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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 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

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.

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).

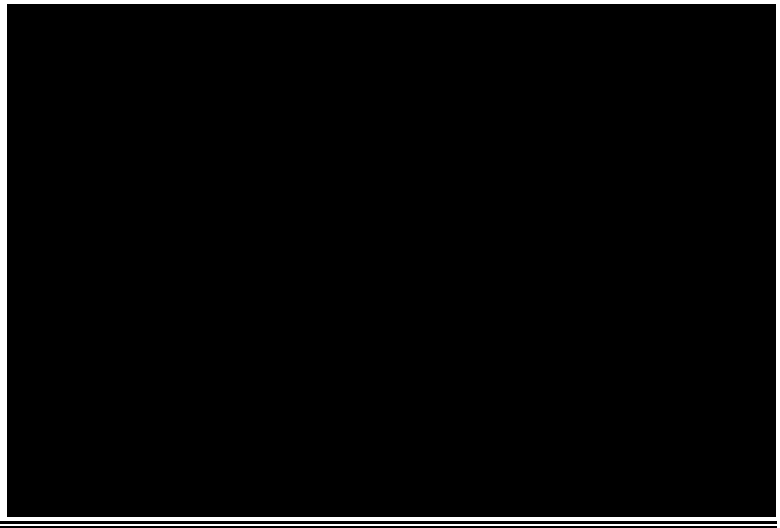
Figure 2.3: Hub Adapters

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

Figure 2.4: Flywheel Assembly

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.

Figure 2.5: Torque/Speed Sensor Attached to Hub Adapter



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

Bus OEM	Bus Chassis	Drive	Engine / Model Year	Fuel	Aftertreatment
NovaBUS	RTS	3 speed	DDC Series 50 / 1998	Diesel [A]	Oxidation Catalyst
Neoplan	AN440T	5 speed	Cummins L10 280G / 1998	CNG	Oxidation Catalyst
New Flyer	C40LF	5 speed	DDC Series 50G / 1999	CNG	Oxidation Catalyst
Orion	V	5 speed	DDC Series 50G / 1998	CNG	Oxidation Catalyst
Orion	VI Hybrid	LMCS Hybrid	DDC Series 30 / 1997 & 1998	Diesel-Electric [B]	NETT Particulate Filter Trap
NovaBUS	RTS Hybrid	Allison Hybrid	DDCVMM 642 DI / 1991 (1998 engine)	Diesel-Electric [C]	Johnson Matthey Continuous Regenerative Trap

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, and MossGas® diesel fuels.

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 the appendix.

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.

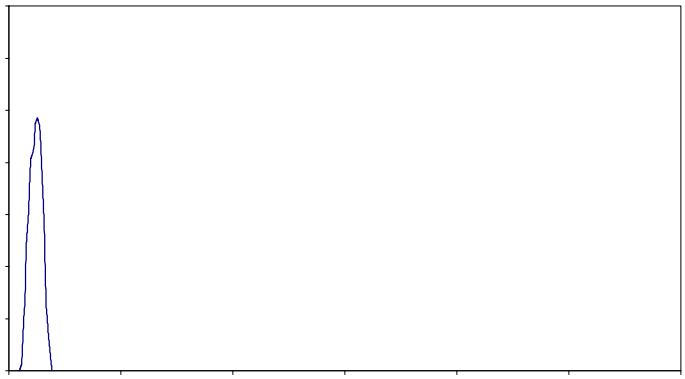
The CBD cycle is typically used to evaluate transit buses and is made up of 14 identical sections containing an acceleration to 20 mph, a cruise at 20 mph, braking to a stop, then dwell. The total cycle covers 2.0 miles over 600 seconds. While the CBD cycle is repeatable from a driver in the loop standpoint, 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

Figure 2.6

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 1970s. 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

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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 ic 0.184 fuel at partial loads and when
idling. This, combined with low internal losses, allows a diesel engine to achieve the high fuel

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 (CH_4), 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

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.

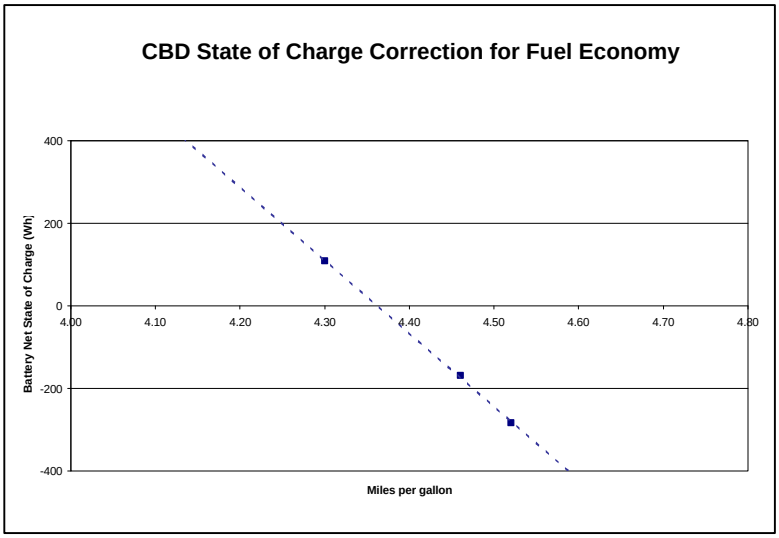
When a hybrid-electric bus operates in a charge-depleting mode, it effectively borrows energy from the battery to complete the drive cycle test. This, therefore, skews the results, as calculated by the WVU laboratory, to seem better (i.e., fuel economy is higher and emissions lower). Basically the results 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 zero 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 SOC 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.

Figure 2.12



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 (CO_2) and water (H_2O).

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 continuously regenerative trap (CRT) control. The Orion-LMCS hybrid was also tested on both the

0.066i 6 --0.904- 6generallh1y 9 56ol.646ll-te.red orrol.B6161662iLsr16161 T4nbph th 2ei2 Tc m5ot:1612b1616961662iLsr161616164

PARTICULATE EMISSIONS

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 (NO_2), ground-level ozone (O_3), particulate matter (PM) and sulfur dioxide (SO_2). 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).[8]

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
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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.[10]

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. 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 NO_2. The 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

[10] 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

4.3.1 NMOC Time Series

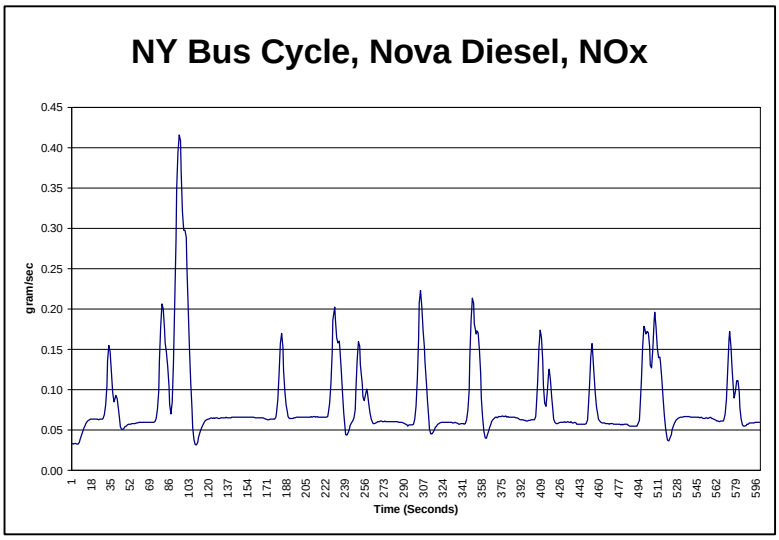
4.3.1 NMOC Time Series

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.

Figure 4.6



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 from a diesel engine at idle. 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.[11] 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

approximately 4 g/bhp-hr).[12]

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.

Figure 4.11

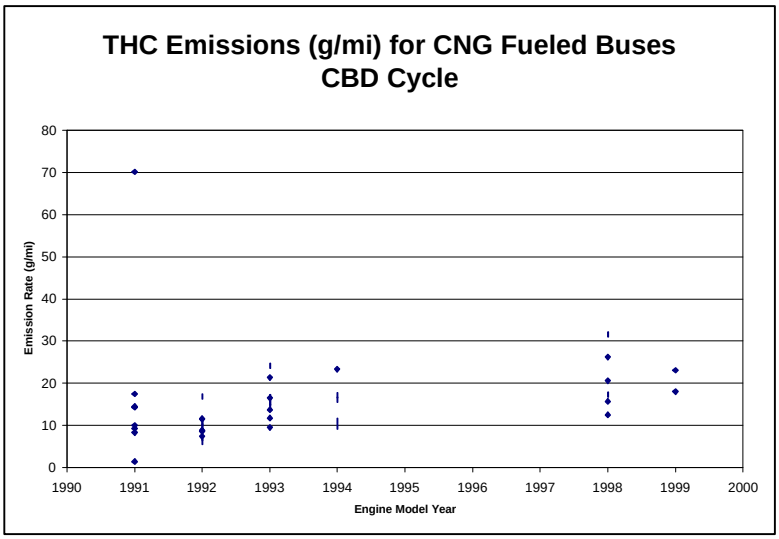
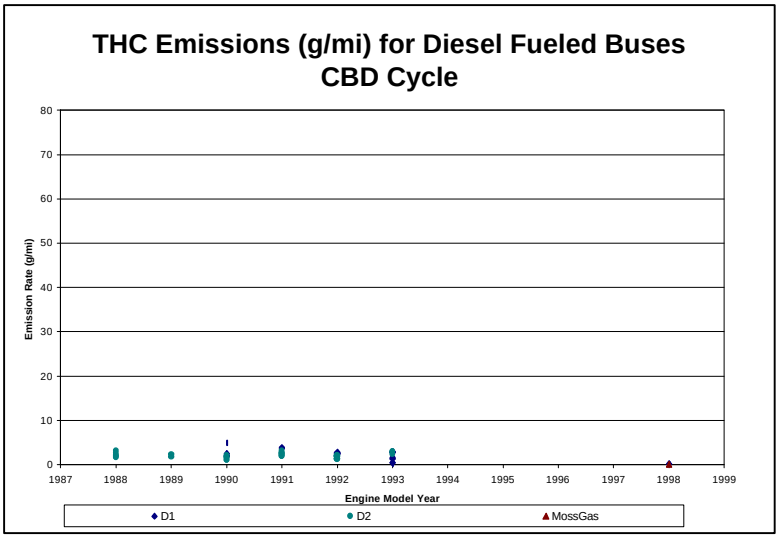


Figure 4.12



[12] Transit Cooperative Research Program, Report 38, Guidebook for Evaluating, Selecting, and Implementing Fuel Choice for Transit Bus Operations, ARCADIS Geraghty & Miller, Inc., 1998

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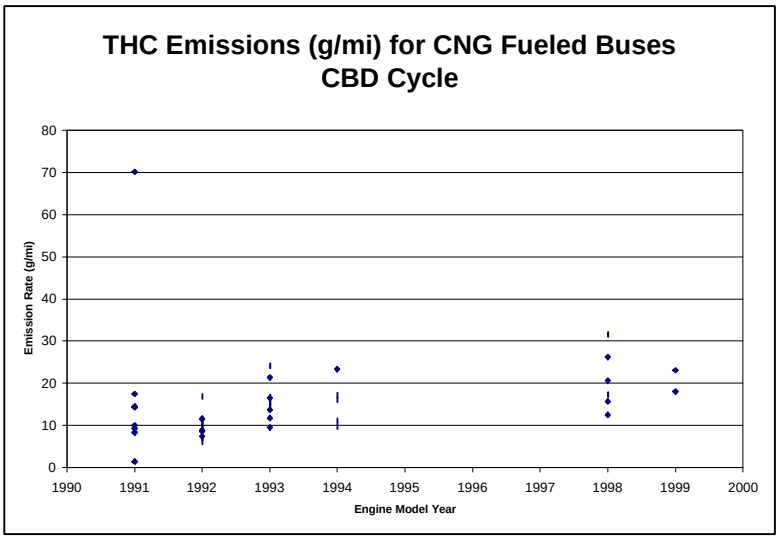
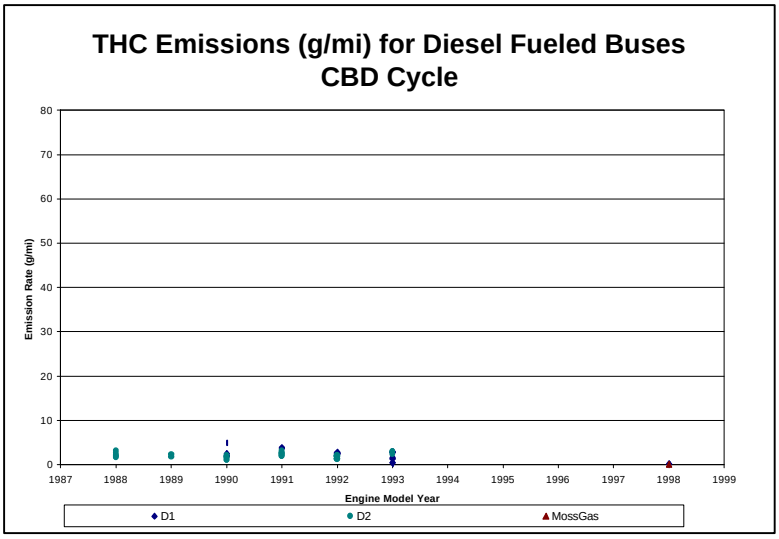


Figure 4.12

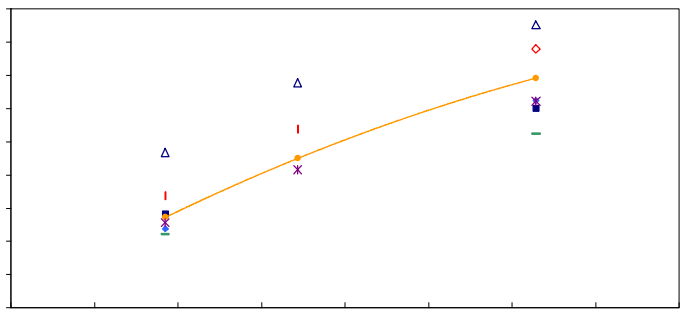


[12] Transit Cooperative Research Program, Report 38, Guidebook for Evaluating, Selecting, and Implementing Fuel Choice for Transit Bus Operations, ARCADIS Geraghty & Miller, Inc., 1998

decelerates, the less kinetic energy can be recovered due primarily to limitations in the vehicle energy storage device (batteries) and their ability to accept energy quickly. 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. Fuel economy benefits will also be realized due to smaller engines in the hybrid vehicles, which translates into lower idle, or dwell losses.

5.2 Dynamometer Measured Results

Figure 5.2



The fuel economy benefits of hybrids are borne out in Figure 5.2. The dynamometer data charted here is contained in the Appendix. 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 miles per gallon 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 do 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

Table 5.1: Curb, Gross and Test Weight of Buses

OEM/Chassis/Fuel	Curb/GVW (lbs)	Test Weight (lbs)	Passenger Capacity
Neoplan AN440T CNG	29,820/40,600	34,170	56
Nova RTS diesel	28,200/39,500	32,250	52
Orion V CNG	33,225/41,800	37,495	55
New Flyer C40LF CNG	29,600/37,920	33,650	52
TMC RTS Diesel	26,950/36,900	31,300	56
Nova RTS Allison Hybrid Diesel	30,600/36,900	34,735	53
Orion VI LMCS Hybrid Diesel	31,315/41,640	35,140	49

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 and that significant 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.

Fuel economy is represented as equivalent miles per diesel gallon for CNG buses, 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 for all cycles show a clear fuel economy improvement (highlighted in Figures 5.3, 5.4 and 5.5) for hybrid-electric technology over conventional

Figure 5.3

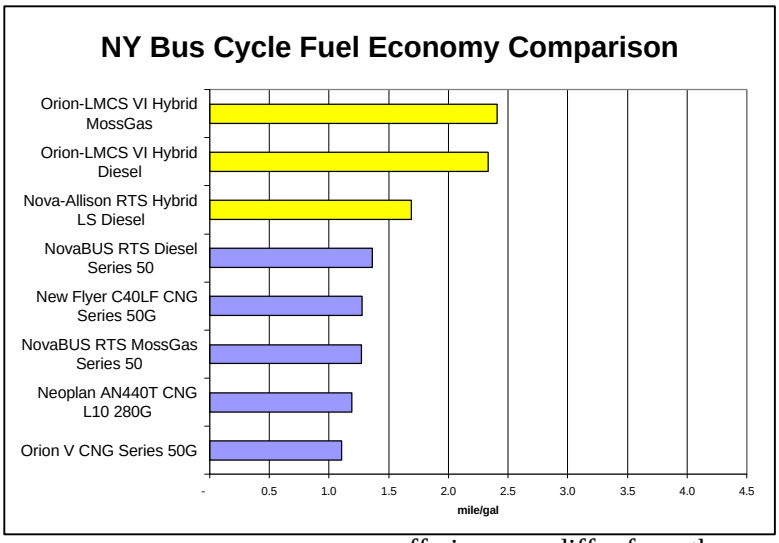


Figure 5.4

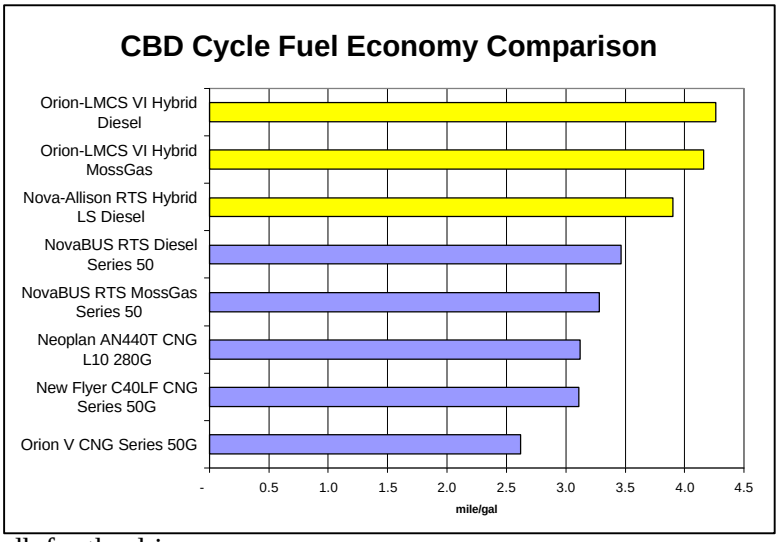
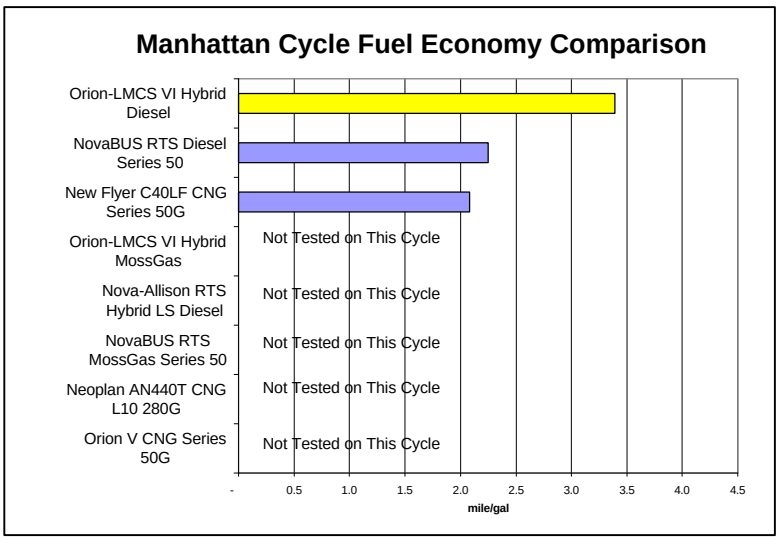


Figure 5.5



diesel and CNG buses. As expected, conventional diesel buses exhibited better fuel economy than comparable CNG buses. This is primarily due to higher vehicle weight and lower overall engine efficiency for the CNG buses, as the CNG engines have a lower compression ratio and are throttled versus high compression, non-throttled for the diesel engine. 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 5.5.

5.3 In-Use Fuel Economy

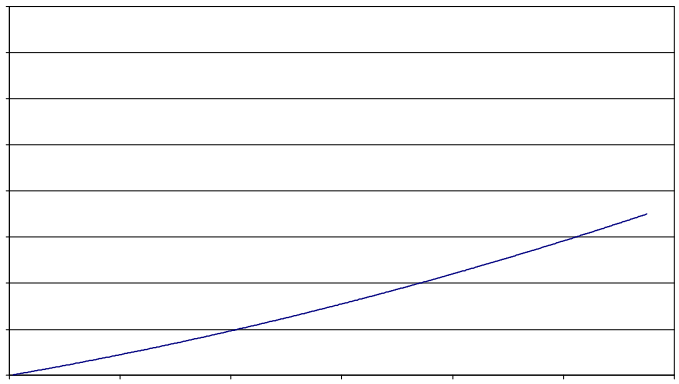
An important objective of the NAVC testing project was to correlate dynamometer testing with actual in-use performance of the buses to determine whether the drive cycles and the WVU lab were indicative of actual in-use operation. The only performance metric that can be captured during real world operation 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.

5.3.1 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)
- Hill climbing (potential energy)
- Mechanical system losses (internal friction and engine losses)
- Road/wind load (external friction)
- Accessories (including air conditioning)

Figure 5.6



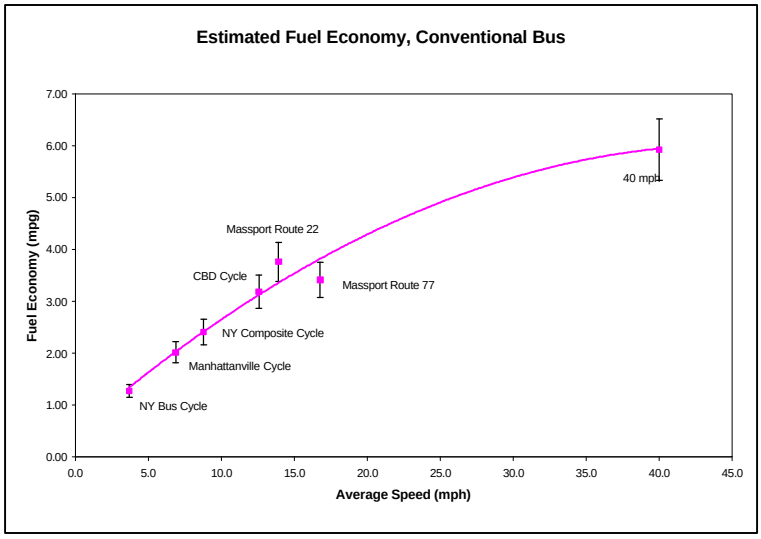
Depending upon the duty cycle of the vehicle any one of these energy consumption categories may dominate the total energy consumed and determine the ultimate in-use fuel economy of the vehicle. In a hybrid vehicle, kinetic and potential energy can be recovered via regenerative braking. This has the effect 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 5.6, 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.

5.3.2 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 5.7.

Figure 5.7



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 two significantly different 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 5.7. The trend line has been included simply to highlight a general trend upward in fuel economy as average cycle speed increases.

5.3.3 Hybrid Vehicle Energy Economy and Recovery

Current hybrid-electric vehicles can attribute a majority of their increased fuel economy to the capture of regenerative braking energy. Some additional benefit can also be attributed to increased engine efficiency, although some of this increased engine efficiency is lost due to battery inefficiency. As a general rule most vehicles can stop far faster than they accelerate with braking only limited by tire slippage. 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).

Figure 5.8 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.

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.[13] 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) /F0 12t P0with thgt..ÿÿÿ

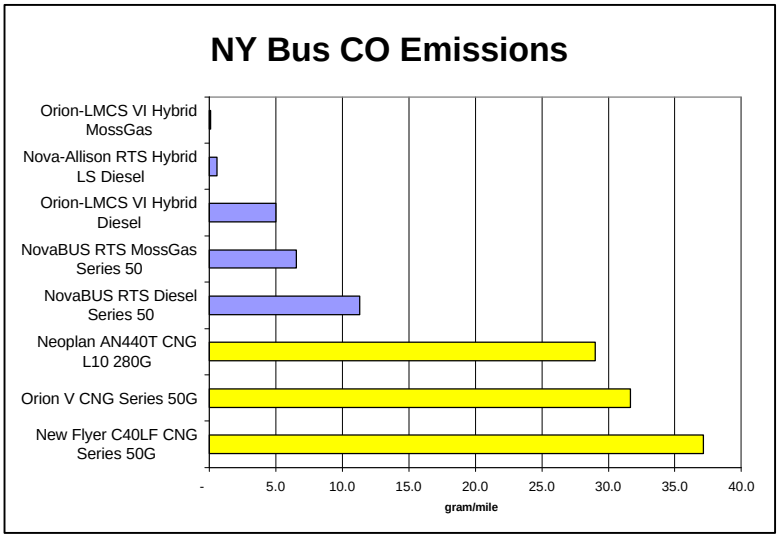
7.0 Carbon Monoxide Emissions

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 CO_2.

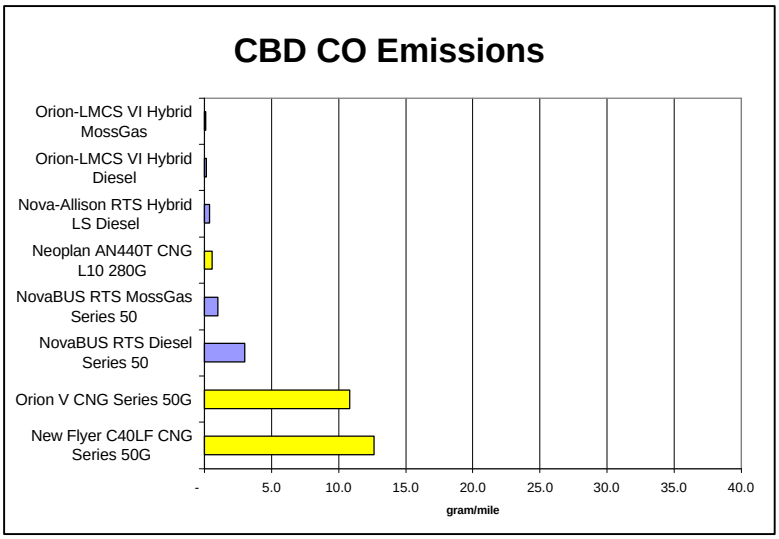
Figure 7.1



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.

Figure 7.2



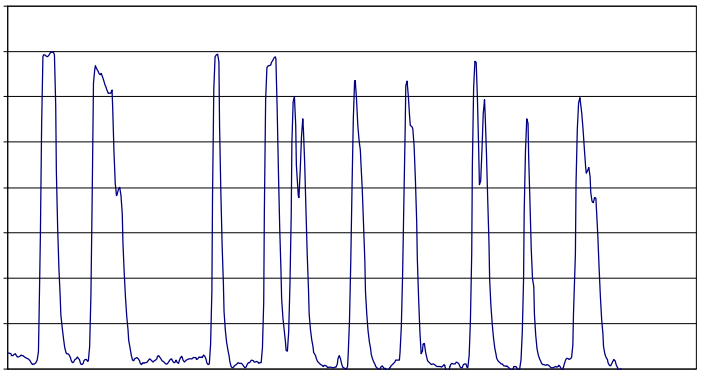
As was the case with HC emissions, the CO emissions from the CNG buses (highlighted in Figures 7.1 and

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



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Appendix A – Test Results

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

	Emission Rate (g/mile)						Fuel Economy
	CO	**NOx**	**NMOC**	**PM**	**CO_2**	**CH_4**	**(mpg)**
CBD Cycle							
Orion-LMCS VI Hybrid Diesel	0.1	19.2	0.08	0.12	2,262	0.0	4.3
Orion-LMCS VI Hybrid Diesel (no regen.)	0.04	22.0	0.12	0.24	2,625	0.0	3.7
Orion-LMCS VI Hybrid MossGas	0.1	18.5	0.03	0.02	2,218	0.0	4.2
Nova-Allison RTS Hybrid LS Diesel	0.4	27.7	bdl	bdl	2,472	0.0	3.9
Nova-Allison RTS Hybrid LS Diesel (no regen.)	1.0	32.1	0.03	0.07	3,010	0.0	3.1
NovaBUS RTS Diesel Series 50	3.0	30.1	0.14	0.24	2,779	0.0	3.5
NovaBUS RTS MossGas Series 50	1.0	32.2	0.05	0.09	2,816	0.0	3.3
Neoplan AN440T CNG L10 280G	0.6	25.0	0.60	0.02	2,392	14.6	3.1
New Flyer C40LF CNG Series 50G	12.7	14.9	3.15	0.02	2,343	17.4	3.1
Orion V CNG Series 50G	10.8	9.7	2.36	0.02	2,785	23.7	2.6
NY Bus Cycle							
Orion-LMCS VI Hybrid Diesel	5.0	40.5	1.13	0.16	4,251	0.0	2.3
Orion-LMCS VI Hybrid Diesel (no regen.)	3.0	50.0	2.00	bdl	5,500	0.0	1.5
Orion-LMCS VI Hybrid MossGas	0.1	32.0	0.50	bdl	3,930	0.0	2.4
Nova-Allison RTS Hybrid LS Diesel	0.6	58.9	0.07	bdl	5,430	0.0	1.7
NovaBUS RTS Diesel Series 50	11.3	72.0	0.60	0.70	7,076	0.0	1.4
NovaBUS RTS MossGas Series 50	6.6	72.3	0.15	0.37	7,272	0.0	1.3
Neoplan AN440T CNG L10 280G	29.0	113.2	4.84	0.14	6,090	65.4	1.2
New Flyer C40LF CNG Series 50G	37.2	26.2	4.35	bdl	5,610	75.1	1.3
Orion V CNG Series 50G	31.7	15.3	6.64	0.11	6,535	66.7	1.1
Manhattan Cycle							
Orion-LMCS VI Hybrid Diesel	0.1	22.6	0.18	bdl	2,841	0.0	3.4
NovaBUS RTS Diesel Series 50	6.0	40.3	0.25	0.48	4,268	0.0	2.3
New Flyer C40LF CNG Series 50G	26.3	21.4	2.10	bdl	3,395	62.3	2.1

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

Note that for the CBD and NY Bus cycles, the hybrid-electic 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

	Emission Rate (g/mile)						Fuel Economy
	CO	**NOx**	**NMOC**	**PM**	**CO_2**	**CH_4**	**(mpg)**
NY Composite Cycle							
Orion-LMCS VI Hybrid Diesel	0.2	19.9	0.38	0.14	2,250	0.0	4.2
NovaBUS RTS Diesel Series 50	7.0	31.5	0.22	0.46	3,227	0.0	3.0
Orion V CNG Series 50G	25.7	12.4	4.57	0.03	3,165	50.5	2.2
Route #22 Cycle							
NovaBUS RTS MossGas Series 50	2.0	26.9	0.15	0.10	2,386	0.0	3.9
Neoplan AN440T CNG L10 280G	2.8	24.8	0.87	0.03	1,889	11.9	3.9
Orion V CNG Series 50G	8.9	6.8	1.80	0.03	2,225	17.2	3.3
Route #77 Cycle							
Neoplan AN440T CNG L10 280G	2.7	23.1	0.69	0.05	1,973	11.4	3.7

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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.