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About DARPA and NAVC

The Defense Advance Research Projects Agency (DARPA) was created in 1958 to ensure technological superiority for U.S. military forces by fostering innovation and pursuing high-payoff, frequently high-risk projects. DARPA serves as the central research and development organization for the Department of Defense (DoD). It manages and directs selected basic and applied research and development projects for DoD, and pursues research and technology where the payoff is both very high and where success may provide dramatic advances for traditional military roles and missions and dual-use applications.

The DARPA mission is to develop imaginative and innovative research ideas offering a significant technological impact that will go well beyond the normal evolutionary developmental approaches; and, to pursue these ideas from the demonstration of technical feasibility through the development of prototype systems.

The DARPA Tactical Technology Office (TTO) fulfills this mission by engaging in the development of aeronautic, space and land systems as well as embedded processors and control systems. The main goal of the TTO is to create highly capable systems that enable “order of magnitude” improvement in military capabilities.

This project was developed and funded under the TTO Electric and Hybrid Vehicle Technology Program. The DARPA Electric and Hybrid Vehicle Technology Program, under the direction of program manager Dr. Robert Rosenfeld, pursues research, development, and demonstrations of technologies for electric and hybrid vehicles that address military missions, modernization, and cost mitigation. Established by Congress in FY 1993, the program has pursued technology development and prototype demonstrations that are essential for future military systems, enhancing national energy security, and facilitating compliance by the Armed Services with federal clean air legislation.

The DARPA Electric and Hybrid Vehicle Technology program has recently evolved into the Advanced Vehicle Technologies Program (AVP), administered by the U.S. Department of Transportation (DOT). The AVP combines the best in transportation technologies and innovative program elements to produce new vehicles, components, and infrastructure for medium- and heavy-duty transportation needs.

The NAVC is a public-private partnership of companies, public agencies, and university and federal laboratories working together to promote advanced vehicle technologies in the Northeast United States. The NAVC Board of Directors is appointed by the eight Northeast governors, the mayor of New York City, the New England Governors' Conference, and the Northeast States for Coordinated Air Use Management. Our participants have initiated over 50 projects, spanning a wide range of technology areas including electric, hybrid-electric and fuel cell propulsion systems, electric and natural gas refueling, energy storage and management, and lightweight structural composites. The NAVC receives funding from the DARPA Electric and Hybrid-Electric Vehicle Program and the Department of Transportation's Advanced Vehicle Technologies Program, as well as other sources.
Acknowledgements

The Northeast Advanced Vehicle Consortium (NAVC) thanks the Defense Advanced Research Projects Agency (DARPA) for the funding and support of this project. This project is part of the DARPA Electric and Hybrid-Electric Vehicle Program. Future projects will be funded through the Department of Transportation’s (DOT’s) Advanced Vehicle Program. Additional testing of the hybrid-electric buses was performed by West Virginia University (WVU) with funding from the U.S. Department of Energy (DOE), Office of Transportation Technologies under a separate directive from the National Renewable Energy Laboratory (NREL). While the NREL work is ongoing, initial test data has been shared between the two programs and as a result each benefits from a wider range of available information. We recognize Dr. Robert Rosenfeld of DARPA, Shang Hsiung of DOT and Paul Norton and Keith Vertin of NREL for their personal assistance.

NAVC thanks M.J. Bradley & Associates for their excellent work on the project, particularly Thomas Balon, the lead author; Paul Moynihan, MJB&A staff engineer; and Amy Stillings, MJB&A staff analyst. NAVC staff working on the project included Sheila Lynch, Executive Director and Thomas Webb, Project Director.

We thank West Virginia University (WVU) for spending the better part of 1999 at our disposal and for sharing and carrying forward the wealth of knowledge they possess with regard to heavy-duty chassis emission testing. We personally thank Dr. Nigel Clark and David McKain for their oversight and data management, Jim Kopasko and Byron Rapp for their site management of the transportable laboratories and the rest of the WVU staff for their participation.

In addition, NAVC thanks the Massachusetts Port Authority (Massport), New York City Metropolitan Transit Authority (NYC MTA) and the New York City Department of Transportation (NYC DOT) for providing both buses and support personnel for the duration of this program. We recognize Doug Wheaton at Massport, Dana Lowell, Bill Parsley and Gordon Coor at NYC MTA and Mark Simon and Susan McSherry at NYC DOT for their personal efforts in advanced vehicle technologies. We would also like to mention the participation of the New York Department of Environmental Conservation (NY DEC) who conducted a significant amount of sampling on a variety of pollutants and toxic compounds. This work is ongoing.

NAVC would also like to thank Massport, the City of New York Department of Environmental Protection (NYC DEP) and Queens Surface for the use of their facilities. We are especially grateful to Lazlo Goldberger and the Mobile Systems Unit of the NYC DEP at Frost St. in Brooklyn, NY for the extended use of their facility for a large part of 1999.

Without the on site support of the Hybrid-Electric manufacturers, we would not have been able to conduct much of the emission testing effectively and we are very thankful for their support of this effort. We recognize Tim Grewe, Dave Mikoryak, Duwayne Robertson, Jim Sherman, Bill Schuhle and Steve Tilyou of Lockheed Martin Control Systems and Edward Bass, Fred Cartwright, Brian Pannell, Robert Tejchma and Pat Wildemann of Allison Transmission. We would also like to thank Mark Brager of Orion Bus Industries for his extensive involvement throughout the project.
Executive Summary

The Northeast Advanced Vehicle Consortium initiated the testing of hybrid-electric buses to demonstrate the energy efficiency and emission performance of “State of the Art” hybrid-electric heavy-duty vehicles with respect to late model conventional diesel heavy-duty vehicles and alternative fuel CNG buses. Funded by the Defense Advance Research Projects Agency, this project serves as an independent demonstration of near term commercial technology in real world demonstration.

An independent team of engineers and scientists facilitated the evaluation consisting of personnel from M.J. Bradley & Associates and West Virginia University. Project participants included transit operators from Boston, Massachusetts and New York City who own and operate the buses. Several original equipment bus manufacturers, engine manufacturers and hybrid drive system manufacturers were on hand to assure that the testing was uniformly conducted and reviewed.

West Virginia University has conducted a significant amount of chassis based heavy-duty vehicle emission testing utilizing their transportable emission laboratories. This body of work has included a significant amount of urban bus testing, primarily on the central business district, emission test cycle. This project goes a step further by evaluating urban buses over six different emission test cycles with average speeds ranging from 3 to 17 mph and with duty cycles ranging from 4 to 18 stops per mile.

The Western Virginia University emission laboratories are equipped to measure nitrogen oxides, carbon monoxide, carbon dioxide, organic compounds and particulate matter. In addition fuel economy for each vehicle was calculated on a mile per gallon basis. Fuel economy for CNG buses was converted to diesel equivalent gallons so direct comparisons could be made. For the hybrid-electric vehicles, the major energy paths were monitored so that total energy and specifically net battery energy could be evaluated and accounted for with a state of charge correction.

Several different fuel variations were evaluated to determine the effects of sulfur in fuel with respect to particulate emissions. These fuels included conventional D1 distillate auto diesel with a sulfur content of about 0.03% (~300 ppm), ultra low city diesel with a sulfur content of less than 20-ppm, synthetic diesel fuel with an essentially zero sulfur content and natural gas. Testing evaluations included two hybrid vehicle models, three compressed natural gas bus models and one diesel bus model. Each of the vehicles was equipped with exhaust aftertreatment including oxidation catalysts for the conventional buses and catalyzed particulate filters for the hybrid-electric buses.

The project evaluated each of the vehicles against a derived fuel economy curve comparing emission trends against average drive cycle speed. Both in-use data and dynamometer test data was then evaluated against this benchmark. A strong correlation between the dynamometer data, actual vehicle in-use fuel economy and theoretical estimated fuel economy values was used to validate the West Virginia University Laboratories test methods and equipment.

The results of this program demonstrate that diesel hybrid-electric vehicles offer reduced drive cycle emissions relative to conventional diesel buses, comparable to that achieved by conventional CNG buses and in most cases setting the in-use benchmark. Only emissions of nitrogen oxides from the hybrids failed to set the performance benchmark. The CNG-like particulate emissions of these diesel hybrid-electric buses were facilitated by the use of low sulfur diesel fuel and catalyzed particulate filters. The project confirmed significant fuel economy benefits of greater than 100 percent over a comparable CNG bus when operated on severe duty cycles such as New York Bus.
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List of Acronyms

Ah  amp-hour
APU  Auxiliary Power Unit
AVP  Advanced Vehicle Technologies Program
BDL  Below Detection Limit
CAA  Clean Air Act
CARB  California Air Resources Board
CBD  Central Business District Drive Cycle
CEMR  College of Engineering and Mineral Resources
CH₄  Methane
cm  centimeter
CNG  Compressed Natural Gas
CO  Carbon Monoxide
CO₂  Carbon Dioxide
CVS  Critical Flow Venturi System
D₁  #1 diesel fuel
D₂  #2 diesel fuel
DARPA  Defense Advanced Research Projects Agency
DEC  Department of Environmental Conservation
DEP  Department of Environmental Protection
DOD  Depth of Discharge
DoD  Department of Defense
DOE  Department of Energy
DOT  Department of Transportation
EHVP  Electric and Hybrid-Electric Vehicle Program
EPA  Environmental Protection Agency
FY  Fiscal Year
g/bhp-hr  gram per brake horsepower hour
g/mi  gram/mile
gal  gallon
GHG  Greenhouse Gas
GVW  Gross Vehicle Weight
GWP  Global Warming Potential
H₂O  Water
HC  Hydrocarbons
hp  Horsepower
IPCC  Intergovernmental Panel on Climate Change
kWh  kilowatt-hour
lbs  pounds
LLD  Load-Leveling Device
LMCS  Lockheed Martin Control Systems
LNG  Liquified Natural Gas
LS  Low Sulfur
mm  millimeter
mmBtu  million British Thermal Unit
mpg  mile per gallon
mph  mile per hour
<table>
<thead>
<tr>
<th>Acronym</th>
<th>Definition</th>
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<tr>
<td>N$_2$O</td>
<td>Nitrous Oxide</td>
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<tr>
<td>NAAQS</td>
<td>National Ambient Air Quality Standards</td>
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<tr>
<td>NAVC</td>
<td>Northeast Advanced Vehicle Consortium</td>
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<tr>
<td>NMHC</td>
<td>Non-Methane Hydrocarbon Concentration</td>
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<tr>
<td>NMOC</td>
<td>Non-Methane Organic Compounds</td>
</tr>
<tr>
<td>NMVOC</td>
<td>Non-Methane Volatile Organic Compounds</td>
</tr>
<tr>
<td>NO</td>
<td>Nitrogen Oxide</td>
</tr>
<tr>
<td>NO$_2$</td>
<td>Nitrogen Dioxide</td>
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<tr>
<td>NOx</td>
<td>Nitrogen Oxides</td>
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<tr>
<td>NREL</td>
<td>National Renewable Energy Laboratory</td>
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<td>NY Bus</td>
<td>New York Bus Drive Cycle</td>
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<tr>
<td>NY Composite</td>
<td>New York Composite Drive Cycle</td>
</tr>
<tr>
<td>NYC</td>
<td>New York City</td>
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<tr>
<td>NYC MTA</td>
<td>New York City Metropolitan Transit Authority</td>
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<tr>
<td>O$_3$</td>
<td>Ozone</td>
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<tr>
<td>OEM</td>
<td>Original Equipment Manufacturer</td>
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<tr>
<td>PAH</td>
<td>Polycyclic Aromatic Hydrocarbons</td>
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<tr>
<td>Pb</td>
<td>Lead</td>
</tr>
<tr>
<td>PM</td>
<td>Particulate Matter</td>
</tr>
<tr>
<td>PNGV</td>
<td>Partnership for a New Generation of Vehicles</td>
</tr>
<tr>
<td>ppm</td>
<td>parts per million</td>
</tr>
<tr>
<td>Regen</td>
<td>Regenerative braking</td>
</tr>
<tr>
<td>SAE</td>
<td>Society of Automotive Engineers</td>
</tr>
<tr>
<td>scfm</td>
<td>Standard Cubic Feet per Minute</td>
</tr>
<tr>
<td>SO$_2$</td>
<td>Sulfur Dioxide</td>
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<tr>
<td>SO$_4$</td>
<td>Sulfate</td>
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<tr>
<td>SOC</td>
<td>State-of-Charge</td>
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<tr>
<td>THC</td>
<td>Total Hydrocarbon</td>
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<tr>
<td>TMC</td>
<td>Transportation Manufacturing Corporation</td>
</tr>
<tr>
<td>TOC</td>
<td>Total Organic Compounds</td>
</tr>
<tr>
<td>TTO</td>
<td>Tactical Technology Office</td>
</tr>
<tr>
<td>UNFCCC</td>
<td>United Nations Framework Convention of Climate Change</td>
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<tr>
<td>VOC</td>
<td>Volatile Organic Compound</td>
</tr>
<tr>
<td>Wh</td>
<td>watt-hour</td>
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<td>WVU</td>
<td>West Virginia University</td>
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<tr>
<td>ZEB</td>
<td>Zero-Emission Bus</td>
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1.0 Introduction

1.1 Background
Public transit operators are being asked to take significant steps toward achieving emission reductions from their transit fleets. Transit operators know that in order to attain these goals they are going to have to purchase newer and more expensive state of the art buses and potentially upgrade their infrastructure.

Recently, hybrid-electric buses have garnered increasing attention with demonstration proof of concepts that include fuel cell hybrids, CNG hybrids and diesel hybrids in both series and parallel hybrid layouts. Generally speaking, a hybrid is defined as carrying at least two sources of motive energy on board and using electric drive to provide partial or complete drive power to the vehicle’s wheels. In a series hybrid, only the electric motor drives the wheels and the engine is used to provide electrical energy. In a parallel hybrid, the electric motor and engine are both connected to the wheels and can both power the vehicle. The hybrid-electric technology is not fuel specific. Hybrid drive applications have been tested using diesel, CNG and propane fuels. It only makes sense that a hybrid-electric bus manufacturer would choose to utilize a mature engine technology when introducing a hybrid-electric architecture to limit the number of things that could go awry and to target the largest potential portion of a relatively small market with a single product. Several manufacturers have developed production hybrid bus models, well beyond the experimental stage. Many of these vehicles have boasted significant improvements in fuel economy with lower emissions than diesel buses. Hybrid technology is likely to improve and produce even lower emissions as time goes on.

Today’s diesel buses are substantially cleaner than diesel buses of only ten years ago. This trend is documented in several chapters of this report. Diesel buses have also benefited in reduced emission levels due to the use of oxidation catalysts (lower PM), cleaner fuels (lower sulfur/PM) and improved engine controls. In addition, both CNG and diesel buses benefit from newer five speed transmissions versus three speed units. Additional aftertreatment technologies such as lean NOx reduction catalysts and regenerative particulate traps will undoubtedly lower conventional bus emissions further in the future—lower than originally thought possible with diesel fuel. Of course the diesel fuel itself may have to change to accommodate these new technologies and transit operators can expect that at a minimum ultra-low sulfur diesel will almost certainly be required to allow aftertreatment control of PM to attain stringent PM standards.

Over the last several years many proactive transit agencies have converted part or all of their fleet to compressed natural gas (CNG). While earlier generation CNG buses had their problems, late model CNG buses are very consistent and recent model year CNG buses have produced air quality improvements with both lower nitrogen oxide (NOx) (an ozone precursor) and particulate matter (PM) emissions (respiratory irritants and likely carcinogenic compounds). Many CNG transit agencies have also noticed fuel economy penalties, but the decreased emissions and increased public awareness that the buses are indeed cleaner were deemed worth it. The addition of closed loop, exhaust oxygen sensor feedback to CNG buses and oxidation catalysts to both diesel and CNG buses have reduced emissions even further, primarily hydrocarbons (HC) and PM. Also, natural gas fueling systems have improved over the last decade with fewer occurrences of failure. Today, CNG buses are among the cleanest transit vehicles in service, while still achieving a high level of reliability and safety.

Several medium- and heavy-duty transportation related research projects were directed previously by the Defense Advanced Research Projects Agency (DARPA) under the Electric and Hybrid-
Electric Vehicle Program (EHVP) and now by U.S. Department of Transportation (DOT) under the Advanced Vehicle Technologies Program (AVP). Both the EHVP and the AVP were designed to complement the activities of the Partnership for a New Generation of Vehicles (PNGV) and other programs. Both electric and hybrid-electric vehicles are supported by this program and it is important to understand that the architecture of the electric vehicle (electric drive specifically) is an important enabling technology. Electric drive allows not only the capture of regenerative braking energy that is normally lost as heat in a conventional vehicle, but also enables the use of non-mechanical power units such as fuel cells.

Global climate change has also become an issue that cannot be ignored and as a result fuel economy is back on the table. In the 1970’s gasoline engine modifications in automobiles were made to reduce emissions, that also resulted in poor fuel economy. The introduction of fuel injection and catalyst aftertreatment overcame this hurdle and now light-duty gasoline engines are both efficient and boast very low emission levels. But despite this clean engine management technology, fuel economy remains an issue due to the proliferation of trucks and sport utility vehicles, which have much lower fuel economy due to poor aerodynamics and increased vehicle weight. Many automobile manufacturers have embraced the hybrid-electric drive as the next evolutionary step because the recovery of regenerative braking energy can largely offset the losses associated with greater vehicle weight.

All vehicles—both mechanical and hybrid-drive—will continue to evolve to the extent possible, given the current limitations of the fuels and the internal combustion engine, as well as the current state of development of fuel cell technologies. The results of this project have been presented in a harmonized fashion to allow the reader to reach his or her own conclusions depending upon which pollutant is of greatest concern. This harmonized approach involves the evaluation of all pollutants simultaneously, searching for technology options that produce co-benefits and not solutions that are counter productive (i.e., decrease NOx levels at the expense of increased HC and carbon monoxide (CO)).

This report does not fully answer all of the questions on the table, but does provide a baseline starting point for discussions. It has been theorized that with ultra-low particulate levels comes a preponderance of ultra-fine nanoparticles in the PM composition. While this report evaluates the total PM emission and its sulfur component, it does not get into the composition of the carbon-based particulate or its relative size distribution. This report also does not specifically address the presence of potential carcinogenic and toxic compounds in diesel exhaust. These issues will need to be pursued and evaluated in detail for both CNG and diesel in the future.

1.2 Chassis-Based Testing – Emissions and Fuel Economy Characterization

Independent test data demonstrating the emissions and fuel economy of alternative fueled and hybrid buses have been a scarce commodity. Much of the emissions data for alternative fuel buses has been collected using disparate methodologies and without peer review. The results of this program demonstrate that diesel hybrid-electric vehicles do offer reduced drive cycle emissions relative to conventional diesel buses, in many cases similar to that achieved by conventional CNG buses. These lower emissions are the result of reduced engine transient operation and improved vehicle fuel economy. Hybrid-electric technology demonstrates a measurable advantage in city driving situations, when operated on stop-and-go, low-speed service applications. In this environment, regenerative braking can be utilized to recover kinetic energy normally lost to heat during mechanical braking. The testing also verified that over the last decade significant emission reductions have been achieved on conventional diesel and CNG bus
technologies through implementation of exhaust aftertreatment oxidation catalysts for the control of CO, HC and PM.

The fuel economy and distance-specific (or per mile) emission rate of a transit bus engine cannot be quantified as a single number once the engine has been installed in a specific vehicle. Fuel economy and per mile emission rates are highly dependent upon the duty cycle of the vehicle and other vehicle parameters (e.g., weight, size, and passenger loads.) As such, comparison across buses cannot be made unless testing has been performed using a standardized test protocol and the comparisons are made against the same duty cycle. Transit buses have, in the past, been chassis tested predominantly on the CBD cycle for relative comparisons. There is however a concern that the CBD may not be the best evaluation tool for transit buses as it relies on a significant amount of steady state operation at a speed of 20 mph. To alleviate this issue, the NAVC project performed testing on six separate drive cycles with significant differences in their characteristics. These cycles simulated a range of duty cycles from very slow stop-and-go urban driving to higher speed semi-arterial driving. Each cycle is described in detail in Chapter 2.

Assessing emissions from hybrid-electric vehicles poses some difficulty in that the source of emissions (the engine) is not directly coupled to the vehicle drivetrain and, unlike light-duty vehicles, heavy-duty engines are certified independent of the vehicle. The current method for U.S. Environmental Protection Agency (EPA) emissions certification includes testing the engine alone on an engine dynamometer against a standardized load cycle. This method works on conventional vehicles because vehicle driving speed and engine loads are directly related. In hybrid-electric vehicles, however, the engine is de-coupled from the wheels and a control algorithm is used, relying on several independent vehicle-operating parameters, which in turn are used to determine engine load. For example, on a conventional bus layout, the accelerator pedal controls the fuel delivery rate to the engine so when the pedal is depressed, more fuel is delivered to the engine. In a hybrid-electric vehicle, the accelerator pedal basically signals the vehicle computer, which in turn determines what amount of power is delivered by the battery and whether any additional power is required of the engine to either provide motive power or battery charging power. While emissions from a conventional engine-powered vehicle rise and fall with power delivered at the rear axle by the engine, emissions from a hybrid vehicle rise and fall with power delivered by the engine, which may or may not follow vehicle speed and load. There is currently no method to directly relate emissions from heavy-duty engines to chassis emissions since it is difficult to determine variables such as drivetrain losses. Additionally, variables such as auxiliary loads (e.g., air conditioning, compressed air) may not be accurately simulated in heavy-duty engine certification. This issue of the engine being de-coupled from the vehicle load is addressed by testing the entire vehicle on a chassis dynamometer, as done in this emission-testing program.

Unlike engine dynamometer testing, chassis dynamometer testing is more representative of actual in-use vehicle operation as it accounts for the losses and operation associated with the specific vehicle into which the engine is installed. Chassis testing can also accurately measure the system benefits of hybrids including the recovery of braking energy through regenerative braking, greater drive line efficiency and reduced transient operation of the engine powering the auxiliary power unit (APU).

Recognizing the need to conduct chassis dynamometer testing of hybrid vehicles, NAVC initiated the “Hybrid-Electric Drive Heavy-Duty Vehicle Testing Project” funded by the DARPA Electric and Hybrid-Electric Vehicle Program\(^1\). The NAVC designed this program to demonstrate the

\(^1\) Additional testing was conducted by WVU with funding from the U.S. Department of Energy (DOE), Office of Transportation Technologies, under a separate directive from the National Renewable Energy Lab (NREL). This data is included in the NAVC program.
current energy efficiency and emission performance of “state-of-the-art” hybrid-electric heavy-duty vehicles and provide for the estimation of hybrid vehicle performance under a variety of operating circumstances. To appropriately benchmark hybrid-electric vehicle performance a comparison must be made to conventional vehicles, including diesel and CNG buses. To this end, NAVC brought together a number of bus manufacturers and operators to participate in this program. West Virginia University (WVU) College of Engineering and Mineral Resources (CEMR) performed all emission testing under the direction of M.J. Bradley & Associates, Inc. (MJB&A). The WVU Department of Mechanical & Aerospace Engineering operates two transportable heavy-duty vehicle chassis dynamometers and mobile emissions laboratories that are capable of determining the emissions and fuel economy from heavy-duty vehicles. Details about the WVU laboratories are included in Chapter 2. The WVU laboratories have been utilized to gather emissions data from a large variety of heavy-duty vehicles throughout North America. Data from the laboratories are submitted to the National Renewable Energy Laboratory (NREL), who maintains a database of emissions from both conventional and alternatively fueled light- and heavy-duty vehicles. A majority of the data collected by WVU is from alternative (CNG, alcohol, biofuel) and conventional diesel fuel transit buses operated in metropolitan and urban areas. The NREL database spans heavy-duty buses with engines varying from model year 1988 through 1998. A variety of bus and engine manufacturers are represented in the database. A majority of the data for buses is on the Central Business District (CBD) duty cycle.

1.3 Testing Program Results

While not every bus was tested on every cycle, Appendix A provides two tables that summarize the test results of this program. In addition, general vehicle information for each bus, along with comparison charts for fuel economy and emissions on the NY Bus cycle are provided for each bus in Appendix B. In each comparison chart, the buses are ranked highest to lowest for fuel economy and lowest to highest for emissions, with the best performing bus at the top of each chart. The bus being evaluated in each section has its emissions highlighted, which allows for the comparison of all pollutants simultaneously.
2.0 Methodology

2.1 Transportable Heavy-Duty Vehicle Chassis Dynamometer

West Virginia University designed, constructed and now operates two Transportable Heavy-Duty Vehicle Emissions Testing Laboratories. These laboratories travel to transit agencies, trucking facilities, and other locations across the county where the laboratory is set up to measure alternative fuel and diesel control vehicle emissions and fuel economy. A large portion of the research and testing performed by WVU is done under a grant from the Department of Energy (DOE). The main objective of this research is to contribute information to a DOE/WVU database that can be used to ascertain emissions performance and fuel efficiency of alternatively fueled vehicles. Several technical papers have been presented on the design of the two laboratories and on emissions data collected from both conventional and alternatively fueled vehicles.\(^2\) In addition, WVU has performed extensive work funded by DOE and NREL to support the development of heavy-duty driving cycles and to assess emissions from new engine and fuel technologies.

Figure 2.1: Dynamometer Test Bed and Instrument Trailer

The transportable laboratory consists of a dynamometer test bed, instrumentation trailer and support trailer (Figure 2.1). The test bed is transported to the test site by a tractor truck where it is lowered to the ground. Each subject vehicle is prepared by removing the outer drive wheels and replacing them with special hub adapters. The subject vehicle is then driven onto the test bed where it is supported with jacks (Figure 2.2) and secured with chains. Adapter

plates are then attached to the vehicle to provide a connection between the drive axle of the vehicle (Figure 2.3) and the inertial flywheels and power absorbers of the dynamometer. Gearboxes transmit drive axle power to flywheel sets. The flywheel sets consist of a series of selectable discs used to simulate vehicle inertia (Figure 2.4).

During the test cycle, torque cells and speed transducers at the vehicle hubs (Figure 2.5) monitor axle torque and speed.

The instrumentation trailer holds both the emissions measurement system for the laboratory and the data acquisition and control hardware necessary for the operation of the test bed. Exhaust from the vehicle is piped into a 45-cm dilution tunnel at the instrumentation trailer (see Figure 2.1). The tunnel mixes the exhaust with ambient air, which both cools and dilutes the exhaust. Dilution tunnel flow is controlled using a critical flow venturi system (CVS). A two-stage blower system maintains critical flow through the venturi throat restrictions to maintain a known and nearly constant mass flow of dilute exhaust during testing. The flow can be varied from 500 scfm to 3000 scfm by adjusting the CVS.
Dilute exhaust samples are drawn, using heated sampling probes and sample lines, from a sample plane located 15 feet from the mouth of the dilution tunnel. Levels of CO$_2$, CO, NOx and HC are measured continuously then integrated over the complete test. A sample of the ambient (dilution) air is continuously collected throughout the test in a Tedlar bag and analyzed at the end of each test to establish background. These background measurements are then subtracted from the integrated continuous measurements after taking into account the dilution ratio employed in the tunnel.

In addition to continuous, integrated and background samples, additional exhaust samples are drawn from the dilution tunnel and collected in 3 liter Tedlar bags for test runs on vehicles powered by CNG and LNG. These samples are then sent to the WVU speciation laboratory to determine non-methane hydrocarbon concentration (NMHC) using gas chromatography analysis.

A gravimetric measurement of PM is obtained using 70-mm fiberglass filters. The filters are conditioned for temperature and humidity in an environmental chamber before each weighing to reduce error due to variation in water content per CFR 40, Part 86, Subpart N.

The fuel consumption of the vehicle is estimated based on a carbon balance. The amount of carbon per gallon of fuel (or gallon equivalent for CNG) is determined by laboratory analysis, and is then compared against the total amount of carbon measured by the analyzers in the dilution tunnel during a test cycle. The total integrated quantity is then used to calculate fuel efficiency.

### 2.2 Test Buses

The NAVC project included five, hybrid-electric, Orion VI buses from Orion Bus Industries, equipped with Lockheed Martin Control Systems powerplants (Orion-LMCS), and one hybrid-electric RTS bus from Nova Bus Incorporated (NovaBUS), equipped with an Allison

#### Table 2.1: Forty-Foot Buses Tested Under the NAVC Program

<table>
<thead>
<tr>
<th>Bus OEM</th>
<th>Bus Chassis</th>
<th>Drive</th>
<th>Engine / Model Year</th>
<th>Fuel</th>
<th>Aftertreatment</th>
</tr>
</thead>
<tbody>
<tr>
<td>NovaBUS</td>
<td>RTS</td>
<td>3 speed</td>
<td>DDC Series 50 / 1998</td>
<td>Diesel $^A$</td>
<td>Oxidation Catalyst</td>
</tr>
<tr>
<td>Neoplan</td>
<td>AN440T</td>
<td>5 speed</td>
<td>Cummins L10 280G / 1998</td>
<td>CNG</td>
<td>Oxidation Catalyst</td>
</tr>
<tr>
<td>New Flyer</td>
<td>C40LF</td>
<td>5 speed</td>
<td>DDC Series 50G / 1999</td>
<td>CNG</td>
<td>Oxidation Catalyst</td>
</tr>
<tr>
<td>Orion</td>
<td>V</td>
<td>5 speed</td>
<td>DDC Series 50G / 1998</td>
<td>CNG</td>
<td>Oxidation Catalyst</td>
</tr>
<tr>
<td>Orion</td>
<td>VI Hybrid</td>
<td></td>
<td>DDC Series 30 / 1997 &amp; 1998</td>
<td>Diesel-Electric $^B$</td>
<td>NETT Particulate Filter Trap</td>
</tr>
</tbody>
</table>

$^A$ – The NovaBUS was tested on D1, and MossGas® diesel fuels.  
$^B$ – The Orion-LMCS bus was tested on D1, low sulfur D1, and MossGas® diesel fuels.  
$^C$ – The Nova-Allison bus was tested on low sulfur D1 diesel fuel.
Transmission hybrid powerplant (Nova-Allison). Each of the hybrid-electric vehicles is of series configuration and is equipped with an integrated oxidation catalyst/regenerative particulate trap. The Orion-LMCS hybrid-electric bus is a pre-commercial hybrid design with approximately 15 to 20 units in service. The Nova-Allison hybrid is a proof-of-concept prototype demonstration vehicle and is not in production at this time. In addition to the hybrid-electric buses, the project conducted dynamometer efficiency and emissions testing on state of the art closed loop, oxygen sensor feedback, catalyst controlled CNG buses and catalyst controlled diesel buses. Bus emission and fuel economy measurements were performed in Boston, Massachusetts and in Brooklyn, New York during the spring and fall of 1999. Each bus tested during this project was equipped with a recent model year (1997 – 1999) engine with relatively low mileage. A profile of each recent model year (1997-1999) bus tested under this program is included in appendix B.

2.3 Drive Cycles

Emission levels and fuel economy are influenced by a number of factors, such as acceleration rates, braking distance and amount of idle (or dwell). As such, the drive cycle has a significant effect on measured emission levels and fuel economy. Since there is no definitive cycle for testing heavy-duty transit vehicles and an extensive database exists only for certain driving cycles, this testing project used a variety of drive cycles with varying average speed and number of stops per mile to develop a more rounded comparison between the buses and different fuel types. The central business district (CBD), which appeared as the Society of Automotive Engineers (SAE) recommended practice J1376, is commonly used to evaluate transit buses, but the project team was concerned that the test cycle did not accurately reflect actual service routes in New York City. So in addition to CBD testing, the project team developed the Manhattan cycle which contains patterns similar to the acceleration and deceleration rates used during actual in-service use. Four other testing cycles were used during the program. These include the New York Bus (NY Bus) cycle (similar to the Manhattan but with a lower average speed), the New York Composite cycle (contains a wider range of acceleration and deceleration rates than NY Bus) and two routes derived from actual in-service airport shuttle routes, Route #22, and Route #77.

The CBD cycle is typically used to evaluate transit buses and is made up of 14 identical sections containing an acceleration to 20 mph, a cruise at 20 mph, braking to a stop, then dwell. The total cycle covers 2.0 miles over 600 seconds. While the CBD cycle is repeatable from a driver in the loop standpoint, it has several drawbacks that limit its effectiveness as an evaluation tool. The acceleration rate is fixed which tends to favor buses with five speed transmissions and larger engines. The cycle is dominated by the 20-mph cruise, which penalizes buses that are not geared for optimum efficiency at that speed.
particular speed. The deceleration from 20-mph is twice as fast as the acceleration to 20-mph, 4.5 seconds versus 9 seconds, which is not typical of actual in-use driving. The average speed for the CBD cycle is 12.6 mph, generally faster than that observed by most transit operations.

The NY Bus cycle was developed previously using real-world speed-time data from heavy-duty vehicles in service in New York City. It is a statistically derived cycle, which was developed from data collected from both transit buses and trucks in the 1970’s. The cycle lasts for 571 seconds, similar to the CBD, however, the total distance traveled is only 0.6 mile. The NY Bus cycle was used to evaluate greater variation in the acceleration and deceleration rates as well as lower overall speed than the CBD to better represent inner city transit bus use. During this project, comparisons were made between dynamometer testing results and actual in-use data observed in New York City and at Logan International Airport. While the NY Bus cycle better reflects actual in-use operation than the CBD, its average speed of 3.7 mph is slower than typically observed by New York City Metropolitan Transit Authority (NYC MTA).

During this project, it became apparent that a new cycle was needed to more accurately reflect driving conditions in the New York City Metropolitan area. WVU developed a new cycle utilizing actual in-use route segments data logged from NYC MTA buses operating in Manhattan. Speed-time data was collected for both conventional and hybrid-electric buses over several different NYC MTA bus routes. The raw data collected from the buses was broken into two categories depending upon the type of bus, whether conventional or hybrid. This segmented data was then broken into micro-trips consisting of an acceleration to speed from a stop and deceleration to a stop. Of the 399 micro-trips established, 287 were from conventional buses and the remaining 112 from Orion-LMCS hybrid buses. Five of each type of micro-trip were combined randomly and statistically compared to the original data set. Many combinations were examined, and the final set of
ten micro-trips consists of the combination that most closely statistically matches the original data set. To increase the total energy demand of the cycle and to allow for greater accuracy, the cycle was extended to consist of 20 micro-trips covering 2.1 miles in 1,083 seconds. Figure 2.8 shows the first half of the cycle, which is identical to the second half, along a scale that is consistent with the CBD and NY Bus figures. The Manhattan cycle is similar to the NY Bus cycle but with a higher average speed of 6.9 mph. This average speed is consistent with that observed by buses in service for the NYC MTA. The use of this cycle in the testing allowed for the direct comparison of actual in-use fuel economy data, gathered from buses operating in Manhattan, to fuel economy data gathered on the WVU dynamometer.

The New York City Composite cycle is similar to the NY Bus cycle with respect to local inner city driving in that the acceleration and deceleration rates cover a wider range of variation than the CBD. The NY Composite cycle represents a mix of inner city and urban transit bus use that allows for the bus to reach and sustain greater speeds. The average speed of the NY Composite cycle is 8.8 mph. A very limited number of buses were run on the NY Composite cycle, as it is an extremely difficult cycle for both the driver and the bus itself to follow accurately due to the large number of rapid speed changes. Buses that are powerful enough to follow the cycle are penalized by following a difficult cycle while less powerful buses effectively cheat the cycle, getting better fuel economy as a result. While data collected on this cycle is included in the appendix, the use of this cycle to collect meaningful emission comparison data is not recommended.

Two additional routes were developed specifically for this project to correlate dynamometer testing results with actual in-use fuel economy. These are the Routes #22 and #77. Both were developed using data logged from buses in service along these two service routes at Logan International Airport, in Boston, Massachusetts. The Route #22 cycle is a mix of inter terminal stop-and-go passenger service and two...
cruise elements at 30 mph, which represents a round trip to the subway station along the airport access road. The Route #77 is similar to Route #22 except that some additional highway cruise and inner city traffic elements are included as the bus leaves the airport and travels to a satellite parking lot. The average speed for Route 22 is 13.9 mph while the average speed for Route 77 is 16.8 mph.

Testing a variety of bus types on a variety of different cycles with varying average speeds provided far more insight than could otherwise have been obtained through extensive testing on a single cycle. The project data gives a feel for how vehicle fuel-economy increases as the average speed of the cycle increases and the number of stops per mile decreases.\(^3\)

2.4 Conventional Fuels and Alternative Fuels

In addition to conducting testing across a variety of different cycles, various fuels, including CNG, D1 diesel fuel (~300-ppm sulfur on average), low sulfur diesel fuel (~20-ppm sulfur) and synthetic diesel fuel (essentially zero sulfur) were also utilized. The synthetic diesel chosen was MossGas®.

2.4.1 Diesel

Diesel fuel is a complex mixture of hydrocarbon molecules produced by blending byproducts of crude oil refining. After crude oil is distilled into different components, usually several refinery streams are recombined along with appropriate additives to produce commercial diesel fuel. Besides the addition of additives, for the most part the composition of diesel fuel has remained unchanged for some time with the only substantial difference being lower sulfur levels.

The two kinds of diesel fuel used during this project were transportation grade D1 (~300 ppm sulfur), and low sulfur diesel. The low sulfur diesel used was BP Amoco Ultra Low Sulfur City Diesel, conforming to ASTM D-975 diesel fuel specifications. Diesel fuel can burn in a wide range of air-fuel mixtures allowing a diesel engine to use very little fuel at partial loads and when idling. This, combined with low internal losses, allows a diesel engine to achieve the high fuel economy for which it is noted. Diesel fuel infrastructure is well established to produce, transport, and store diesel fuel easily without additional cost to transit system operators.

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\(^3\) See discussion of fuel economy results in Chapter 5.
2.4.2 Synthetic Diesel

Synthetic diesel fuel can be manufactured from a number of different sources including natural gas, gasified coal, and biomass. Synthetic diesel fuel is made using the Fischer-Tropsch synthesis process. The synthetic diesel utilized during this project was MossGas®, a synthetic diesel fuel (10% aromatic blend), which in this case is manufactured using olefin distillate derived from natural gas. The Fischer-Tropsch process reforms natural gas into carbon monoxide and hydrogen, which then is fed into a circulating fluidized bed reactor. This reactor is equipped with a Fischer-Tropsch catalyst that reacts with the hydrogen and carbon monoxide to produce a light synthetic oil. This byproduct is further refined into diesel-grade fuel. Advantages to synthetic diesel fuel are its very low sulfur content (near zero), it can be used in unmodified diesel engines, and it can be transported through the existing petroleum infrastructure.

2.4.3 CNG

Unlike diesel fuel, which is a mixture of many different hydrocarbon compounds, natural gas is a simple hydrocarbon fossil fuel that in pipeline grade consists of about 85 to 99 percent methane (CH₄), essentially zero sulfur, is clean burning and relatively inexpensive and abundant. The use of natural gas in light- and heavy-duty vehicles is extensive due to its low comparative price to conventional fuels, its potential for reduced emissions and the relative ease of its utilization with minor modifications to existing internal combustion engines. Methane has a very low energy density at room temperature and pressure. Practically, this is addressed by compressing the natural gas. Compressed natural gas provides improved energy density and makes it possible to have a realistic storage volume. As a fuel source for heavy-duty vehicles, on-board storage is required in large compressed gas cylinders. These compressed gas cylinders add a considerable weight penalty to the vehicle, as much as several thousand pounds.

Natural gas can be combusted in an internal combustion engine in a number of ways including stoichiometric (spark ignited, equal parts fuel and air), lean-burn (also spark ignited, but more air then necessary) and dual-fuel diesel (compression ignited, also primarily lean burn). Most of the CNG buses offered today in the United States have lean burn engines to minimize NOx emissions without the need for a NOx aftertreatment device. In addition to NOx emissions reductions, CNG fueled buses offer reductions in PM emissions. Emission performance for buses of each fuel type are further discussed in other chapters.

2.5 State-of-Charge Correction

During any given test cycle, the average energy expended by a conventional or alternative-fueled bus is equal to the amount of power provided by the engine. This is not the case for a hybrid-electric bus with an additional electrical energy storage device. The engine on a hybrid-electric heavy-duty vehicle is electronically controlled such that it basically reacts not only to the load that the bus experiences (e.g., acceleration), but also to the state-of-charge (SOC) of the energy storage device. All of the hybrid-electric buses tested in this program were equipped with lead-acid batteries as their load-leveling device (LLD). The LLD does as its name implies. When the vehicle requires more power than the engine can provide; the load-leveling device provides the additional energy. The LLD is also available to capture regenerative braking energy. In heavy-duty hybrid-electric vehicles, the engine is designed to operate in an optimum performance band. This performance band is a tradeoff between fuel economy and emissions, however, by limiting both the operating range and transient operation of the engine, improvements in both can still be achieved.

In a hybrid-electric vehicle the load-leveling device receives energy via two mechanisms, regenerative braking and the APU generator. Since the engine reacts not only to the acceleration
loads, but also to the battery SOC, the engine is not necessarily load following. For example, if a bus experiences a particularly difficult acceleration up a steep incline, energy from the batteries can be borrowed. The batteries may be sufficiently depleted to require recharging during cruise. If this occurs, the engine ramps up to generate excess energy that is provided to the batteries to maintain their SOC within a specified range. Over the course of a day’s operation the battery SOC may fluctuate up and down several times.

Two terms associated with hybrid-electric buses are charge-sustaining and charge-depleting. The former implies that the vehicle derives all of its fuel from the APU, while the latter implies that the vehicle must eventually be recharged via the electric utility grid. All of the hybrid vehicles tested under this program are of the charge sustaining variety although grid connection charging may be performed to normalize the batteries every once in a while for maintenance purposes. Just because a vehicle is charge sustaining in general however does not mean that over the course of a relatively short period of time, such as during a ten minute test cycle, that the battery state of charge will be sustained.

In an ideal world when the bus finishes an emission test cycle, the batteries would have the same SOC at the end of the test as at the beginning (a net SOC difference of zero.) This would allow the data to be used uncorrected. This is currently how SAE J1711 (a SAE recommended practice for light-duty hybrid test procedures) covers SOC corrections by limiting the SOC differential to 1 percent of the energy expended during the cycle.

When a hybrid-electric bus operates in a charge-depleting mode, it effectively borrows energy from the battery to complete the drive cycle test. This, therefore, skews the results, as calculated by the WVU laboratory, to seem better (i.e., fuel economy is higher and emissions lower). Basically the results seem better than reality because less fuel is being used to cover the same distance. Conversely, when the engine puts more energy into the batteries than needed, to bring the batteries back up to optimal SOC, the results are skewed to seem worse because more fuel was used to cover the cycle.

To evaluate the performance of the hybrid-electric buses relative to the conventional and alternatively fueled buses, and amongst each other, the fuel economy and emissions data for each hybrid-electric bus were corrected to account for fluctuations in the battery SOC. For all hybrid-electric bus test runs, the data as calculated by the WVU laboratory were plotted against the net change in SOC of the batteries for the bus. Both the Orion-LMCS and Nova-Allison hybrid-electric buses were equipped with a mechanism to measure net change in SOC of the battery pack. Total current (amp) into and out of the battery pack is measured continuously and a cumulative integrated current (Ah) is calculated. The net Ah taken from or supplied to the batteries is then multiplied by the average system voltage to determine net watt-hours (Wh) values used for the corrections. The Ah method more effectively accounts for battery efficiency losses by averaging out the voltage drop associated with removing power from the batteries and the voltage spikes that occur when the batteries receive power. This net change in SOC, in Wh, was provided at the end of each test. If the net change in battery SOC was not zero during the test, a correction was necessary. After the SOC information was plotted against fuel economy and emissions data, a linear interpolation, or in some cases extrapolation, was performed to establish what the fuel economy or emissions would be at a net change in SOC of zero. In other words, the data was corrected to a net zero change in SOC. In addition, an average (consistent with SAE J1711) was performed for data points where the net change in energy during a test was within 1 percent of the total energy expended throughout the entire test.

Figures 2.12 shows an example SOC correction for one of the Orion-LMCS hybrids on the CBD cycle.
There is a limit to how far you can correct for SOC during a short duration cycle. SAE J1711 limits the differential to 1 percent and does not call for the correction of data within this range. Linear interpolation, or extrapolation, like that shown in Figure 2.12, can be used to correct the data provided the net change in SOC is within a reasonable range. In most cases the apparent trend of the data remained linear with net changes in SOC as large as 20 percent of the total energy expended over the course of the cycle. A vehicle that typically maintains its battery net SOC change within this differential is generally more load following and as a result battery losses are minimized. When a vehicle does not maintain this differential due to significant energy transfer through the batteries the efficiency of the batteries themselves has a pronounced effect on the vehicle efficiency and the relationship between net SOC and fuel economy (also emissions) becomes non-linear.

Because the net SOC limit is based on percentage of the total energy expended on the cycle, one of the ways to increase this tolerance is to run several back to back cycles. On several of the hybrid buses this was done utilizing a triple CBD and in each case the fuel economy results were similar to the single CBD runs. There were however measurable reductions in HC emissions (which were already very small) due to the elimination of the catalyst warm up at the beginning of each cycle.
3.0 Particulate Emissions

3.1 Overview

Combusting fuel in an external combustion unit such as a boiler results in relatively long combustion residence times and relatively complete combustion. In an internal combustion engine, fuel has a limited duration in which to burn and is also combusted in a relatively small space resulting in high peak flame temperatures. As a result, incomplete combustion is a potential issue with internal combustion engines. Incomplete combustion products such as carbon monoxide (CO) and volatile organic compounds (VOC) are typically controlled in an oxidation catalyst, which converts these compounds to carbon dioxide (CO₂) and water (H₂O).

Particulate matter (PM) from internal combustion engines is composed of a combination of carbon particles, on the surface of which, organic compounds are adsorbed. If there is sulfur in the fuel, sulfur compounds will also be present in the particulate along with some metals from the fuel, lubricating oil and wear products. While sulfur emissions are a concern, it is the adsorbed organic fraction that poses the largest toxic risk associated with the particulate. Because the carbon particles are generally less than 2.5 microns (greater than 90 percent, by mass, are less than 1 micron), they typically remain airborne and can be inhaled into the lungs where the adsorbed organic compounds can potentially cause damage. All fuels produce carbon particles as a result of incomplete combustion. The organic fraction is dependent upon the fuel combusted, its combustion residence time, combustion temperature, engine lubricant, and whether an oxidation catalyst or regenerative particulate trap is installed. Several things can initiate the formation of carbon particulate emissions, either separately or in combination, including incomplete combustion from engine over fueling, engine misfiring, lubricant combustion and impurities in the fuel.

Testing for particulate emissions in diesel exhaust has presented a problem for researchers for some time. Smoke opacity and integrated dilute particulate filtration are two methods that have been used in the past. Smoke opacity works well for an engine that produces substantial amounts of visible smoke. For example, smoke opacity measurements would be applicable to an older diesel-powered truck that exhibits puff or full load visible smoke. It is unlikely that conventional opacity meters can even detect the ultra fine particulate matter exhausted by modern diesel and CNG engines.

Integrated dilute particulate filtration (used by WVU in the NAVC program) is achieved by passing a diluted amount of exhaust gas across a filter and then measuring the change in filter mass after the test is completed. Filters are conditioned with respect to temperature and humidity before both pre- and post-test weighing.

Particulate emissions measurement techniques (specifically the dilution tunnel) are under scrutiny, as the way in which the exhaust gas from the bus is diluted has a pronounced effect on the formation of particulate and its size distribution. Other issues include whether sulfur dioxide, sulfuric acid and sulfates are captured and included as part of the particulate sample. For example, at 300 ppm sulfur in D1 diesel fuel, the theoretical sulfur emission rate on the CBD cycle is about 0.3 g sulfur/mi. Obviously, since most reported PM values from this test program are below this value, not all sulfur compounds are detected by current PM sampling technologies. Of additional concern is whether different test facilities capture sulfur compounds in the same way. Stationary combustion sources such as boilers convert nearly all sulfur in the fuel to sulfur...
dioxide prior to being emitted. Combustion in an internal combustion engine however, typically converts only a relatively small portion of the sulfur in the cylinder with the remaining sulfur potentially converted in the aftertreatment device, atmosphere and beyond the sampling train. Once in the dilution tunnel, sulfur emissions are sensitive to humidity levels, which will affect their collection in the PM sampling equipment.

3.2 PM Emissions

PM emissions from the hybrid vehicles were generally 50 to 70 percent lower than a conventional diesel. In several cases, the actual reduction could not be quantified, as the measurement equipment did not have the sensitivity to quantify the mass emissions from the hybrids. Several systems on the hybrid buses are responsible for these PM reductions, the ability to utilize regenerative braking, less transient engine management and regenerative particulate trap control. The Orion-LMCS hybrid was also tested on both the CBD and NY Bus test cycles with its regenerative braking system turned off. Over the CBD cycle, the Orion-LMCS hybrid and conventional DDC Series 50 diesel engine buses produced roughly equal amounts of PM. No correlation can be drawn from this as additional sulfur compounds can be converted in the trap offsetting potential carbon particulate reductions. This is still a considerable feat considering the smaller engine and greater weight of the hybrid bus. On the NY Bus cycle, without regenerative braking, the Orion-LMCS hybrid bus performed better than the conventional diesel, with PM emissions below the detection limit (BDL) of the measurement equipment.

Figure 3.1

NY Bus Cycle PM Emissions

PM emissions from the CNG buses, powered by DDC Series 50G engines were consistently around 80 to 90 percent lower than a conventional diesel bus. Figures 3.1 and 3.2 provide a graphical comparison of the PM emissions of each bus type tested during this project.

The CNG and hybrid buses had comparable PM performance on each cycle when the hybrids were operated on very low sulfur fuels. When the Orion-LMCS hybrid was operated on
conventional D1 diesel fuel (300-ppm sulfur), CNG bus PM levels were 50 to 80 percent lower than the hybrid’s levels. The Nova-Allison bus exhibited PM emission rates consistently lower than CNG buses as this bus was operated exclusively on very low sulfur diesel. With the Nova-Allison hybrid buses regenerative braking disabled, hybrid PM emissions increased slightly giving CNG a small advantage.

Anecdotal observations and empirical calculations based on the sulfur content of the fuel indicate that the WVU sampling system does in fact capture some sulfur compounds (sulfuric acid, sulfates). However, the exact form of the sulfur compounds is not clear. The presence of sulfur compounds was confirmed by back-to-back tests on the same vehicles with different fuels. Both a conventional Nova RTS with a Series 50 engine, equipped with an oxidation catalyst, and an Orion-LMCS hybrid with a Series 30 engine, equipped with a particulate filter trap were tested first on conventional D1 diesel fuel. Then the fuel systems were flushed and the buses were re-tested with MossGas®. The D1 diesel fuel contains about 300 ppm (0.03 percent) sulfur while the MossGas® has essentially zero sulfur content. Some additional CBD cycles were performed on two Orion-LMCS hybrid buses utilizing the low sulfur (LS) diesel fuel (<20 ppm sulfur) that is typically used in the Nova-Allison hybrid bus. The PM value for the Orion-LMCS hybrid on LS diesel was 0.01 gram per mile, which compares favorably with the MossGas® value of 0.02 gram per mile as both of these values are basically at the detection limit of the equipment.

The particulate data from these back-to-back runs is charted in Figure 3.3 with the upper blue bars in each pair depicting results with conventional D1 diesel fuel and the lower yellow bars depicting the PM emission utilizing the zero sulfur MossGas® fuel. Once the sulfur in the fuel has been eliminated the hybrid PM values fall in line with those seen from the cleanest conventional CNG vehicles. Also, low sulfur diesel fuel may encourage better long-term performance of the aftertreatment devices.

Figure 3.3

The charted results in Figure 3.3 (D1 diesel vs. MossGas®) show a strong correlation between fuel sulfur content and particulate emissions. Calculated sulfur in fuel emissions are roughly 0.8 g sulfur/mi on the NY Bus cycle and 0.3 g sulfur/mi on the CBD. While sulfate (SO₄) is considered a particulate it is not listed as carcinogenic. As shown in Figure 3.3, reducing the

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*California Air Resources Board (CARB) “Proposed Identification of Diesel Exhaust as a Toxic Air Contaminant”, April 22, 1998. CARB identified over 40 substances that are listed by the U.S. EPA as hazardous air pollutants or by CARB as toxic air contaminants, many of which were detected or predicted to be present in diesel exhaust. Many of these compounds are polycyclic aromatic hydrocarbons (PAH) and PAH derivatives that have been found to be potent mutagens and carcinogens. The document finds that solid carbon particles comprise a majority of diesel PM₁₀ composition that facilitate the presence of adsorbed toxic organic compounds. The finding discusses sulfur emissions but does not present a finding that they are a contributing factor to the carcinogenic potential of diesel exhaust.*
amount of sulfur in the fuel can eliminate a significant portion of PM emissions. It is evident that the reduction or elimination of sulfur in diesel fuel has significant benefits with regard to the reduction of particulate emissions in addition to increasing the performance potential of aftertreatment, emission control devices.

The remaining exhaust particulate is comprised mostly of unburned carbon, organic compounds and other inert contaminants. The noticeable difference in particulate emissions on the synthetic fuel between the conventional NovaBUS diesel and the Orion-LMCS hybrid is achieved partially by engine management in the hybrid and partially by the use of a regenerative particulate trap on the hybrid-electric buses to burn off and complete the combustion of unburned carbon. While there is very little PM mass remaining, there may still be a significant particle count. These smaller and numerous nanoparticles may pose a greater inhalation risk and the need to determine the exact composition of this material warrants further in depth testing.

Particulate emissions from several of the hybrid and CNG buses were near or below the detection limit of the WVU PM measuring equipment. On the CBD cycle, the WVU detection limit is approximately 0.01 to 0.02 g/mi. This is not due to the accuracy of the weighing equipment, but is in fact limited by ambient conditions. In the WVU sampling tunnel, ambient dilution air is drawn in unfiltered. To account for ambient particulate, a background filter is recorded and the background filter net change in mass is subtracted from the PM filter mass collected during the actual test runs. As bus PM emissions get lower and approach 0.01 g/mi, the PM emissions from the bus exhaust begins to fall below the variability of the background PM levels resulting in background readings that are near or higher than filters from actual emission tests. Filtering the dilution air would appear to be a partial solution. While ambient PM undoubtedly differs from diesel and CNG bus exhaust in composition, when exhaust PM levels approach ambient, ultra-clean buses are potentially removing as much PM as they are emitting.

Visual observation of the particulate filters showed a slightly gray filter (left) reflecting a mass below the detection limit of the WVU equipment. A gray filter (center) reflects a mass above the detection limit. The last black filter (right) was well above the detection limit of the WVU equipment. This slight discoloration of the filter on the far left in Figure 3.4 indicates that there is in fact some remaining particulate emission but there is too little mass for accurate weighing considering the sampling equipment and method used. For this reason the particulate emissions for these vehicles should be considered BDL and not zero. To place these extremely low PM measurements for both the low sulfur diesel hybrid and CNG buses in context, at 0.02 g/mile over the course of a year, a 40-foot transit bus would emit about 540 grams of particulate (assuming 27,000 mi/yr), or about 1.2 lbs/yr.

**Figure 3.4: Particulate Filters**
3.3 Historical PM Emissions

An historical review of bus PM test data reveals that CNG engines have always produced little PM and diesel PM emissions have declined significantly. The historical emissions from the last ten years were taken from a WVU and DOE data set and compared to the emissions from buses tested under this program. Figure 3.5 illustrates that PM emissions from CNG buses have remained low over the past decade. Because most current CNG engines employ lean burn NOx combustion strategies, a majority of the PM from a CNG engine is from lubricant consumption. This distinction is important as the formation of carbon particulate and adsorption of soluble organic compounds from the lubricant onto the carbon particulate could likely contribute to a particulate make-up from a CNG engine that is very similar to that from diesel fuel combustion. An additional point that should be noted is that lubricant composition for diesel and CNG engines differs somewhat with regard to ash content (higher for CNG engines) and other additives.

Figure 3.6 shows that diesel PM emissions have decreased as regulatory drivers have placed more and more stringent limitations on the amount of allowable particulate. The urban bus standard for PM has changed considerably over the last decade. In 1990, the standard was 0.6 g/bhp-hr, which was then lowered to 0.1 g/bhp-hr in 1993, 0.07 g/bhp-hr in 1994, and most recently to the current level of 0.05 g/bhp-hr in 1996. Of particular interest are the results with synthetic MossGas® fuel (zero-sulfur) with values of 0.09 g/mi for a Series 50 diesel on the CBD cycle as compared to the Series 50G CNG values of 0.02 g/mi. This places synthetic diesel fuel within an order of magnitude (just a little over 4x) of CNG versus the two orders of magnitude (100x) from previous generation equipment.
4.0 NOx and NMOC Emissions

4.1 Ozone Precursor Overview

Under the Clean Air Act (CAA), the U.S. EPA is responsible for setting National Ambient Air Quality Standards (NAAQS) for six criteria pollutants; carbon monoxide (CO), lead (Pb), nitrogen dioxide (NO₂), ground-level ozone (O₃), particulate matter (PM) and sulfur dioxide (SO₂). Of these pollutants, ozone is not attributable to direct emissions but is instead a function of ozone precursor emissions. Oxides of nitrogen (NOx) and volatile organic compounds (VOCs) are regulated as precursors for ozone. Many urban regions of the U.S. are considered non-attainment for the ozone NAAQS.

VOCs are defined in a regulatory sense as any compound of carbon that participates in atmospheric photochemical reactions. By definition VOCs are the subset of organic compounds that are considered ozone precursors. This definition exempts several compounds, including many fluorinated hydrocarbons (primarily refrigerants), methane, ethane, carbon monoxide, carbon dioxide, acetone and several others. It should be noted that this list is updated as compounds are determined to be non-reactive with respect to ground level ozone. Diesel fuel, compressed natural gas (CNG) and other petroleum products are principally hydrocarbon compounds (HCs)—organic compounds consisting exclusively of the elements of carbon and hydrogen. When hydrocarbon compounds are burned, exhaust emissions consist of primarily HCs. As a result, the organic emissions from diesel vehicles are generally referred to as hydrocarbons. These may include unburned hydrocarbons (paraffins, olefins, aromatic hydrocarbons), partially burned hydrocarbons (aldehydes, ketones, carboxylic acids) and products/derivatives of thermal cracking (acetylene, ethylene, hydrogen, polycyclic hydrocarbons and carbon).⁵

For transportation sector purposes, HCs can generally be used synonymously with the VOC designation. The exception to this rule occurs in vehicles and internal combustion equipment that combusts natural gas. A large percentage—95 percent or more—of the HC exhaust from a natural gas fueled vehicle is unburned fuel, in this case methane. Because methane is not considered a VOC, HC emission values from natural gas vehicles are usually divided into methane and non-methane hydrocarbon (NMHC). HC and NMHC designations are usually reserved for transportation sources, but to allow for the inclusion of additional organic compounds (that don’t meet the narrow “only hydrogen and carbon” definition of hydrocarbon) that may be present, the broader term non-methane organic compound (NMOC) is used throughout this report.

There is an assumption that NMOC is equivalent to non-methane volatile organic compound (NMVOC) where the volatile designation presupposes that the compounds in question are in fact reactive with respect to ground level ozone. According to a study prepared by the Colorado School of Mines, however, the NMOC portion of CNG HC includes substantial amounts of ethane and propane.⁶ The ethane contribution comes primarily from ethane present in the CNG fuel that is, like methane, not combusted. Like methane, ethane is not generally considered a VOC however the emission standards for NMHC effectively include ethane. A complete analysis

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⁶ Robert L. McCormick et al., In-Use Emissions from Natural Gas Fueled Heavy-Duty Vehicles, May 3 1999 SAE International Spring Fuels and Lubricants Meeting and Exposition, 1999-01-1507
of the exhaust HC samples was not performed during this project and as a result we are unable to determine the percentage ethane in the total hydrocarbons (THC) samples. According to the Colorado School of Mines paper, ethane comprises about 60 to 80 percent of the NMHC, however, ethane content is dependent upon the source of the CNG fuel and it has also been published that ethane comprises as little as 33 to 40 percent of the NMHC range.\(^7\)

In the lean-burn NOx optimization strategy, there is a continuous tradeoff between NOx emissions on one-hand and NMHC and CO emissions on the other hand when utilizing a lean combustion optimization strategy. Because both NOx and VOCs are considered ozone precursors it is important that emission reductions from one of these compounds are not achieved at the expense of the other, as this would negate the desired effect from an air quality standpoint. Combined emission standards are a solution when the reduction of one pollutant would result in increases of another pollutant with similar air quality impacts. In 2004 the Federal Urban Bus NOx Standard of 4.0 g/bhp-hr will become a combined standard of 2.4 or 2.5 g/bhp-hr for NOx plus NMHC\(^8\). In the latter standard NMHC is limited to 0.5 g/bhp-hr of the total.

### 4.2 NOx and NMOC

Each of the vehicles tested under this program was equipped with an oxidation catalyst for the control of CO, HC and PM. In the cases of the hybrid electric buses a particulate trap integrated with oxidation catalyst material was used. While HC emissions from a diesel engine are already quite low, including the oxidation catalyst helps the particulate trap regenerate by converting NO in the engine exhaust to \(\text{NO}_2\). The \(\text{NO}_2\) then helps oxidize carbon particles caught in the trap. The combined values of NOx and NMOC emissions are charted in Figures 4.1 and 4.2.

NOx emissions from the Orion-LMCS hybrid buses were 30 to 40 percent lower than a conventional diesel vehicle. This result is interesting given these hybrid buses utilized diesel engines certified to the same NOx standard of 4.0 g/bhp-hr. Only about a third of this benefit is attributable to regenerative braking. The Orion-LMCS hybrid was tested on both the NY Bus cycle and the CBD cycle with its regenerative braking system turned off and in both cases NOx emissions were still 20 to 30 percent lower than the conventional DDC Series 50 diesel engine.

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7 Ralph D. Nine et al., Hydrocarbon Speciation of a Lean Burn Spark Ignited Engine, 1997 SAE International Fall Fuels and Lubricants Meeting and Exposition, 972971

8 As part of a settlement agreement between EPA and several engine manufacturers, emission reductions of 80 percent, compared to current levels, will be achieved by October 1, 2002, 15 months before those standards are scheduled to take effect. Additional information about the settlement is available from the EPA at: http://es.epa.gov/oeca/ore/aed/diesel/
bus. As these vehicles were not equipped with aftertreatment for the control of NOx, the remaining NOx benefit must be attributed to differences in engine operation.

NOx emissions from the DDC Series 50G engine CNG buses were consistently 50 to 60 percent lower than a conventional diesel bus. CNG buses set the ozone precursor benchmark with hybrid-electric buses a close second. Not surprisingly, this is consistent with engine certification data where the DDC Series 50G engine is typically around 2.0 g/bhp-hr NOx while the DDC Series 50 diesel is close to the standard at 4.0 g/bhp-hr NOx. The general trend in NOx emissions versus average cycle speed is illustrated in Figure 4.3.

However, NOx results for CNG buses were not consistent as CNG buses tested had both the lowest and highest measured NOx emissions in the NY Bus cycle. CNG buses equipped with the Cummins L10 280G engine demonstrated high NOx over a majority of the cycles indicating that this engine was tuned more toward stoichiometric operation. CNG vehicles that did exhibit very low NOx levels were accompanied by higher NMOC and CO emissions.

### 4.3 Time Series Data

As with any testing program, this program generated a significant amount of time series data. Presenting all of this data would be cumbersome to say the least but some level of detail is necessary to evaluate the relative differences between CNG, diesel and hybrid-electric vehicles and their associated operating parameters. Because of analyzer response times, tunnel dilution and other factors, this data does not necessarily represent what is instantaneously being emitted from the vehicle but is more accurately a look at a several second rolling average. Some direct comparisons can still be made because the runs from each bus were conducted under the same circumstances with the same equipment and analyzers.
4.3.1 NMOC Time Series
Oxidation catalysts are used primarily to oxidize HCs. As a result, looking at the HC time series data gives an indication of whether the catalyst was operating correctly. Figure 4.4 indicates that the oxidation catalyst on the Nova Diesel Series 50 engine was operating as expected with only a slight warm up required following extended idle periods. It is obvious that a large portion of the NMOC emission from this diesel bus was emitted during the first few acceleration ramps.

Figure 4.5 illustrates a NY Bus cycle run for the Nova-Allison hybrid bus. Once again only the first few acceleration ramps are necessary for the catalyst to reach optimum operating temperature.

HC emissions from a CNG bus cannot be used for direct comparison to Figures 4.4 and 4.5 because the breakout of THC between methane and NMOC is not available in real time. The methane/NMOC split is known to vary with engine load, and does not reflect only the CNG consumption. The CNG bus time series data does not illustrate any catalyst warm up. The catalyst was either operating properly, or had little effect with regard to the oxidation of methane emissions.
4.3.2 NOx Time Series

No aftertreatment controls for the reduction of NOx were installed on any of the vehicles tested under this project. As a result it is expected that NOx emissions would track with power delivered to the cycle.

A comparison between Figures 4.6 and 4.7 shows that baseline NOx emissions at low load idle or dwell for the diesel engine are high when compared to a CNG bus. Figure 4.7 illustrates that the CNG bus NOx emission rate is superior under both idle and full load conditions. This difference tends to manifest itself as you move toward drive cycles that include substantial idle periods such as the NY Bus cycle. Under these circumstances the overall NOx ratio between the CNG and diesel buses tends to favor CNG buses.

Hybrid buses (Figure 4.8) can avoid this engine idle issue to some extent by shutting the engine off or keeping the engine under load, both of which reduce NOx. In the case of the Orion-LMCS hybrid, loading the engine near idle lowers NOx emissions and produces useful energy that helps recharge the batteries and can be utilized later. The result for the hybrid buses is a lower idle NOx baseline and lower peak NOx emission during acceleration due to energy assistance from the load leveling device.
4.4 **Historical NOx and NMOC Emissions**

An historical view helps put diesel and CNG emissions into perspective and once again shows that there are no absolutes when referring to bus emissions. Only THC historical emissions data are available.\(^9\) The CNG total organic compound (TOC) values are primarily methane. Emissions listed for 1996 and before were measured by WVU on the same test equipment but under previous programs. Emissions values for 1998 and 1999 model year engines were measured during this testing project. Only conventional buses are included in these historical charts.

The historical NOx data for CNG buses in Figure 4.9 indicate a trend towards lower NOx. The median NOx rate for 1998 and 1999 CNG engines is about 15 grams per mile on the CBD cycle. Figure 4.10 shows that NOx emission values for diesel buses have also declined over the last ten years. The median NOx rate for 1998 and 1999 diesel engines tested under this program is about 30 gram per mile (on the CBD cycle) or about twice that of CNG buses.

Once again, this dynamometer comparison of CNG NOx versus diesel NOx correlates well with certification data where CNG engines have been certified at half the NOx rate of diesels (or CNG 2.0 g/bhp-hr to new diesel engines at approximately 4 g/bhp-hr).\(^{10}\)

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\(^9\) Emission data from the DOE website can be accessed through a database query at http://www.ott.doc.gov/ohvt/heavy_vehicle/hv/emisbus.html; West Virginia University collected this data on their transportable dynamometer laboratories, which spans heavy-duty buses from 1988 through 1998 on the CBD cycle.

Figures 4.11 and 4.12 show the emission trend of THC emissions for CNG and diesel buses. While diesel bus THC emissions have fallen dramatically (likely due to the switch from two-stroke to four-stroke technology and the installation of oxidation catalysts), THC emissions from CNG buses have actually increased, due to lean fuel mixture operation to reduce NOx. While the fuel lean combustion mixture is implemented as a NOx reduction strategy, the oxygen sensor used for feedback control has limited capabilities. As a result, fuel-lean combustion in a CNG engine which relies heavily on this sensor will typically result in lower NOx emissions at the expense of higher HC and CO emissions.
5.0 Fuel Economy

5.1 Overview

An important objective of the NAVC testing project was to correlate dynamometer testing with actual in-use performance of the buses to determine whether the drive cycles and the WVU lab were indicative of actual in-use operation. The only performance metric that can currently be captured during real world operation is fuel economy. Where available from transit operators, in-use fuel economy data was collected for each vehicle type for comparison to dynamometer test results and estimated fuel economy numbers. In-use fuel economy was available for each bus type tested under this program with the exception of the NYC MTA New Flyer CNG buses.

Transit buses consume energy to provide both motive power and to support auxiliary systems. Factors which ultimately govern the fuel economy of the bus are: vehicle inertia (vehicle and passenger weight) or acceleration (kinetic) energy; vehicle drag coefficient and frontal area, and tire rolling resistance (commonly referred to as road load); and accessory requirements, such as air conditioning, compressed air and power steering. An important additional factor is the efficiency with which power is transferred to the wheels. An example of the estimated energy expended per mile for the NY Bus, CBD and Manhattan cycles is shown in Figure 5.1. The estimates in this figure are for power delivered to the wheels and auxiliary systems and do not account for drive system or engine efficiency. This is why two vehicles achieve different fuel economy on the same cycle.

Acceleration energy and auxiliary systems such as air conditioning tend to dominate cycles with low average speeds such as the NY Bus and Manhattan cycles. In the CBD cycle, energy consumption is more evenly distributed between accessory load, road load and acceleration energy (kinetic energy). Eventually there is a point during steady state cruise operation, where acceleration energy is near zero and the energy consumption is dominated by road load and accessory load only.

5.1.1 Hybrid Vehicle Energy Economy and Recovery

A majority of the substantial fuel economy benefit derived from today’s hybrid-electric vehicles comes from the recovery of kinetic energy (the lower part of each bar in Figure 5.1) through regenerative braking. However, the amount of regenerative braking energy recovered is affected by the cycle on which the vehicle is operating. As a general rule most vehicles can stop far faster than they accelerate with braking only limited by tire slippage. The faster a vehicle decelerates, the less kinetic energy can be recovered due to technological limitations in the vehicle energy...
storage device (batteries) and their ability to accept energy quickly. Acceleration on the other hand is usually limited by engine power or in the case of a hybrid vehicle, drive system power. This is relevant to hybrid buses because the total amount of regenerative braking captured in a hybrid vehicle is limited by the total power handling capacity of the drive motor, controller and load leveling device (batteries). Despite this limitation the total amount of kinetic energy in any given urban cycle is significant and large improvements in fuel economy are expected as a result of recovering just a portion of this energy. Some additional benefit can also be attributed to increased engine efficiency of smaller engines in the hybrid vehicles, which translates into lower idle or dwell losses, although some of this increased engine efficiency is lost due to battery inefficiency.

Figure 5.2 provides a representation of horsepower (hp) and speed across one element of the CBD cycle. A vehicle on the CBD cycle is accelerated to 20 mph in 9 seconds and then decelerated to a stop in 4 1/2 seconds. If road load is ignored for a moment, the total amount of specific energy that is supplied to accelerate the vehicle must subsequently be removed from the system to decelerate the vehicle. Because the vehicle in the CBD cycle is stopping twice as fast as it accelerated, the total specific power for deceleration is roughly two times that of the acceleration. In most cases the peak power reserve of the drive system components is sufficiently high to accommodate this phenomena with the load-leveling device (battery) being the limiting factor. This rapid deceleration from speed is unique to the CBD cycle and as a result lower regenerative braking energy capture is seen on this cycle. In on-road operation, buses generally decelerate at about the same rate as they accelerate to maintain passenger comfort. If this on-road deceleration rate was applied to the CBD cycle, not only would a hybrid bus capture more kinetic energy, but both a hybrid and a conventional bus would travel further than the CBD cycle dictates. A modified CBD cycle would be more representative of actual deceleration rates, with the bus coasting for a period prior to applying the service brake. The way the CBD cycle is currently structured, in order to meet the prescribed deceleration rate, the driver must apply the brakes quickly and hard, which effectively forces the service brakes to take over the brunt of braking duties as opposed to regenerative braking. If the bus is allowed to coast for a portion of the deceleration, similar to real-world conditions, more regenerative braking energy can be captured, thus allowing for even further increased fuel economy and reduced emissions proportional to the increased distance covered.

5.1.2 Estimating Vehicle Energy Consumption

To better understand the performance of the different transit buses, the total energy consumption was considered for each cycle. In a transit bus the total energy consumption is composed of
several categories: acceleration (kinetic energy); road/wind load (external friction); hill climbing (potential energy); accessories (including air conditioning); and mechanical system losses (internal friction and engine losses).

Depending upon the duty cycle of the vehicle any one of these energy consumption categories may dominate the total energy consumed and determine the ultimate in-use fuel economy of the vehicle. In a hybrid vehicle, kinetic and potential energy can be recovered via regenerative braking. This has the effect of increasing fuel economy by reducing the amount of power that needs to be supplied by the engine. It also has the effect of increasing the dominance of certain friction components to the point where road load or even air conditioning loads may determine the ultimate fuel economy of the vehicle. As shown in Figure 5.3, aerodynamic losses are minimal for most of the transit duty cycles because maximum urban transit speeds are generally less than 25 mph. Road load is therefore usually dominated by tire and drive system friction losses.

5.1.3 Estimating Vehicle Fuel Economy

Based on the speed-time plots for each cycle, energy consumption and fuel economy was estimated for a typical transit bus. Total energy consumption for a typical 35,140-lb (half-seated load weight) transit bus was estimated as a baseline for comparison. These fuel economy estimates were then plotted against average vehicle speed for each cycle as shown in Figure 5.4.

A vehicle’s fuel economy is dependent upon two primary operational variables, the average speed of the vehicle and the number of times that vehicle comes to a stop. Generally speaking most transit bus cycles are similar in that when the average speed of a cycle increases the number of stops per mile decrease. It is however possible for two drive cycles to have the same average speed but with different speed-time profiles and stops per mile. Because of this it is expected that
not all drive cycles would fall onto the trend line shown in Figure 5.4. The line has been included to highlight a general trend upward in fuel economy as average cycle speed increases.

5.2 Dynamometer Measured Results

The fuel economy benefits of hybrids are borne out in Figure 5.5. The dynamometer data charted here is contained in Appendix A. There were consistent fuel economy improvements of nearly one mile per gallon for the Orion-LMCS Hybrid and nearly one half of a mile per gallon for the Nova-Allison Hybrid over conventional buses on the NY Bus, CBD and Manhattan cycles. While these may seem like small numbers, bear in mind that on the NY Bus cycle the best performing diesel buses only achieved 1.4 mpg fuel economy versus 2.3 mpg for the Orion-LMCS hybrid-electric bus. This equates to about a 65 percent fuel economy improvement for the Orion-LMCS Hybrid on the NY Bus cycle over a conventional diesel.

The hybrid-electric vehicles tested under the NAVC project are essentially conventional buses with hybrid-electric drive systems. As a result, the hybrid-electric buses weigh more than conventional diesel buses (CNG buses are heavier as well) due to the extra weight associated with the batteries (or CNG tanks in a CNG bus). Much of the additional energy used for accelerating this weight can be recovered via regenerative braking in the hybrid-electric vehicle, although inefficiencies in the drive motors, differential and batteries prevent the capture of all of this energy. Vehicle weight is a continuing concern from a passenger carrying capacity standpoint and needs to be considered so that a fully loaded bus does not exceed its gross vehicle weight (GVW). When reviewing the fuel economy and emission data in this report bear in mind that the weight of each manufacturers’ current model offering may differ from the values tested under this project as manufacturers are working to reduce overall vehicle weight. As a result, significant

Table 5.1: Curb, Gross and Test Weight of Buses

<table>
<thead>
<tr>
<th>OEM/Chassis/Fuel</th>
<th>Curb/GVW (lbs)</th>
<th>Test Weight (lbs)</th>
<th>Passenger Capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neoplan AN440T CNG</td>
<td>29,820/40,600</td>
<td>34,170</td>
<td>56</td>
</tr>
<tr>
<td>Nova RTS diesel</td>
<td>28,200/39,500</td>
<td>32,250</td>
<td>52</td>
</tr>
<tr>
<td>Orion V CNG</td>
<td>33,225/41,800</td>
<td>37,495</td>
<td>55</td>
</tr>
<tr>
<td>New Flyer C40LF CNG</td>
<td>29,600/37,920</td>
<td>33,650</td>
<td>52</td>
</tr>
<tr>
<td>Nova RTS Allison Hybrid Diesel</td>
<td>30,600/36,900</td>
<td>34,735</td>
<td>53</td>
</tr>
<tr>
<td>Orion VI LMCS Hybrid Diesel</td>
<td>31,315/41,640</td>
<td>35,140</td>
<td>49</td>
</tr>
</tbody>
</table>
weight differences could have an effect on the emission test values. For comparison purposes, the curb, GVW, and the test weight for each bus tested are listed in Table 5.1.

The test weight for each bus was determined by multiplying half of the seated and standing passenger capacity (also shown in Table 5.1) by 150 lb and then adding an additional 150 lb for the driver. The amount of CNG consumed during the test has been converted to a diesel equivalent gallon based on a conversion factor of 137 cubic feet of natural gas per gallon of diesel fuel.

The results show a clear fuel economy improvement for hybrid-electric technology over conventional diesel and CNG buses regardless of test cycle (see Figures 5.6, 5.7, and 5.8). As expected, conventional diesel buses exhibited better fuel economy than comparable CNG buses, which pay a fuel economy penalty due to higher vehicle weight and lower overall engine efficiency. CNG engines have a lower compression ratio and are throttled versus diesel engines that are high compression, non-throttled. Not all of the buses were run on the Manhattan cycle due to time and budget constraints but as expected the fuel economy results on the Manhattan cycle lie between the NY Bus cycle and the CBD cycle as shown in Figure 5.8.
5.3 Buses In-Use and on the Dynamometer

Dynamometer testing was conducted on a variety of drive cycles but some comparison to the vehicles in actual service must be performed to determine whether the dynamometer testing is representative of the actual in-use operation and fuel economy. Initial dynamometer testing on the NY Bus and NY Composite cycles indicated that the actual duty cycle of the buses operating out of the NYC MTA Manhattanville depot was somewhere in between these two cycles with an average speed of between 6 and 7 mph.

5.3.1 Massport Neoplan CNG Operating at Logan International Airport, Boston, MA

The in-use and dynamometer test data for the Massport Neoplan CNG buses, shown in Figure 5.9, correlates well with average estimated values. Actual in-use fuel economy is lower than that seen on the WVU dynamometer. However, the lower fuel economy is more likely due to excess idle and the use of climate control on the buses during the in-use data collection period. The test weight of the Neoplan buses was 34,170 which is near the assumed estimated weight of 35,410 and as a result the dynamometer data falls very close to the trend line.

5.3.2 NYC MTA NovaBUS Diesel Operating in Manhattan, NY

NY MTA buses are operated in and around Manhattan and, with the exception of the express buses, all of the routes typically have low average speeds of between 6 and 7 mph. In service data indicated that average route speeds and fuel economy were somewhere above that of the NY Bus cycle and lower than the NY Composite or CBD cycles typically used by WVU. As a result the Manhattan cycle was created to allow in-use fuel economy comparison to the WVU test data. Figure 5.10 shows a comparison of in-use
data to dynamometer test data. In general the Nova diesel buses on the WVU dynamometer exceeded average fuel economy estimates by 5 to 10 percent. This is most likely due to the increased efficiency of the diesel engines and the fact that the actual test weight of the Nova RTS bus was 32,250 lb versus the 35,140 lb used to estimate the baseline. In-use fuel economy for these buses did correlate well to the dynamometer data for the Manhattan cycle with actual in-use fuel economy slightly lower than that achieved on the dynamometer but still higher than baseline. Dynamometer data for the Nova Diesel did not, however, correlate well with the NY Composite cycle where it exceeded fuel economy estimates by nearly 25 percent. This is likely due to the 3-speed transmission, which made following the NY Composite cycle difficult for the driver.

5.3.3 NYC MTA New Flyer CNG Operating in Brooklyn, NY

The NY MTA New Flyer CNG buses dynamometer test data compares well to estimated fuel economy, as shown in Figure 5.11. In-use data for the New Flyer CNG buses was not available and as a result it is not possible to estimate which cycle would be representative of actual in-use operation since they are operated out of Brooklyn and not Manhattan. There is however sufficient dynamometer data to suggest that the dynamometer test results are sufficiently representative of different operating modes to allow comparison of the Nova diesel Series 50 and New Flyer Series 50 G CNG buses to each other. The test weight of this bus was 33,560 lbs, near that of the Nova RTS bus. The only significant difference between the buses is a 5-speed transmission in the New Flyer versus a 3-speed transmission in the Nova. The Series 50 diesel engine fuel economy is about 10 percent better than its Series 50G CNG equivalent.

Figure 5.11

5.3.4 NYC MTA Nova-Allison Diesel Hybrid Operating in Manhattan, NY

The NY MTA Nova-Allison hybrid bus in-use data correlates well to the dynamometer fuel economy test data and is much improved over conventional vehicles. For the Nova-Allison hybrid, turning off the regenerative braking...
system resulted in reduced fuel economy numbers that were commensurate with conventional buses, as illustrated in Figure 5.12. This tends to reinforce the fact that a majority of the fuel economy increase is attributable to regenerative braking and not to enhanced engine efficiency. This is only partially true as any increased engine efficiency is partially lost due to battery inefficiency when load leveling. What is indicated is that the combination of a smaller engine, more efficient operating modes and batteries is no less efficient than an automatic transmission. The Nova-Allison hybrid had limited in-use data with relatively few miles traveled (2,072) during the scope of this project, however the in-use fuel economy data available was higher than conventional diesel buses. Visually observed fuel economy on the Manhattan cycle is roughly proportional to the increases observed on the NY Bus and CBD cycles.

5.3.5 NYC MTA Orion-LMCS Diesel Hybrid Operating in Manhattan, NY
For the Orion-LMCS hybrid, in-use fuel economy was much improved over conventional diesel and CNG buses. On the WVU dynamometer the Orion-LMCS bus fuel economy consistently exceeded conventional buses as shown in Figure 5.13. Two important comparisons can be made for the Orion-LMCS hybrid bus. Vehicles were tested on both the NY Bus and the CBD cycle with the regenerative braking system turned off. On the NY Bus cycle where the engine is predominately operated at low power, fuel economy fell to a value consistent with a conventional bus although still slightly improved. On the CBD cycle fuel economy fell but remained significantly higher than a conventional vehicle. This increase is most likely attributable to increased engine and drive system efficiency and the fact that the LMCS auxiliary power unit is powerful enough to provide a majority of the drive power, relying less on the batteries and their associated efficiency losses for load leveling. Once again the NY Composite cycle appears to be an outlier on the apparent fuel economy trend.

5.3.6 NY DOT Orion V CNG Operating in Brooklyn, NY
NY DOT buses are operated in and around Queens and Brooklyn. In-use data was compared to estimates of fuel economy as well as dynamometer test data, as shown in Figure 5.14. In general the dynamometer average fuel economy for these buses was lower than estimated. The Orion V CNG was the heaviest bus tested during this project, at 37,495 lbs, and this difference in weight would explain the difference in fuel economies since the fuel economy estimate was established using a baseline bus weight of 35,140 lbs. Dynamometer data for the Orion Series 50G CNG buses did correlate and trend well with each of the cycles. In-use fuel economy for these buses appears to correlate well to the dynamometer data. Route data was not available for the DOT.
Depot. While the in-use fuel economy was charted against the CBD cycle, the in-use data indicates an average speed and duty cycle somewhere between the NY Composite and CBD cycles.

5.3.7 In-Use Summary
Several trends were established from the comparison of estimated fuel economy, dynamometer tested fuel economy and actual in-use fuel economy.

- Dynamometer test results correlate and trend well with estimated values with the exception of the NY composite cycle.
- In-use fuel economy is consistently lower than the dynamometer test data presumably due to increased off-cycle idle and the use of climate control systems.
- The derived cycles (Manhattan, Routes 22 and 77) appear representative of in-use operation.
- CNG buses were less fuel-efficient than their diesel equivalent by 10 to 20 percent (attributable to reduced engine efficiency and increased vehicle weight).

For comparison purposes all conventional bus dynamometer data is plotted against estimated values in Figure 5.15. There is a direct relationship between average route speed and fuel economy.
6.0 Carbon Dioxide and Methane Greenhouse Gas Emissions

6.1 Overview

The United Nations Framework Convention on Climate Change (UNFCCC) uses the term climate change to describe only the change in climate brought about by human activity. The Intergovernmental Panel on Climate Change (IPCC), appointed by the United Nations and the World Meteorological Organization, has issued a series of comprehensive documents assessing the climate change issue and the pollutants (labeled greenhouse gases or GHGs) which contribute to this effect. Research indicates average global temperatures are rising and the rate at which they are rising is also increasing with the average global temperature higher by nearly 1°F over the last decade.\(^\text{11}\) The temperature change coincides with significant increases in global concentrations of GHGs.

The global warming potential (GWP) of a greenhouse gas is the ratio of global warming, or radiative forcing (both direct and indirect), from one unit mass of a greenhouse gas to one unit mass of carbon dioxide (CO\(_2\)) over a period of time.\(^\text{12}\) GWPs recommended by the IPCC for nitrous oxide (N\(_2\)O) and methane (CH\(_4\)) are included in Table 6.1. Three additional criteria pollutants, nitrogen oxides (NOx), non-methane volatile organic compounds (NMVOC), and carbon monoxide (CO) are also included in Table 6.1. These pollutants do not directly affect global warming but instead have an indirect affect by influencing the formation and destruction of other greenhouse gases (specifically tropospheric and stratospheric ozone).

Currently there is no agreed upon method to estimate the contribution of gases that have an indirect affect on global warming, however the GWPs for NOx, NMVOC and CO were listed in the IPCC First Assessment Report, 1990 and are included here for reference.

For transit buses there are several ways to reduce GHG emissions:

- improve fuel efficiency;
- shift to lower-carbon fuels (CNG) and advanced vehicle technologies (hybrid-electric); and
- assure more complete combustion or post combustion oxidation.

Despite the fact that emission rates of most pollutants have been dramatically reduced in newer CNG and diesel buses, they remain a large source of criteria pollutants, air toxics and GHGs in

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\(^{11}\) P.D. Jones, et. al., Global and Hemispheric Temperature Anomalies-Land and Marine Instrumental records (Oak Ridge National Laboratory, TN), 1999

\(^{12}\) This paragraph is paraphrased from the U.S. EPA Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-1997, April 1999

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Table 6.1: Global Warming Potentials of Selected Pollutants

<table>
<thead>
<tr>
<th>Pollutant</th>
<th>Global Warming Potential*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon Dioxide (CO(_2))</td>
<td>1</td>
</tr>
<tr>
<td>Methane (CH(_4))</td>
<td>21</td>
</tr>
<tr>
<td>Nitrous Oxide (N(_2)O)</td>
<td>310</td>
</tr>
<tr>
<td>Carbon Monoxide (CO)</td>
<td>3</td>
</tr>
<tr>
<td>Non-Methane Volatile Organic Compounds (NMVOC)</td>
<td>11</td>
</tr>
<tr>
<td>Nitrogen Dioxide (NO(_2))</td>
<td>7</td>
</tr>
</tbody>
</table>

* To determine CO\(_2\) equivalent
many areas. The GHGs most closely identified with the transportation sector include CO₂, N₂O and CH₄.

Emission testing for N₂O was not conducted during this project. A default emission factor of 0.03 gram per kilometer (0.048 g/mi) for heavy-duty diesel vehicles was used, so that the GHG impact of N₂O emissions can be characterized in relation to the other pollutants. When multiplied by its GWP (310), the GHG impact for N₂O is about 15 g/mi as CO₂. This value is relatively insignificant in relation to the magnitude of CO₂ and CH₄ emissions from buses.

To put the GWP contribution of each pollutant in context, all of the pollutants have been shown for comparison in Figure 6.1. To keep the analysis simple, as well as limit the discussion to agreed upon GWPs, only emissions of CO₂ and CH₄ have been charted in the bus comparison section found in the Appendix B.

### 6.2 Results

As seen in Figures 6.1 and 6.2, the hybrid buses exhibited the lowest total GHG emissions. The Orion-LMCS and Nova-Allison hybrid buses exhibited a 20 to 40 percent, and 10 to 20 percent reduction in GHG emissions, respectively, than a conventional diesel bus. This can be primarily attributed to the capture of energy via regenerative braking to reduce the operating load on the engine.

Petroleum fuels such as diesel fuel have hydrogen to carbon ratios of about 2.2 to 1, while natural gas has a ratio of 4 to 1. For every million British Thermal Unit (mmBtu) of heating value there is 31.9 lb of carbon (117 lb CO₂/mmBtu) for natural gas versus 44.0 lb carbon/mmBtu (161 lb CO₂/mmBtu) for diesel fuel.

As a result of this lower carbon content, carbon dioxide emissions for a CNG bus could be nearly 40 percent lower than a diesel bus. However,

---

several factors conspire to prevent the lower carbon benefit from being as large as it first appears. As can be seen in Figures 6.1 and 6.2, the percentage reduction in GHG emissions is essentially nil on the NY Bus and CBD cycles. The Orion V DDC Series 50G CNG bus actually had higher total GHG emissions than a Nova RTS DDC Series 50 diesel bus.

CNG buses have roughly 20 percent poorer fuel economy on urban driving cycles. This is due primarily to engine throttling losses under part load operation and greater vehicle weight. CNG buses consume more fuel for the same output, effectively canceling out nearly half of the CO$_2$ benefit. The second factor is the emission of unburned fuel or methane, which is itself a greenhouse gas with a global warming potential 21 times that of CO$_2$. To derive the total GHG impact, the grams per mile methane emission rate from each CNG bus was multiplied by 21 and this value was then added to the total CO$_2$ emission rate to determine the overall CO$_2$ equivalent greenhouse gas impact. So even though the CNG buses emit less CO$_2$, the impact from the released methane creates a larger GHG impact.

As a function of their greater fuel economy, the hybrid buses have total GHG emissions far lower than that of a CNG or conventional diesel buses.

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14 Reducing Greenhouse Gases & Air Pollution, STAPPA/ALAPCO, October 1999; Also see Table 6.1
7.0 Carbon Monoxide Emissions

7.1 Overview
Carbon monoxide (CO) is generally a local emission issue with the impact typically occurring in low lying areas such as urban canyons. CO affects the ability of blood to carry oxygen and results in impaired cardiovascular, pulmonary and nervous systems. While most areas of the U.S. are in attainment for CO, many areas in the Northeast such as New York City, Westchester and Nassau counties in New York State, and the northeastern portion of New Jersey have been designated as moderate CO non-attainment areas. The Code of Federal Regulations lists several areas as Serious CO non-attainment including, the Los Angeles South Coast Air Basin, CA, Denver-Boulder, CO, Las Vegas, NV, Phoenix, AZ and Spokane, WA. Some of these areas have demonstrated attainment with the CO NAAQS, but have yet to be delisted.

Excess CO emissions are usually associated with cold engine startups and engine operation in open loop mode. Once the engine has warmed to operating temperature the oxidation catalyst is usually sufficient to complete at least partial combustion of excess HC and CO into CO₂.

7.2 CO Results
The hybrid electric buses exhibited the lowest CO emission of any of the buses tested representing a 70 percent reduction from a conventional diesel bus. Based on the time series data later in this chapter it appears that a majority of this benefit is attributable to reduced transient operation of the engine with the remainder attributable proportionately to increased fuel economy and potentially more effective aftertreatment control due to reduced engine idle.

As was the case with HC emissions, the CO emissions from the CNG buses (highlighted in Figures 7.1 and 7.2) are roughly 300 percent...
higher than the diesel buses. The CNG buses tested under this project all employ lean burn combustion strategies that result in excess CO emissions when optimizing for low NOx emissions. This type of combustion strategy typically maintains more than sufficient oxygen in the catalyst for oxidation, however, the catalyst operating parameters as well as the catalyst washcoat must be optimized for reducing CO. Catalysts do not approach 100 percent efficiency and have operational temperature requirements (i.e., need to reach operating temperature before they become effective).

CO emission rates do trend with average cycle speed with increased emission rates associated with lower average speed cycles. The percentage difference between the CNG buses and the diesel buses was generally proportional to the changes in vehicle fuel economy.

### 7.3 CO Time Series Data

The oxidation catalyst is potentially able to complete the oxidation of CO into CO$_2$. The time series data in Figures 7.4 and 7.5 show that the CO emission rate for the conventional diesel and CNG buses track with the power delivered to the cycle indicating that the catalysts may not be all that effective with regard to CO oxidation. All testing during the NAVC project was conducted after a 20-minute, hot dwell with
the engine operating and the idle time limit defeated. As a result there were no specific engine cold start issues. While the two figures (7.4 and 7.5) appear similar, the idle CO baseline for the CNG bus is consistently higher than that of the diesel bus increasing the total CO emission (the total area under the curve).

In Figure 7.6 for the Orion-LMCS hybrid you can see only a faint indication of power delivered to the cycle as the engine in the hybrid bus is only partially load following. Not only were overall CO emissions lower for the Orion-LMCS hybrid but during this specific test, the net state of charge of the battery pack increased (additional energy was put into the battery pack). While not presented here, the CO trace for the Nova Allison hybrid bus was similar to the Orion-LMCS hybrid.

7.4 Historical CO Emissions

Historical CO emission data are available from the DOE website for heavy-duty buses ranging in age from 1988 through 1998 model years. This data was collected by WVU on their transportable dynamometer.

As shown in Figures 7.7 and 7.8, CO emissions from diesel and CNG buses have declined over time. As most areas are in attainment for CO, there is currently no driving force to lower these emissions from urban bus fleets.
Tables A.1 and A.2 contain the average emission and fuel economy results of this testing program. Test results are grouped by drive cycle for ease of comparison.

Table A.1: Summary of Dynamometer Test Results for the CBD, NY Bus and Manhattan Drive Cycles

<table>
<thead>
<tr>
<th></th>
<th>CO</th>
<th>NOx</th>
<th>NMOC</th>
<th>PM</th>
<th>CO₂</th>
<th>CH₄</th>
<th>Fuel Economy (mpg)</th>
</tr>
</thead>
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<tr>
<td><strong>CBD Cycle</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Orion-LMCS VI Hybrid Diesel</td>
<td>0.1</td>
<td>19.2</td>
<td>0.08</td>
<td>0.12</td>
<td>2,262</td>
<td>0.0</td>
<td>4.3</td>
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<tr>
<td>Orion-LMCS VI Hybrid Diesel (no regen.)</td>
<td>0.04</td>
<td>22.0</td>
<td>0.12</td>
<td>0.24</td>
<td>2,625</td>
<td>0.0</td>
<td>3.7</td>
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<tr>
<td>Orion-LMCS VI Hybrid MossGas</td>
<td>0.1</td>
<td>18.5</td>
<td>0.03</td>
<td>0.02</td>
<td>2,218</td>
<td>0.0</td>
<td>4.2</td>
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<tr>
<td>Nova-Allison RTS Hybrid LS Diesel</td>
<td>0.4</td>
<td>27.7</td>
<td>bdl</td>
<td>bdl</td>
<td>2,472</td>
<td>0.0</td>
<td>3.9</td>
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<tr>
<td>Nova-Allison RTS Hybrid LS Diesel (no regen.)</td>
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<td>32.1</td>
<td>0.03</td>
<td>0.07</td>
<td>3,010</td>
<td>0.0</td>
<td>3.1</td>
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<tr>
<td>NovaBUS RTS Diesel Series 50</td>
<td>3.0</td>
<td>30.1</td>
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<td>0.24</td>
<td>2,779</td>
<td>0.0</td>
<td>3.5</td>
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<td>0.07</td>
<td>2,816</td>
<td>0.0</td>
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<tr>
<td>Neoplan AN440T CNG L10 280G</td>
<td>0.6</td>
<td>25.0</td>
<td>0.60</td>
<td>0.02</td>
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<td>14.9</td>
<td>3.15</td>
<td>0.02</td>
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<td>17.4</td>
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<td>Orion V CNG Series 50G</td>
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<td>9.7</td>
<td>2.36</td>
<td>0.02</td>
<td>2,785</td>
<td>23.7</td>
<td>2.6</td>
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<table>
<thead>
<tr>
<th></th>
<th>CO</th>
<th>NOx</th>
<th>NMOC</th>
<th>PM</th>
<th>CO₂</th>
<th>CH₄</th>
<th>Fuel Economy (mpg)</th>
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<tr>
<td><strong>NY Bus Cycle</strong></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Orion-LMCS VI Hybrid Diesel</td>
<td>5.0</td>
<td>40.5</td>
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<td>0.16</td>
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<td>0.0</td>
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<td>0.0</td>
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<td>58.9</td>
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<td>5,430</td>
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<td>NovaBUS RTS Diesel Series 50</td>
<td>11.3</td>
<td>72.0</td>
<td>0.60</td>
<td>0.70</td>
<td>7,076</td>
<td>0.0</td>
<td>1.4</td>
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<tr>
<td>NovaBUS RTS MossGas Series 50</td>
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<td>72.3</td>
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<td>0.37</td>
<td>7,272</td>
<td>0.0</td>
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<td>Neoplan AN440T CNG L10 280G</td>
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<td>113.2</td>
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<td>26.2</td>
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<tr>
<td>Orion V CNG Series 50G</td>
<td>31.7</td>
<td>15.3</td>
<td>6.64</td>
<td>0.11</td>
<td>6,535</td>
<td>66.7</td>
<td>1.1</td>
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<table>
<thead>
<tr>
<th></th>
<th>CO</th>
<th>NOx</th>
<th>NMOC</th>
<th>PM</th>
<th>CO₂</th>
<th>CH₄</th>
<th>Fuel Economy (mpg)</th>
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<td><strong>Manhattan Cycle</strong></td>
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<td></td>
<td></td>
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<td></td>
<td></td>
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<tr>
<td>Orion-LMCS VI Hybrid Diesel</td>
<td>0.1</td>
<td>22.6</td>
<td>0.18</td>
<td>bdl</td>
<td>2,841</td>
<td>0.0</td>
<td>3.4</td>
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<tr>
<td>NovaBUS RTS Diesel Series 50</td>
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<td>40.3</td>
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<td>4,268</td>
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<tr>
<td>New Flyer C40LF CNG Series 50G</td>
<td>26.3</td>
<td>21.4</td>
<td>2.10</td>
<td>bdl</td>
<td>3,395</td>
<td>62.3</td>
<td>2.1</td>
</tr>
</tbody>
</table>

bdl – Indicates that the result was below the detection limit of the equipment.

Note that for the CBD and NY Bus cycles, the hybrid-electric buses operating without regenerative braking achieved fuel economy comparable to conventional buses.
Table A.2: Summary of Dynamometer Test Results for the NY Composite and Routes 22 & 77 Drive Cycles

<table>
<thead>
<tr>
<th>Emission Rate (g/mile)</th>
<th>Fuel Economy (mpg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO</td>
<td>NOx</td>
</tr>
<tr>
<td>NY Composite Cycle</td>
<td>Orion-LMCS VI Hybrid Diesel</td>
</tr>
<tr>
<td>NovaBUS RTS Diesel Series 50</td>
<td>7.0</td>
</tr>
<tr>
<td>Orion V CNG Series 50G</td>
<td>25.7</td>
</tr>
<tr>
<td>Route #22 Cycle</td>
<td>NovaBUS RTS MossGas Series 50</td>
</tr>
<tr>
<td>Neoplan AN440T CNG L10 280G</td>
<td>2.8</td>
</tr>
<tr>
<td>Orion V CNG Series 50G</td>
<td>8.9</td>
</tr>
<tr>
<td>Route #77 Cycle</td>
<td>Neoplan AN440T CNG L10 280G</td>
</tr>
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</table>
Appendix B – Bus Profiles
NY Bus Cycle Comparison Profiles

The following profiles provide general vehicle information for each bus along with comparison charts for fuel economy and emissions on the NY Bus cycle. In each comparison chart, the buses are ranked highest to lowest for fuel economy and lowest to highest for emissions, with the best performing bus at the top of each chart. The bus being evaluated in each section has its emissions highlighted. This approach allows for the comparison of all pollutants simultaneously.
## Orion-LMCS Hybrid Electric

**Operator** | New York City Transit Authority  
**Fleet Owner** | New York City Transit Authority  
**Model Year** | 1998  
**Chassis** | Orion VI  
**Gross Vehicle Weight (GVW) (lb.)** | 41,640  
**Curb Weight (lb.)** | 31,315  
**Vehicle Tested Weight (lb.)** | 35,140  
**Total Passenger Capacity** | 49  
**Engine** | Detroit Diesel Series 30, (Navistar 444)  
**Fuel** | D1 Diesel  
**Transmission** | LMCS Hybrid Electric Drive
Orion-LMCS VI Hybrid-Electric

NY Bus Cycle Fuel Economy Comparison

NY Bus Cycle CO2, CH4 Emissions

NY Bus Cycle NOx Emissions

NY Bus Cycle PM Emissions

NY Bus Cycle CO Emissions

NY Bus Cycle NMOC Emissions
## NOVA-Allison Hybrid Electric

![NOVA-Allison Hybrid Electric Bus](image)

### Vehicle Information

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<thead>
<tr>
<th>Operator</th>
<th>New York City Transit Authority</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fleet Owner</td>
<td>New York City Transit Authority</td>
</tr>
<tr>
<td>Model Year</td>
<td>1991</td>
</tr>
<tr>
<td>Chassis</td>
<td>TMC RTS (NovaBus)</td>
</tr>
<tr>
<td>Gross Vehicle Weight (GVW) (lb.)</td>
<td>36,900</td>
</tr>
<tr>
<td>Curb Weight (lb.)</td>
<td>30,600</td>
</tr>
<tr>
<td>Vehicle Tested Weight (lb.)</td>
<td>34,735</td>
</tr>
<tr>
<td>Total Passenger Capacity</td>
<td>52</td>
</tr>
<tr>
<td>Engine</td>
<td>VM Motori VM642</td>
</tr>
<tr>
<td>Fuel</td>
<td>Low Sulfur Diesel</td>
</tr>
<tr>
<td>Transmission</td>
<td>Allison Transmission Hybrid Electric Drive</td>
</tr>
</tbody>
</table>

**NOVABUS Inc.**
P.O. Box 5670
Roswell, New Mexico 88202
Telephone: (505) 347-2011
Facsimile: (505) 347-7547
[http://www.novabuses.com](http://www.novabuses.com)

**Allison Transmission**
Telephone: (317) 242-5000
Nova-Allison RTS Hybrid Electric

NY Bus Cycle Fuel Economy Comparison

NY Bus Cycle NOx Emissions

NY Bus Cycle CO Emissions

NY Bus Cycle PM Emissions

NY Bus Cycle NMOC Emissions
NOVA Diesel

NOVABUS Inc.
P.O. Box 5670
Roswell, New Mexico 88202
Telephone: (505) 347-2011
Facsimile: (505) 347-7547
http://www.novabuses.com

Vehicle Information

<table>
<thead>
<tr>
<th>Operator</th>
<th>New York City Transit Authority</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fleet Owner</td>
<td>New York City Transit Authority</td>
</tr>
<tr>
<td>Model Year</td>
<td>1999</td>
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<tr>
<td>Chassis</td>
<td>Nova RTS</td>
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<td>Gross Vehicle Weight (GVW) (lb.)</td>
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</tr>
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<td>Curb Weight (lb.)</td>
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<td>Fuel</td>
<td>D1 Diesel</td>
</tr>
<tr>
<td>Transmission</td>
<td>3 speed automatic</td>
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</table>
NovaBus RTS Detroit Diesel Series 50

NY Bus Cycle Fuel Economy Comparison

NY Bus Cycle NOx Emissions

NY Bus Cycle CO2, CH4 Emissions

NY Bus Cycle CO Emissions

NY Bus Cycle PM Emissions

NY Bus Cycle NMOC Emissions
Neoplan CNG

Neoplan USA Corporation
700 Gottlob Auwaerter Drive
Lamar, Colorado  81052
Telephone: (719) 336-3256
Facsimile: (719) 336-4201
Coach Sales of Neoplan, Inc., NJ
Telephone: (908) 289-3373
www.neoplanusa.com
sales@neoplanusa.com

Vehicle Information

<table>
<thead>
<tr>
<th>Operator</th>
<th>Massachusetts Port Authority, Logan Airport</th>
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</thead>
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<td>Fleet Owner</td>
<td>Paul Revere Transportation</td>
</tr>
<tr>
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<td>1998</td>
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<tr>
<td>Chassis</td>
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<td>Gross Vehicle Weight (GVW) (lb.)</td>
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<td>Engine</td>
<td>Cummins L10 280G</td>
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<tr>
<td>Fuel</td>
<td>CNG</td>
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<tr>
<td>Transmission</td>
<td>5 speed automatic</td>
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</table>
Neoplan AN440T Cummins L10 280G

NY Bus Cycle Fuel Economy Comparison

NY Bus Cycle CO2, CH4 Emissions

NY Bus Cycle NOx Emissions

NY Bus Cycle PM Emissions

NY Bus Cycle CO Emissions

NY Bus Cycle NMOC Emissions

Agreement No.: NAVC1098-PG009837  2/15/00  B-9
New Flyer CNG

Vehicle Information

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</tr>
<tr>
<td>Chassis</td>
<td>New Flyer C40LF</td>
</tr>
<tr>
<td>Gross Vehicle Weight (GVW) (lb.)</td>
<td>37,920</td>
</tr>
<tr>
<td>Curb Weight (lb.)</td>
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<tr>
<td>Total Passenger Capacity</td>
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</tr>
<tr>
<td>Engine</td>
<td>Detroit Diesel Series 50G</td>
</tr>
<tr>
<td>Fuel</td>
<td>CNG</td>
</tr>
<tr>
<td>Transmission</td>
<td>5-speed automatic</td>
</tr>
</tbody>
</table>
New Flyer C40LF CNG Detroit Diesel Series 50G

NY Bus Cycle Fuel Economy Comparison

NY Bus Cycle CO2, CH4 Emissions

NY Bus Cycle NOx Emissions

NY Bus Cycle PM Emissions

NY Bus Cycle CO Emissions

NY Bus Cycle NMOC Emissions
Orion V CNG

Orion Bus Industries
Base Road, P.O. Box 449
Oriskany, New York 13424
Telephone: (315) 768-8101
Facsimile: (315) 768-6520
http://www.transit-center.com/Orion
OrionCNG@aol.com

Vehicle Information

<table>
<thead>
<tr>
<th>Operator</th>
<th>New York City Department of Transportation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fleet Owner</td>
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<tr>
<td>Model Year</td>
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<tr>
<td>Engine</td>
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<tr>
<td>Fuel</td>
<td>CNG</td>
</tr>
<tr>
<td>Transmission</td>
<td>5 speed automatic</td>
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</table>
## NY V Detroit Diesel Series 50G

### NY Bus Cycle Fuel Economy Comparison

<table>
<thead>
<tr>
<th>Model</th>
<th>Mileage (miles)</th>
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<tbody>
<tr>
<td>Orion LMCS VI Hybrid MossGas</td>
<td>20.00</td>
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<tr>
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<tr>
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<td>19.00</td>
</tr>
<tr>
<td>NovaBUS RTS Diesel Series 50</td>
<td>18.00</td>
</tr>
<tr>
<td>New Flyer C40LF CNG Series 50G</td>
<td>20.00</td>
</tr>
<tr>
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<td>17.50</td>
</tr>
<tr>
<td>Neoplan A440T CNG L10 280G</td>
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</tr>
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### NY Bus Cycle CO2, CH4 Emissions

<table>
<thead>
<tr>
<th>Model</th>
<th>Emissions (gram/mile)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orion LMCS VI Hybrid MossGas</td>
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<tr>
<td>Orion LMCS VI Hybrid Diesel</td>
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<td>1,100</td>
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<tr>
<td>NovaBUS RTS Diesel Series 50</td>
<td>1,250</td>
</tr>
<tr>
<td>New Flyer C40LF CNG Series 50G</td>
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</tr>
<tr>
<td>NovaBUS RTS MossGas Series 50</td>
<td>1,150</td>
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<tr>
<td>Neoplan A440T CNG L10 280G</td>
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### NY Bus Cycle NOx Emissions

<table>
<thead>
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<th>Model</th>
<th>Emissions (gram/mile)</th>
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<td>Neoplan A440T CNG L10 280G</td>
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### NY Bus Cycle PM Emissions

<table>
<thead>
<tr>
<th>Model</th>
<th>Emissions (gram/mile)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orion V CNG Series 50G</td>
<td>BDL</td>
</tr>
<tr>
<td>New Flyer C40LF CNG Series 50G</td>
<td>BDL</td>
</tr>
<tr>
<td>Orion LMCS VI Hybrid MossGas</td>
<td>BDL</td>
</tr>
<tr>
<td>Orion LMCS VI Hybrid Diesel</td>
<td>BDL</td>
</tr>
<tr>
<td>Nova-Allison RTS Hybrid LS Diesel</td>
<td>BDL</td>
</tr>
<tr>
<td>NovaBUS RTS Diesel Series 50</td>
<td>BDL</td>
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<tr>
<td>NovaBUS RTS MossGas Series 50</td>
<td>BDL</td>
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<tr>
<td>Neoplan A440T CNG L10 280G</td>
<td>BDL</td>
</tr>
</tbody>
</table>

### NY Bus Cycle CO Emissions

<table>
<thead>
<tr>
<th>Model</th>
<th>Emissions (gram/mile)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orion LMCS VI Hybrid MossGas</td>
<td>20.00</td>
</tr>
<tr>
<td>New Flyer C40LF CNG Series 50G</td>
<td>18.00</td>
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<tr>
<td>Orion LMCS VI Hybrid Diesel</td>
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<tr>
<td>Nova-Allison RTS Hybrid LS Diesel</td>
<td>17.00</td>
</tr>
<tr>
<td>NovaBUS RTS Diesel Series 50</td>
<td>16.00</td>
</tr>
<tr>
<td>NovaBUS RTS MossGas Series 50</td>
<td>17.00</td>
</tr>
<tr>
<td>Neoplan A440T CNG L10 280G</td>
<td>18.00</td>
</tr>
<tr>
<td>Orion V CNG Series 50G</td>
<td>19.00</td>
</tr>
</tbody>
</table>

### NY Bus Cycle NMOC Emissions

<table>
<thead>
<tr>
<th>Model</th>
<th>Emissions (gram/mile)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nova-Allison RTS Hybrid LS Diesel</td>
<td>50.00</td>
</tr>
<tr>
<td>NovaBUS RTS Hybrid LS Diesel</td>
<td>55.00</td>
</tr>
<tr>
<td>Orion LMCS VI Hybrid Diesel</td>
<td>50.00</td>
</tr>
<tr>
<td>NovaBUS RTS Diesel Series 50</td>
<td>55.00</td>
</tr>
<tr>
<td>New Flyer C40LF CNG Series 50G</td>
<td>50.00</td>
</tr>
<tr>
<td>NovaBUS RTS MossGas Series 50</td>
<td>55.00</td>
</tr>
<tr>
<td>Neoplan A440T CNG L10 280G</td>
<td>50.00</td>
</tr>
<tr>
<td>Orion V CNG Series 50G</td>
<td>55.00</td>
</tr>
</tbody>
</table>

### NY Bus Cycle CO2, CH4 Emissions

<table>
<thead>
<tr>
<th>Model</th>
<th>Emissions (gram/mile)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orion V CNG Series 50G</td>
<td>BDL</td>
</tr>
<tr>
<td>New Flyer C40LF CNG Series 50G</td>
<td>BDL</td>
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<tr>
<td>Orion LMCS VI Hybrid MossGas</td>
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<tr>
<td>Orion LMCS VI Hybrid Diesel</td>
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<tr>
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<td>NovaBUS RTS MossGas Series 50</td>
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<td>Neoplan A440T CNG L10 280G</td>
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</tr>
<tr>
<td>Orion V CNG Series 50G</td>
<td>BDL</td>
</tr>
</tbody>
</table>
Appendix C– Biodiesel Bus Performance
Biodiesel Bus Performance

An additional component of the NAVC project involved the testing of biodiesel-fueled transit buses. Biodiesel refers to fuel produced from vegetable or animal oils. Alone, it has similar physical characteristics as diesel, and is nonvolatile. When blended with diesel fuel, it offers the advantage of lowering the overall sulfur content of the blend as compared to the base stock. Usually in the United States, it is a methyl soy ester, where the esterification process insures higher shelf life than pure soybean oil. However, it also lowers the energy density, which correlates to lower engine power and torque.

Biodiesel is a renewable resource and as such, biodiesel blends offer reduced greenhouse gas (GHG) emissions due to carbon sequestration. As an example, plants consume carbon, which is then sequestered until the oil byproducts are combusted, releasing carbon back into the atmosphere as CO₂. As long as additional plants are re-grown, the carbon is recycled, rather than creating a net increase in atmospheric carbon. This effectively provides a closed-loop system for the carbon and CO₂. The biodiesel fuel utilized in the test buses was a biomass fuel in a #2 diesel (D2) stock (20% biomass/80% D2). As a result, the CO₂ emissions associated with biodiesel can essentially be discounted by 20%. The GHG percentage reduction is 20% because the fuel has 20% biomass. If, for example, the fuel had 10% biomass, the GHG percentage reduction would be 10%.

The biodiesel-fueled buses tested during this project are Transportation Manufacturing Corporation (TMC) forty-foot transit buses equipped with 1988 model year DDC 6V92LH engines. Although the buses had high mileage (>500,000), the engines had been overhauled within approximately 100,000 miles. The buses are also each retrofit with an exhaust muffler with a catalyst module incorporated within. As a result of their age, direct comparison between fuel economy and emission data cannot be directly compared to other buses tested under this project. To appropriately evaluate the performance of the biodiesel buses tested, comparison to other buses of similar vintage must be made. In order to do these, historical emissions data were taken from a WVU and DOE data set and compared to the emissions from buses tested under this program. Historical fuel economy data is not available from the database.

Table C.1 provides a summary of the results for the biodiesel buses tested under this program. Figures C.1 through C.5 show a combination of the data from the DOE database and the NAVC.

<table>
<thead>
<tr>
<th>Emission Rate (g/mi)</th>
<th>Fuel Economy (mpg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CBD Cycle</td>
<td>CO</td>
</tr>
<tr>
<td>8.5</td>
<td>27.9</td>
</tr>
<tr>
<td>NY Bus Cycle</td>
<td>16.9</td>
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<tr>
<td>Route 22 Cycle</td>
<td>4.5</td>
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<tr>
<td>Route 77 Cycle</td>
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</table>

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16 Emission data from the DOE website for heavy-duty buses from 1988 – 1998, on the CBD cycle, can be accessed through a database query at [http://www.ott.doe.gov/ohvt/heavy_vehicle/hv/emisbus.html](http://www.ott.doe.gov/ohvt/heavy_vehicle/hv/emisbus.html); West Virginia University collected this data on their transportable dynamometer laboratories.
project by engine model year on the CBD cycle. Since the DOE database contains data only for the CBD cycle, emission data from the other cycles is not represented graphically.

These biodiesel buses performed comparably to other 1988 model year biodiesel and diesel buses with lower than average NOx and CO emissions and higher than average PM and THC emissions. The results are generally inconclusive except that the TMC biodiesel was no better or worse than conventional diesel fueled buses. It appears that at the very least, a 20% GHG benefit can be achieved with little emissions tradeoff.
Figure C.4

Comparison of PM Emissions (g/mi) for Diesel Fueled Buses By Model Year
Central Business District Cycle

Figure C.5

Comparison of CO2 Emissions (g/mi) for Diesel Fueled Buses By Model Year
Central Business District Cycle