Comparison of Modern CNG, Diesel and Diesel Hybrid-Electric Transit Buses:

Efficiency & Environmental Performance

MJB & A

CONCORD, MA - WASHINGTON, DC

47 JUNCTION SQUARE DRIVE
CONCORD, MA 01742
978-405-1275
www.mjbradley.com

Table of Contents

List of Figures

List of Tables

Executive Summary

Transit managers today face complex decisions about what fuels and propulsion technologies to commit to for their fleets when purchasing new buses. There are two main engine/fuel options: 1) compression-ignition engines that operate on diesel fuel, and 2) spark-ignition engines that operate on natural gas. Both of these options are readily available commercially and are already well established in the transit industry. According to the Public Transportation Association there are more than 47,000 transit buses currently in service that burn diesel fuel and more than 12,000 that operate on natural gas[1]. Most natural gas powered transit buses store on-board fuel as a high-pressure compressed gas, so called "compressed natural gas", or CNG[2].

There are also two main options for propulsion system technology: 1) a traditional automatic transmission, and 2) a hybrid-electric system[3]. A hybrid-electric system combines one or more electric motors/generators with an energy storage system, power electronics, and controls to either replace or supplement an automatic or automated manual transmission. The use of a hybrid-electric propulsion system allows for collection and re-use of kinetic energy normally wasted in braking, and may allow for engine down-sizing and partial electric-only operation, including engine shut-off at idle. All of this can result in reduced fuel use compared to a bus equipped with an automatic transmission. The transit bus industry was the first major heavy-duty vehicle market to implement hybrid-electric technology, and today there are more than 4,500 hybrid-electric transit buses in service[1].

When evaluating the choice of fuel and technology there are many factors to consider, both economic and environmental. This report focuses on the environmental considerations of transit bus fuel and technology choice, including three issues at the forefront of current US policy: efficiency, air quality, and climate change. This report compares the efficiency and environmental performance of modern transit buses equipped with the three most common engine/propulsion system options: diesel, hybrid diesel-electric (hybrid), and compressed natural gas (CNG)[3]. All of the data used to compare these transit bus technology options was collected by the Altoona Bus Research & Testing Center under the Federal Transit

[1] American Public Transportation Association, 2011 Public Transportation Fact Book, 62nd Edition, April 2011

[2] It is also possible to store and use natural gas in the form of a cryogenic liquid, so called liquefied natural gas, or LNG. Typically natural gas vehicles only store onboard fuel as LNG if more than 400 miles range between fueling events is required. Only a minority of current natural gas buses are LNG buses.

[3] Fully electric buses that store on-board energy in chemical batteries that are re-charged from the grid, and which do not include an internal combustion engine, are also beginning to become available on a limited commercial basis. These types of buses were not included in this analysis because comparative ABRTC test data was not available.

Administration's new model bus testing program. For each bus fuel economy (miles per diesel gallon equivalent, MPDGE) was measured on seven different test cycles with average speed ranging from 6.8 MPH to 38.0 MPH. Emissions of nitrogen oxides (NOx), particulate matter (PM), non-methane hydrocarbons (NMHC), methane (CH_4), carbon monoxide (CO), and carbon dioxide (CO_2) were measured on three test cycles with average speed ranging from 6.8 MPH to 18.9 MPH.

Two sets of buses are compared, which represent the full suite of technology options as implemented on two different bus platforms by two different manufacturers. All of the tested buses were equipped with EPA 2010 compliant engines and are therefore representative of expected performance from new buses purchased in the future.

The results of the comparison, as described more fully in section 2, indicate that:

EFFICIENCY & FUEL CONSUMPTION

- CNG and diesel buses have similar over-all drivetrain efficiency. Of 14 direct comparisons (diesel and CNG versions on the same bus platform) the diesel bus had higher fuel economy over ten different tests, while the CNG bus had higher fuel economy on one test and the diesel and CNG versions had virtually identical fuel economy on three tests.
- Hybrid buses consistently have higher average fuel economy than the diesel and CNG versions of the same bus platform on slow- and medium-speed test cycles (< 18 MPH); on these cycles average fuel economy of the hybrid buses was between 7% and 44% higher than the average fuel economy of the diesel version of the same bus. On higher-speed test cycles the hybrid buses generally have the same or lower average fuel economy than the diesel version of the same bus. On slow- and medium-speed duty cycles the annual fuel savings from operating new hybrid buses instead of new diesel buses could be as high as 3,100 gallons per bus. According to data reported to the National Transit Database, approximately 75% of U.S. transit agencies, and 90% of U.S. transit buses on average operate in slow- and medium-speed duty cycles (<16 MPH).

AIR QUALITY

- CNG buses consistently have lower NOx emissions and higher CO emissions than diesel and hybrid buses across all duty cycles. Annual reductions in NOx emissions from operating new CNG buses instead of new diesel buses could be as high as 82 pounds per bus. Annual increases in CO emissions from operating new CNG buses instead of new diesel buses could be as high as 1,000 pounds per bus.
- Hybrid buses generally have slightly lower NOx emissions than diesel buses, but on several tests hybrid NOx emissions were higher than from the diesel version of the same bus.

- Diesel and hybrid buses both have very low PM emissions, equivalent to only about one third or less of the allowable EPA standard. PM was not measured for the CNG buses.
- All three technologies have very low NMHC emissions, equivalent to only about one fourth or less of the allowable EPA standard.

CLIMATE IMPACTS

- Diesel and CNG buses emit very similar levels of CO_2 from their tailpipes (g/mi); while natural gas has lower carbon content than diesel fuel this advantage is eroded by generally higher fuel economy for diesels. This result is different than reported results for other heavy-duty vehicles (for example long-haul trucks) due to differences in engine technology and duty cycle. Hybrid buses generally emit lower CO_2 (g/mi) than diesel or CNG buses due to their higher fuel economy.
- Total wells-to-wheels GHG emissions (g CO_2-e/mi) are generally slightly higher from CNG buses than from diesel buses, due primarily to the “upstream” impact of methane emissions from natural gas production and processing. The increase in total annual GHG emissions from operating new CNG buses instead of new diesel buses could be as high as 13.3 tons CO_2-e per bus.
- Total wells-to-wheels GHG emissions are generally lower from hybrid buses than from diesel or CNG buses due to their higher fuel economy. The reduction in total annual GHG emissions from operating new hybrid buses instead of new CNG buses could be as high as 54.5 tons CO_2-e per bus.

1 Data Sources and Methodology

This analysis uses data on fuel economy and exhaust emissions from different transit bus models, which was collected at the Altoona Bus Research & Testing Center (ABRTC), in Altoona PA. The ABRTC conducts required testing for all new transit bus models under the Federal Transit Administration's new model bus testing program. The goal of ABRTC is to "ensure better reliability and in-service performance of transit buses by providing an unbiased and accurate comparison of bus models through the use of an established set of test procedures"[4].

The ABRTC conducts tests on a range of bus types, from 20-foot shuttle buses to 60-foot articulated transit buses. This analysis focuses only on 40-41 foot low floor transit buses; this bus type makes up approximately 62% of the current U.S. fleet used for fixed-route service[5]. In addition, the intent of this analysis is to compare the efficiency and environmental performance of new buses that will be purchased in the future, so we have only included data from tests conducted since 2010 when the most stringent EPA emission standards went into effect; all of the buses included in this analysis were equipped with engines complaint with EPA 2010 standards.

See table 1 for a summary of all 40-41 foot low-floor transit buses tested at ABRTC since 2010.

Table 1 40-foot Transit Buses Tested at ABRTC Since 2010

ABRTC Report	Make	Model	Model Year	Size (ft.)	Engine Make/Model	Type
PTI-BT-R1205	New Flyer	C40LF	2011	41	Cummins ISL G280	CNG
PTI-BT-R1211	New Flyer	XD40	2011	40	Cummins ISL 9 280	Diesel
PTI-BT-R1015	New Flyer	XDE40	2010	40	Cummins ISB 6.7 280	Hybrid
PTI-BT-R1117	Daimler	Orion VII	2010	41	Cummins ISL G280	CNG
PTI-BT-R1202-P	Daimler	Orion VII	2012	41	Cummins ISL 280	Diesel
PTI-BT-R1007	Daimler	Orion VII	2010	41	Cummins ISB 6.7	Hybrid
PTI-BT-R1016	Gillig	Low Floor	2010	40	Cummins ISL G280	CNG
PTI-BT-R1206-P	Gillig	Low Floor	2012	41	Cummins ISB 6.7 280H	Hybrid
PTI-BT-R1011	NABI	416.15	2010	40	Cummins ISL 280	Diesel

[4] Altoona Bus Research & Testing Center website (http://www.altoonabustest.com/)
[5] National Transit Database, 2011 database, Revenue Vehicle Inventory

From this group of buses we chose to compare the first six, which provide a direct comparison of available technology options (CNG, Diesel, Hybrid) on each of two different bus platforms. See Table 2 for a summary of the specifications of these six buses, as tested at ABRTC.

The last three buses shown in Table 1 were not included in the analysis because they do not provide a direct comparison of all technologies on the same bus platform.

Table 2 Specification of Buses Included in This Analysis

	PTI-BT-R1205	PTI-BT-R1211	PTI-BT-R1015	PTI-BT-R1117	PTI-BT-R1202-P	PTI-BT-R1007
Manuf	New Flyer of America			Daimler Buses North America		
Type	CNG	Diesel	Hybrid	CNG	Diesel	Hybrid
Platform	C40LF	XD40	XDE40	Orion VII	Orion VII	Orion VII
Curb Weight	31, 201 lb	27,730 lb	27,870 lb	31,610 lb	29,310 lb	29,730
Engine	MY2010 Cummins ISLG 280	MY2011 Cummins ISL9 280	MY2010 Cummins ISB 6.7 280	MY2010 Cummins ISLG 280	MY2011 Cummins ISL 280	MY2010 Cummins ISB 6.7 280
Transmission	Allison B400R	Allison B400R	BAE / HDS200	Allison B400R	ZF Ecolife	BAE HybriDrive
Tires	Goodyear Metromiler B305/70R 22.5	Goodyear Metromiler B305/70R 22.5	Firestone City Transport 305/70R 22.5	Michelin XZU2 305/70R 22.5	Michelin XZU2 305/70R 22.5	Goodyear Metromiler B305/70R 22.5
Alternator	EMP/P450	Delco Remy 8600191	BAE / Electronic Alternator Supply	Delco Remy 8600191	EMP/ P450	BAE/BAE Hybrid System
Air Compressor	Wabco HD 30.4	Wabco 4938827	Wabco 636CC	Wabco CP9456	Wabco CP9456	Wabco CP9686

For this analysis we used data collected in two different types of tests at ABRTC, the Fuel Economy Test and the Emissions Test. In the fuel economy test buses are operated over a series of specific test cycles on a test track and, for liquid-fueled vehicles, average fuel use over each test segment is determined gravimetrically[6]. For gaseous fueled vehicles average fuel use over each test segment is determined using a laminar type flow meter installed in the vehicle fuel system.

For the emissions tests buses are mounted on a large-roll chassis dynamometer and exercised over a series of specific drive cycles. During testing the engine exhaust is routed to a full-scale dilution tunnel equipped with an emission sampling system. For all buses emissions analyzers

[6] A portable fuel tank is installed on the vehicle and hooked to the engine. The fuel tank is weighed before and after each test segment to determine the weight of fuel consumed.

are used to determine average emissions (grams per mile, g/mi) of oxides of nitrogen (NOx), carbon monoxide (CO), carbon dioxide (CO_2), and hydrocarbons (HC) over each drive cycle. For diesel fueled buses particulate matter (PM) is also measured, and for natural gas fueled buses methane (CH_4) is measured. ABRTC does not measure PM emissions from CNG buses or methane emission from diesel buses. From measured CO_2 emissions average fuel use over each drive cycle is determined based on carbon balance[7].

See Table 3 for a summary of the different test cycles used for the ABRTC fuel economy and emissions tests. These cycles cover a wide range of potential operating conditions for transit buses, from very low speed urban operation with many stops per mile (Manhattan Cycle) to medium speed urban/suburban operation (CBD, OCC), to very high-speed commuter type service with few stops per mile (Arterial, Commuter, UDDS).

According to data submitted by U.S. transit agencies to the National Transit Database, most transit buses operate in slow- or medium-speed duty cycles. The average in-service speed of transit buses in 2011 was 12.9 miles per hour (MPH); for that year 75% of all transit agencies, which operated 90% of all buses, had average in-service speed of less than 16 MPH[8].

Table 3 Test Cycles Used by Altoona Bus Research & Testing Center

Test Type	Name	Abbrev	Max Speed (MPH)	Avg Speed (MPH)	Stops/mi
Fuel Economy	Central Business District	CBD	20.0	12.7	7.0
	Arterial	ART	40.0	27.0	2.0
	Commuter	COM	40.0	38.0	0.3
	Average of above cycles	AVG	40.0	19.6	2.4
Emissions	Manhattan Cycle	MAN	25.4	6.8	10.0
	Orange County Cycle	OCC	41.0	12.0	5.0
	Urban Dynamometer Drive Cycle	UDDS	58.0	18.9	1.3

This analysis uses the measured fuel economy from both the ABRTC fuel economy and emissions tests to compare the efficiency of the different bus types. For CNG buses ABRTC reports measured fuel use in units of miles per pound of natural gas. In order to compare

[7] The total mass (grams) of carbon (CO plus HC plus CO_2) emitted in the exhaust must equal the total mass of carbon entering the engine as fuel. The carbon content of the diesel fuel (grams/gallon) is measured, and is used to calculate the amount of fuel (gallons) used, based on the measured mass of carbon in the exhaust.

[8] National Transit Database, Annual database RY2011; (www.ntdprogram.gov/ntdprogram/data.htm). Average speed is calculated by dividing reported total vehicle miles by reported total vehicle hours. This data covers 79,112 buses operated by 447 agencies.

directly to diesel and hybrid buses, for this report these values were converted to units of miles per diesel gallon equivalent (MPDGE) using standard values of 128,450 btu/gallon for #2 diesel fuel and 20,269 btu/lb for natural gas[9].

To compare the environmental performance of the different bus types (g/mi emissions of NOx, PM, HC, CH_4, CO, CO_2, GHG) this analysis uses data from the ABRTC emissions tests only.

For each bus the following greenhouse gases (GHGs) are included in the analysis: carbon dioxide (CO_2) and methane (CH_4). In addition, for diesel buses the analysis includes the atmospheric warming effect of black carbon (BC) emitted from the tailpipe as particulate matter (PM)[10]. This analysis assumes that 75% of the mass of PM emitted by diesel engines is BC[11]. While CNG buses also typically emit a small amount of PM and BC from their tailpipes the ABRTC test data does not include PM emissions from the tested CNG buses, so it was not included.

In this analysis emissions of CH_4 and BC are converted to "carbon dioxide equivalents" (CO_2-e) using their "global warming potential" (GWP)[12]. For each bus, total GHGs per mile are calculated using equation 1:

$$\text{Total GHG } (CO_2\text{-e}) \text{ [g/mi]} = CO_2 \text{ [g/mi]} + (GWP_{CH4} \times CH_4 \text{ [g/mi]}) + (GWP_{BC} \times BC \text{ [g/mi]})$$

Equation 1

Table 4 GWP Values Used in the Analysis

	GWP20	GWP100	Source
Carbon Dioxide (CO_2)	1	1	Definition
Methane (CH_4)	86	34	IPCC 2013
Black Carbon (BC)	3,200	900	IPCC 2013

The GWP values used in this analysis are shown in Table 4; these are the latest values determined by the Intergovernmental Panel on Climate Change[13].

Most greenhouse gases, including carbon dioxide, stay in the atmosphere for hundreds of years – atmospheric scientists have therefore typically evaluated the effect of

[9] U.S. Department of Energy, Alternative Fuels & Advanced Vehicles Data Center (www.afdc.energy.gov/afdc/fuels/properties.html). 6.34 lb natural gas = 1 DGE

[10] Black carbon is a solid, not a gas, and its effect on atmospheric warming is different than the effect of "greenhouse gases" such as carbon dioxide and methane. Black carbon in the air warms the atmosphere directly by absorbing sunlight and radiating heat. Black carbon deposited on ice and snow reduces their reflectivity and accelerates melting, which indirectly contributes to further warming.

[11] EPA Technology Transfer Network, Clearinghouse for Inventories and Emission Factors, Speciation, April 26,2005

[12] GWPs are defined in relation to carbon dioxide. By definition the GWP of CO_2 = 1 evaluated over all time horizons.

[13] Intergovernmental Panel on Climate Change, *5th Assessment Report*, September 2013. These GWP values for methane are higher than those in the IPCC 4th assessment report (2007). The 5th assessment report includes GWP values for black carbon for the first time.

GHGs over a 100-year time horizon, using GWP100. Recently, however, there has been growing evidence of the importance of "short-term climate forcers", including both CH_4 and BC, acting over a much shorter time horizon[14]. For that reason we have chosen to provide estimates of total GHGs from all buses using both a 20-year (GWP20) and 100-year (GWP100) time horizon – these are designated in this report as "short-term GHGs" and "long-term GHGs", respectively. As shown in Table 4, in the short term one pound of methane emitted to the atmosphere has 86 times the warming potential of one pound of carbon dioxide (GWP20 = 86), while in the long term it has only 34 times the warming potential (GWP100 = 34). Black carbon is an even more potent climate warmer, particularly in the short term. Over a 20-year time horizon one pound of BC emitted into the atmosphere is estimated to have 3,200 times the warming potential of one pound of CO_2.

When evaluating the total greenhouse gases (GHG) emitted by each bus type we included emissions from the bus tailpipe (as measured by ABRTC) as well as estimated "upstream" emissions from recovery, production and transport of the fuel used by the bus – this provides a "total fuel cycle" or "wells-to-wheels" view of GHG emissions. Data on estimated upstream emissions was taken from the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model developed by the Argonne National Laboratory[15]. National level default values for each fuel pathway were used to calculate CO_2 and CH_4 emissions (grams per megajoule, g/MJ) for the production of diesel fuel (for diesel and hybrid buses) and for the production of compressed natural gas (for CNG buses). These values were converted to mass of emissions per unit of fuel used (grams per diesel gallon equivalent, g/DGE) using a standard value of 135.52 MJ/gallon for diesel fuel[16].

To evaluate potential annual fuel and emission savings from operating one type of bus compared to another, this analysis used 36,424 miles per year per bus. This is the average annual mileage for all U.S. transit buses, as reported by the American Public Transportation Association[17].

[14] Bond, T.C., et al, *Bounding the role of black carbon in the climate system: A scientific assessment,* Journal of Geophysical Research; Atmospheres, Volume 118, Issue 11, June 6, 2013

[15] GREET 1 2013, October 25, 2013

[16] U.S. Department of Energy, Alternative Fuels & Advanced Vehicles Data Center (www.afdc.energy.gov/afdc/fuels/properties.html)

[17] American Public Transportation Association, 2012 Public Transportation Fact Book, Tables 7 and 8

2 Results

2.1 Fuel Economy

See Figure 1 for a comparison of ABRTC measured fuel economy from the CNG, diesel, and hybrid New Flyer buses and Figure 2 for measured fuel economy from the CNG, diesel, and hybrid Daimler buses. As shown, for 14 sets of measurements (two sets of buses times seven test cycles each), the diesel bus had higher fuel economy (MPDGE) than the CNG bus (same bus platform) on ten different tests, the CNG bus had higher fuel economy on one test, and the diesel and CNG buses had virtually identical fuel economy on three tests. For the test cycles over which the diesel bus had higher fuel economy than the CNG bus the increase in fuel economy ranged from 7% (Daimler buses on Commuter Cycle) to 46% (New Flyer buses on UDDS Cycle). For the test in which the CNG bus had higher fuel economy (New Flyer on CBD cycle) the increase in MPDGE was 7%.

Based on the data shown in Figure 1 and 2, a CNG bus with average annual mileage (36,424 miles per year) could use between 600 gallons less and 2,900 gallons[18] more fuel annually than a diesel bus depending on the bus platform and duty cycle.

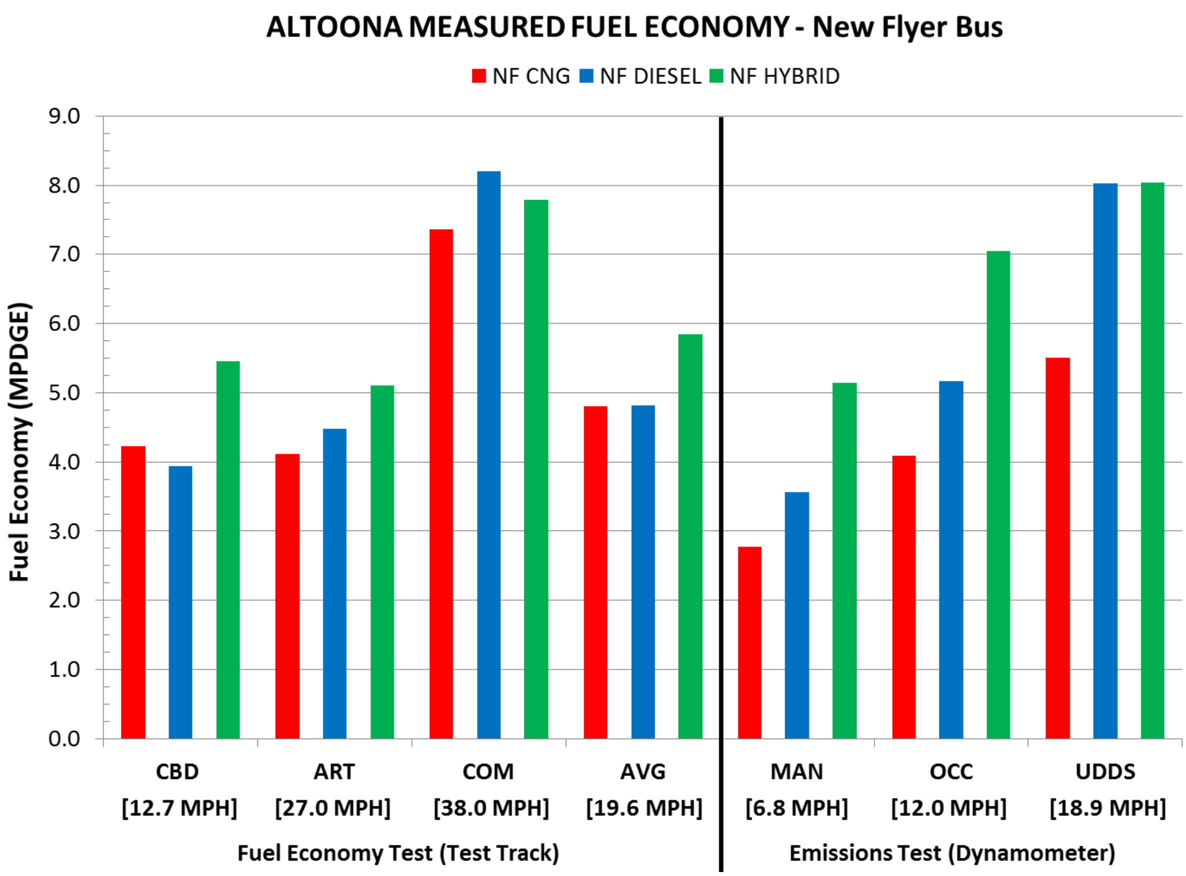


Figure 1 Altoona Measured Fuel Economy – New Flyer Buses

[18] Diesel gallon equivalents

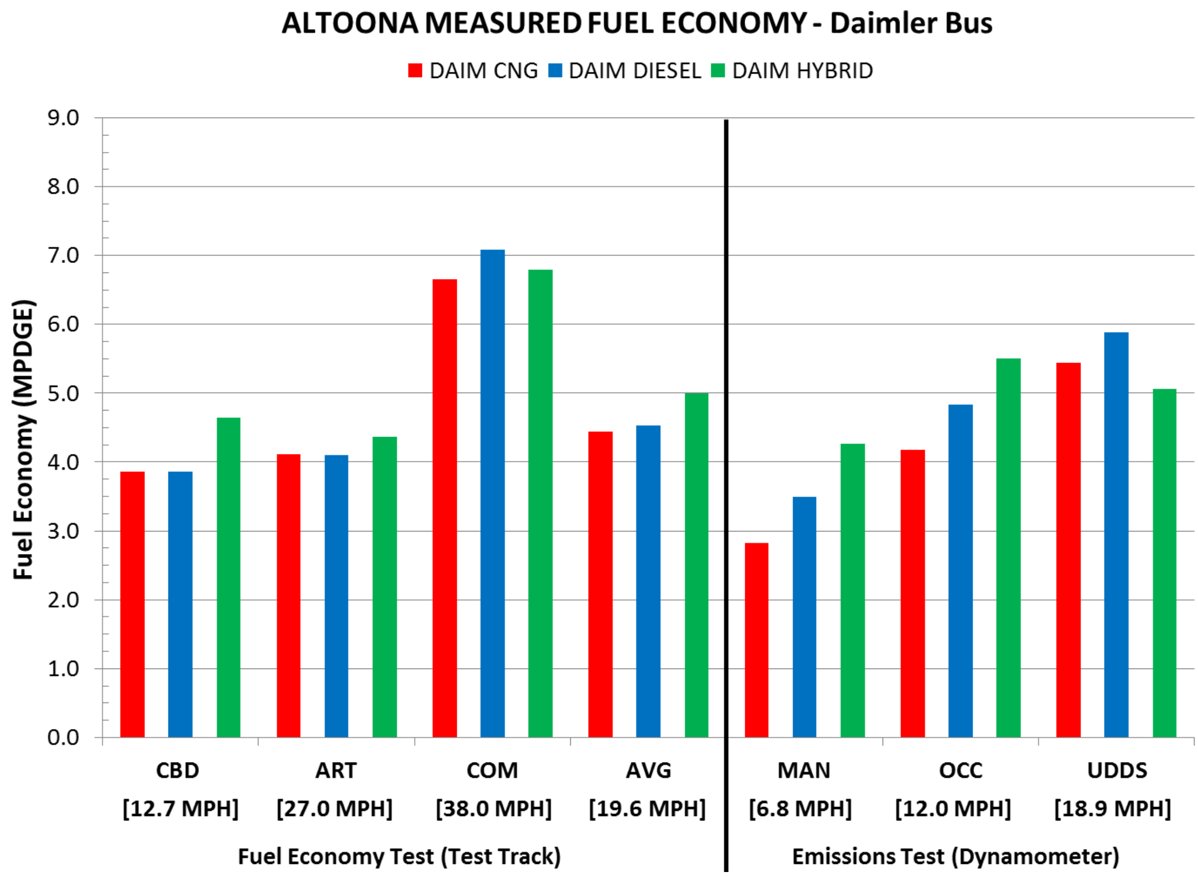


Figure 2 Altoona Measured Fuel Economy – Daimler Buses

Over the 14 sets of measurements the hybrid bus had higher fuel economy than the diesel bus (same bus platform) on ten tests, the diesel bus had higher fuel economy on three tests, and the hybrid and diesel bus had virtually identical fuel economy on one test. The hybrid had higher fuel economy than the CNG bus on all but one test. There is a clear pattern to the differences in fuel economy between the CNG/diesel and hybrid buses: the hybrid buses always had higher measured fuel economy than the diesel and CNG buses on the slow-speed and medium-speed cycles (CBD, MAN, OCC) and fuel economy was the same, or higher, for the diesel bus than the hybrid bus on the high-speed cycles (COMM, UDDS).

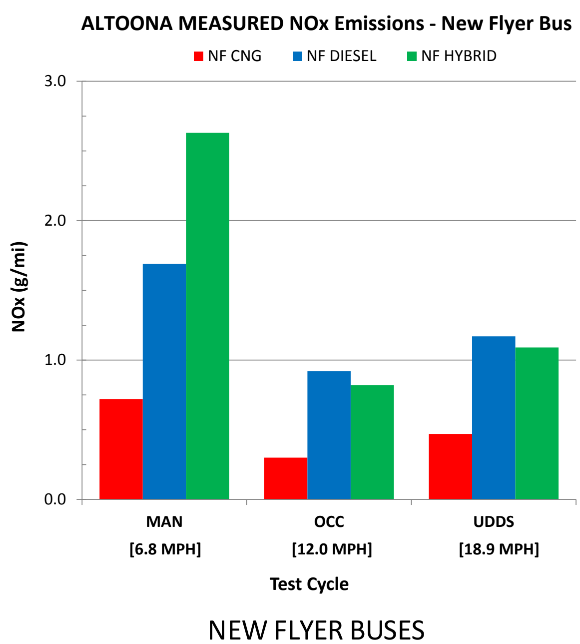
For the slow and medium-speed test cycles the increase in fuel economy for the hybrid buses compared to the diesel buses ranged from 7% (Daimler buses on Arterial Cycle) to 44% (New Flyer buses on Manhattan Cycle). For these same cycles the increase in fuel economy for the hybrid buses compared to the CNG buses ranged from 6% (Daimler buses on Arterial Cycle) to 85% (New Flyer buses on Manhattan Cycle). For virtually all cycles the Daimler hybrid bus had lower measured fuel economy than the New Flyer hybrid bus. On all but two test cycles the Daimler CNG and diesel buses also had lower measured fuel economy than the New Flyer buses of the same technology.

Based on the data shown in Figures 1 and 2, a hybrid bus with average annual mileage (36,424 miles per year) operating in a slow- or medium-speed duty cycle could use between 549 gallons and 3,142 gallons less fuel annually than a diesel bus, or between 507 gallons and 6,052 gallons[19] less fuel annually than a CNG bus, depending on the bus platform and actual duty cycle.

2.2 Emissions

2.1.1 Criteria Pollutants

See figure 3 for a comparison of ABRTC measured NOx emissions from both the New Flyer and Daimler buses. As shown, for both the New Flyer and Daimler bus platform, the CNG version consistently had the lowest NOx emissions of the three technologies on all test cycles. The reduction in NOx emissions for the CNG buses compared to the diesel buses ranged from 0.04 g/mi (Daimler Bus on UDDS cycle) to 1.22 g/mi (Daimler bus on Manhattan cycle). For buses with average annual mileage (36,424 miles per year) the potential annual NOx reduction from operating new CNG buses instead of new diesel buses ranges from 3.2 – 81.8 pounds per bus.



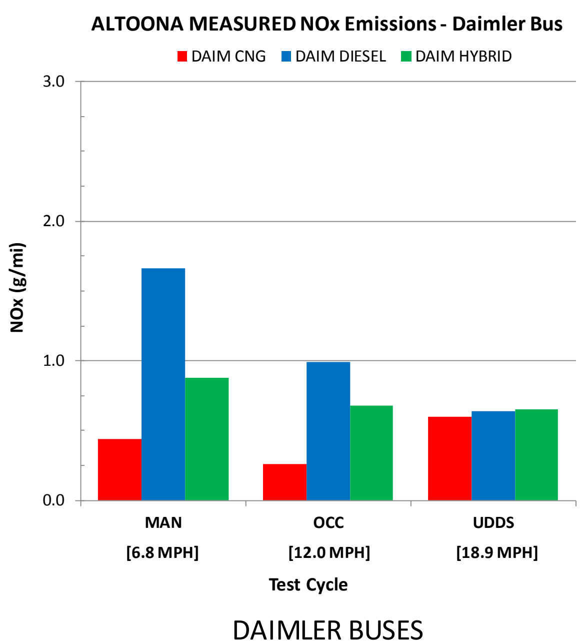


Figure 3 Altoona Measured NOx Emissions

On all but two tests (Daimler bus on UDDS cycle and New Flyer bus on Manhattan Cycle) the hybrid buses also had lower NOx emissions than the diesel buses, but not as low as the CNG buses. The reduction in NOx emissions for the hybrid buses compared to the diesel buses ranged from 0.08 g/mi (New Flyer Bus on UDDS cycle) to 0.78 g/mi (Daimler bus on Manhattan cycle). On the Manhattan Cycle the New Flyer hybrid bus had 0.94 g/mi higher NOx emissions than the New Flyer Diesel bus. For buses with average annual mileage (36,424 miles per year) the potential annual NOx reduction from operating

[19] Diesel gallon equivalents

new hybrid buses instead of new diesel buses ranges from -75.5 pounds (increase) to 62.6 pounds per bus.

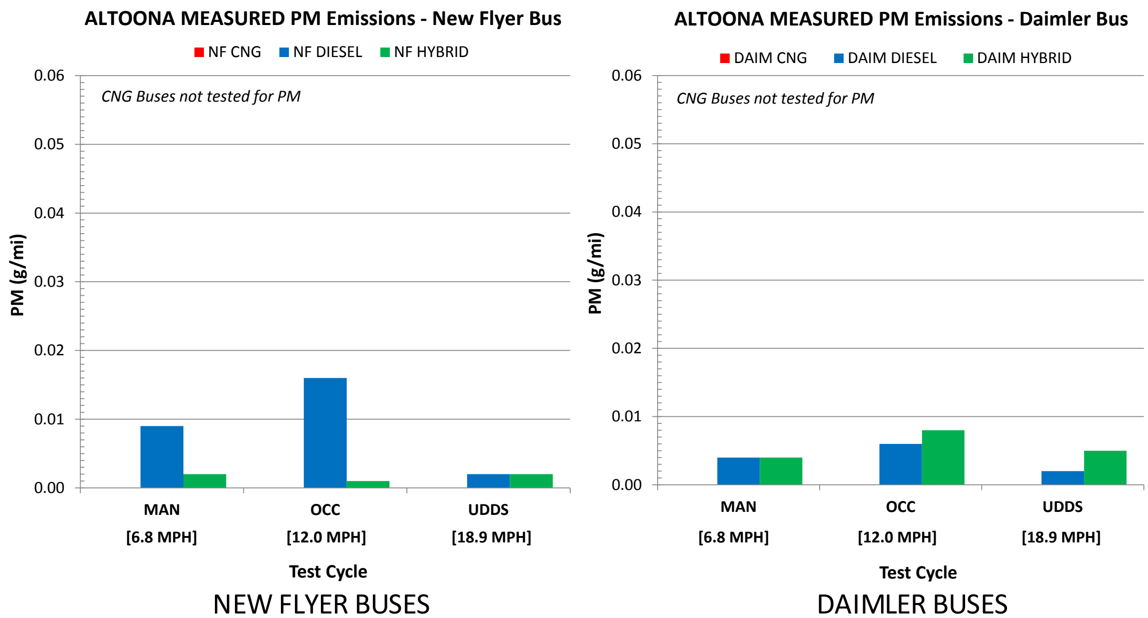


Figure 4 Altoona Measured PM Emissions

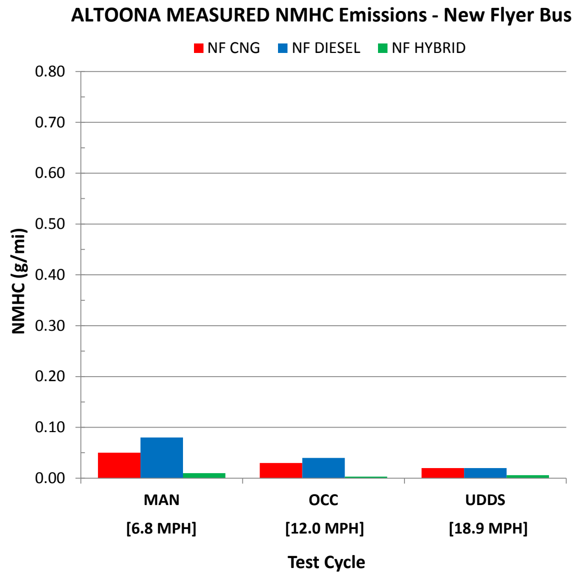
See Figure 4 for a comparison of ABRTC measured PM emissions from both the New Flyer and Daimler diesel and hybrid buses; ABRTC did not measure PM emissions from the CNG buses. As shown, in some cases PM was higher from the diesel bus and sometimes it was higher from the hybrid bus. In all cases, however, PM emissions were very low, and were well below the EPA standard. Given the measured fuel economy from these tests, a bus which just meets the EPA new engine PM standard of 0.01 g/bhp-hr would emit between 0.03 and 0.05 g/mi PM[20].

See Figure 5 for a comparison of ABRTC measured NMHC emissions from both the New Flyer and Daimler buses. As shown, in some cases NMHC was highest from the diesel bus and sometimes it was highest from the CNG bus. In all cases, however, NMHC emissions were very low from all three technologies, and were well below the EPA standard. Given the measured fuel economy from these tests, a bus which just meets the EPA new engine NMHC standard of 0.14 g/bhp-hr would emit between 0.29 and 0.71 g/mi NMHC[16].

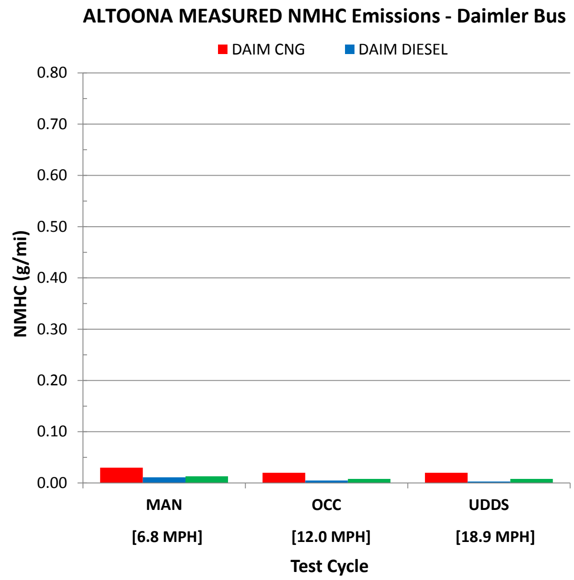
See Figure 6 for a comparison of ABRTC measured CO emissions from both the New Flyer and Daimler buses. As shown, in all cases the CNG buses had significantly higher CO emissions than the diesel and hybrid buses. The increase in CO emissions for the CNG buses compared to the diesel and hybrid buses ranged from 4.4 g/mi (Daimler Bus on UDDS cycle) to 13.2 g/mi (New Flyer bus on Manhattan cycle). For buses with average annual mileage (36,424 miles per year) the potential annual CO increase from

[20] This assumes 33% average engine efficiency.

operating new CNG buses instead of new diesel or hybrid buses ranges from 353 pounds to 1,060 pounds per bus.

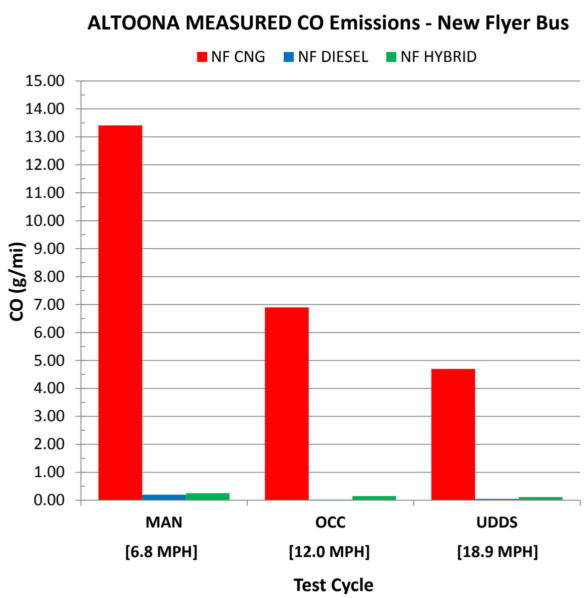


NEW FLYER BUSES

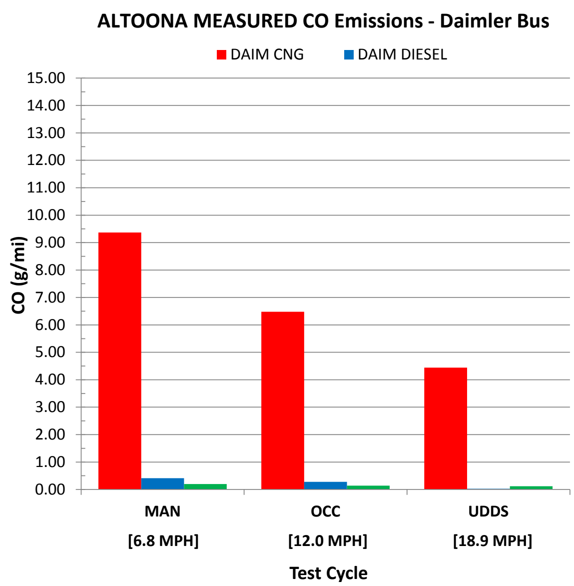


DAIMLER BUSES

Figure 5 Altoona Measured NMHC Emissions



NEW FLYER BUSES



DAIMLER BUSES

Figure 6 Altoona Measured CO Emissions

2.1.2 Green House Gases

See Figures 7 – 10 for estimated total wells-to-wheels GHG emissions from the New Flyer and Daimler buses tested at ABRTC. These figures include measured tailpipe emissions (CO_2, CH_4, and BC) and estimated upstream emissions from fuel production (CO_2, CH_4). In these figures all GHGs were converted to carbon dioxide equivalents (CO_2-e) using appropriate "global warming potential" values (see Section 1). Figures 7 and 8 show estimated GHGs over a 100-year year time horizon (long term), while Figures 9 and 10 show estimated GHGs over a 20-year time horizon (short term).

As shown, for all test cycles measured tail-pipe emissions of CO_2 from the New Flyer CNG bus were virtually the same, or slightly higher than, measured CO_2 emissions from the New Flyer diesel bus. For all test cycles measured tail-pipe emissions of CO_2 from the Daimler CNG bus were slightly lower than measured CO_2 emissions from the Daimler diesel bus. Based on this test data, for buses with average annual mileage (36,424 miles per year) the potential annual change in tailpipe CO_2 emissions from operating new CNG buses instead of new diesel buses ranges from a decrease of 10.4 tons per bus to an increase of 7.2 tons per bus (-15% to +14%).

For the low- and medium-speed test cycles (Manhattan, Orange County) measured tailpipe emissions of CO_2 from the hybrid versions of both the New Flyer and Daimler buses were lower than from the diesel and CNG versions of the same bus; on the higher speed UDDS cycle measured tailpipe CO_2 emissions were lower for the New Flyer hybrid than for the New Flyer diesel or CNG buses, but were higher for the Daimler hybrid than for the Daimler diesel and CNG buses. This is consistent with the fuel economy results discussed in section 2.1.

Based on this test data, for buses with average annual mileage (36,424 miles per year) the potential annual reduction in tailpipe CO_2 emissions from operating new hybrid buses instead of new diesel buses in typical slow- and medium-speed transit duty cycles ranges from 10.1 tons per bus to 34.9 tons per bus (-12% to -31%). The potential annual reduction in tailpipe CO_2 emissions from operating new hybrid buses instead of new CNG buses in typical slow- and medium-speed transit duty cycles ranges from 2.5 tons per bus to 35.7 tons per bus (-3% to -31%).

When measured tail pipe emissions of CH_4 and BC, as well as estimated upstream emissions of CO_2 and CH_4, are added to measured tailpipe emissions of CO_2 total estimated wells-to-wheels GHGs (g CO_2-e/mi) are generally slightly higher for the CNG version of the New Flyer bus, but slightly lower for the CNG version of the Daimler Bus, compared to the diesel version of the same bus. This is primarily due to the effect of upstream CH_4 emissions from production and transport of natural gas fuel. Upstream CO_2 emissions are lower for natural gas than for diesel fuel. Tailpipe emissions of CH_4 (from CNG buses) and BC (from diesel and hybrid buses) are very low relative to total CO_2 emissions, and therefore do not contribute significantly to total wells-to-wheels GHG emissions for any of the buses.

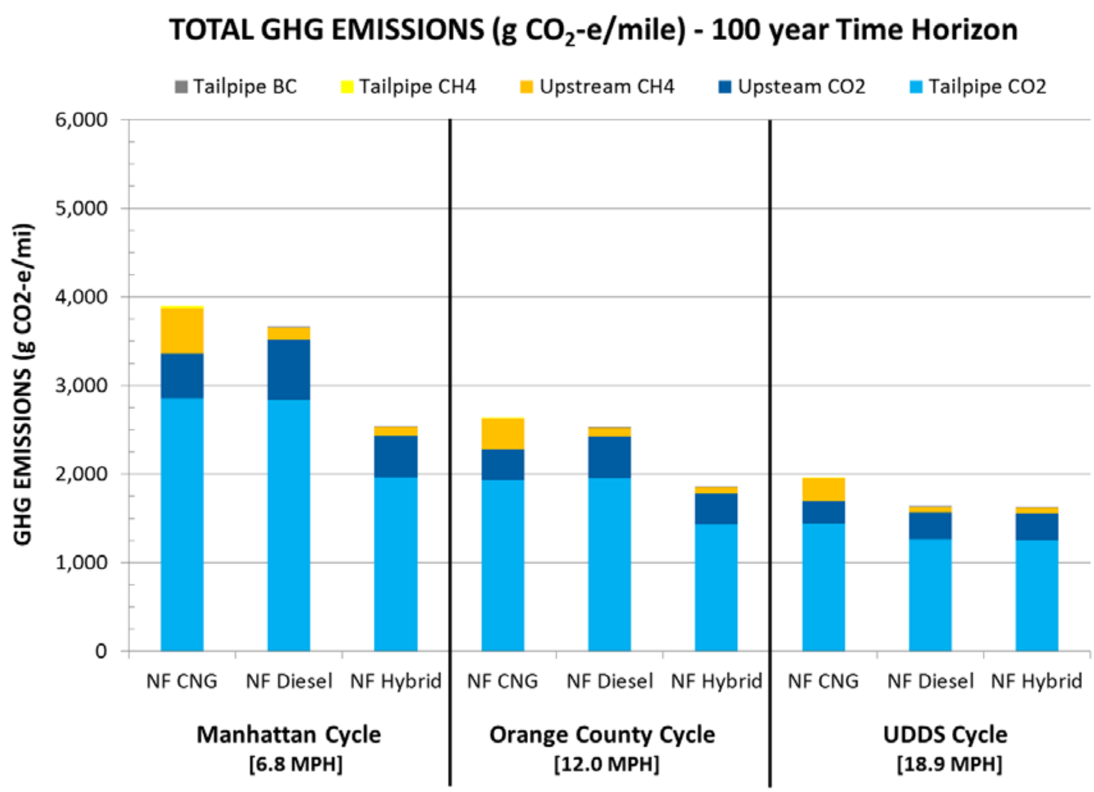


Figure 7 Estimated Long-term Wells –to-Wheels GHG Emissions – New Flyer Buses

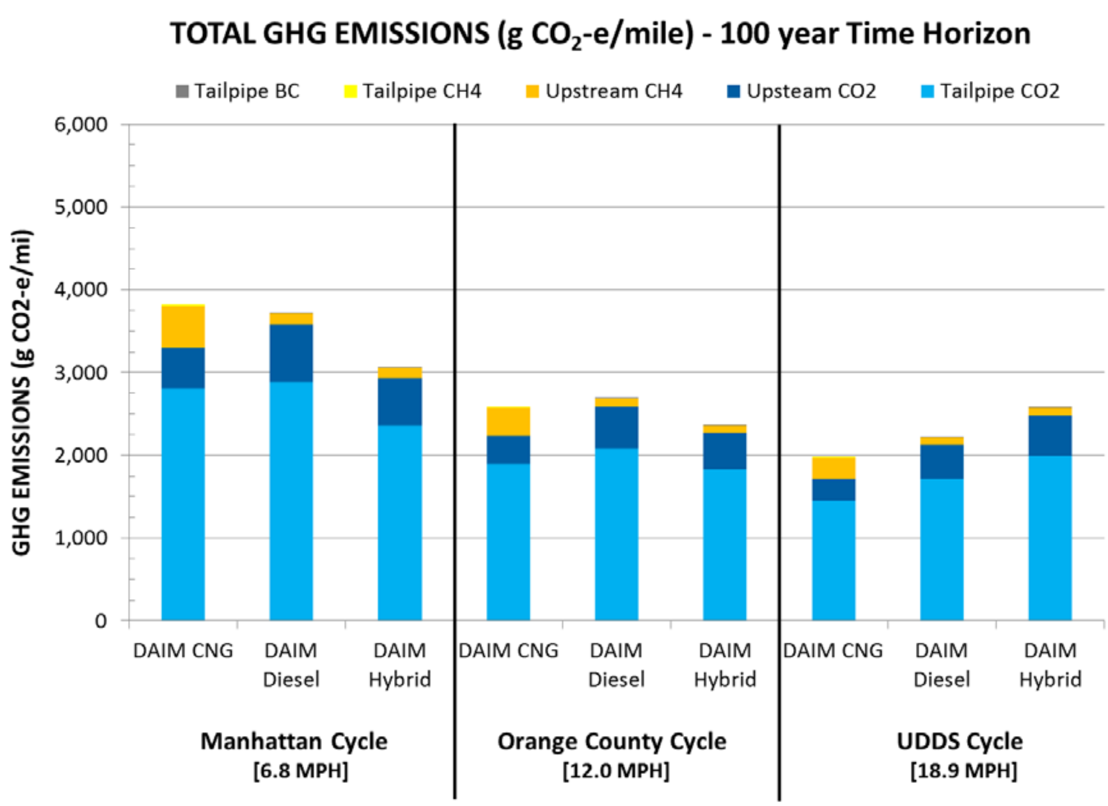


Figure 8 Estimated Long-term Wells –to-Wheels GHG Emissions – Daimler Buses

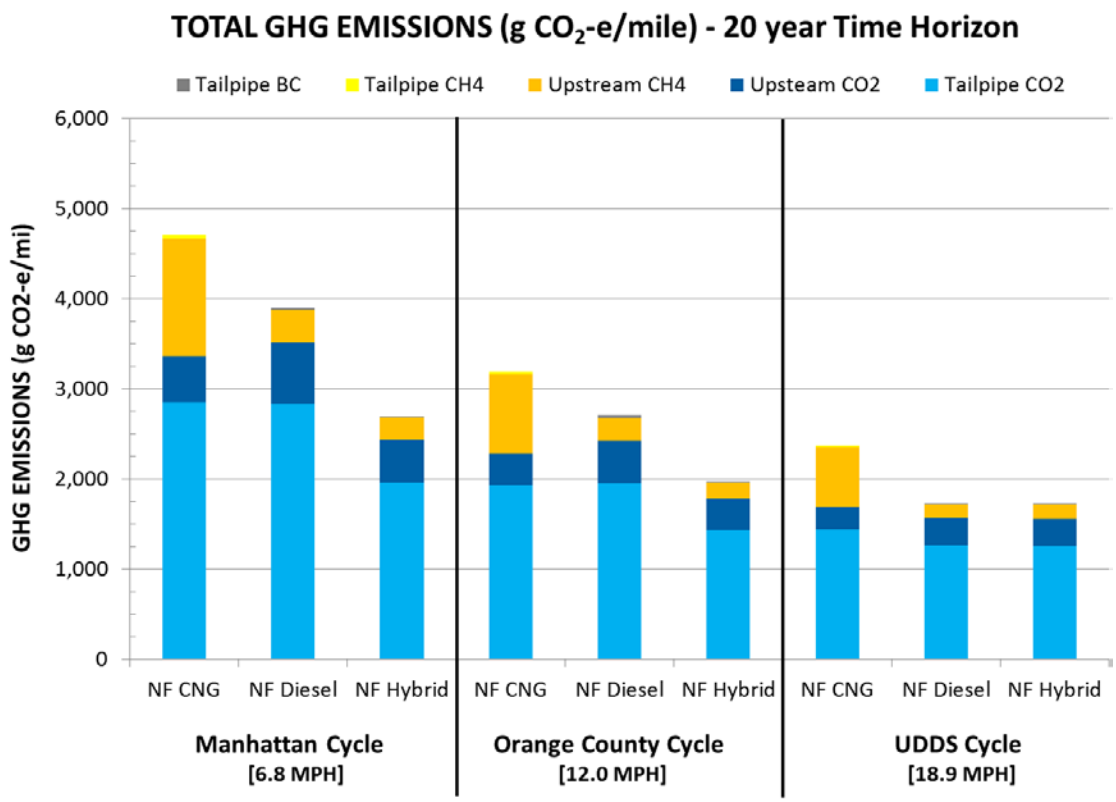


Figure 9 Estimated Short-term Wells –to-Wheels GHG Emissions – New Flyer Buses

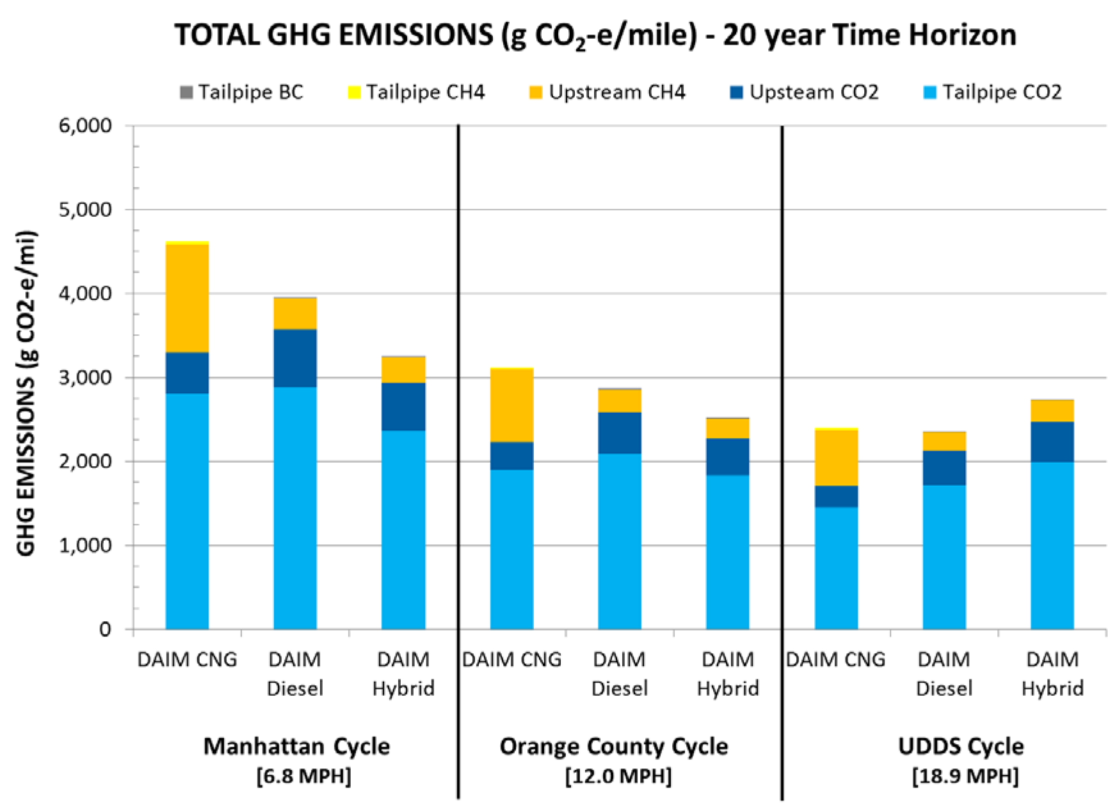


Figure 10 Estimated Short-term Wells –to-Wheels GHG Emissions – Daimler Buses

As shown in Figures 9 and 10 the negative effect of upstream CH_4 emissions from natural gas fuel production are magnified in the short-term (20 years) compared to the long term (100 years) because methane is a short term climate forcer.

Based on the data shown in figures 7 - 10, for buses with average annual mileage (36,424 miles per year) the potential annual change in long-term wells-to-wheels GHG emissions (CO_2-e) from operating new CNG buses instead of new diesel buses ranges from a decrease of 9.1 tons per bus to an increase of 13.3 tons per bus (-10% to +20%). In the short-term the potential annual change in wells-to-wheels GHG emissions (CO_2-e) from operating new CNG buses instead of new diesel buses ranges from an increase of 2.5 tons per bus to an increase of 32.8 tons per bus (+2.5% to +17%).

For buses with average annual mileage (36,424 miles per year) the potential annual change in long-term wells-to-wheels GHG emissions (CO_2-e) from operating new CNG buses instead of new hybrid buses ranges from a decrease of 23.7 tons per bus when operating in higher-speed duty cycles to an increase of 54.5 tons per bus when operating in slow-speed duty cycles (-23% to +25%). In the short-term the potential annual change in wells-to-wheels GHG emissions (CO_2-e) from operating new CNG buses instead of new hybrid buses ranges from a decrease of 13.3 tons per bus when operating in high-speed duty cycles to an increase of 81.2 tons per bus when operating in typical slow-speed duty cycles (-29% to +54%).

Given that assumptions about upstream CH_4 emissions from natural gas production have such a large effect on the wells-to-wheels GHG analysis, it must be noted that there is continuing uncertainty as to the actual level of methane emissions from this activity. This analysis uses the most recent data available, from Argonne's GREET model (see Section 1), which is in turn based on EPA's most recent national greenhouse gas inventory. However, recent studies have indicated that EPA's inventory may over-state methane emissions from some natural gas production steps and understate methane emissions from others[21]. Future revisions to EPA's inventory, and to the GREET model, could either increase or decrease estimated wells-to-wheels GHG emissions from the use of both diesel and CNG buses.

[21] University of Texas, Center for Energy & Environmental Resources, *Unprecedented Measurements Provide Better Understanding of Methane Emissions During Natural Gas Production,* September 16, 2013; http://dept.ceer.utexas.edu/methane/study/index.cfm

REFERENCES

- PTI-BT-R1205, *PARTIAL STURAA TEST 12 YEAR 500,000 MILE BUS from NEW FLYER of AMERICA MODEL C40LF, JUNE 2012*; The Thomas D. Larson Pennsylvania Transportation Institute, Vehicle Systems and Safety Program
- PTI-BT- R1211, *PARTIAL STURAA TEST 12 YEAR 500,000 MILE BUS from NEW FLYER of AMERICA MODEL XD40, NOVEMBER 2012*; The Thomas D. Larson Pennsylvania Transportation Institute, Vehicle Systems and Safety Program
- PTI-BT-R1015, *PARTIAL STURAA TEST 12 YEAR 500,000 MILE BUS from NEW FLYER of AMERICA MODEL XDE40, DECEMBER 2011*; The Thomas D. Larson Pennsylvania Transportation Institute, Vehicle Systems and Safety Program
- PTI-BT-R1117, *PARTIAL STURAA TEST 12 YEAR 500,000 MILE BUS from DAIMLER BUSES NORTH AMERICA LTD. , MODEL ORION VII EPA 10 CNG,* FEBRUARY 2012; The Thomas D. Larson Pennsylvania Transportation Institute, Vehicle Systems and Safety Program
- PTI-BT-R1202-P, *PARTIAL STURAA TEST 12 YEAR 500,000 MILE BUS from DAIMLER BUSES NORTH AMERICA LTD. ,* MODEL ORION VII EPA10 DIESEL APRIL 2012; The Thomas D. Larson Pennsylvania Transportation Institute, Vehicle Systems and Safety Program
- PTI-BT-R1007, *STURAA TEST 12 YEAR 500,000 MILE BUS from DAIMLER BUSES NORTH AMERICA LTD. ,* MODEL ORION VII EPA10, NOVEMBER 2010; The Thomas D. Larson Pennsylvania Transportation Institute, Vehicle Systems and Safety Program

Table 5 Altoona-Measured Fuel Economy all Buses

ABRTC Report	Make	Model	Model Year	Type	Altoona Measured Fuel Economy Miles/DGE						
					Fuel Economy Test				Emissions Test		
					CBD	*ART*	*COM*	*AVG*	*MAN*	*OCC*	*UDDS*
PTI-BT-R1205	New Flyer	C40LF	2011	CNG	4.23	4.12	7.37	4.80	2.77	4.09	5.51
PTI-BT-R1211	New Flyer	XD40	2011	Diesel	3.94	4.48	8.20	4.82	3.56	5.17	8.03
PTI-BT-R1015	New Flyer	XDE40	2010	Hybrid	5.46	5.11	7.79	5.84	5.14	7.05	8.04
PTI-BT-R1117	Daimler	Orion VII	2010	CNG	3.87	4.12	6.65	4.44	2.82	4.17	5.44
PTI-BT-R1202-P	Daimler	Orion VII	2012	Diesel	3.86	4.10	7.09	4.53	3.50	4.84	5.89
PTI-BT-R1007	Daimler	Orion VII	2010	Hybrid	4.64	4.37	6.80	5.00	4.26	5.50	5.06

Table 6 Altoona Measured Emissions, All Buses

Manhattan Cycle

ALTOONA REPORT	Make	Model	Model Year	Size (ft.)	Fuel	Fuel Economy [MPDGE]	EMISSIONS (g/mi)					
							NOx	PM	NMHC	CO	CH4	CO2
PTI-BT-R1205	New Flyer	C40LF	2011	41	CNG	2.77	0.72	NM	0.05	13.41	0.61	2,850
PTI-BT-R1211	New Flyer	XD40	2011	40	Diesel	3.56	1.69	0.009	0.08	0.20	NM	2,830
PTI-BT-R1015	New Flyer	XDE40	2010	40	Hybrid	5.14	2.63	0.002	0.01	0.25	NM	1,960
PTI-BT-R1117	Daimler	Orion VII	2010	41	CNG	2.82	0.44	NM	0.03	9.37	0.48	2,802
PTI-BT-R1202-P	Daimler	Orion VII	2012	41	Diesel	3.50	1.66	0.004	0.01	0.41	NM	2,882
PTI-BT-R1007	Daimler	Orion VII	2010	41	Hybrid	4.26	0.88	0.004	0.01	0.20	NM	2,365

NM= Not measured

Orange County Bus Cycle

	Make	Model	Model Year	Size (ft.)	Fuel	Fuel Economy [MPDGE]	EMISSIONS (g/mi)					
							NOx	PM	NMHC	CO	CH4	CO2
PTI-BT-R1205	New Flyer	C40LF	2011	41	CNG	4.09	0.30	NM	0.030	6.90	0.37	1,932
PTI-BT-R1211	New Flyer	XD40	2011	40	Diesel	5.17	0.92	0.016	0.040	0.02	NM	1,950
PTI-BT-R1015	New Flyer	XDE40	2010	40	Hybrid	7.05	0.82	0.001	0.003	0.15	NM	1,431
PTI-BT-R1117	Daimler	Orion VII	2010	41	CNG	4.17	0.26	NM	0.020	6.48	0.27	1,895
PTI-BT-R1202-P	Daimler	Orion VII	2012	41	Diesel	4.84	0.99	0.006	0.005	0.28	NM	2,084
PTI-BT-R1007	Daimler	Orion VII	2010	41	Hybrid	5.50	0.68	0.008	0.008	0.14	NM	1,832

NM= Not measured

UDDS Cycle

	Make	Model	Model Year	Size (ft.)	Fuel	Fuel Economy [MPDGE]	EMISSIONS (g/mi)					
							NOx	PM	NMHC	CO	CH4	CO2
PTI-BT-R1205	New Flyer	C40LF	2011	41	CNG	5.51	0.47	NM	0.020	4.70	0.20	1,435
PTI-BT-R1211	New Flyer	XD40	2011	40	Diesel	8.03	1.17	0.002	0.020	0.05	NM	1,256
PTI-BT-R1015	New Flyer	XDE40	2010	40	Hybrid	8.04	1.09	0.002	0.006	0.11	NM	1,254
PTI-BT-R1117	Daimler	Orion VII	2010	41	CNG	5.44	0.60	NM	0.02	4.44	0.38	1,453
PTI-BT-R1202-P	Daimler	Orion VII	2012	41	Diesel	5.89	0.64	0.002	0.00	0.03	NM	1,713
PTI-BT-R1007	Daimler	Orion VII	2010	41	Hybrid	5.06	0.65	0.005	0.01	0.12	NM	1,993

NM= Not measured

Table 7 Estimated Wells-to-Wheels GHG Emissions, All Buses

NEW FLYER BUSES			Manhattan Cycle			Orange County Cycle			UDDS Cycle			
		unit	NF CNG	NF Diesel	NF Hybrid	NF CNG	NF Diesel	NF Hybrid	NF CNG	NF Diesel	NF Hybrid	*Notes/Sources*
Fuel Economy		MPDEG	2.77	3.56	5.14	4.09	5.17	7.05	5.51	8.03	8.04	*Altoona Test Data*
Fuel Use		DEG/mi	0.361	0.281	0.194	0.244	0.193	0.142	0.182	0.125	0.124	*= 1 ÷ MPDEG*
Tail pipe Emissions	PM	g/mi	0.000	0.009	0.002	0.000	0.016	0.001	0.000	0.002	0.002	Altoona Test Data
	CH_4	g/mi	0.61	0.00	0.00	0.37	0.00	0.00	0.20	0.00	0.00	
	CO_2	g/mi	2,850	2,830	1,960	1,932	1,950	1,431	1,435	1,256	1,254	
Upsteam Emission Factors (Fuel Production)	CO_2	g/MJ	10.32	17.92	17.92	10.32	17.92	17.92	10.32	17.92	17.92	*GREET 2012*
	CO_2	g/DEG	1,399	2,429	2,429	1,399	2,429	2,429	1,399	2,429	2,429	*= g/MJ x MJ/DEG*
	CH_4	g/MJ	0.31	0.11	0.11	0.31	0.11	0.11	0.31	0.11	0.11	*GREET 2012*
	CH_4	g/DEG	42.0	14.9	14.9	42.0	14.9	14.9	42.0	14.9	14.9	*= g/MJ x MJ/DEG*
SHORT-TERM GHG PER MILE BY SOURCE TYPE	Upsteam CO_2	g CO_2-e/mi	504	682	472	342	470	345	254	302	302	g CO2/DEG x DEG/mi
	Upstream CH_4	g CO_2-e/mi	1,303	360	249	883	248	182	656	160	159	g CH4/DEG x DEG/mi x CH4 GWP20
	Tailpipe CO_2	g CO_2-e/mi	2,850	2,830	1,960	1,932	1,950	1,431	1,435	1,256	1,254	g CO2/mi; Altoona Test Data
	Tailpipe CH_4	g CO_2-e/mi	52	0	0	32	0	0	17	0	0	g CH4/mi (Altoona) x CH4 GWP20
	Tailpipe BC	g CO_2-e/mi	0	22	5	0	38	2	0	5	5	g PM/mi (Altoona) x BC GWP20
	TOTAL	***g CO_2-e/mi***	***4,709***	***3,893***	***2,686***	***3,189***	***2,706***	***1,960***	***2,362***	***1,723***	***1,720***	
LONG-TERM GHG PER MILE BY SOURCE TYPE	Upsteam CO_2	g CO_2-e/mi	504	682	472	342	470	345	254	302	302	g CO2/DEG x DEG/mi
	Upstream CH_4	g CO_2-e/mi	515	142	99	349	98	72	259	63	63	g CH4/DEG x DEG/mi x CH4 GWP100
	Tailpipe CO_2	g CO_2-e/mi	2,850	2,830	1,960	1,932	1,950	1,431	1,435	1,256	1,254	g CO2/mi; Altoona Test Data
	Tailpipe CH_4	g CO_2-e/mi	21	0	0	13	0	0	7	0	0	g CH4/mi (Altoona) x CH4 GWP100
	Tailpipe BC	g CO_2-e/mi	0	6	1	0	11	1	0	1	1	g PM/mi (Altoona) x BC GWP100
	TOTAL	***g CO_2-e/mi***	***3,890***	***3,660***	***2,532***	***2,635***	***2,528***	***1,848***	***1,955***	***1,623***	***1,620***	

DAIMLER BUSES			Manhattan Cycle			Orange County Cycle			UDDS Cycle			
		unit	DAIM CNG	DAIM Diesel	DAIM Hybrid	DAIM CNG	DAIM Diesel	DAIM Hybrid	DAIM CNG	DAIM Diesel	DAIM Hybrid	*Notes/Sources*
Fuel Economy		MPDEG	2.82	3.50	4.26	4.17	4.84	5.50	5.44	5.89	5.06	*Altoona Test Data*
Fuel Use		DEG/mi	0.354	0.286	0.235	0.240	0.207	0.182	0.184	0.170	0.198	*= 1 ÷ MPDEG*
Tail pipe Emissions	PM	g/mi	0.000	0.004	0.004	0.000	0.006	0.008	0.000	0.002	0.005	Altoona Test Data
	CH_4	g/mi	0.48	0.00	0.00	0.27	0.00	0.00	0.38	0.00	0.00	
	CO_2	g/mi	2,802	2,882	2,365	1,895	2,084	1,832	1,453	1,713	1,993	
Upsteam Emission Factors (Fuel Production)	CO_2	g/MJ	10.32	17.92	17.92	10.32	17.92	17.92	10.32	17.92	17.92	*GREET 2013*
	CO_2	g/DEG	1,399	2,429	2,429	1,399	2,429	2,429	1,399	2,429	2,429	*= g/MJ x MJ/DEG*
	CH_4	g/MJ	0.31	0.11	0.11	0.31	0.11	0.11	0.31	0.11	0.11	*GREET 2013*
	CH_4	g/DEG	42.0	14.9	14.9	42.0	14.9	14.9	42.0	14.9	14.9	*= g/MJ x MJ/DEG*
SHORT-TERM GHG PER MILE BY SOURCE TYPE	Upsteam CO_2	g CO_2-e/mi	496	694	570	335	502	441	257	413	480	g CO2/DEG x DEG/mi
	Upstream CH_4	g CO_2-e/mi	1,281	366	301	866	265	233	664	218	253	g CH4/DEG x DEG/mi x CH4 GWP20
	Tailpipe CO_2	g CO_2-e/mi	2,802	2,882	2,365	1,895	2,084	1,832	1,453	1,713	1,993	g CO2/mi; Altoona Test Data
	Tailpipe CH_4	g CO_2-e/mi	41	0	0	23	0	0	33	0	0	g CH4/mi (Altoona) x CH4 GWP20
	Tailpipe BC	g CO_2-e/mi	0	10	10	0	14	19	0	5	12	g PM/mi (Altoona) x BC GWP20
	TOTAL	***g CO_2-e/mi***	***4,620***	***3,952***	***3,245***	***3,120***	***2,865***	***2,525***	***2,407***	***2,348***	***2,738***	
LONG-TERM GHG PER MILE BY SOURCE TYPE	Upsteam CO_2	g CO_2-e/mi	496	694	570	335	502	441	257	413	480	g CO2/DEG x DEG/mi
	Upstream CH_4	g CO_2-e/mi	506	145	119	342	105	92	263	86	100	g CH4/DEG x DEG/mi x CH4 GWP100
	Tailpipe CO_2	g CO_2-e/mi	2,802	2,882	2,365	1,895	2,084	1,832	1,453	1,713	1,993	g CO2/mi; Altoona Test Data
	Tailpipe CH_4	g CO_2-e/mi	16	0	0	9	0	0	13	0	0	g CH4/mi (Altoona) x CH4 GWP100
	Tailpipe BC	g CO_2-e/mi	0	3	3	0	4	5	0	1	3	g PM/mi (Altoona) x BC GWP100
	TOTAL	***g CO_2-e/mi***	***3,820***	***3,724***	***3,056***	***2,582***	***2,695***	***2,371***	***1,986***	***2,213***	***2,577***	

GLOBAL ASSUMPTIONS & CONSTANTS

1 Diesel Equivalent Gallon (DEG) =	128,450 btu =	50.48	hp-hr =	135.52 MJ
Natural Gas Energy Content =	20,268 btu/lb =	6.338	lb/DGE	
U.S. Department of Energy, Alternative Fuels & Advanced Vehicles Data Center (www.afdc.energy.gov/afdc/fuels/properties.html)				

	GWP20	GWP100	
Methane	86	34	*IPCC 5th Assess (2013)*
Black Carbon	3200	900	*IPCC 5th Assess (2013)*
% PM that is BC =		75%	*EPA Technology Transfer Network Clearinghouse for Inventories and Emission Factors, Speciation, April 26,2005*

947.817	btu/MJ
2,544.43	btu/hp-hr
453.59	g/lb