ Propulsion-related System Maintenance	$6,258,817	$6,639,421	$6,270,564	$6,358,882
🟥 Battery Replacement	$0	$0	$0	$6,750,000
▩ Fuel Costs	$24,418,105	$26,882,953	$28,481,818	$22,662,869
☐ Emissions Equipment	$0	$143,409	$143,409	$0
☐ Depot Modification	$875,000	$0	$0	$140,000
◪ Refueling Station	$2,000,000	$0	$0	$0
▦ Vehicle Cost	$34,236,570	$31,970,937	$31,970,937	$53,160,465

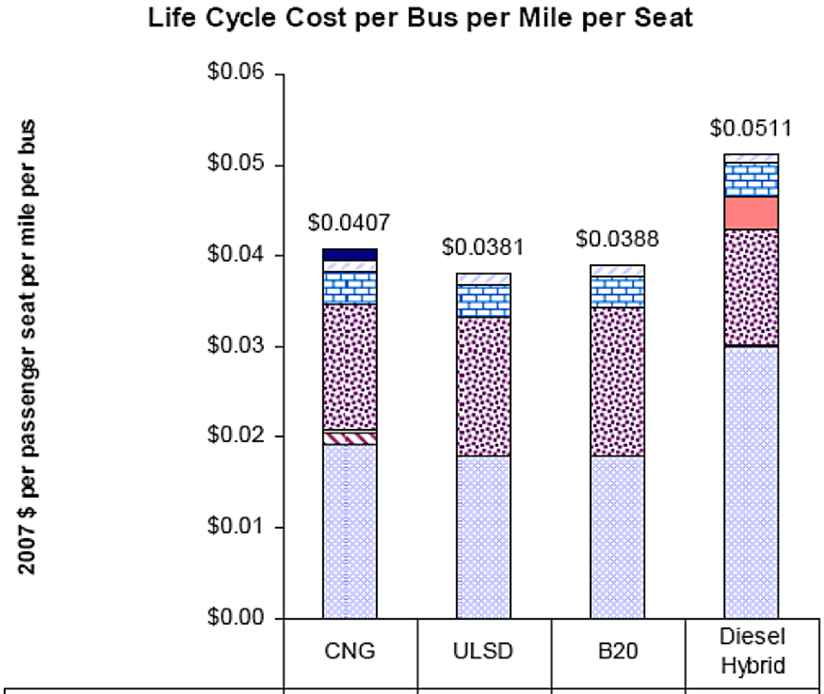
CC = capital cost; OC = operation cost

Figure 3-16

Life cycle cost comparison for 100-bus fleet in 2007

Figure 3-17

Life cycle cost per passenger-seat mile for 100-bus fleet



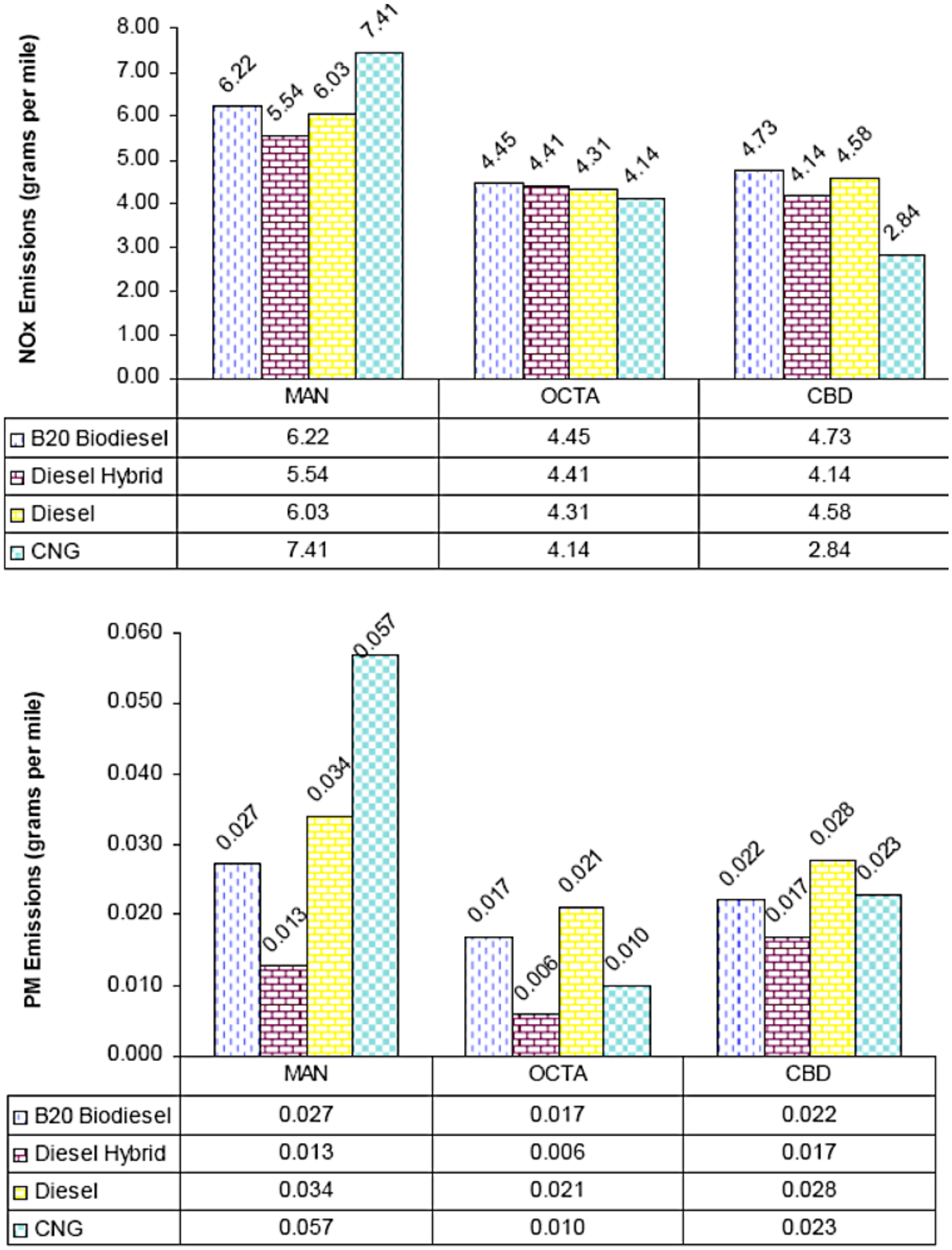
	CNG	ULSD	B20	Diesel Hybrid
Total: CC+OC	$0.0407	$0.0381	$0.0388	$0.0511
■ Compression Electricity	$0.0011	$0.0000	$0.0000	$0.0000
□ Facility Maintenance	$0.0014	$0.0012	$0.0012	$0.0010
⊞ Propulsion-related System Maintenance	$0.0035	$0.0037	$0.0035	$0.0036
🟥 Battery Replacement	$0.0000	$0.0000	$0.0000	$0.0038
▩ Fuel Costs	$0.0138	$0.0151	$0.0160	$0.0128
□ Emissions Equipment	$0.0000	$0.0001	$0.0001	$0.0000
□ Depot Modification	$0.0005	$0.0000	$0.0000	$0.0001
▧ Refueling Station	$0.0011	$0.0000	$0.0000	$0.0000
▨ Vehicle Cost	$0.0193	$0.0180	$0.0180	$0.0299

CC = capital cost, OC = operation cost

The report also presented exhaust emissions for each of the competing 2007 bus technologies. The PM, NOx, and non-methane hydrocarbon (NMHC) emissions of diesel, diesel hybrid, and CNG buses were estimated primarily from recent emissions and fuel consumption studies undertaken by WVU. Since no 2007 field data were available, it was necessary to adjust some emissions for model year using certification standards. Figure 3-18 shows estimated distance-specific NOx and PM emissions for model year 2007 transit bus powertrain and fuel options. Figure 3-19 shows estimated GHG contribution for competing fuel and powertrain options. The complete LCC analysis and emissions estimates can be found in Clark et al. [28].

Figure 3-18

NOx and PM emissions for 2007 model year transit buses

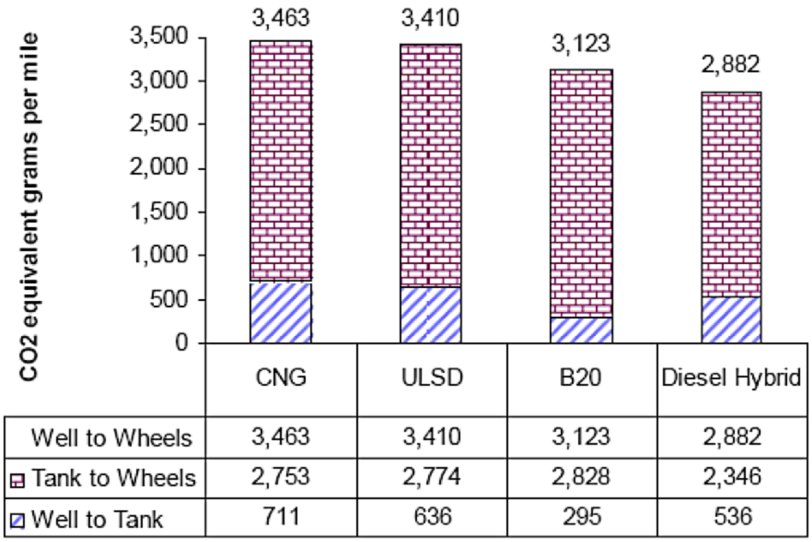


	MAN	OCTA	CBD
☐ B20 Biodiesel	6.22	4.45	4.73
☐ Diesel Hybrid	5.54	4.41	4.14
☐ Diesel	6.03	4.31	4.58
☐ CNG	7.41	4.14	2.84

	MAN	OCTA	CBD
☐ B20 Biodiesel	0.027	0.017	0.022
☐ Diesel Hybrid	0.013	0.006	0.017
☐ Diesel	0.034	0.021	0.028
☐ CNG	0.057	0.010	0.023

Figure 3-19

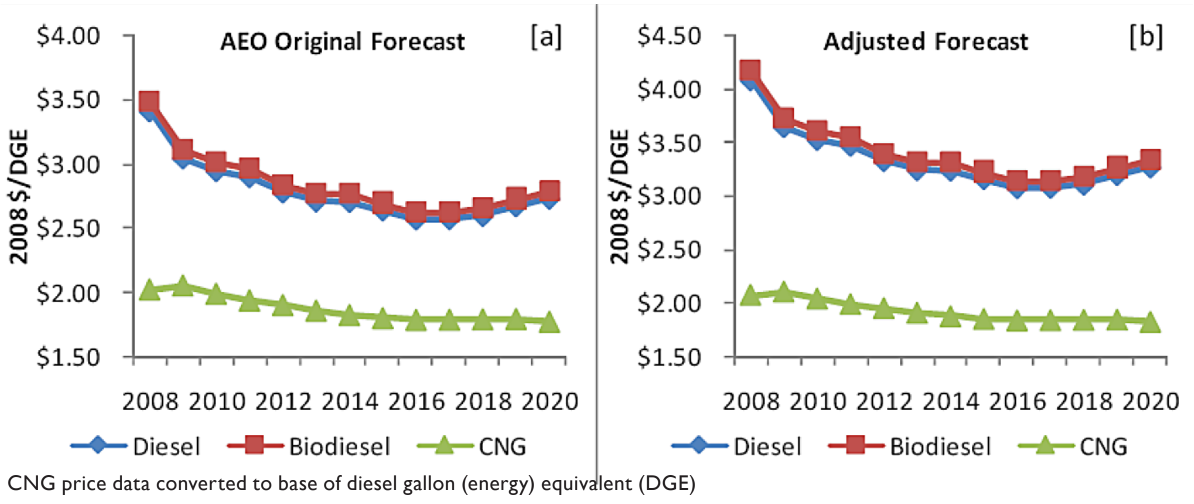
Estimated annual well-to-wheels GHG emissions for 2007 model transit buses



	CNG	ULSD	B20	Diesel Hybrid
Well to Wheels	3,463	3,410	3,123	2,882
▦ Tank to Wheels	2,753	2,774	2,828	2,346
▨ Well to Tank	711	636	295	536

The United States experienced a dramatic increase in fuel prices in 2008 due to prevailing economic conditions. The LCC analysis presented by Clark et al. [28] in 2007 projected a diesel fuel cost of $2.67/gallon and CNG fuel price of $13.34/mcf for 2008. Fuel cost is a major concern in transit bus operation. WVU revisited the 2007 LCC in 2008. The 2007 life cycle costs were recalculated to reflect the new fuel price in 2008. The recalculated life cycle cost was based on the latest U.S. Energy Information Administration (EIA) fuel price forecast [3] and calibrated with the current real-world fuel price. Three additional fuel price scenarios assumed that future fuel price would be 25 percent, 50 percent, and 100 percent higher than the projection in the first price scenario. The updated life cycle costs and additional fuel price scenarios were published in an interim report by Clark et al. [29].

Figure 3-20(a) shows the 2008 Annual Energy Outlook (AEO) from the EIA [30]. In the figure, CNG price data were all converted to the base of diesel gallon (energy) equivalent (DGE). The 2008 AEO did not anticipate the dramatic increase in fuel prices that occurred in 2008. To compensate, the AEO trend line was adjusted upward and aligned with the 2008 average diesel fuel price ($4.07/gal), as shown in Figure 3-20(b). The same procedure was applied to the CNG price forecast by aligning the CNG price curve to $2.01 $/DGE (diesel gallon [energy] equivalent) in 2008. The B20 biodiesel price was projected in the following way. The year 2008 B100 price was taken as the base, and this was an average annual B100 price from available Clean Cities Alternative Fuel Price Reports (four quarterly reports from October 2007 to July 2008) [31]. The average fossil diesel price (from August 2007 to July 2008) was taken from the EIA real-world report [32, 33]. The B20 biodiesel price ($4.16) was calculated by adding 20 percent of the B100 biodiesel price ($4.07) and 80 percent of the fossil diesel price ($3.68). The price was 2 percent higher than the fossil diesel price (it was 4.3 percent in the previous life cycle cost report). It was assumed that the B20 biodiesel price would remain in the same ratio to the fossil diesel price during the 12-year period.



CNG price data converted to base of diesel gallon (energy) equivalent (DGE)

Figure 3-20

2008 AEO fuel price forecast and adjusted fuel price forecast

Table 3-8 shows and compares their average 12-year fuel prices. Figure 3-21 shows the LCC projections using the updated 2008 fuel price forecast. Note that CNG buses become attractive alternative to diesel based on the updated fuel price forecast. Figure 3-22 show LCC projections based on a 100 percent higher fuel price forecast. Additional scenarios may be found in [29].

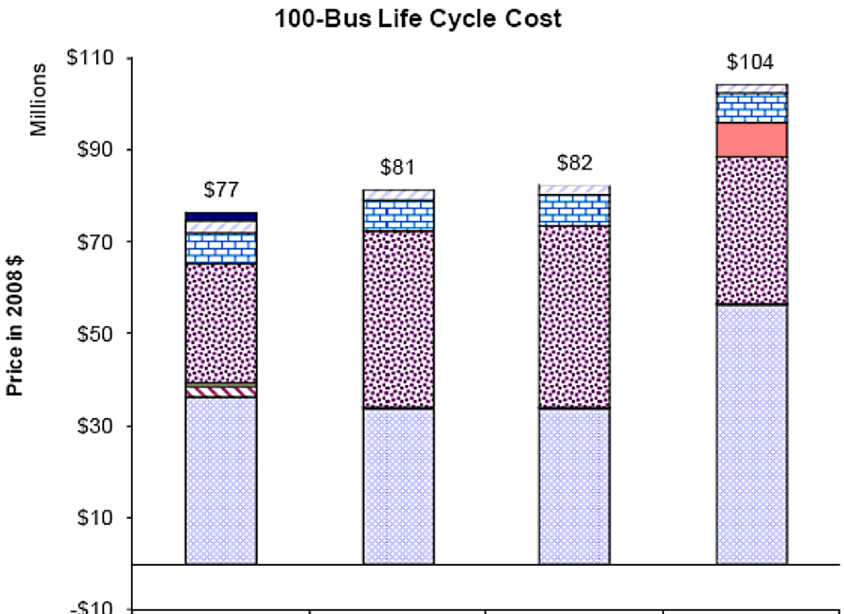
Table 3-8

Average Fuel Price for Four Price Scenarios

Fuels	Case 1	Case 2	Case 3	Case 4
	Adjusted AEO Forecast	*25% Higher than Case 1*	*50% Higher than Case 1*	*100% Higher than Case 1*
Diesel (per gallon)	$3.33	$4.16	$5.00	$6.66
B20 (per gallon)	$3.40	$4.25	$5.10	$6.80
CNG (per DGE)	$1.91	$2.39	$2.87	$3.82

Figure 3-21

Life cycle cost comparison for 100-bus fleet using updated fuel price forecast

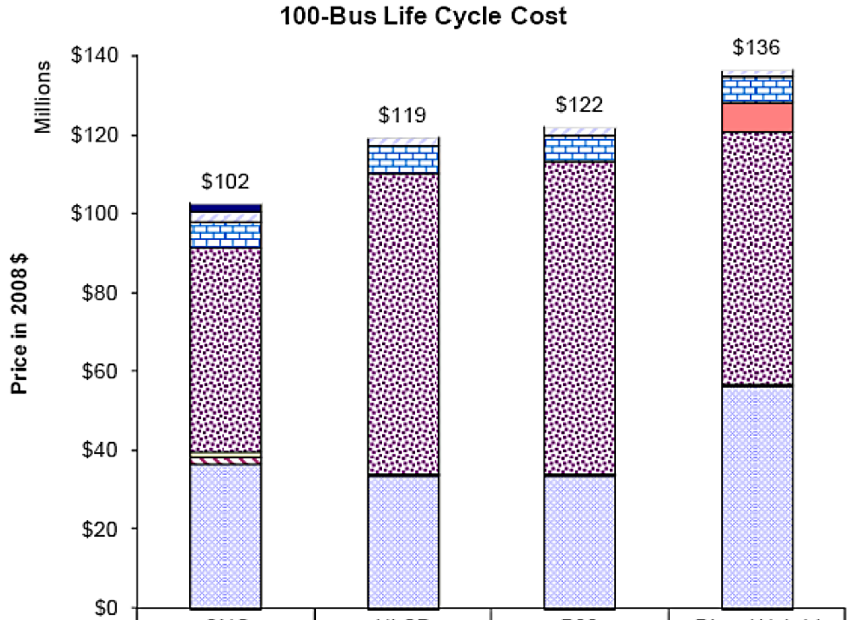


	CNG	ULSD	B20	Diesel Hybrid
Total: CC+OC	$76,523,289	$81,340,149	$82,359,664	$104,334,870
■Compression Electricity	$2,014,342	$0	$0	$0
□Facility Maintenance	$2,589,869	$2,196,633	$2,230,084	$1,851,806
□Propulsion-related System Maintenance	$6,634,346	$7,037,786	$6,646,798	$6,740,415
□Battery Replacement	$0	$0	$0	$7,155,000
□Fuel Costs	$25,946,468	$38,064,523	$39,441,575	$32,089,157
□Emissions Equipment	$0	$152,014	$152,014	$0
□Depot Modification	$927,500	$0	$0	$148,400
□Refueling Station	$2,120,000	$0	$0	$0
□Vehicle Cost	$36,290,764	$33,889,193	$33,889,193	$56,350,093

CC = capital cost, OC = operation cost

Figure 3-22

Total life cycle cost for 100-bus fleet for 12 years without procurement subsidy based on 100% higher fuel price forecast



	CNG	ULSD	B20	Diesel Hybrid
Total: CC+OC	$102,469,757	$119,404,672	$121,801,239	$136,424,027
■Compression Electricity	$2,014,342	$0	$0	$0
□Facility Maintenance	$2,589,869	$2,196,633	$2,230,084	$1,851,806
▦Propulsion-related System Maintenance	$6,634,346	$7,037,786	$6,646,798	$6,740,415
■Battery Replacement	$0	$0	$0	$7,155,000
▩Fuel Costs	$51,892,936	$76,129,046	$78,883,150	$64,178,314
□Emissions Equipment	$0	$152,014	$152,014	$0
□Depot Modification	$927,500	$0	$0	$148,400
▧Refueling Station	$2,120,000	$0	$0	$0
▦Vehicle Cost	$36,290,764	$33,889,193	$33,889,193	$56,350,093

CC = capital cost, OC = operation cost

The TCRP C-15 Life Cycle Cost Analysis and Model was made public in 2009 [34]. It can be used to perform life cycle costs analyses similar to those presented above.

SECTION

4

Task 3 – Integrated Bus Information System

The mission of public transit agencies is to provide safe, efficient, environmentally-conscious, reliable, and cost-effective transportation. Several alternative fuel and hybrid electric propulsion systems are available for transit buses. The choice of fuel and propulsion technology may be influenced by:

- Emissions and GHG implications
- Compliance with federal, state, and local environmental and procurement regulations
- Compliance with State Implementation Plans for transit agencies within non-compliance regions
- Initial investment expense and life cycle costs

Although many studies of transit vehicle emissions have been completed, producing a substantial database of emissions results, the data are scattered throughout disparate sources, and individual studies often compare a few specific technologies under conditions that are specific to a particular transit property. It is well-established that duty cycle has a significant effect on bus emissions and fuel consumption. Tools are needed to assist transit agencies to evaluate fuel and technology impacts on fleet emissions and GHG footprints. Moreover, life cycle costs over the life span of the buses need to be considered.

The objective of Task 3 was to develop online accessible tools to estimate the emissions profile of existing transit fleets and evaluate how integration of new clean diesel, alternative fuel, and hybrid-electric into the fleet will alter the emissions foot print. WVU developed a set of tools for evaluating the pollutant emissions and fuel economy of transit bus fleets. The tools include a searchable database of transit vehicle emissions test data and a transit fleet emissions inventory model. In addition, WVU, Battelle and the Transit Resource Center have developed a transit vehicle LCC model under contract to TCRP Project C-15 [34]. The tools can be accessed on a publicly-available website called the Integrated Bus Information System (IBIS). IBIS is accessible at http://ibis.wvu.edu.

Access to the IBIS website requires a user account. User accounts are necessary so that each user's models and database searches can be saved in progress, allowing the user to return and access work already in progress or models that have been completed. The user account also allows each users model to be viewed only by the owner of the account. A new user can create an account by clicking the "Create Account" link. Email confirmation of the username and password is sent to the user for verification prior to account creations. Returning users can log in with their email address and password. Figure 4-1shows the account login screen. Inactive accounts are periodically deleted by the web manager.

Figure 4-2 shows a screenshot of the IBIS main page, which provides links to access each of the interactive tools as well as a log out option. The following sections describe the development and features of each tool.

Figure 4-1

IBIS account log-in screen

Welcome to IBIS

The Integrated Bus Information System (IBIS) is an internet information resource to help transit agencies evaluate the impact of fuel and propulsion technology choices on criteria emissions, greenhouse gas emissions, fuel efficiency and vehicle life cycle costs. IBIS is intended primarily as tool for use in transit bus procurement activities. IBIS provides three interactive tools:

Transit Bus Emissions Database
a searchable database of chassis dynamometer test results for a wide variety of transit buses. This database includes measured oxides of nitrogen (NOx), hydrocarbons (HC), carbon monoxide (CO), particulate matter (PM), carbon dioxide (CO_2), fuel efficiency (mpg) and other detailed information.

Transit Fleet Emissions Model
a predictive fleet emissions inventory model that can be used to estimate the emissions footprint of an existing transit fleet or to evaluate the impact new transit buses with different fuel and propulsion system technologies on the emissions footprint of the fleet.

Development of the Integrated Bus Information System was funded through a grant from the U.S. Department of Transportation — Federal Transit Administration.
Log in or create an account to get started.

Figure 4-2

IBIS main page

Welcome to IBIS

The Integrated Bus Information System (IBIS) is an internet information resource to help transit agencies evaluate the impact of fuel and propulsion technology choices on criteria emissions, greenhouse gas emissions, fuel efficiency and vehicle life cycle costs. IBIS is intended primarily as tool for use in transit bus procurement activities. IBIS provides three interactive tools:

Transit Bus Emissions Database

a searchable database of chassis dynamometer test results for a wide variety of transit buses. This database includes measured oxides of nitrogen (NOx), hydrocarbons (HC), carbon monoxide (CO), particulate matter (PM), carbon dioxide (CO_2), fuel efficiency (mpg) and other detailed information.

Transit Fleet Emissions Model

a predictive fleet emissions inventory model that can be used to estimate the emissions footprint of an existing transit fleet or to evaluate the impact new transit buses with different fuel and propulsion system technologies on the emissions footprint of the fleet.

Transit Bus Life Cycle Cost Model

Developed for TCRP Project C-15, this LCC model allows the user to compare the total life cycle cost across multiple capital and operating cost categories for conventional and advanced propulsion technologies.

Development of the Integrated Bus Information System was funded through a grant from the U.S. Department of Transportation — Federal Transit Administration.

Transit Vehicle Emissions Database

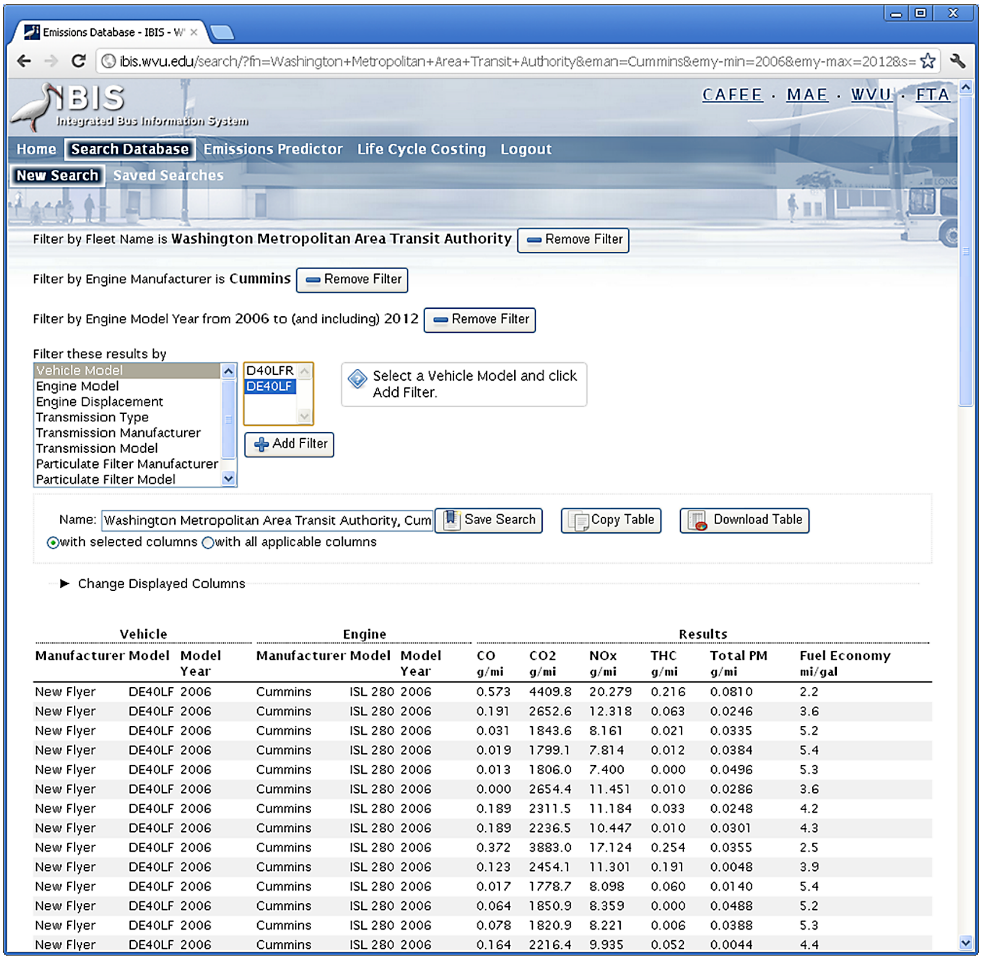
The WVU Transportable Emissions Laboratory has measured the emissions and fuel consumption of more than 850 transit buses, ranging in model year from 1967 to 2011, including buses fueled on type 1 and type 2 low-sulfur diesel fuel, type 1 and type 2 ULSD fuel, synthetic Fischer-Tropsch diesel fuel, biodiesel fuel blends, CNG, LNG, gasoline, and gasoline-ethanol blends. WVU has also characterized the fuel consumption and emissions of both series and parallel architecture diesel hybrid-electric transit buses and series architecture gasoline hybrid electric transit buses. The data from these emissions studies are publically available through a searchable database.

The IBIS Transit Vehicle Emissions Database contains measured emissions data from transit buses tested on a chassis dynamometer. The emissions results contained in the database are the product of many individual emissions studies conducted by WVU beginning in the early 1990s. The data include values for EPA-regulated criteria pollutants NOx, HC, CO, PM, and values of CO_2 and fuel efficiency for a wide range of transit buses over a variety of driving cycles. In some circumstances, data are available for other pollutants, including PM less than 10 micron (PM10), less than 2.5 microns (PM2.5), and less than 1 micron (PM1), as well as methane (CH4) and NMHC. In addition to measured emissions, detailed information is available about the transit bus under test, properties of the test cycle, and properties of the fuels used during the test.

Searching the database can be accomplished through a simple, intuitive user interface. Search criteria include:

- Transit Fleet Name
- Vehicle Type
- Vehicle Manufacture
- Vehicle Model
- Vehicle Model Year
- Engine Manufacturer
- Engine Model
- Engine Model Year
- Engine Combustion Cycle
- Number of Engine Cylinders
- Engine Displacement
- Transmissions Type
- Transmission Manufacturer
- Transmissions Model
- After-treatment Type
- After-treatment Manufacturer
- After-treatment Model
- Fuel Type
- Test Cycle Name

Figure 4-3 shows a screenshot of a sample database search. The user can add progressive filters in any order desired to refine the search. The interactive search engine displays the search results along with an account at the top of the browser of the search criteria that have been applied. As the search is refined, the dynamic search engine only presents search criteria to the user that are relevant to the current subset of results and that would further refine the search results. The user can remove previously-applied filters by clicking the remove filter button.



Filter by Fleet Name is **Washington Metropolitan Area Transit Authority**

Filter by Engine Manufacturer is **Cummins**

Filter by Engine Model Year from 2006 to (and including) 2012

Filter these results by

Vehicle Model
Engine Model
Engine Displacement
Transmission Type
Transmission Manufacturer
Transmission Model
Particulate Filter Manufacturer
Particulate Filter Model

D40LFR
DE40LF

Select a Vehicle Model and click Add Filter.

Name: Washington Metropolitan Area Transit Authority, Cum

● with selected columns ○ with all applicable columns

▶ Change Displayed Columns

Vehicle			Engine			Results					
Manufacturer	Model	Model Year	Manufacturer	Model	Model Year	CO g/mi	CO2 g/mi	NOx g/mi	THC g/mi	Total PM g/mi	Fuel Economy mi/gal
New Flyer	DE40LF	2006	Cummins	ISL 280	2006	0.573	4409.8	20.279	0.216	0.0810	2.2
New Flyer	DE40LF	2006	Cummins	ISL 280	2006	0.191	2652.6	12.318	0.063	0.0246	3.6
New Flyer	DE40LF	2006	Cummins	ISL 280	2006	0.031	1843.6	8.161	0.021	0.0335	5.2
New Flyer	DE40LF	2006	Cummins	ISL 280	2006	0.019	1799.1	7.814	0.012	0.0384	5.4
New Flyer	DE40LF	2006	Cummins	ISL 280	2006	0.013	1806.0	7.400	0.000	0.0496	5.3
New Flyer	DE40LF	2006	Cummins	ISL 280	2006	0.000	2654.4	11.451	0.010	0.0286	3.6
New Flyer	DE40LF	2006	Cummins	ISL 280	2006	0.189	2311.5	11.184	0.033	0.0248	4.2
New Flyer	DE40LF	2006	Cummins	ISL 280	2006	0.189	2236.5	10.447	0.010	0.0301	4.3
New Flyer	DE40LF	2006	Cummins	ISL 280	2006	0.372	3883.0	17.124	0.254	0.0355	2.5
New Flyer	DE40LF	2006	Cummins	ISL 280	2006	0.123	2454.1	11.301	0.191	0.0048	3.9
New Flyer	DE40LF	2006	Cummins	ISL 280	2006	0.017	1778.7	8.098	0.060	0.0140	5.4
New Flyer	DE40LF	2006	Cummins	ISL 280	2006	0.064	1850.9	8.359	0.000	0.0488	5.2
New Flyer	DE40LF	2006	Cummins	ISL 280	2006	0.078	1820.9	8.221	0.006	0.0388	5.3
New Flyer	DE40LF	2006	Cummins	ISL 280	2006	0.164	2216.4	9.935	0.052	0.0044	4.4

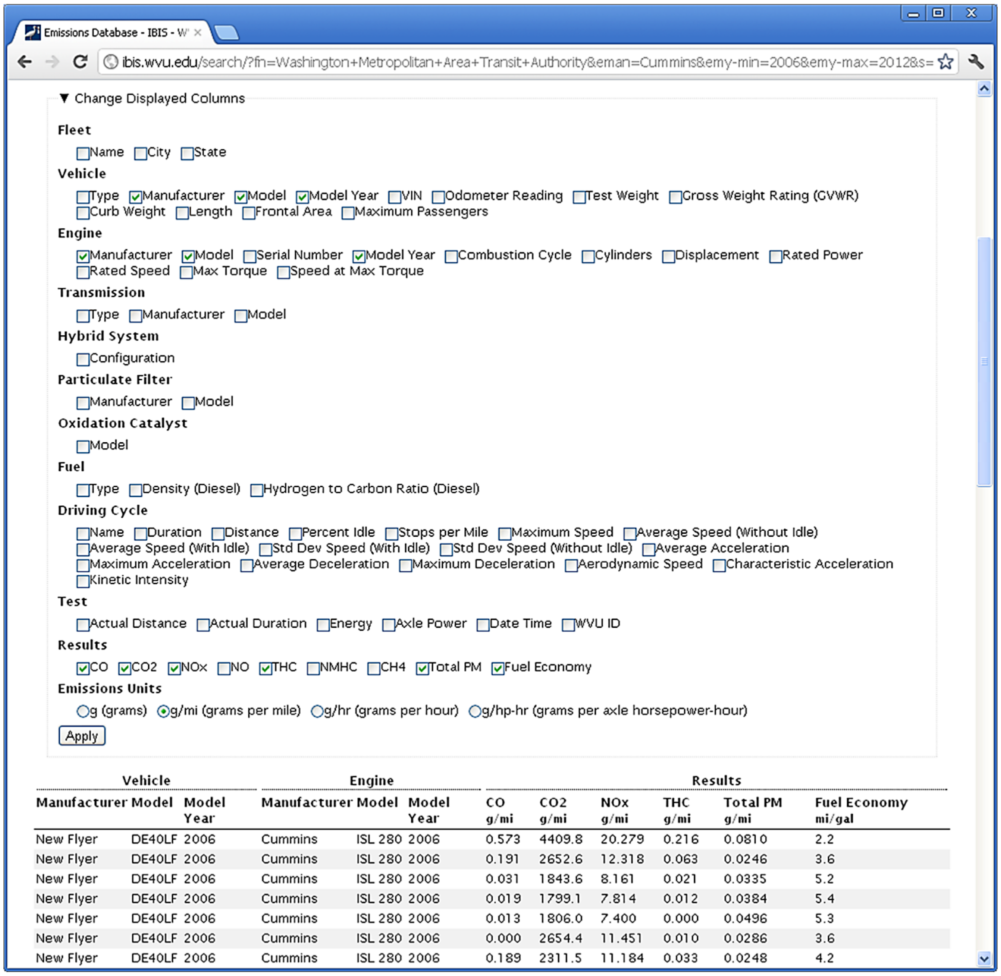
Figure 4-3

Sample emissions database search

The search results are displayed with a default set of columns. However, the user may select data columns to display in the results by clicking on the “Change Displayed Columns” link. Figure 4-4 shows the interface that allows the user to select which columns to display. Available results include information about the vehicle, engine, transmissions, after-treatment system, fuel, and driving cycle, as well as emissions and fuel economy results. Results can be displayed on mass, distance-specific, time-specific, and axle power specific units. The user is presented with options to save the search so that he or she may return to it at a later time, copy the search results to the clipboard, or download the search results as a comma delimited text file that can be easily imported into Microsoft Excel for further analysis. The user has the option of downloading only the data fields that are displayed or all data fields.

Figure 4-4

Selection of result fields to display



ibis.wvu.edu/search/?fn=Washington+Metropolitan+Area+Transit+Authority&eman=Cummins&emy-min=2006&emy-max=2012&s=

▼ Change Displayed Columns

Fleet

☐Name ☐City ☐State

Vehicle

☐Type ☑Manufacturer ☑Model ☑Model Year ☐VIN ☐Odometer Reading ☐Test Weight ☐Gross Weight Rating (GVWR)
☐Curb Weight ☐Length ☐Frontal Area ☐Maximum Passengers

Engine

☑Manufacturer ☑Model ☐Serial Number ☑Model Year ☐Combustion Cycle ☐Cylinders ☐Displacement ☐Rated Power
☐Rated Speed ☐Max Torque ☐Speed at Max Torque

Transmission

☐Type ☐Manufacturer ☐Model

Hybrid System

☐Configuration

Particulate Filter

☐Manufacturer ☐Model

Oxidation Catalyst

☐Model

Fuel

☐Type ☐Density (Diesel) ☐Hydrogen to Carbon Ratio (Diesel)

Driving Cycle

☐Name ☐Duration ☐Distance ☐Percent Idle ☐Stops per Mile ☐Maximum Speed ☐Average Speed (Without Idle)
☐Average Speed (With Idle) ☐Std Dev Speed (With Idle) ☐Std Dev Speed (Without Idle) ☐Average Acceleration
☐Maximum Acceleration ☐Average Deceleration ☐Maximum Deceleration ☐Aerodynamic Speed ☐Characteristic Acceleration
☐Kinetic Intensity

Test

☐Actual Distance ☐Actual Duration ☐Energy ☐Axle Power ☐Date Time ☐WVU ID

Results

☑CO ☑CO2 ☑NOx ☐NO ☑THC ☐NMHC ☐CH4 ☑Total PM ☑Fuel Economy

Emissions Units

○g (grams) ●g/mi (grams per mile) ○g/hr (grams per hour) ○g/hp-hr (grams per axle horsepower-hour)

Vehicle			Engine			Results					
Manufacturer	**Model**	**Model Year**	**Manufacturer**	**Model**	**Model Year**	**CO g/mi**	**CO2 g/mi**	**NOx g/mi**	**THC g/mi**	**Total PM g/mi**	**Fuel Economy mi/gal**
New Flyer	DE40LF	2006	Cummins	ISL 280	2006	0.573	4409.8	20.279	0.216	0.0810	2.2
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New Flyer	DE40LF	2006	Cummins	ISL 280	2006	0.189	2311.5	11.184	0.033	0.0248	4.2

This resource will be useful for transit managers who are familiar with emissions test results and want to compare actual emissions and fuel consumption performance of different transit vehicle technologies. The resource will also be of interest to universities and research institutions conducting research studies related to transit bus emissions and fuel consumption.

Transit Fleet Emissions Inventory Model

Diesel fuel is the most commonly-used fuel in transit accounting for more than 70 percent of the national bus fleet in 2009, including conventional-drive and diesel-electric hybrid buses [27]. In communities where transit vehicles operate frequently, tailpipe emissions accumulate around localized hotspots such as transit bus depots, intermodal transfer stations, and maintenance facilities [27]. Transit agencies are increasingly pressured by federal, state and local legislation, public boards, and environmental interest groups to employ fuel-efficient, low-emitting vehicles. In addition to stringent EPA and California Air Resources Board (CARB) emissions standards, many transit agencies are or may soon be impacted by other state and local legislation. Environmental regulations and pressure from municipalities, boards, and local contingencies for "green" transportation place additional pressures on transit vehicle procurement process that, in some instances, may lead to purchase of vehicles that are not the best option for the particular transit agency. All aspects including fuel efficiency, emissions, life cycle cost, maintenance, and operation need to be considered.

Emissions and fuel consumption is a heavily-dependent duty cycle, which is determined by the types and characteristics of the routes on which they operate. For strategic planning, bus procurement, and ensuring compliance with state and local environmental policies, transit fleet managers may want to estimate the emissions footprint of their current bus fleet or compare the impact of different new bus technologies on the emissions profile of the fleet. There are several models available for predicting emissions, the most widely used being EPA's MOVES model [35] and CARB's EMFAC model [36]. MOVES is an emissions inventory models intended primarily for use in the development of State Implementation Plans (SIP) and regional conformity analysis. MOVES include default databases of meteorology, vehicle demographics, vehicle activity data, and fuel and emissions program data for the entire United States. A recognized limitation is that the databases, derived from a variety of sources, do not necessarily include the most accurate or up-to-date information available at the local level for a local level analysis. MOVES also use default driving behavior source types and road type distributions. MOVES is best suited for state and national level analyses and is difficult to use for a transit agency level analysis for comparison of fuel and technology options.

WVU developed a Transit Fleet Emissions Inventory Model specifically targeted for use to compare bus technologies for procurement activities. A challenge in developing such a model is that many transit agencies, particularly smaller agencies, have limited data characterizing the duty cycle of their transit buses and routes. Developing a model with simple inputs of information available to most transit agencies requires some sacrifice in prediction accuracy.

Modeling Methodology

To model a fleet in IBIS, the user defines a set of "virtual buses." Each virtual bus represents the characteristics of an actual vehicle in the existing fleet or a vehicle that is being considered for purchase. The characteristics defined for each virtual vehicle include:

- Vehicle Parameters
- Driving Characteristics

The vehicle parameters include technical characteristics of the vehicle such as type of fuel, powertrain type (conventional or hybrid), length, model year, curb weight, occupancy, engine rated power, after-treatment equipment, displacement, number of cylinders, transmission type, type of heating system, and capacity of air conditioning. The driving characteristics describe the manner in which the vehicle is driven in service and include average speed with idle, number of starts/stops per mile, percentage idle, standard deviation of speed with idle, and kinetic intensity. A fleet is then comprised by specifying the number of each virtual vehicle. Model outputs include:

- Fuel economy
- CO_2 emissions
- CO emissions
- NOx emissions
- Total HC emissions
- PM emissions

The fuel economy and emissions models were developed from a set of “reference vehicles” (RV) for which extensive reliable chassis dynamometer data were available and for which polynomial models of the six output variables were built through linear regression as functions of driving cycle characteristics. These models were referred to as backbone models (BM). A linear regression algorithm was implemented in Matlab to model the fuel consumption and the emissions as polynomials, with the five driving cycle parameters as independent variables. As expected, the average speed was found to be the most important parameter. For each of the output models, four different polynomial models were eventually developed. Each of them had, as independent variables, average speed plus one of the other four driving parameters. An example of the fuel economy modeled as a polynomial function of average speed with idle and standard deviation of speed for a 2006 model year diesel fueled reference vehicle is presented in Figure 4-5. The carbon dioxide emissions for a CNG-fueled vehicle, as predicted by a backbone model, function of average speed and percentage idle are shown in Figure 4-6.

Figure 4-5

Backbone model of fuel economy for a 2006 diesel-fueled bus

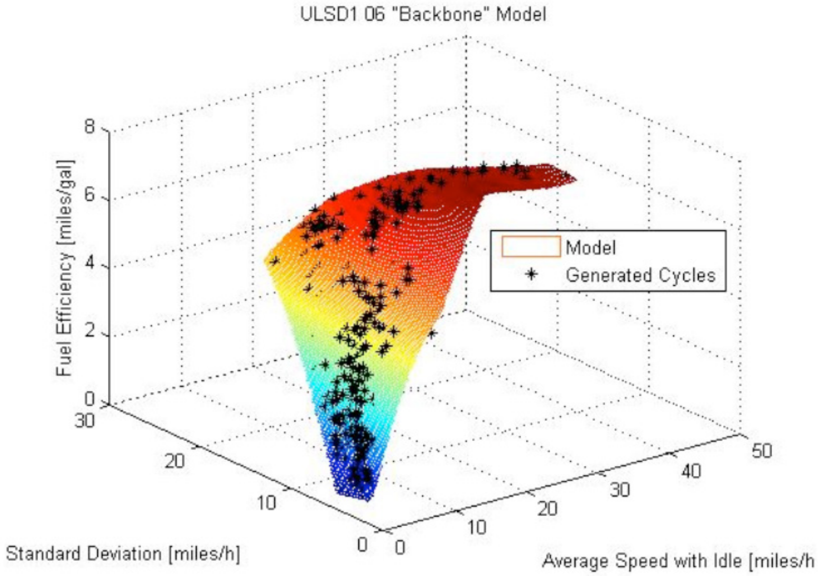
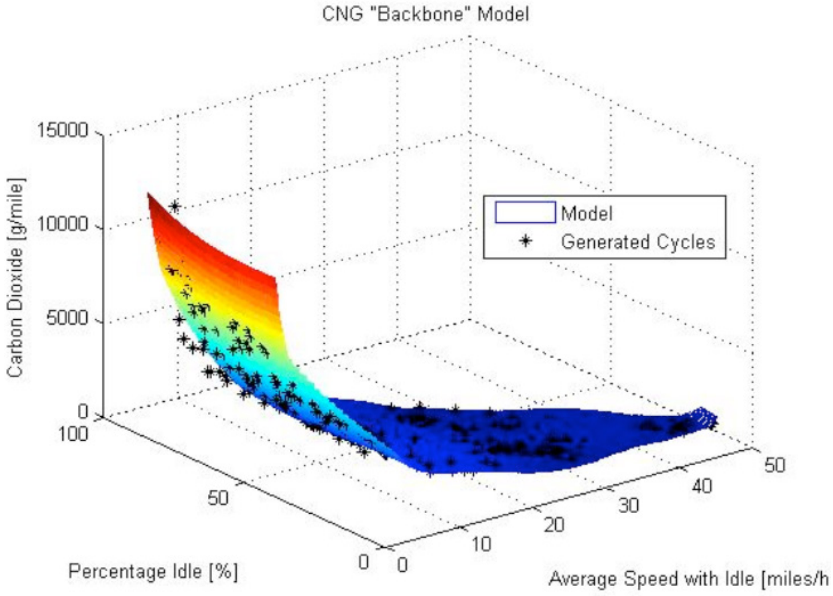


Figure 4-6

Backbone model of CO_2 emissions for a CNG-fueled vehicle



User Interface

The intent of the IBIS Transit Fleet Emissions Model is to provide fleet-level emissions inventory predictions for the purposes of comparing available transit bus fuel and powertrain options to assist with vehicle procurement decisions and fleet planning. The model was designed to predict the emissions of a fleet of transit buses composed of various technologies with sufficient accuracy to evaluate the emissions impact of different vehicle technology options using input data that are available at the transit agency. Figure 4-7 shows the IBIS data entry interface. In preparation for using the IBIS model, the transit manager would compile information on the number, power train type (conventional or hybrid), fuel type (diesel or CNG), and model year. Diesel fuel and CNG are the primary fuels in transit use. The buses included in the model could represent existing buses in the fleet as well as buses that are under consideration for purchase. Buses should be grouped into the following model year categories:

- 1988–1990
- 1991–1993
- 1994–1997
- 1998–2002
- 2003–2006
- 2007–2010
- Post 2010

These model year groups correspond to changes in the EPA emissions regulations for heavy-duty urban buses. Within these model year categories, the user may also want to group buses that operate over similar routes together as subgroups. The user should also collect data on number of miles traveled annually by each subgroup of buses. The model currently categorizes vehicle technologies into broad classifications of conventional (non-hybrid) diesel, conventional CNG, and diesel-electric hybrid. Specific vehicle and engine manufacturers are not distinguished because the model is intended to compare technologies rather than individual manufacturers, and the model does not provide the necessary fidelity to distinguish the performance differences between different manufacturers.

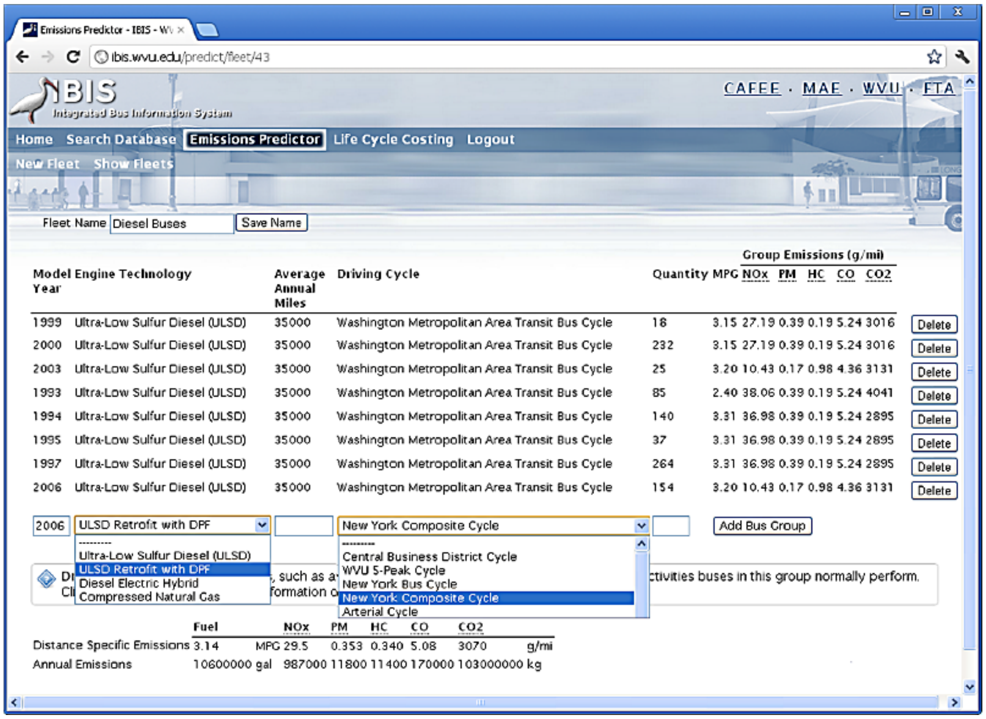
The second category of data that will be needed to model a fleet of buses in IBIS relates to characterizing the duty cycles that represent how the buses are driven. The user has the option of selecting from a set of standard duty cycles that are commonly used for testing buses on a chassis dynamometer. These standard driving cycles were developed from real-world operation data. The user can also specify a custom duty cycle by entering numeric values of the cycle metrics. Vehicle duty cycles are characterized in IBIS by a variety of engineering metrics. The metrics were meant to numerically describe specific characteristics of the driving activity. A brief description of the cycle metrics follows:

- Average Speed is defined as distance traveled divided by cycle time, $\overline{U}=D/T$. It links idle with driving periods and has been widely used to characterize driving behaviors. Average speed is the primary explanatory variable for prediction of fuel economy and emissions of transit buses.
- Percentage Idle represents the fraction of time that the bus is at stand-by.
- Stops per Mile represent the average number of stops that the bus makes per mile traveled. All types of stops are included, e.g., pick-up or traffic stops, and are not differentiated. Stops per mile is related to average speed such that the larger its value, the lower the average speed.
- Standard Deviation of Speed represents the transient character of the drive cycle. For a given average speed, a higher value signifies a more transient operation (with lots of accelerations and decelerations), whereas a lower value implies a more constant speed and more cruise. Given the conditions assumed above, the cycle with higher standard deviation of speed would have higher emissions and lower fuel economy and also would be more suitable for hybrid vehicle operation.
- Kinetic Intensity is an important factor for hybrid vehicles because a cycle energy use analysis shows that high values of kinetic intensity translate into higher fractions of available braking energy and give room to fuel economy improvements through hybridization.

Data to develop a custom duty cycle may come from GPS data logging of actual vehicle activity or from route profiles. The IBIS model was developed with the understanding that many transit agencies may not have information that allows the calculation of all five cycle metrics. Average speed has been identified as the metric with the strongest influence on vehicle emissions. When creating a customized duty cycle, the user must supply a value of average speed. The user has the option to provide as many of the metrics as possible. Prediction accuracy improves as more metrics are provided; however, in many cases, average speed alone provides acceptable results. The user can also select from a set of pre-defined duty cycles that historically have been used to characterize transit bus operation. If the user selects a pre-defined driving cycle, the metric are automatically computed. Figure 4-7 shows the Transit Fleet Builder interface. Each fleet can comprise a single type of bus or multiple bus types and technologies.

Figure 4-7

Transit Fleet Builder Interface screen



Fleet Name Diesel Buses

Model Year	Engine Technology	Average Annual Miles	Driving Cycle	Quantity	MPG	NOx	PM	HC	CO	CO2
						Group Emissions (g/mi)				
1999	Ultra-Low Sulfur Diesel (ULSD)	35000	Washington Metropolitan Area Transit Bus Cycle	18	3.15	27.19	0.39	0.19	5.24	3016
2000	Ultra-Low Sulfur Diesel (ULSD)	35000	Washington Metropolitan Area Transit Bus Cycle	232	3.15	27.19	0.39	0.19	5.24	3016
2003	Ultra-Low Sulfur Diesel (ULSD)	35000	Washington Metropolitan Area Transit Bus Cycle	25	3.20	10.43	0.17	0.98	4.36	3131
1993	Ultra-Low Sulfur Diesel (ULSD)	35000	Washington Metropolitan Area Transit Bus Cycle	85	2.40	38.06	0.39	0.19	5.24	4041
1994	Ultra-Low Sulfur Diesel (ULSD)	35000	Washington Metropolitan Area Transit Bus Cycle	140	3.31	36.98	0.39	0.19	5.24	2895
1995	Ultra-Low Sulfur Diesel (ULSD)	35000	Washington Metropolitan Area Transit Bus Cycle	37	3.31	36.98	0.39	0.19	5.24	2895
1997	Ultra-Low Sulfur Diesel (ULSD)	35000	Washington Metropolitan Area Transit Bus Cycle	264	3.31	36.98	0.39	0.19	5.24	2895
2006	Ultra-Low Sulfur Diesel (ULSD)	35000	Washington Metropolitan Area Transit Bus Cycle	154	3.20	10.43	0.17	0.98	4.36	3131
2006	ULSD Retrofit with DPF		New York Composite Cycle							

	Fuel	NOx	PM	HC	CO	CO2	
Distance Specific Emissions	3.14 MPG	29.5	0.353	0.340	5.08	3070	g/mi
Annual Emissions	10600000 gal	987000	11800	11400	170000	103000000	kg

Figure 4-8 shows an example of the Transit Fleet Emissions Model output screen comparing various transit bus fuel and propulsion technology options.

Fleet Name	Total Vehicles	Created	Fuel MPG	NOx g/mi	PM g/mi	HC g/mi	CO g/mi	CO2 g/mi	
1994 Diesel Buses Scheduled for Replacement	140	Today	3.31	37.0	0.395	0.193	5.24	2900	Forget
Retrofit with DPF	140	Today	3.18	37.0	0.0546	0.0305	0.754	3060	Forget
2006 Diesel w/o DPF	140	Today	3.20	10.4	0.172	0.978	4.36	3130	Forget
2006 Diesel w/ DPF	140	Today	3.07	10.4	0.0488	0.115	0.628	3310	Forget
2006 Diesel Hybrid w/ DPF	140	Today	4.15	9.24	0.0106	0.0335	0.0730	2130	Forget
2006 CNG	140	Today	2.53	21.7	0.0164	26.5	0.488	2530	Forget

Figure 4-8

Sample Transit Fleet Emission Model output screen

Comparison with other Emission Inventory Models

The IBIS Transit Fleet Emissions Model was compared to the EPA's MOBILE6 [37] and MOVES [35 emissions inventory models. MOBILE6 and MOVES are intended to model the aggregate emissions of all vehicle type operating over all road types within a specified region. As such, these models use aggregate databases representing the types and distribution of vehicles and the types and distribution of roadways. It is somewhat difficult to model transit buses in isolation. For the comparison with MOBILE6 and MOVES, individual simulations were performed to obtain emissions results for the various model year groups over each of the 11 standard driving cycles plus 2 custom cycles with average speeds of 32 mph and 38 mph.

In this example, a transit bus was modeled operating over an arterial route. The input file header included the pollutants that were required as outputs and the components comprising total particulate matter. It also included the vehicle type (in this case, only transit buses), the model year of the vehicle, and the amount of time for which the bus operated. The run section included output data characteristics along with fuel characteristics and the variation of temperature at which the vehicle was operated. The scenario section included the filenames of the databases required to calculate the PM and the size of the particulates. Furthermore, it included the year during which the emissions were modeled, the season, the altitude, the sulfur content of the diesel fuel, and the average speed value and the type of driving for that average speed. The arterial type was chosen since it was the driving type that most closely matched normal usage of transit buses within a city.

In the case of MOVES2009, a graphic user interface (GUI) was used to enter the appropriate data to obtain the corresponding comparison with the IBIS model. For a transit fleet analysis, a local or county scale typically would be used; however, to perform a local or county level analysis, MOVES requires that the user provide a set of custom databases. These databases require detailed data regarding road type distributions, vehicle population distributions, etc., which were difficult to obtain. Therefore, a national scale was selected, taking into account that specific factors for the local area were not verified and were based on default national values. A time span for a normal weekday was used, and a time of operation from 9:00 AM to 5:00 PM. For the vehicle type, a transit bus fueled with diesel was selected. To analyze properly the driving characteristics of each cycle, a similar approach to MOBILE6 was used. The "Arterial" driving type was selected to describe the driving characteristics of the cycles. In MOVES, the Arterial driving type was included in the Urban Restricted and Unrestricted access options, with some standard allocation of average speeds and the amount of driving that occurred for the "Arterial" driving type. Hence, it was required to use the data importer to generate a table describing the road type distribution and average speed distribution for each cycle allocating percentages for each of the speed bins. In the Pollutants tab, the pollutants corresponding to IBIS were selected, including the same particulate size as the particulates measured in the IBIS model.

Figure 4-9 shows a comparison of predicted emissions for 2003–2006 model year conventional-drive diesel powered transit buses over a range of average speeds. Two simulations were conducted using the IBIS Transit Fleet Emissions Model. The points indicated by the "x" and marked "Simulator (5 parameters)" used all five cycle metrics in IBIS. The points marked with an "o" and designated "Simulator (Avg. Speed) specified only the average duty cycle speed. The top left panel shows predicted total HC emissions. The IBIS model using five parameters and only average speed agreed fairly well with the EPA MOVES model across the average speed domain. MOBILE6 agreed with IBIS and MOVES at higher average duty cycle speeds but predicted significantly lower HC emissions at low average speeds. The top right panel shows predicted CO emissions. IBIS and MOVES showed similar trends across the entire speed domain, whereas MOBLE6 predicted significantly higher CO emissions. In terms of NOx emissions, the WVU IBIS model agreed more closely with EPA's MOBILE6 model than with MOVES at low average speeds. At average cycle speeds above 12 mph, MOBILE6 and MOVES were in very close agreement. Below 12 mph, NOx emissions predicted by the MOVES model rose more steeply with decreasing average speed than did the predictions of MOBILE6 and IBIS. NOx emissions predicted by IBIS were slightly lower than the MOBILE6 predictions across the entire average cycle speed domain.

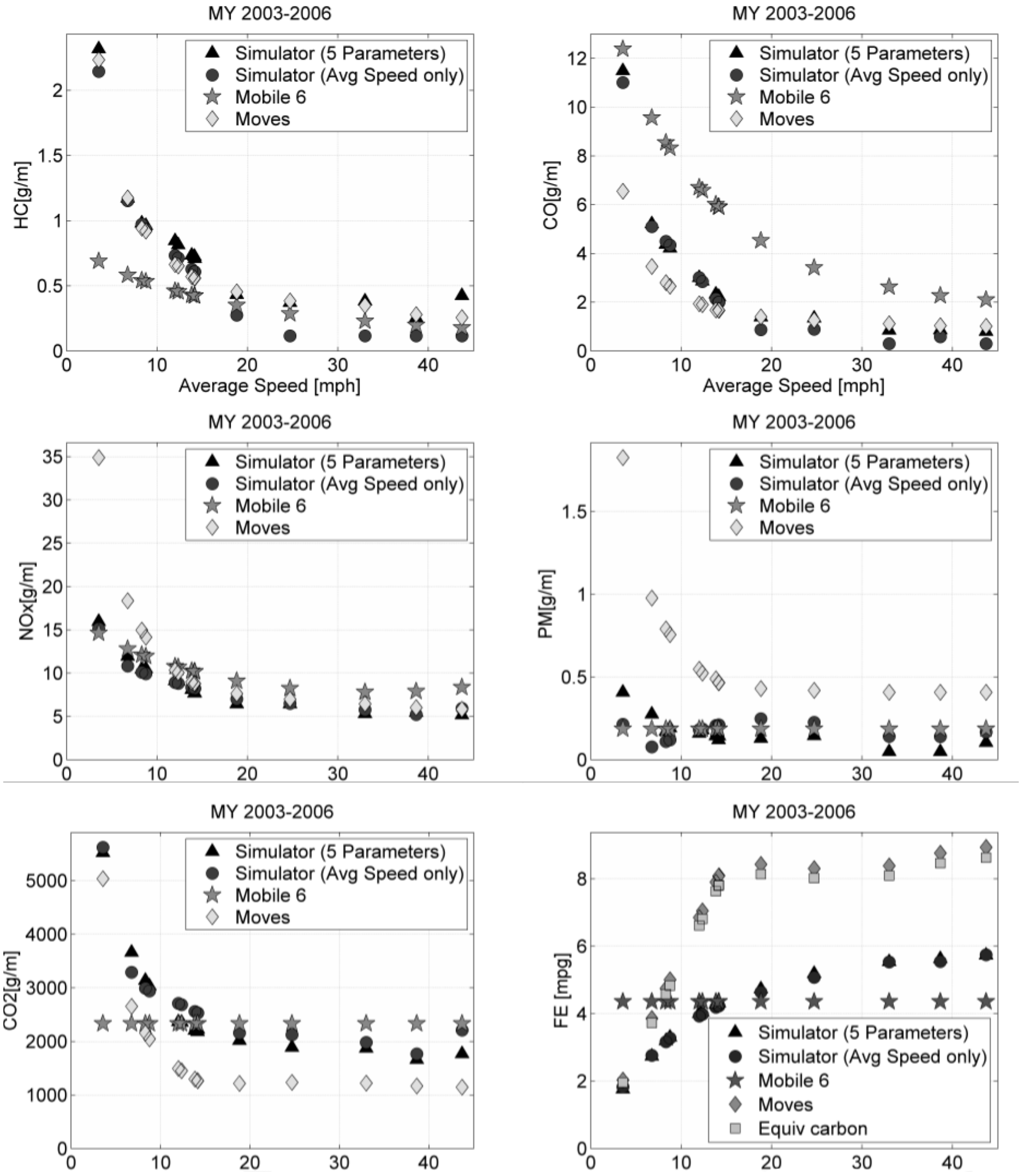


Figure 4-9

Comparison of IBIS, MOBILE6 and MOVES emissions for 2003–2006 diesel transit buses

Figure 4-10 shows a comparison of results between IBIS, MOBILE6 and MOVES for 1998–2002 model year diesel transit buses. In this model year group, IBIS predicted significantly lower HC emissions than EPA's MOVES model and slightly lower CO emissions. Predicted IBIS and MOVES NOx emissions showed acceptable agreement at low cycle speeds; however, MOVES predicted lower NOx emissions at average cycle speeds above 15 mph. Both IBIS and MOVES exhibited similar trends for PM emissions but MOVES predicted slightly higher values. Carbon dioxide and fuel economy results showed the same behavior as in the 2003–2006 model year category with MOVES exhibiting substantially lower CO_2 emissions and high fuel economy.

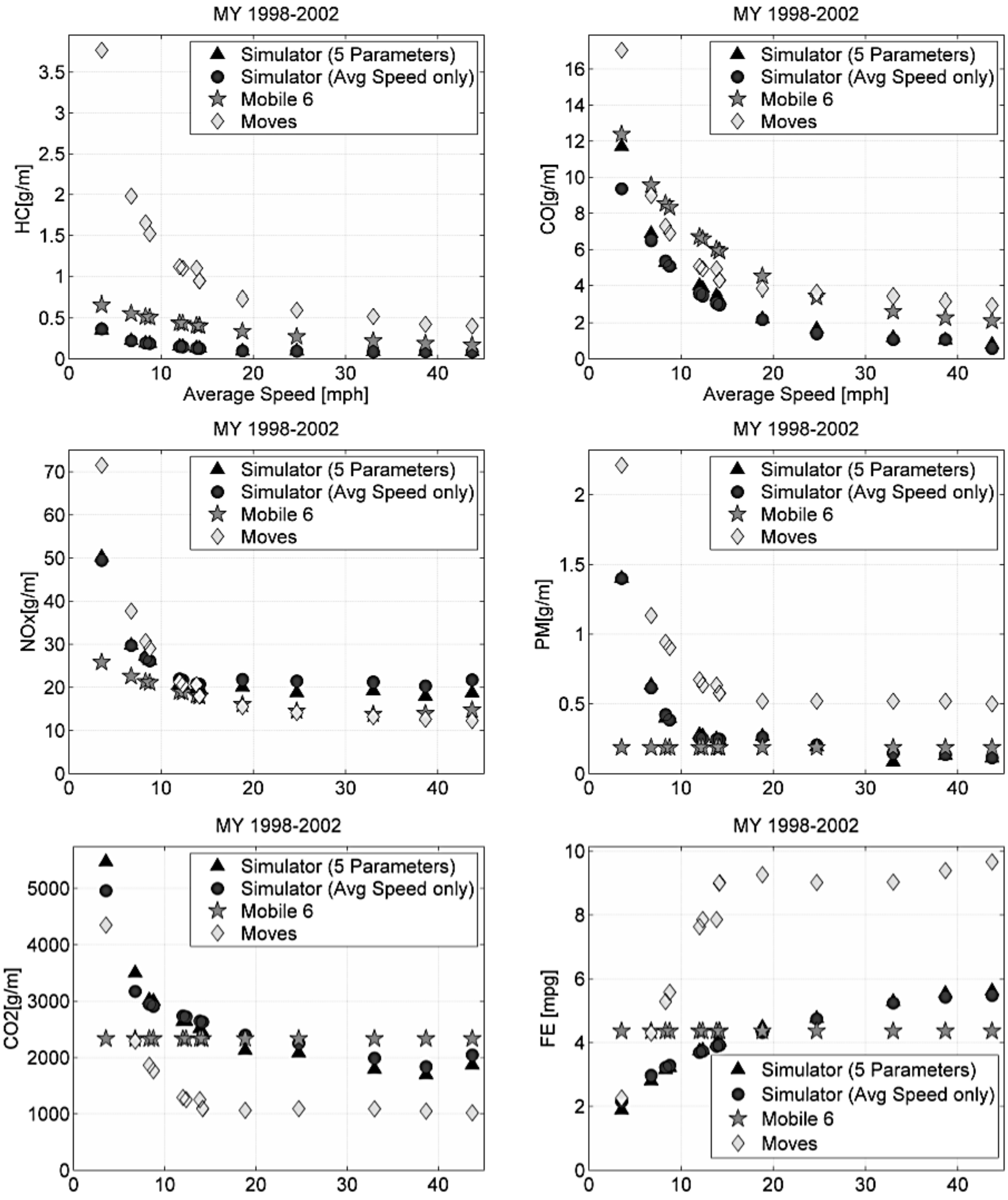


Figure 4-10

Comparison of IBIS, MOBILE6 and MOVES emissions for 1998–2002 diesel transit buses

PM emissions were more difficult to model due to the lack of a continuous PM data for model development. For PM emissions, which were quantified by weighing the PM mass accumulated on filter media, no continuous second-by-second data existed. Due to the lack of continuous PM data, only 12 data points were available (one per test cycle) to characterize PM emissions variation as a function of duty cycle. EPA's MOBILE6 model, curiously, predicted constant PM emissions as a function of average speed. WVU's IBIS model agreed well with the EPA MOVES model at cycle average speeds above approximately 12 mph. At low average duty cycle speeds, the MOVES model predicted rapidly increasing PM emissions with decreasing speed. The five-parameter IBIS model also predicts an increase in PM emissions with decreasing average speed but at a lower rate of change than for the MOVES model.

Agreement of the three models for CO_2 was poorer than expected. CO_2 results predicted by MOBILE6 did not vary with average duty cycle speed as would be expected based on experimental data. WVU's IBIS model and EPA's MOVES model showed similar trends with average speed; however, MOVES predicted much lower CO_2 emissions in general than the IBIS model, which was developed based on chassis dynamometer measurements. In general, fuel consumption varies in direct proportion to CO_2 emissions. The lower right panel of Figure 4-10 shows predicted fuel economy. MOBILE6 assumed constant fuel consumption as a function of duty cycle average speed. Fuel economy as predicted by the WVU IBIS model shows increasing fuel efficiency with average duty cycle speed as expected. The authors are skeptical about the CO_2 and fuel economy predictions by MOVES. CO_2 emissions can be directly related to fuel consumption by a carbon balance, which relates carbon in the fuel to carbon emissions. In the lower right panel of Figure 4-10, the diamonds represent fuel economy computed from total energy expenditure results from MOVES, and the squares represent fuel economy estimated from the CO_2 emissions results from MOVES. Both of these methods indicate fuel economy approaching 8 miles/gallon which is not realistic for a transit bus.

The version of MOVES used for these comparisons did not offer the option to model CNG as a fuel. Therefore, no comparison was possible. The next release of MOVES is expected to include CNG as a fuel option. MOVES and MOBILE6 do not currently allow hybrid powertrains to be modeled as a distinct option so no comparison of hybrid electric transit buses was possible.

This comparison between the IBIS Transit Fleet Emissions Model, MOBILE6, and MOVES was also published in *Transportation Research Record* [12].

Summary

Public transit agencies are pressured to employ alternative fuels and advanced vehicle technologies to replace conventional diesel-powered buses. Pressure arises from federal, state, and local environmental regulations, public boards, environmental groups, and local citizens. The most predominant alternatives to conventional diesel buses include CNG and diesel-electric hybrid buses. Emerging technologies including gasoline and CNG hybrids, and battery electric and fuel-cell-powered buses are in various stages of pre-production development. The decision of which alternative technology to embrace is often difficult and should carefully consider regulatory constraints, fuel efficiency, emissions implications, initial investment and lifecycle costs and maintenance, reliability, and availability.

The IBIS Transit Fleet Emissions Model allows a transit agency to evaluate the effect of vehicle procurement choices on their fleet emissions profile. The model uses simple input information that is available to most transit fleet managers. A comparison of the emissions predictions from the IBIS Transit Fleet Emissions Model against more sophisticated EPA MOBILE6 and MOVES models was performed. The comparison included buses ranging in model year from 1998 to present (in the interest of brevity, only 2003–2006 results were shown here). The easy-to-use IBIS model, which was specifically designed to compare technologies for the purposes of bus procurement, showed satisfactory agreement with MOBILE6 and MOVES models. Together with a searchable transit vehicle emissions test results database and a LCC model developed under contract to TCRP, the IBIS emissions model will provide a valuable resource for transit bus procurement activities.

Life Cycle Cost Model

WVU, working with Battelle and the Transit Resource Center, performed TCRP C-15, Assessment of Hybrid-Electric Transit Bus Technology, and developed a Transit Bus Life Cycle Cost Model [34]. The development of the LCC Model was completed with funding from TCRP in 2009. The LCC Model and report are available for download from the TCRP website. WVU has implemented an online version of the TCRP LCC Model and is in the process of securing permission from TCRP to include the LCC Model as part of the IBIS tools.

The TCRP LCC Model was developed based on infrastructure cost, vehicle cost, operating cost, and maintenance cost data collected over an 18-month period at four transit properties—New York City Transit, King County Metro in Seattle, Washington Metropolitan Area Transit in the District of Columbia, and Long Beach Transit in California. Table 4-1 lists the cost factors for which data were collected at the four transit properties. Detailed accounts regarding the data collection, LCC model development, model structure, and sample LCC analyses can be found in references [34] and [38].

The TCRP LCC Model was included as one of the web applications featured through IBIS at the request of FTA project managers. The online LCC Model version allows transit fleet managers to model multiple vehicle procurement scenarios to predict the life cycle costs associated with different transit bus fuel and propulsion technologies. The model presents default costs based on the data collected at the four transit agencies. However, the user can override the default values if more specific or current costing information is available. The model then computes the projected capital and operating costs for the fleet of buses under consideration and presents the results in tabular and graphical format.

Table 4-1

Life Cycle Cost Model Cost Factors [38]

Capital Costs		
Bus Purchase	Bus basic price	Price for onboard equipment and standard warranty
	Purchase incentives	Potential price credits to adopt new, advanced technologies
	Extended warranty	Additional cost to cover bus power train system for additional years beyond the standard warranty
Staff Training	Operator training	Training cost on driving new technology buses
	Mechanic training	Training cost on servicing new technology buses
Fueling Facilities	CNG fueling station and maintenance facilities	Cost to build new fueling infrastructure and upgrade or build maintenance facilities necessary for CNG bus maintenance
Diagnostic Equipment	Tools/equipment	New tools required to service new technology buses
Spare Parts	Spare battery packs	Price to keep spare battery packs in inventory
Other Costs/Credits	One-time credit	Total Credits (not associated with bus price) in initial vehicle purchase
	One-time cost	Total uncategorized costs in initial vehicle purchase
Operating Costs		
Bus Maintenance	Scheduled	Parts and labor costs for regular preventive maintenance
	Non-scheduled	Parts and labor costs for other failures
Facility Maintenance	CNG station	Incremental CNG station maintenance cost relative to diesel or gasoline
Fuel Use and Cost	Fuel price	Projected fuel price of lifetime of bus
	Fuel economy	Function of average operation speed adjusted by HVAC and accessory loads
Rehabilitation/ Replacement	Engines	Cost of rebuilding or replacing engine
	Transmissions	Cost of rebuilding or replacing transmission of hybrid propulsion system
	Battery packs	Cost of replacing energy storage system for hybrid-electric buses

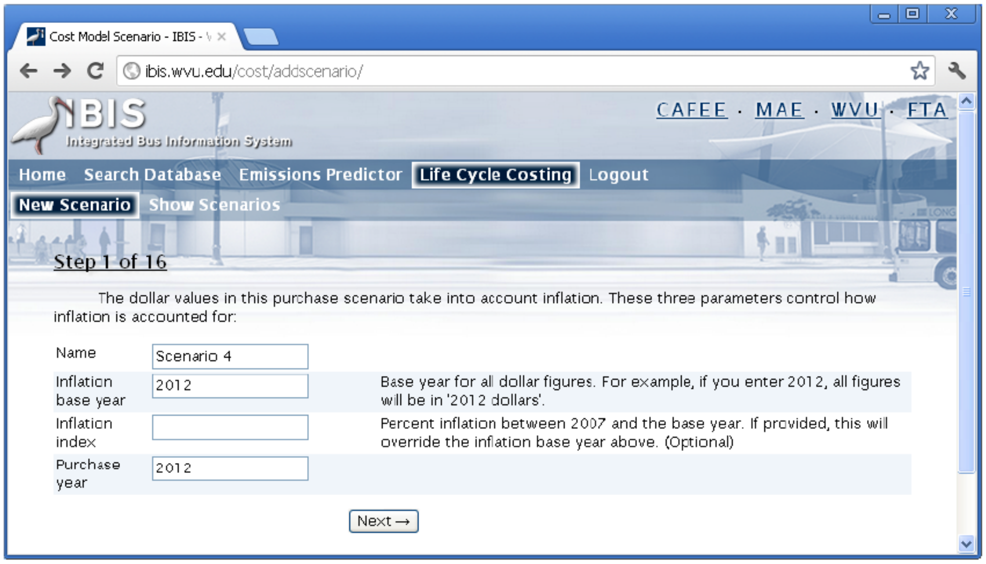
LCC Model User Interface

The IBIS online version of the TCRP LCC Model uses a wizard style user interface to acquire input from the user. The interface provides descriptions of each require input field. Figure 4-11 shows the first screen presented to the users upon starting a new purchase scenario. The screen allows the user to specify a name for the scenario, specify the purchase year, and specify parameters related to inflation.

The second input screen (Figure 4-12) collects information regarding the number and type of buses purchased, the number of years the buses will remain in service, additional warranty coverage being purchased, and the frequency of engine and transmission rehabilitation. The third input screen (Figure 4-13) collects information on the cost of each bus, the cost of any extended warranty that was purchased, and any purchase credits that are available to be applied to the purchase price. These credits may include federal, state, or local programs designed to encourage adoption of alternative fuel or green technologies. A range of default values a provided based on data collected at the between 2005 and 2007.

Figure 4-11

LCC Model User Interface Step 1



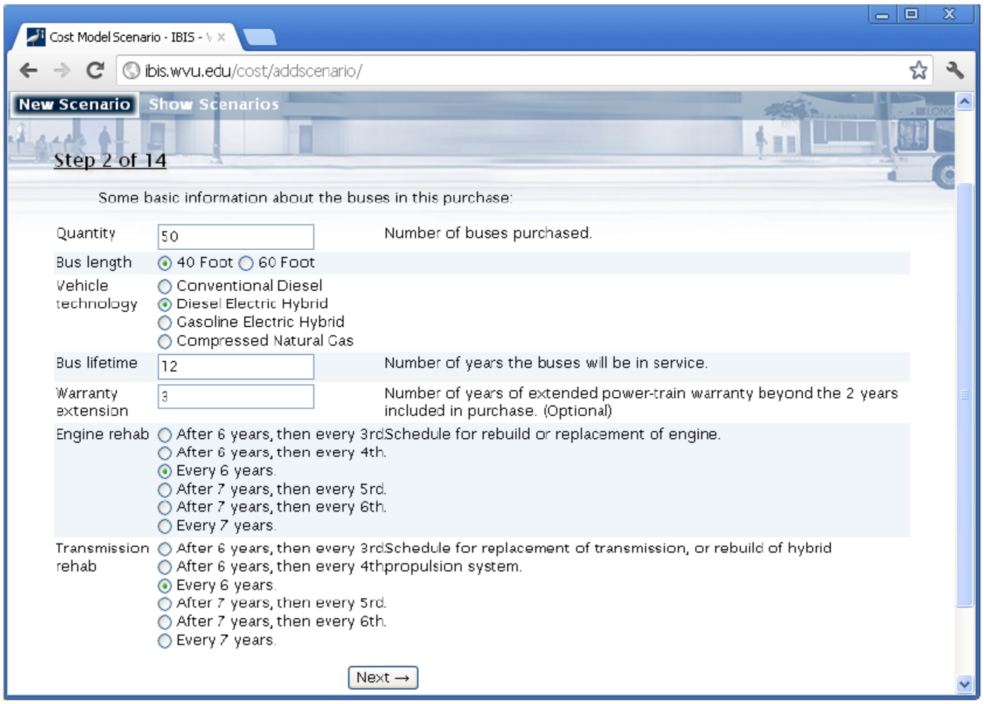
Step 1 of 16

The dollar values in this purchase scenario take into account inflation. These three parameters control how inflation is accounted for:

Name	Scenario 4	
Inflation base year	2012	Base year for all dollar figures. For example, if you enter 2012, all figures will be in '2012 dollars'.
Inflation index		Percent inflation between 2007 and the base year. If provided, this will override the inflation base year above. (Optional)
Purchase year	2012	

Figure 4-12

LCC Model User Interface Step 2



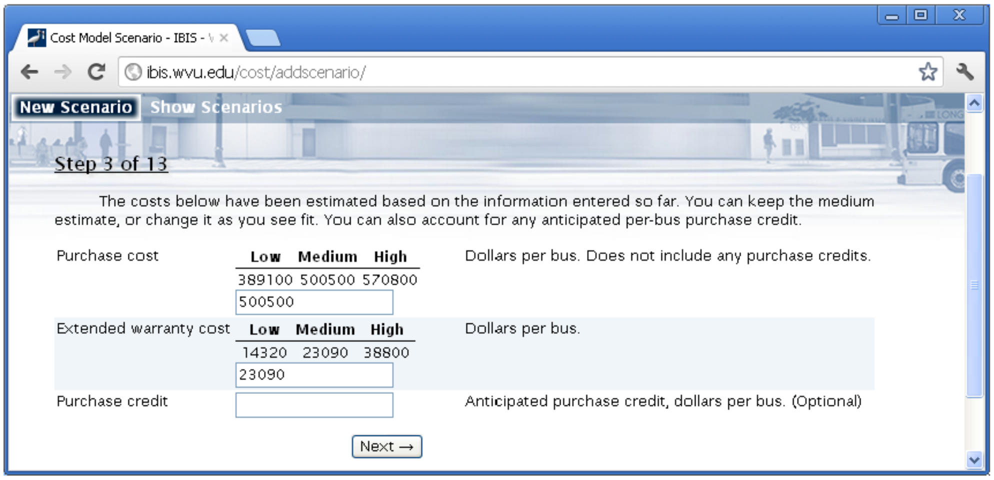
Step 2 of 14

Some basic information about the buses in this purchase:

Quantity	50	Number of buses purchased.
Bus length	● 40 Foot ○ 60 Foot	
Vehicle technology	○ Conventional Diesel ● Diesel Electric Hybrid ○ Gasoline Electric Hybrid ○ Compressed Natural Gas	
Bus lifetime	12	Number of years the buses will be in service.
Warranty extension	3	Number of years of extended power-train warranty beyond the 2 years included in purchase. (Optional)
Engine rehab	○ After 6 years, then every 3rd ○ After 6 years, then every 4th. ● Every 6 years. ○ After 7 years, then every 5rd. ○ After 7 years, then every 6th. ○ Every 7 years.	Schedule for rebuild or replacement of engine.
Transmission rehab	○ After 6 years, then every 3rd ○ After 6 years, then every 4th ● Every 6 years. ○ After 7 years, then every 5rd. ○ After 7 years, then every 6th. ○ Every 7 years.	Schedule for replacement of transmission, or rebuild of hybrid propulsion system.

Figure 4-13

LCC Model User Interface Step 3



Step 3 of 13

The costs below have been estimated based on the information entered so far. You can keep the medium estimate, or change it as you see fit. You can also account for any anticipated per-bus purchase credit.

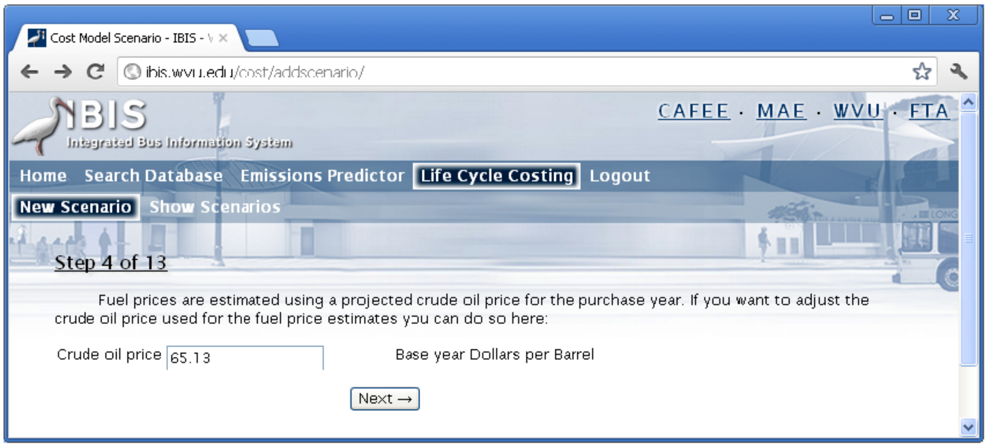
	Low	Medium	High	
Purchase cost	389100	500500	570800	Dollars per bus. Does not include any purchase credits.
	500500			
Extended warranty cost	14320	23090	38800	Dollars per bus.
	23090			
Purchase credit				Anticipated purchase credit, dollars per bus. (Optional)

User input screens 4 through 7 collect information used to determine the cost of fuel consumed over the life of the buses. Fuel costs are impacted by the cost of the fuel as well as the fuel efficiency of the buses. Projections of future fuel costs were developed based on several fuel and energy price projections, including those of the EIA, World Energy, Technology and Climate Policy Outlook, California Energy Commissions, and others. These energy price projections were used to develop future price trends that are then adjusted by shifting the trend lines upward or downward based on current crude oil, natural gas prices, or refined fuel prices. Additional detail on the methodology used to determine future fuel prices may be found in reference [34].

Input screen 4 (Figure 4-14) allows the user to enter the current crude oil price or current natural gas price. The example shown is for diesel-fueled buses. Based on the fuel price enter and the underlying price projection methodology, the model calculates a current pre-tax fuel price range which is presented user on input screen 5 (Figure 4-15). The user can alter the pre-tax fuel cost to reflect the agencies specific fuel contract price if more accurate price information is available. The model also presents an estimated default value for federal fuel tax. The user can override the default value if necessary. Screen 5 also allows the user to provide information about state and local fuel taxes as well as any fuel credits that may be applicable. If the user has a negotiated contract fuel cost that included taxes, he can enter the contract fuel price and enter zero in the tax fields.

Figure 4-14

LCC Model User Interface Step 4



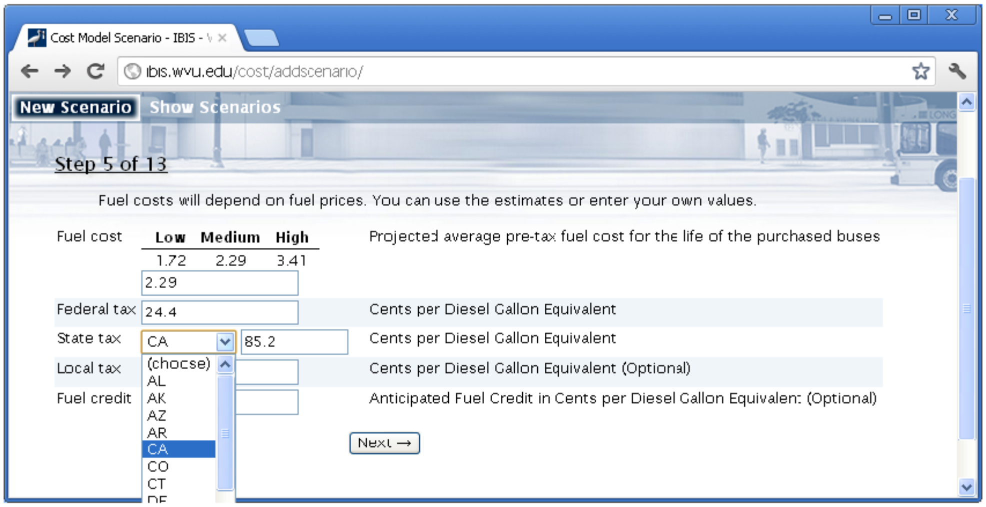
Step 4 of 13

Fuel prices are estimated using a projected crude oil price for the purchase year. If you want to adjust the crude oil price used for the fuel price estimates you can do so here:

Crude oil price 65.13 Base year Dollars per Barrel

Figure 4-15

LCC Model User Interface Step 5



Step 5 of 13

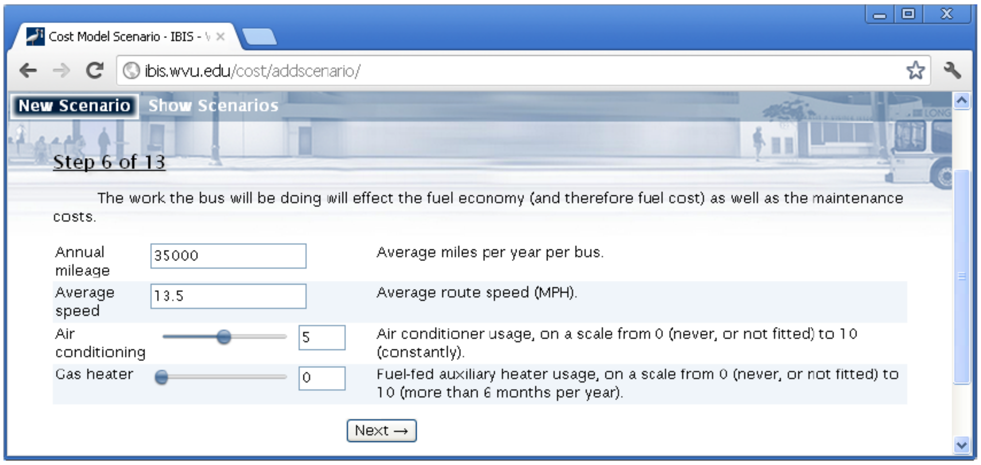
Fuel costs will depend on fuel prices. You can use the estimates or enter your own values.

Fuel cost	Low Medium High 1.72 2.29 3.41 2.29	Projected average pre-tax fuel cost for the life of the purchased buses
Federal tax	24.4	Cents per Diesel Gallon Equivalent
State tax	CA 85.2	Cents per Diesel Gallon Equivalent
Local tax		Cents per Diesel Gallon Equivalent (Optional)
Fuel credit		Anticipated Fuel Credit in Cents per Diesel Gallon Equivalent (Optional)

The total cost of fuel used over the life of the buses is also a function of the fuel economy of the buses in their normal operation. Fuel economy is strongly influenced by the manner in which the buses are driven, the "duty cycle." A significant volume of research has shown that the average speed of the vehicle duty cycle is a strong indicator of vehicle fuel economy. Fuel economy trends for each type of vehicle were developed as a function of average speed from chassis dynamometer testing of transit buses as well as in-use fueling records collected from the four transit properties. Details on the calculation of fuel economy can be found in TCRP Report 132 [34]. The user is prompted to provide the average speed of buses in the fleet on screen 6 (Figure 4-16). Fuel economy is also influence by heating ventilation and air conditioning (HVAC) loads and the presence of any auxiliary fuel fired heaters. The screen also captures information about the frequency of HVAC usage. The calculated fuel economy is presented to the user on screen 7 (Figure 4-17) and can be modified if the transit agency has more accurate fuel economy data for their particular operation.

Figure 4-16

LCC Model User Interface Step 6

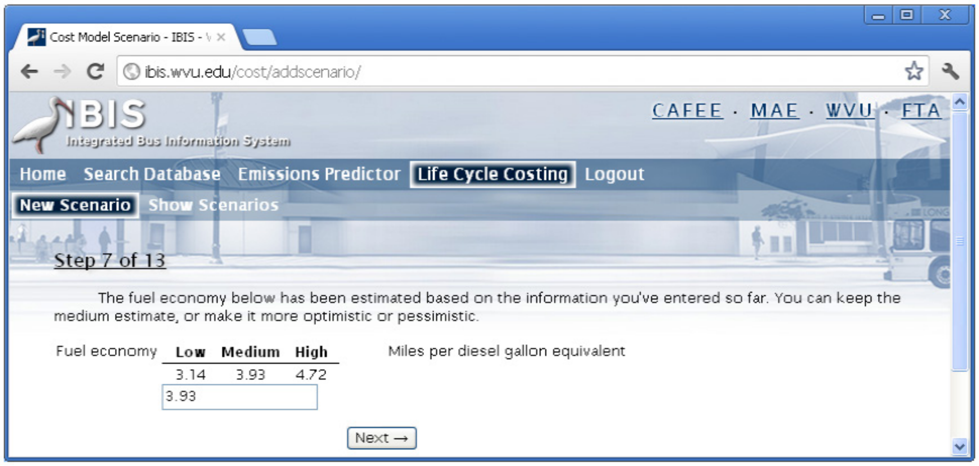


The work the bus will be doing will effect the fuel economy (and therefore fuel cost) as well as the maintenance costs.

Annual mileage	35000	Average miles per year per bus.
Average speed	13.5	Average route speed (MPH).
Air conditioning	5	Air conditioner usage, on a scale from 0 (never, or not fitted) to 10 (constantly).
Gas heater	0	Fuel-fed auxiliary heater usage, on a scale from 0 (never, or not fitted) to 10 (more than 6 months per year).

Figure 4-17

LCC Model User Interface Step 7



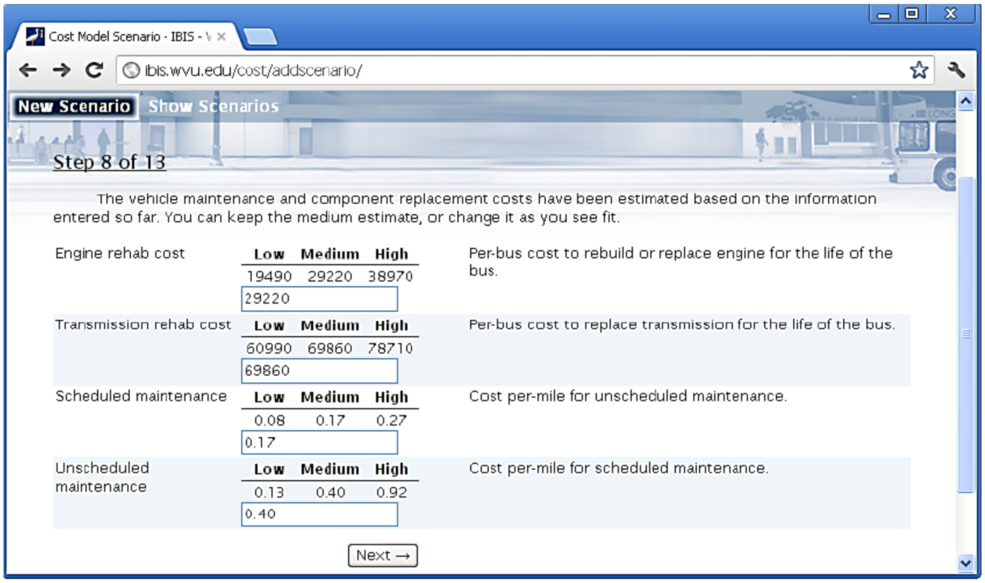
The fuel economy below has been estimated based on the information you've entered so far. You can keep the medium estimate, or make it more optimistic or pessimistic.

Fuel economy	Low	Medium	High	
	3.14	3.93	4.72	Miles per diesel gallon equivalent
	3.93			

Input screen 8, shown in Figure 4-18, is related to vehicle maintenance costs. Cost factors included on this screen include engine rebuild or replacement cost, transmission rebuild or replacement cost, and scheduled and unscheduled maintenance costs. Low, median, and high cost estimates are provided for each. Engine and transmission rehabilitation costs default estimates were determined from data collected from the four transit properties and from engine, transmission, and vehicle manufacturers. Scheduled and unscheduled maintenance costs were determined based on data collected at the four transit properties over an 18-month period between 2005 and 2007. The user can adjust these costs if more recent or accurate data specific to their transit operation are available.

Figure 4-18

LCC Model User Interface Step 8



Step 8 of 13

The vehicle maintenance and component replacement costs have been estimated based on the information entered so far. You can keep the medium estimate, or change it as you see fit.

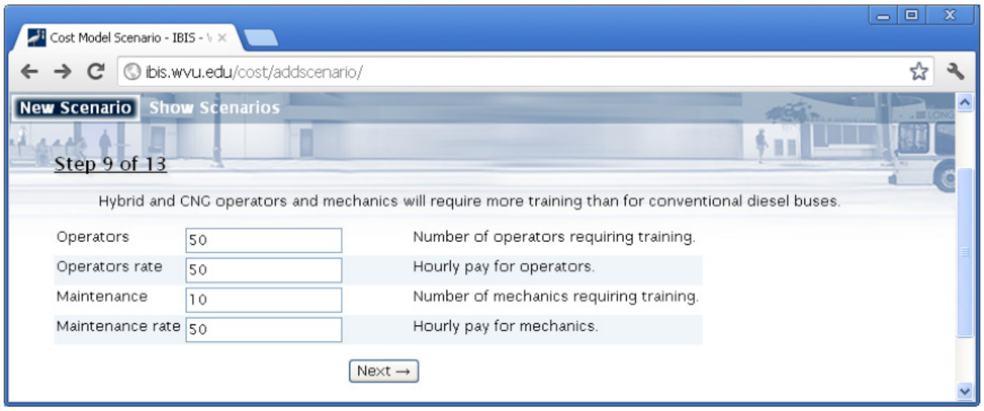
	Low	Medium	High		
Engine rehab cost	19490	29220	38970	29220	Per-bus cost to rebuild or replace engine for the life of the bus.
Transmission rehab cost	60990	69860	78710	69860	Per-bus cost to replace transmission for the life of the bus.
Scheduled maintenance	0.08	0.17	0.27	0.17	Cost per-mile for unscheduled maintenance.
Unscheduled maintenance	0.13	0.40	0.92	0.40	Cost per-mile for scheduled maintenance.

Input screen 9, shown in Figure 4-19, acquires information needed to determine the costs of operator and mechanic training that may be associated with a change in vehicle fuel or propulsion technology. The LCC Model assumes that the operators and mechanics are already familiar with conventional diesel vehicles. The costs associated with training displayed on screen 10 (Figure 4-20) are the incremental costs relative to conventional diesel vehicles required for alternative fuel or hybrid-electric vehicles. The user can modify the default training cost if more specific information is available.

Hybrid-electric and CNG buses require additional diagnostic equipment compared to conventional diesel buses. Additionally, a transit agency may elect to purchase spare energy storage systems for hybrid electric buses. Input screens 11 (Figure 4-21) and 12 (Figure 4-22) address these additional costs.

Figure 4-19

LCC Model User Interface Step 9



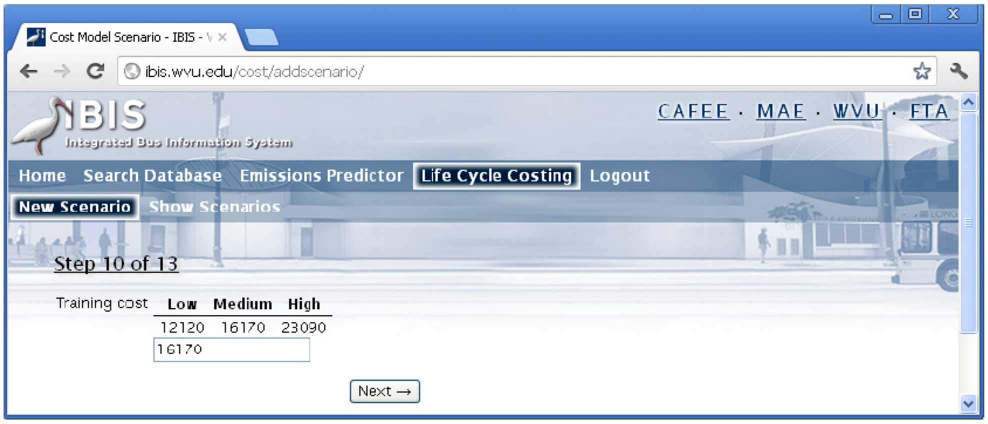
Step 9 of 13

Hybrid and CNG operators and mechanics will require more training than for conventional diesel buses.

Operators	50	Number of operators requiring training.
Operators rate	50	Hourly pay for operators.
Maintenance	10	Number of mechanics requiring training.
Maintenance rate	50	Hourly pay for mechanics.

Figure 4-20

LCC Model User Interface Step 10

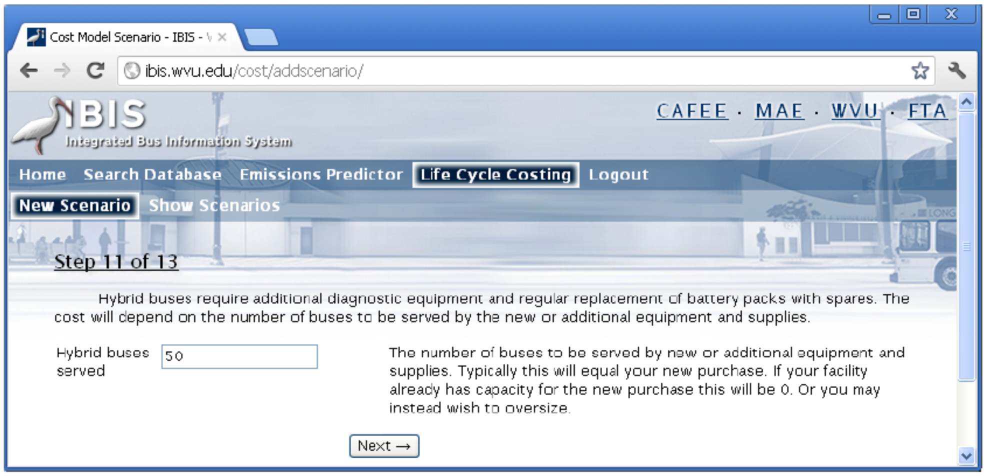


Step 10 of 13

Training cost	Low	Medium	High
	12120	16170	23090
	16170		

Figure 4-21

LCC Model User Interface Step 11



Step 11 of 13

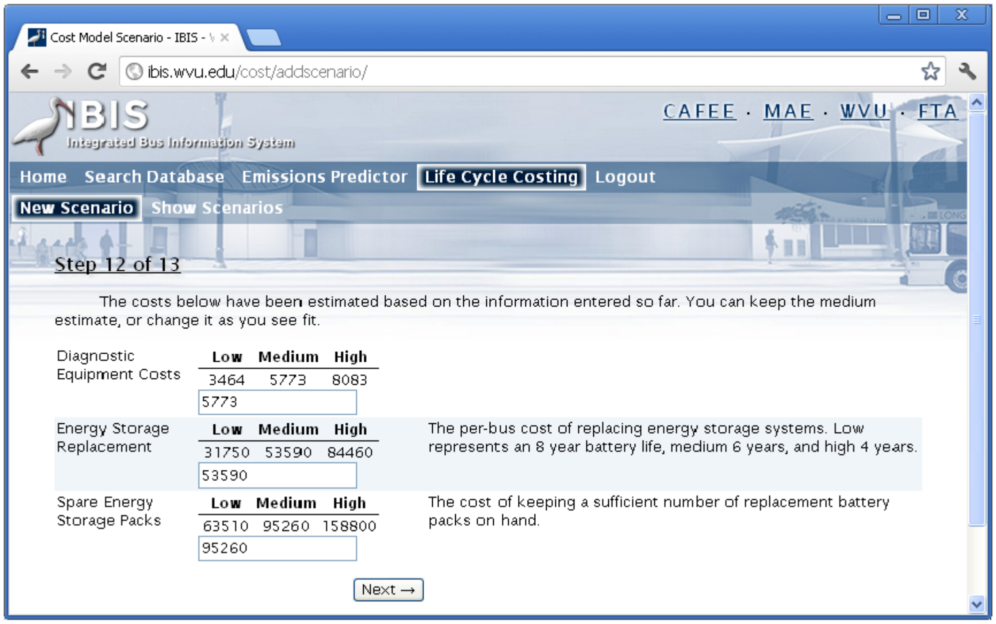
Hybrid buses require additional diagnostic equipment and regular replacement of battery packs with spares. The cost will depend on the number of buses to be served by the new or additional equipment and supplies.

Hybrid buses served: 50

The number of buses to be served by new or additional equipment and supplies. Typically this will equal your new purchase. If your facility already has capacity for the new purchase this will be 0. Or you may instead wish to oversize.

Figure 4-22

LCC Model User Interface Step 12



Step 12 of 13

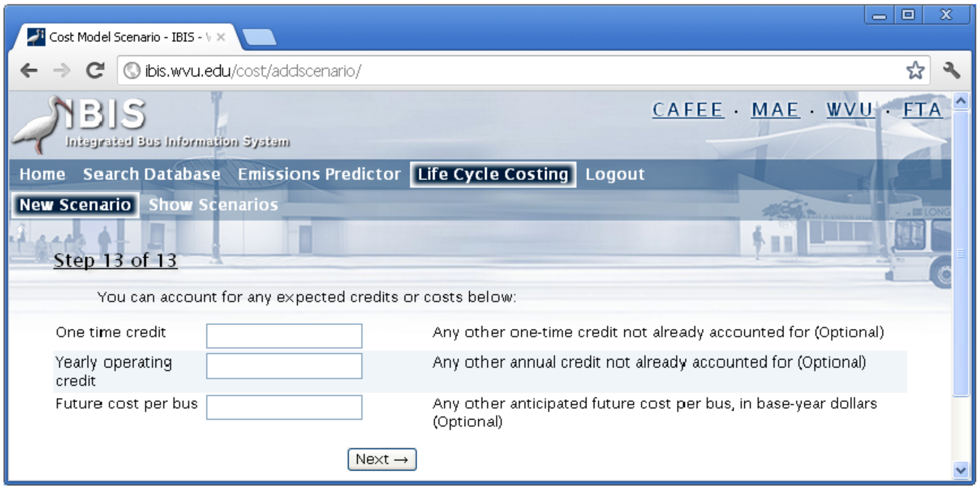
The costs below have been estimated based on the information entered so far. You can keep the medium estimate, or change it as you see fit.

	Low	Medium	High	
Diagnostic Equipment Costs	3464	5773	8083	
	5773			
Energy Storage Replacement	31750	53590	84460	The per-bus cost of replacing energy storage systems. Low represents an 8 year battery life, medium 6 years, and high 4 years.
	53590			
Spare Energy Storage Packs	63510	95260	158800	The cost of keeping a sufficient number of replacement battery packs on hand.
	95260			

The final LCC Model input screen, shown in Figure 4-23, addresses any additional purchase or operating credits that may be available that were not specifically accounted for previously.

Figure 4-23

LCC Model User Interface Step 13



Step 13 of 13

You can account for any expected credits or costs below:

One time credit		Any other one-time credit not already accounted for (Optional)
Yearly operating credit		Any other annual credit not already accounted for (Optional)
Future cost per bus		Any other anticipated future cost per bus, in base-year dollars (Optional)

The LCC example illustrated here was for purchase of diesel hybrid-electric transit buses. The number of input screens and the type of information required will vary for non-hybrid diesel buses, non-hybrid CNG buses, and gasoline electric hybrid buses.

LCC Model Case Study – Long Beach Transit

Long Beach Transit (LBT) operates in a region of southern California where regulations adopted by the South Coast Air Quality Management District (SAQMD) mandates that transit agencies purchase alternative-fueled buses when replacing existing buses or expanding their bus fleets. These regulations preclude the purchase of diesel-powered buses. To comply with the SAQMD rules, LBD elected to purchase New Flyer transit buses with gasoline hybrid-electric transit buses manufactured by ISE Corporations beginning in 2005. By 2010, the LBT gasoline hybrid electric bus fleet numbered 87 buses and had accumulated more than 10 million miles of revenue passenger service. Although the gasoline hybrid program was considered to be successful, it had not fully lived up to expectations. LBT fleet managers expressed concerns including:

- Lower-than-expected fuel economy
- Lower reliability than legacy diesel fleet

- Higher capital and operating costs
- Premature failure of certain components major components including engines, ultracapacitors, and inverters
- Concern over anticipated high maintenance cost after the warranty has expired

Noting these concerns, LBT contracted with WVU to evaluate the gasoline hybrid pathway against other alternative fuel options and to determine an alternative fuel strategy for the next 10-year period. A major aspect of the evaluation was an LCC comparison of the available technology options. WVU used the TCRP LCC Model described above to conduct an LCC analysis, which is presented here as a case study to demonstrate use of the LCC Model in a real-world application.

The LBT case study considered a purchase of 75 40-ft transit buses. The competing technologies were gasoline hybrid electric buses available at the time from New Flyer with ISE hybrid propulsion systems and non-hybrid CNG buses. SCAQMD fleet procurement rules precluded diesel and diesel hybrid-electric buses. However, conventional non-hybrid diesel buses were included in the analysis to provide a basis for cost comparison. Table 4-2 lists the values used for the LBT case study.

Table 4-2

LBT Life Cycle Cost Case Study Model Inputs

	Gasoline Hybrid	Conventional CNG	Conventional Diesel
Purchase Year	2010	2010	2010
Inflation Index	Default	Default	Default
Buses in Purchase	75	75	75
Bus length	40-ft	40-ft	40-ft
Bus Life Expectancy	12 yrs	12 yrs	12 yrs
Extended Warranty included with Purchase	3 yrs	3 yrs	3 yrs
Engine Rebuild Schedule	7th yr; every 5th yr thereafter	6th yr; every 4th yr thereafter	6th yr; every 4th yr thereafter
Transmission Rebuild Schedule	7th yr; every 6th yr thereafter	6th yr; every 4th yr thereafter	6th yr; every 4th yr thereafter
Purchase Price	$621,830/bus	$469,830/bus	$441,830/bus
Extended Warranty Cost	Included in price	Included in price	Included in price
Purchase Credits	N/A	N/A	N/A
Crude Oil Price	$81.27/bbl	N/A	$81.27/bbl
Infrastructure Cost	N/A	$5,710,000	N/A
Infrastructure Maintenance	N/A	Default	N/A
Natural Gas Price	N/A	$8.47/mcf	N/A
Pre-Tax Fuel Price	$2.78/gal	Default	$2.41/gal
Federal Fuel Taxes	Default	Default	Default
State Fuel Taxes	Default–CA	Default–CA	Default–CA
Local Fuel Taxes	N/A	N/A	N/A
Fuel Credit	N/A	N/A	N/A
Annual Mileage	40,000 mi	40,000 mi	40,000 mi
Duty Cycle Speed	13.5 mph	13.5 mph	13.5 mph
Air Conditioning	Default	Default	Default
Gas Heater	N/A	N/A	N/A
Fuel Economy	3.89 mpgde*	Default	3.55 mpgde
Engine Rebuild Cost	$20,669	Default	Default
Transmissions Rebuild Cost	$60,000	Default	Default
Scheduled Maintenance	$0.08/mi	Default	$0.16/mi
Unscheduled Maintenance	$0.42/mi	Default	$0.59.mi
Training Costs	Default	Default	Default
Diagnostic Equipment	N/A	N/A	N/A
Battery Replacement Cost	$45,000	N/A	N/A
Training Costs	Default	Default	Default
Spare Battery Packs	0	N/A	N/A
Spare Battery Pack Cost	N/A	N/A	N/A
5710One Time Credit			
Annual Operating Credit			
Future per Bus Credit			

*Miles per gallon diesel equivalent

Figure 4-24 shows a graphical display the LCC comparison of the three technologies considered in the Long Beach Transit case study. The graphical display subdivides the LCC into vehicle capital costs, other capital costs (fueling/maintenance infrastructure and diagnostic equipment), scheduled and unscheduled maintenance costs, fuel costs, and other variable costs. Figure 4-25 shows the LCC results in tabular form.

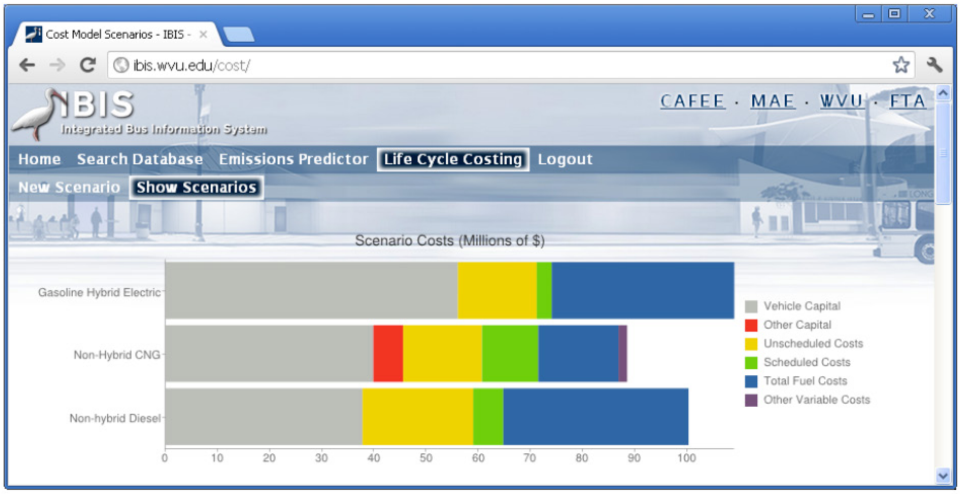
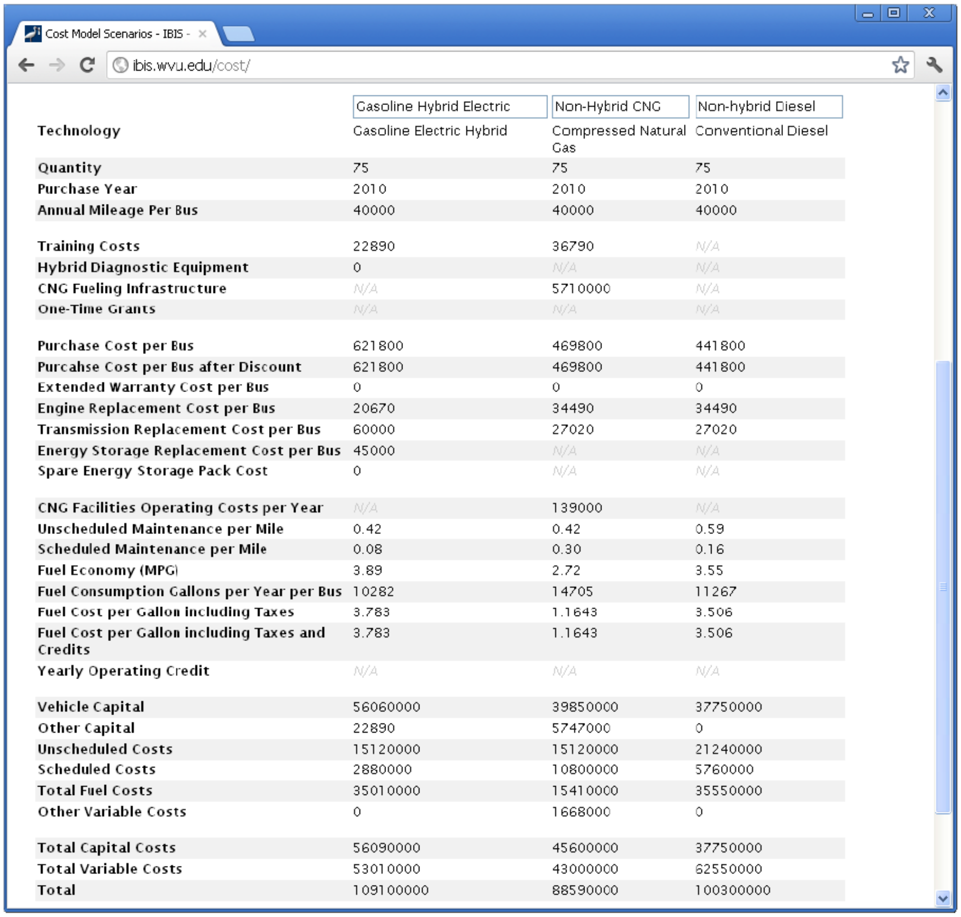


Figure 4-24

Long Beach Transit LCC case study graphical results



	Gasoline Hybrid Electric	Non-Hybrid CNG	Non-hybrid Diesel
Technology	Gasoline Electric Hybrid	Compressed Natural Gas	Conventional Diesel
Quantity	75	75	75
Purchase Year	2010	2010	2010
Annual Mileage Per Bus	40000	40000	40000
Training Costs	22890	36790	N/A
Hybrid Diagnostic Equipment	0	N/A	N/A
CNG Fueling Infrastructure	N/A	5710000	N/A
One-Time Grants	N/A	N/A	N/A
Purchase Cost per Bus	621800	469800	441800
Purcahse Cost per Bus after Discount	621800	469800	441800
Extended Warranty Cost per Bus	0	0	0
Engine Replacement Cost per Bus	20670	34490	34490
Transmission Replacement Cost per Bus	60000	27020	27020
Energy Storage Replacement Cost per Bus	45000	N/A	N/A
Spare Energy Storage Pack Cost	0	N/A	N/A
CNG Facilities Operating Costs per Year	N/A	139000	N/A
Unscheduled Maintenance per Mile	0.42	0.42	0.59
Scheduled Maintenance per Mile	0.08	0.30	0.16
Fuel Economy (MPG)	3.89	2.72	3.55
Fuel Consumption Gallons per Year per Bus	10282	14705	11267
Fuel Cost per Gallon including Taxes	3.783	1.1643	3.506
Fuel Cost per Gallon including Taxes and Credits	3.783	1.1643	3.506
Yearly Operating Credit	N/A	N/A	N/A
Vehicle Capital	56060000	39850000	37750000
Other Capital	22890	5747000	0
Unscheduled Costs	15120000	15120000	21240000
Scheduled Costs	2880000	10800000	5760000
Total Fuel Costs	35010000	15410000	35550000
Other Variable Costs	0	1668000	0
Total Capital Costs	56090000	45600000	37750000
Total Variable Costs	53010000	43000000	62550000
Total	109100000	88590000	100300000

Figure 4-25

Long Beach Transit LCC case study results table

SECTION

5

Industry Outreach

Throughout the program, WVU publicized the results and outcomes of the work through peer reviewed journal papers, conference papers, technical reports, and presentations at relevant industry conferences and meetings. The following sections list the publications and presentations that resulted directly from the performance of this work. Copies of available journal papers, conference papers, posters, technical reports, and conference presentations are provided in the addenda of this report.

Peer Reviewed Journal Publications

1. Wayne, W. S., Perhinschi, M. G., Clark, N. N., Tamayo, S., and Tu, J., "Integrated Bus Information System (IBIS) – A Vehicle Procurement Resource for Transit," *Transportation Research Record: Journal of the Transportation Research Board*, No. 2233, Transportation Research Board of the National Academies, Washington, D.C., 2011, pp. 1–10.
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3. Wayne, W. S., Sandoval, J. A. and Clark, N. N., "Emissions Benefits from Alternative Fuels and Advanced Technology in the U.S. Transit Bus Fleet." *Energy & Environment*, Vol. 20, No. 4 pp. 497-515, August 2009.
4. Wayne, W. S., Clark, N. N., Khan, ABM S., Gautam, M., Thompson, G. J., and Lyons, D. W., "Regulated and Non-Regulated Emissions and Fuel Economy from Conventional Diesel, Hybrid-Electric Diesel and Natural Gas Transit Buses," *J. Transportation Research Forum,* Vol. 47, No. 3, Transportation Research Forum, Fargo ND, pp105-125, October 2008.

Conference Publications

5. Nix, A. C., Sandoval, J. A., Wayne, W. S., Clark, N. N., and McKain, D. L., "Fuel Economy and Emissions Analysis of Conventional Diesel, Diesel-Electric Hybrid, Biodiesel and Natural Gas Powered Transit Buses, 2011 Wessex Institute of Technology Energy and Sustainability Conference, Alicante, Spain, April 2011.
6. Clark, N. N., Wayne, W. S., Khan, AMB S., Lyons, D. W., Gautam, M., McKain, D. L., Thompson, G. J., and Barnett, R. A., "Effects of Average Driving Cycle Speed on Lean-Burn Natural Gas Bus Emissions and Fuel

Economy," SAE 2007-01-0054, 2007 Fuels and Emissions Conference, Cape Town, South Africa, January 2007.

7. Wayne, W. S., Khan, ABM S., Clark, N. N., Lyons, D. W., Gautam, M., and Thompson, G. J., "Effect of Average Speed and Idle Duration on Exhaust Emissions from a Diesel Bus Tested on Fourteen Drive Cycles," 86th Annual Transportation Research Board Meeting, Washington DC, January 2007.
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9. Iyer, S. S., Klinikowski, D. J., Litzinger, T. A., Wayne, W. S. and Clark, N. N., "Diesel Emissions Measurement on Transit Buses," 9th International Symposium on Heavy Vehicle Weights and Dimensions, State College, PA, June 2006.

Poster Sessions

10. Wayne, W. S., Perhinschi, M. G., Clark, N. N., Tamayo, S., and Tu, J., "Integrated Bus Information System (IBIS) – A Vehicle Procurement Resource for Transit," *Proceedings of the Transportation Research Board 90th Annual Meeting*, Washington DC, January 2011.
11. Tu, J., Perhinschi, M. G., Marlowe, C., Tamayo, S., Wayne, W. S., and Clark, N. N., "Development of Integrated Bus Information System for Evaluation of Emissions and Fuel Economy of Transit Buses," 21st CRC Real World Emissions Workshop, San Diego CA, March 2011.
12. Clark, N. N., Wayne, W. S., Thompson, G. J., Gautam, M., Shade, B. C., McKain, D. L., and Jarrett, R.P., "Cycle Dependence of Fuel Efficiency and Emissions for Articulated Transit Buses, "21st CRC Real World Emissions Workshop, San Diego CA, March 2011.
13. Tu, J., Wayne, W. S., Perhinschi, M., Marlowe, C., Tamayo, S., and Clark, N. N., "Development of Duty Cycle Generator Based on Genetic Algorithm for Emissions and Fuel Economy Modeling," 19th CRC On-Road Vehicle Emissions Workshop, San Diego, CA March 2009.
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Conference Presentations

15. Clark, N. N., Wayne, W. S., Perhinschi, M. G., McKain, D. L., Khan, AMB S., Marlow, C., Zhen, F., Tu, J., and Tamayo, S., "Integrated Bus Information System (IBIS)," 2008 APTA Bus Technical Maintenance and Procurement Workshop and Annual Meeting, San Diego CA, October 2008.
16. Kulyk, W., Belanger, M., Klinikowski, D., and Wayne, S., "Adding Brake Performance and Emissions Testing to the Bus Testing Program, APTA Bus Technical, Maintenance and Procurement Workshop, New Orleans, LA, October 31, 2007.
17. Sandoval, J. A., and Wayne, W. S., "Environmental Benefits of Alternative Fuels and Advanced Technology in Public Transit," 2007 APTA Bus Technical Maintenance and Procurement Workshop, New Orleans, LA, October 2007.
18. Clark, N. N., Wayne, W. S., Lyons, D. W., Gautam, M., Thompson, G. J., and Khan, ABM. S., "Regulated Emissions for Diesel and Compressed Natural Gas Transit Buses," 13th Diesel Engine-Efficiency and Emissions Research Conference, Detroit, MI, August 2007.
19. Wayne, W. S., Clark, N. N., Khan, ABM S., Gautam, M., Thompson, G., Lyons, D., McKain, D., and Barnett, R., "Hybrid-Electric Transit Buses: Emissions and Fuel Economy Measurement," APTA Bus and Paratransit Conference, Nashville, TN, May 2007.
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Technical Reports

21. Wayne, W. S., and McKain, D.L., "FTA New Model Bus Testing Program Emissions Laboratory Correlation Study," Technical Report, West Virginia University, Morgantown WV, June 2012.
22. Clark, N. N., Zhen, F., Wayne, W. S., and Lyons, D. W., "Additional Transit Bus Life Cycle Cost Scenarios Based on Current and Future Fuel Prices," U.S. Department of Transportation, Federal Transit Administration, Report No. FTA-WV-26-7006.2008.1, September 2008.
23. Clark, N. N., Zhen, F., Wayne, W. S. and Lyons, D. W., "Transit Bus Life Cycle Cost and Year 2007 Emissions Estimation," U.S. Department of Transportation, Federal Transit Administration, Report No. FTA-WV-26-7004.2007.1, July 2007.

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25. Wayne, W.S., Barnett, R., Shahan, M., "Gaseous Sampling System for Measuring Transit Bus Emissions at the Pennsylvania Transportation Institute," Interim Technical Report submitted to the Federal Transit Administration, May 25, 2007.
26. Lyons, D. W., Gautam, M., Clark, N. N., Thompson, G. J., Wayne, W. S., Riddle, W. C., and Carder, D. K., "Survey of On-Board Emissions Measurement Technologies," Interim Technical Report submitted to the Federal Transit Administration, August 1, 2006.

SECTION

6

Conclusions

The selection of transit bus fuel and propulsion technology has important financial, environmental, and public perception implications for transit agencies. Transit agencies operating in certain area where state or regional emissions regulations and procurement rules mandate or encourage alternative fuels and transit agencies operating in environmental non-compliance regions must consider the environmental implications of new vehicle procurement. Most transit properties strive to reduce their environmental footprint.

Non-hybrid diesel-fueled buses remain the predominant technology in the transit fleet. Diesel buses offer the lowest capital vehicle costs and have been regarded as a very reliable technology. However, the complexity and cost of conventional diesel buses has increased in response to stricter emissions regulations. Natural-gas-powered buses have an increasingly popular choice for transit, particularly in some areas where conventional diesel-powered fleets are prohibited or discouraged Natural-gas-powered buses offer extremely low PM mass emissions and NOx emissions, and stoichiometric combustion natural gas buses boast improved fuel efficiency. Low natural gas fuel prices also make CNG and LNG attractive options. Hybrid electric buses offer the potential for fuel savings for transit operators and potential for reduced exhaust emissions as a result of their ability to recover and reuse energy lost during braking, engine downsizing, reduced transient operation, idle engine-stop, and flexible engine control. Conversely, each technology may have disadvantages, including upfront capital infrastructure costs, the cost of additional diagnostic equipment, higher maintenance costs, and uncertainty associated with adopting a difference technology. The advantages and disadvantages must be carefully weighed given the transit agencies' unique operational goals and constraints. Compounding the difficulty of fleet planning and procurement is the dearth of information, resources, and tools to enable the evaluation of environmental, economic, and operational implications of the various fuel and technology choices for transit vehicles.

During this project, WVU developed resources to assist transit agencies to evaluate the efficiency, emissions, and LCC implications of transit vehicle choices. The outcomes of this project included the following:

1. Implementation of a legislatively-mandated emissions test of all new model transit buses as part of the Altoona Bus Testing Program.
2. Characterization of the fuel efficiency and emissions of legacy and new model transit buses and distribution of emissions data, analysis, and conclusions regarding transit bus emissions into the public domain.

3. Development of a large searchable, publicly-available database of transit bus emissions data through the IBIS Transit Vehicle Emissions Database.
4. Development of a simple-to-use Transit Fleet Emission Inventory Model that can be used to estimate the emissions and fuel efficiency implications of new bus purchases.
5. Online implementation of the TCRP Transit Bus Life Cycle Cost Model.
6. Dissemination of transit bus emissions, fuel efficiency, and LCC information through a wide range of technical reports, journal and conference papers, and conference presentations.

This Emissions Testing Component of the Altoona Bus Testing Program that WVU helped FTA and PTI develop and implement will continue to provide vital information and data that transit agencies can use to compare the fuel efficiency and emissions performance of competing bus technologies they are considering for purchase. This program will provide a standardized and carefully controlled testing process that will yield consistent and comparable emissions results.

The Transit Vehicle Emissions Database provides transit managers, regulatory bodies, engine and vehicle manufacturers, academia, and researchers access to emissions test results from conventional diesel, CNG, LNG, and diesel hybrid-electric transit buses covering model years from 1967 to 2011. The database can be searched based on a variety of criteria. These data are useful to transit agencies for comparing fuel and technology options and to academia and researchers for use in environmental research studies.

The Transit Fleet Emission Model provides a tool to compare the fuel and emissions performance of commercially-available transit bus fuel and propulsion technology options on the fleet-wide emissions footprint. The model can be used to estimate the emissions footprint of an existing fleet of buses and to evaluate how replacement of older existing buses with new-model conventional diesel, CNG, or diesel hybrid buses will impact the emissions output of the fleet. Although more sophisticated emissions inventory models such as the EPA MOVES model exist, these existing models are intended to model total vehicle fleet, which includes light-duty passenger vehicle as well as commercial vehicles, on a regional or state scale for State Implementation Plan development. These existing models are not suited to performing a fleet scale analysis or to comparing competing transit bus fuel and propulsion technologies. The IBIS Transit Fleet Emissions Model provides a simple-to-use tool to estimate the emissions of a transit fleet and evaluate the impact of integrating new bus technologies into the fleet.

The financial implications associated with the capital, maintenance, fuel, and operating costs of the available technologies are equally important in selection of transit vehicle fuel and propulsion options. The TCRP LCC Model provides transit fleet managers with a tool to compare and contrast the life cycle costs of the various technologies.

The resources developed through this research program will assist transit agencies to better understand and evaluate the efficiency and emissions advantages and disadvantages of conventional and alternative transit bus fuel and propulsion options for the purpose of fleet planning and vehicle procurement.

SECTION 7

Recommendations for Future Work

Technology is constantly evolving. To keep the IBIS Transit Vehicle Emissions Database, Transit Fleet Emissions Model, and Life Cycle Cost model current, continuous updates will be necessary. Future work should include the following activities.

1. Update the Transit Vehicle Emissions Database

Emissions test data from new model transit vehicle tested by PTI through the Altoona Bus Testing Program should be incorporated into the IBIS Transit Vehicle Emissions Database. This will require logistical cooperation with PTI to translate the electronic PTI data files into a format suitable for import into the IBIS Database.

Emissions data gathered by the WVU Transportable Emissions Laboratory during future research studies whose sponsors agree to make the study result publically available should be added to the IBIS Transit Vehicle Emissions Database.

2. Update the IBIS Transit Fleet Emissions Model

The IBIS Transit Fleet Emission Model was developed based on chassis dynamometer emissions test results of buses representing each technology and model years. Chassis dynamometer testing needs to be conducted and emissions models need to be developed for:

- Model year 2007–2009 non-hybrid diesel buses
- Model year 2010 and newer non-hybrid diesel buses
- Model year 2010 and newer diesel hybrid buses

3. Update the Default Cost Factors in the Life Cycle Cost Model

The TCRP LCC Model default cost factors were developed based on infrastructure cost, vehicle cost, operating cost, and maintenance cost data collected at four transit properties—New York City Transit, King County Metro in Seattle, Washington Metropolitan Area Transit in the District of Columbia, and Long Beach Transit in California over an 18-month period beginning in 2005. The LCC Model provides high, low, and median default values for the various cost factors considered. The user can override the default values with values that are specific to their particular transit operation, if available, or use the suggested default values. Although the computation engine underlying the LCC Model does not require modification, the default costing factors need to be updated to reflect current prices and future cost projections. Moreover, significant technology advances including actively-managed DPF and u-SCR for diesel vehicles and stoichiometric combustion engines for CNG and LNG vehicles have entered the market. These technologies were not addressed in the previous LCC Model and may alter the cost factors. The LCC Model should be updated to address these new technologies and to update the LCC cost factors to reflect current capital and operating costs.

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