West Virginia University CAFEE

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In-Use Emissions and Performance Testing of Propane-Fueled Engines

PERC Docket 20893

School Bus Results

Submitted To:

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1 Executive Summary

Propane autogas school buses are a proven way to dramatically decrease oxides of nitrogen (NO_X) emissions in American communities.

According to a recent study commissioned by the Washington, D.C.-based Propane Education & Research Council (PERC), NO_X emissions measured from propane autogas school buses were substantially lower than those measured from diesel school buses. The study was conducted in 2018 by West Virginia University's Center of Alternatives Fuels, Engines, and Emissions (CAFEE).

The findings are significant due to the fact that NO_X are one of the biggest challenges to air quality in the United States. They are a predominant non-attainment concern for many areas in the United States, especially in California. Oxides of nitrogen are highly reactive gases composed of nitrogen and oxygen. They form when hydrocarbon fuels are burned at high temperatures. The United States government regulates NO_X transportation emissions because they affect human health and the environment. According the U.S. Energy Department's Alternative Fuels Data Center, approximately 55 percent of manmade NO_X emissions come from motor vehicles like school buses, which are ubiquitous across the country.

Completed in 2018, the study involved two types of tests at different times of the year on four Blue Bird school buses. A model year 2015 propane autogas school bus and a model year 2014 diesel school bus were tested in January/February 2018. Subsequently, a model year 2017 propane autogas bus and a model year 2017 diesel bus were tested in July/August 2018.

Distance-specific NO_X emissions measured from the diesel school buses were significantly higher than those measured from the propane autogas school bus for both tests conducted in early 2018:

- NO_X emissions were 15 to 19 times higher for the diesel school bus over a hot-and cold-start city route.
  - For this route, the propane autogas bus reduced NO_X by 95 percent.
- NO_X emissions were 34 times higher for the diesel school bus over a stop-and-go route similar to actual usage.
  - For this route, NO_X was reduced by 96 percent and carbon dioxide by 13 percent with the propane autogas bus.

Subsequent testing performed in late 2018 with newer model year and lower mileage propane autogas and diesel buses confirmed the findings from the previous testing.

2 Introduction

The Propane Education and Research Council (PERC) contracted the West Virginia University (WVU) Center for Alternative, Fuels, Engines, and Emissions (CAFEE) to perform a research program titled *In-Use Emissions and Performance Testing of Propane-Fueled Engines*, PERC docket 20893. As the title suggests, the goal of this program was to establish exhaust emissions and performance characteristics of propane-fueled vehicles/engines through in-use testing methods in comparison to vehicles/engines fueled with other common transportation fuels. To accomplish this goal, a portable emissions measurement system (PEMS) was installed on test vehicles. These vehicles were exercised over predetermined routes while emissions and performance measurements were collected with the PEMS. This document presents results from PEMS testing of school buses, a sub task of the overall project. A description of the test vehicles, test routes, PEMS equipment and results is provided in the subsequent sections for propane powered school busses and diesel-powered school busses.

3 Test Vehicles

Four test vehicles, two spark-ignited propane powered school busses and two compression-ignited diesel-powered school busses were utilized to generate the results presented herein. All vehicles were manufactured by the Blue Bird Corporation. Each bus was nearly identical with the exception of mileage as well as engine and transmission differences between the propane and diesel buses. Each bus had 24 bench seats and 1 driver seat. Assuming 125 pounds per passenger and 48 passengers, each bus was loaded with 6,000 pounds of weight equally distributed throughout the bus. Before, during, and after PEMS testing each vehicle was inspected for any damage or malfunction, including malfunction indicator lamps that would influence emissions testing results. None were observed.

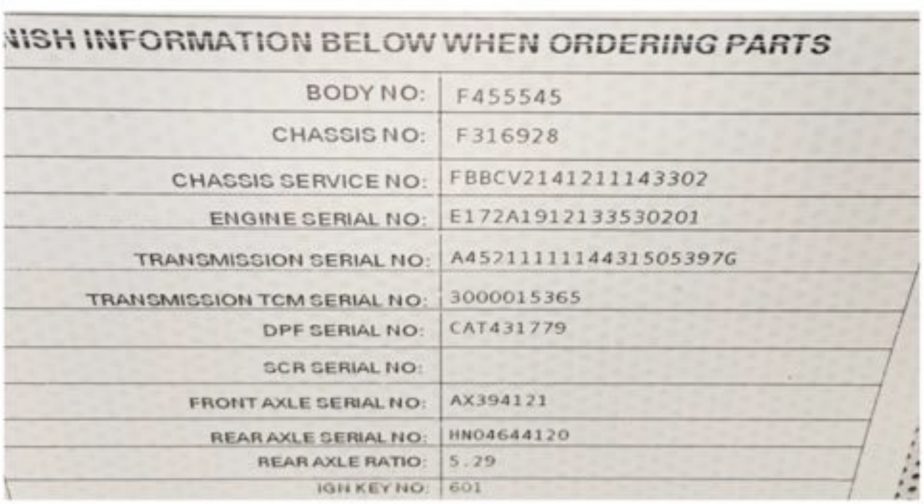
3.1 2015 Blue Bird Propane School Bus

In-use PEMS testing of a Blue Bird propane school bus (Figure 1) was performed during January of 2018. Specifications of the test vehicle are displayed in Table 1. Figure 2 and Figure 3 provide vehicle and drivetrain information for the 2015 Blue Bird propane school bus.

Table 1: 2015 Blue Bird Propane School Bus Test Vehicle Specifications

Manufacturer	Blue Bird Body Company
Fuel	HD-5 Propane (LPG)
Engine	Spark-Ignited 6.8 Liter, 10 Cylinder
Engine Model Year	2015
OEM Fuel Injection System	Port-Fuel Injection
Exhaust Aftertreatment	Three-Way Catalyst (TWC)
Mileage at Commencement of Testing	35,492 Miles

Figure 1: 2015 Blue Bird Propane School Bus



NISH INFORMATION BELOW WHEN ORDERING PARTS

BODY NO:	F455545
CHASSIS NO:	F316928
CHASSIS SERVICE NO:	FBBCV2141211143302
ENGINE SERIAL NO:	E172A1912133530201
TRANSMISSION SERIAL NO:	A45211111144315053976
TRANSMISSION TCM SERIAL NO:	3000015365
DPF SERIAL NO:	CAT431779
SCR SERIAL NO:	
FRONT AXLE SERIAL NO:	AX394121
REAR AXLE SERIAL NO:	HN04644120
REAR AXLE RATIO:	5.29
IGN KEY NO:	601

Figure 2: Vehicle Information for 2015 Blue Bird Propane School Bus

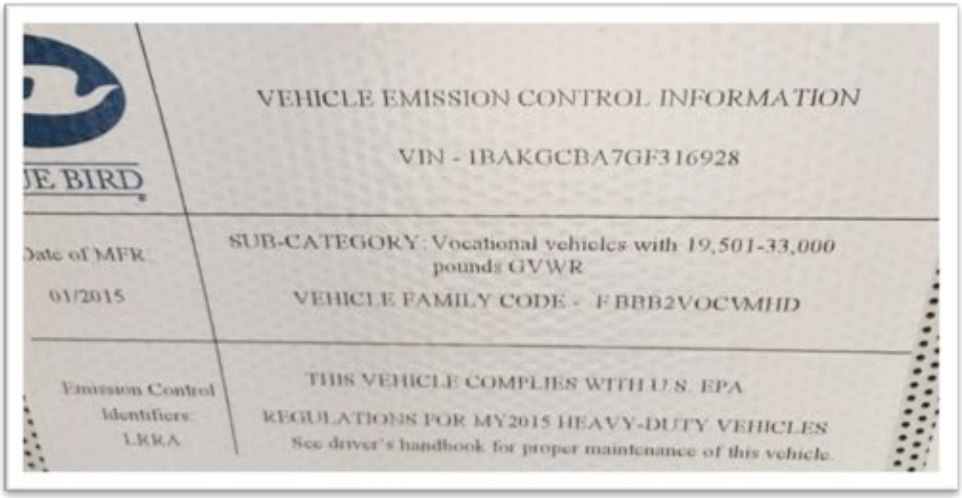


Figure 3: Vehicle Information for 2015 Blue Bird Propane School Bus

3.2 2014 Blue Bird Diesel School Bus

In-use PEMS testing of a Blue Bird Diesel School Bus (Figure 4) was performed during February of 2018. Specifications of the test vehicle are displayed in Table 2. Figure 5 and Figure 6 provide vehicle and drivetrain information for the 2014 Blue Bird diesel school bus.

Manufacturer	Blue Bird Body Company
Fuel	Ultra-Low Sulfur Diesel
Engine	Compression-Ignited ISB 6.7 Liter, 6 Cylinder
Engine Model Year	2014
OEM Fuel Injection System	Common Rail Direct Injection
Exhaust Aftertreatment	Diesel Oxidation Catalyst (DOC), Diesel Particulate Filter (DPF), Selective Catalytic Reduction (SCR) System
Mileage at Commencement of Testing	57,666 Miles

Table 2: 2014 Blue Bird Diesel School Bus Test Vehicle Specifications

Figure 4: 2014 Blue Bird Diesel School Bus

FURNISH INFORMATION BELOW WHEN ORDERING PARTS	
BODY NO:	F453938
CHASSIS NO:	F315321
CHASSIS SERVICE NO:	FBBCV2140917100943
ENGINE SERIAL NO:	73728481
TRANSMISSION SERIAL NO:	6311313877
TRANSMISSION TCM SERIAL NO:	BK0689A141940221
DPF SERIAL NO:	56243145103
SCR SERIAL NO:	43249140470
FRONT AXLE SERIAL NO:	AX383143
REAR AXLE SERIAL NO:	HN04569744
REAR AXLE RATIO:	5.29
IGN KEY NO:	601

Figure 5: Vehicle Information for 2014 Blue Bird Diesel School Bus

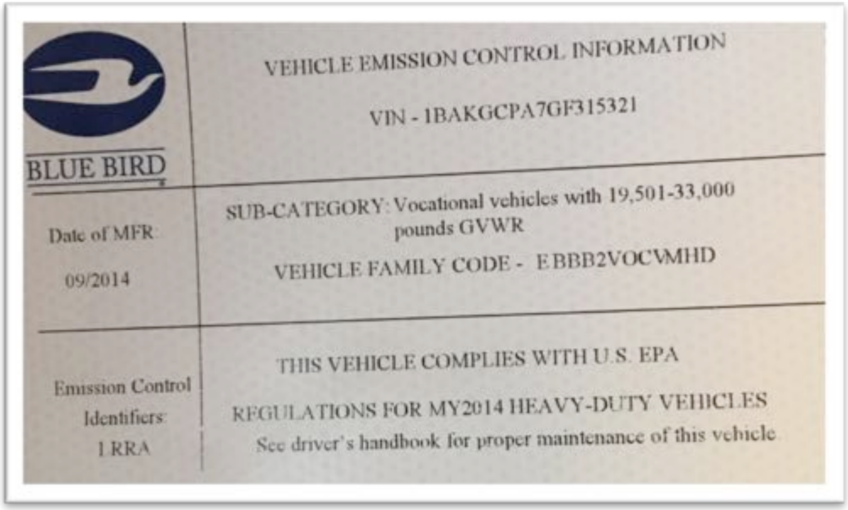


Figure 6: Vehicle Information for 2014 Blue Bird Diesel School Bus

3.3 2017 Blue Bird Propane School Bus

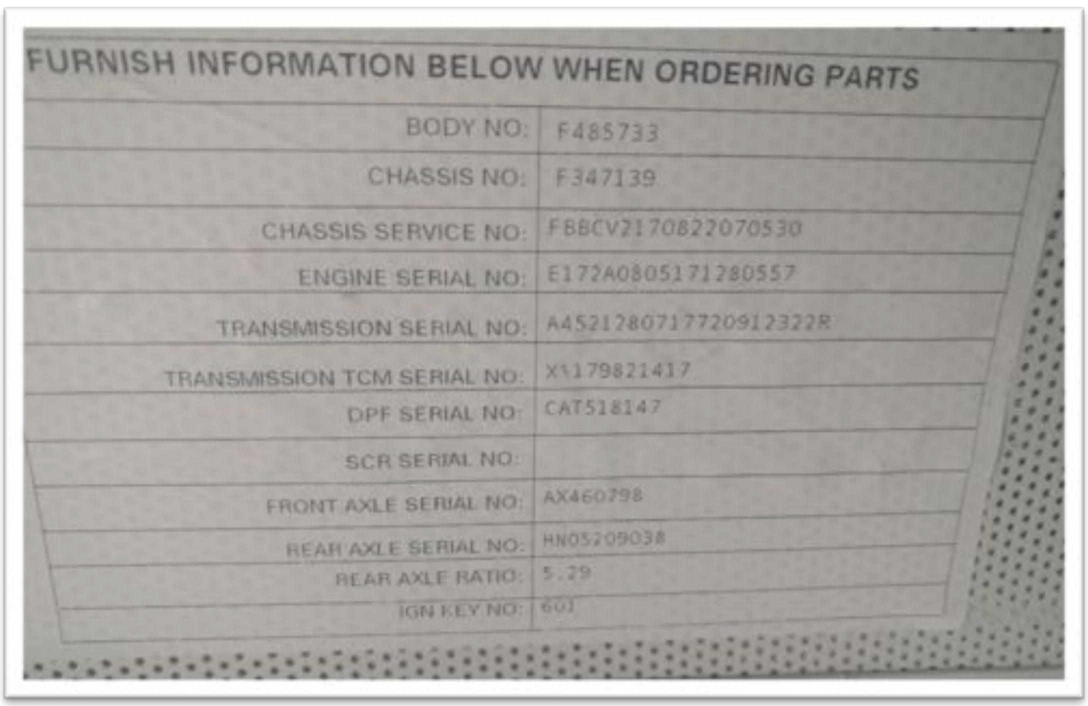
In-use PEMS testing of a 2017 Blue Bird Propane School Bus (Figure 7) was performed during August of 2018. Specifications of the test vehicle are displayed in

Table 3. Figure 8 and Figure 9 provide vehicle and drivetrain information for the 2017 Blue Bird Propane school bus.

Manufacturer	Blue Bird Body Company
Fuel	HD-5 Propane (LPG)
Engine	Spark-Ignited 6.8 Liter, 10 Cylinder
Engine Model Year	2017
OEM Fuel Injection System	Port-Fuel Injection
Exhaust Aftertreatment	Three-Way Catalyst (TWC)
Mileage at Commencement of Testing	2,497 Miles

Table 3: 2017 Blue Bird Propane School Bus Test Vehicle Specifications

Figure 7: 2017 Blue Bird Propane School Bus



FURNISH INFORMATION BELOW WHEN ORDERING PARTS

BODY NO:	F485733
CHASSIS NO:	F347139
CHASSIS SERVICE NO:	FBBCV2170822070530
ENGINE SERIAL NO:	E172A0805171280557
TRANSMISSION SERIAL NO:	A4521280717720912322R
TRANSMISSION TCM SERIAL NO:	X\179821417
DPF SERIAL NO:	CAT518147
SCR SERIAL NO:	
FRONT AXLE SERIAL NO:	AX460798
REAR AXLE SERIAL NO:	HN05209038
REAR AXLE RATIO:	5.29
IGN KEY NO:	601

Figure 8: Vehicle Information for 2017 Blue Bird Propane School Bus

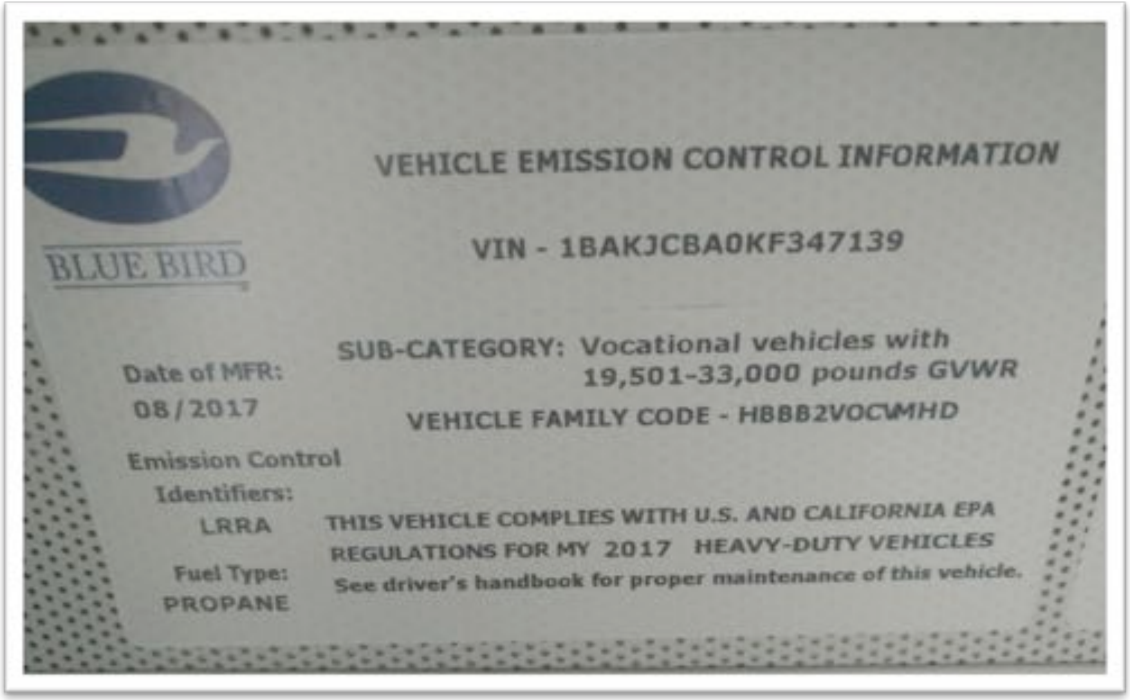


Figure 9: Vehicle Information for 2017 Blue Bird Propane School Bus

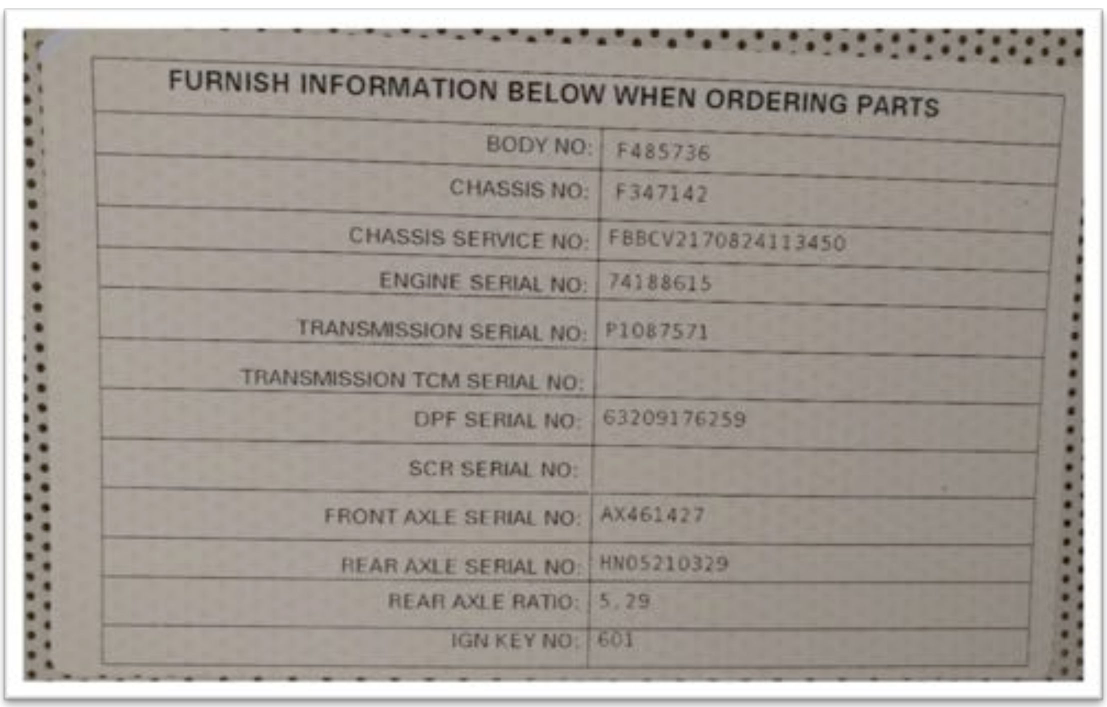
3.4 2017 Blue Bird Diesel School Bus

In-use PEMS testing of a 2017 Blue Bird diesel school bus (Figure 4) was performed during July of 2018. Specifications of the test vehicle are displayed in Table 2. Figure 5 and Figure 6 provide vehicle and drivetrain information for the 2017 Blue Bird diesel school bus. Note that approximately 4000 miles were accrued on this school bus to prior to testing to ensure the aftertreatment system was de-greened.

Table 4: 2017 Blue Bird Diesel School Bus Test Vehicle Specifications

Manufacturer	Blue Bird Body Company
Fuel	Ultra-Low Sulfur Diesel
Engine	Compression-Ignited ISB 6.7 Liter, 6 Cylinder
Engine Model Year	2017
OEM Fuel Injection System	Common Rail Direct Injection
Exhaust Aftertreatment	Diesel Oxidation Catalyst (DOC), Diesel Particulate Filter (DPF), Selective Catalytic Reduction (SCR) System
Mileage at Commencement of Testing	4057 Miles

Figure 10: 2017 Blue Bird Diesel School Bus



FURNISH INFORMATION BELOW WHEN ORDERING PARTS	
BODY NO:	F485736
CHASSIS NO:	F347142
CHASSIS SERVICE NO:	FBBCV2170824113450
ENGINE SERIAL NO:	74188615
TRANSMISSION SERIAL NO:	P1087571
TRANSMISSION TCM SERIAL NO:	
DPF SERIAL NO:	63209176259
SCR SERIAL NO:	
FRONT AXLE SERIAL NO:	AX461427
REAR AXLE SERIAL NO:	HN05210329
REAR AXLE RATIO:	5.29
IGN KEY NO:	601

Figure 11: Vehicle Information for 2017 Blue Bird Diesel School Bus

Figure 12: Vehicle Information for 2017 Blue Bird Diesel School Bus

4 Test Routes

The vehicles described in Section 3 were exercised over two previously established in-use testing routes in Morgantown WV; the Morgantown route and Stop and Go route. Each vehicle was exercised over the Morgantown route 6 times, including 3 cold starts (overnight soak) and 3 hot starts, and exercised over the Stop and Go route 3 times for a total of 9 test routes per vehicle. The 2017 Propane and Diesel school Buses were also tested over the Stop and Go route an additional 3 times utilizing a longer stop period.

4.1 Morgantown Route

The Morgantown Route consists of city and highway driving. It begins and ends at the WVU CAFEE Vehicle and Engine Testing Laboratory (VETL). For the cold start Morgantown Route, each vehicle was started and allowed to idle for 5 minutes. After leaving the VETL the vehicle travels approximately 7.4 miles to the interstate through city traffic. Once on the interstate the vehicle travels around the southeastern corner of Morgantown on interstate 68 for approximately 17.3 miles. The vehicle then returns to the VETL by means of a new route consisting of city driving, traveling a distance of approximately 6.5 miles. The total mileage traveled is approximately 31.1 miles. The peak elevation change is approximately 403 feet.

A road map detailing the Morgantown Route is presented below in Figure 13, a characteristic vehicle speed trace for the Morgantown Route is provided in Figure 14 and Figure 15 for cold and hot start tests, respectively, and a plot of the altitude trace for the Morgantown Route is given in Figure 16.

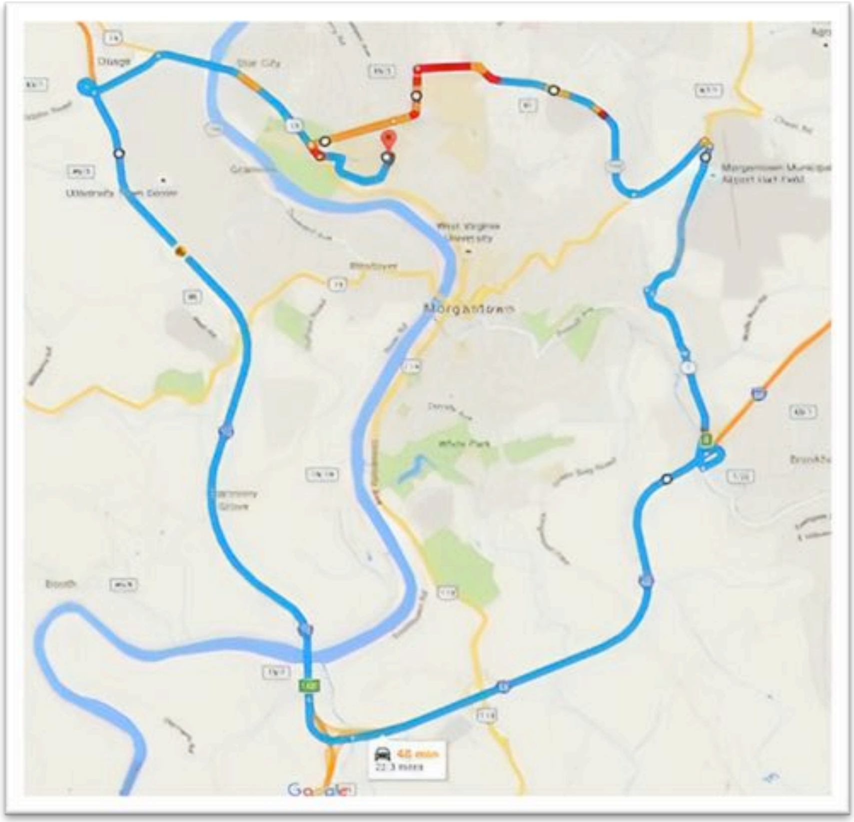


Figure 23: Map of the Morgantown Test Route

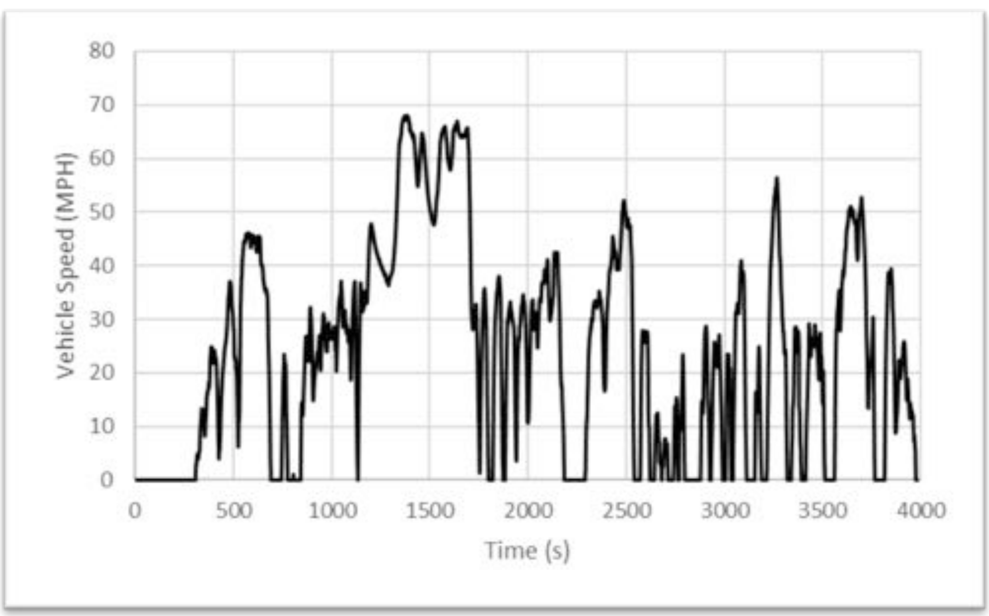


Figure 14: Characteristic Vehicle Speed Trace for the Morgantown Route for a School Bus - Cold Start

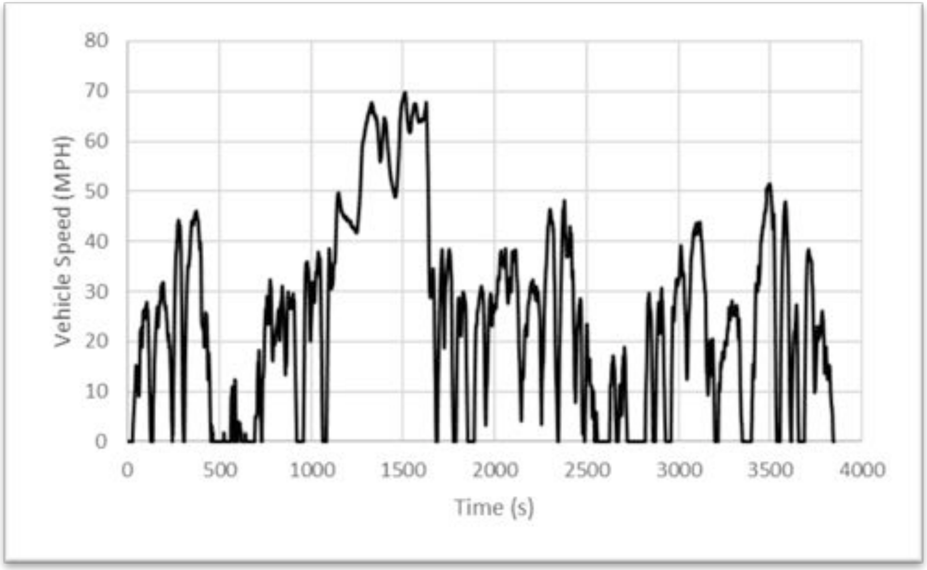


Figure 15: Characteristic Vehicle Speed Trace for the Morgantown Route for a School Bus - Hot Start

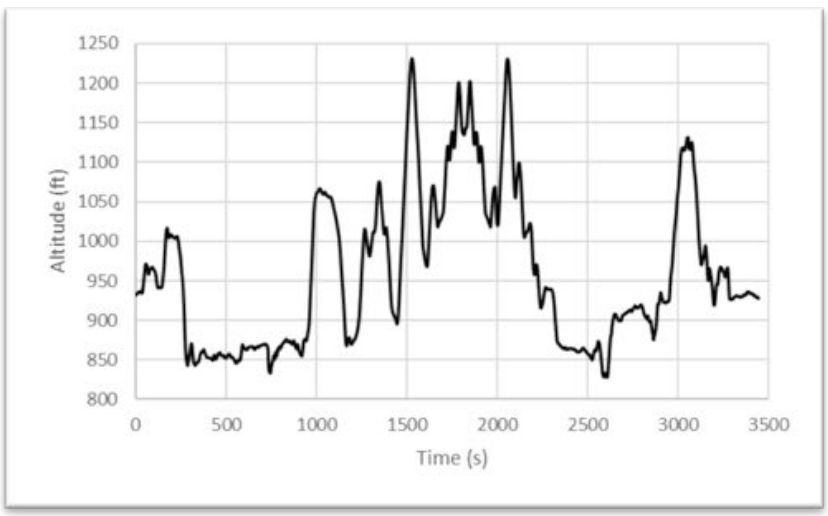


Figure 16: Plot of the Altitude Trace for the Morgantown Test Route

4.2 Stop and Go Route

The Stop and Go route consists of a series of loops through the industrial park that houses the WVU CAFEE VETL facility. During the testing of the 2015 propane school bus and 2014 diesel school bus, each loop the bus traveled approximately 0.25 miles, stopped for 2 minutes, traveled approximately 0.5 miles (including a 50ft elevation change), and stopped for two minutes. The testing of the 2017 school buses used a similar cycle with 2-minute stops, but were also exercised over an additional cycle with 5-minute stops. These cycles were designed to simulate the low speed operation and passenger pick up typical of a school bus.

Depicted below is a characteristic vehicle speed trace for the Stop and Go Route with 2-minute stops and 5-minute stops in Figure 17 and Figure 15, respectively, and a characteristic plot of the elevation changes throughout the route in Figure 19.

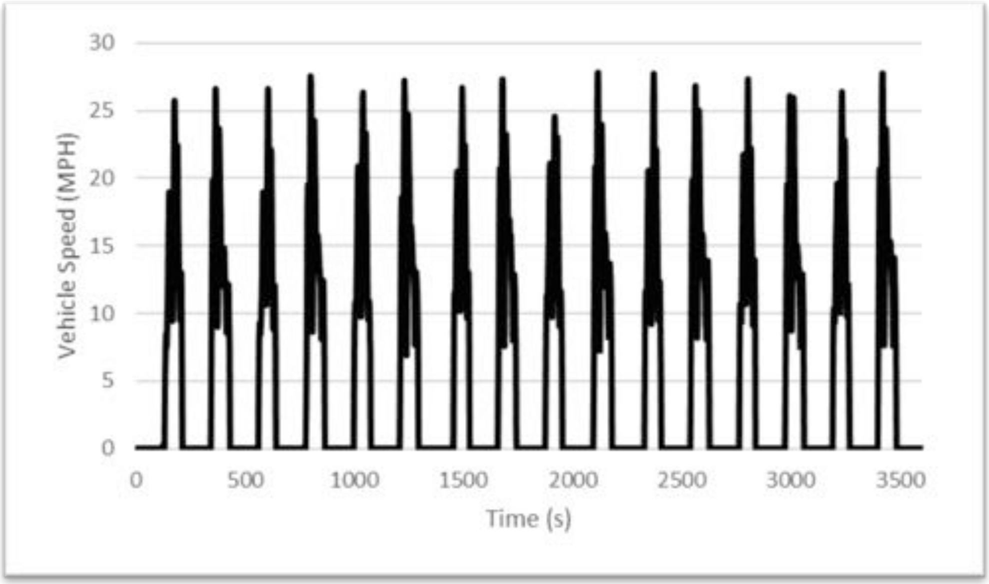


Figure 17: Characteristic Vehicle Speed Trace for the Stop and Go Route (2 Minute)

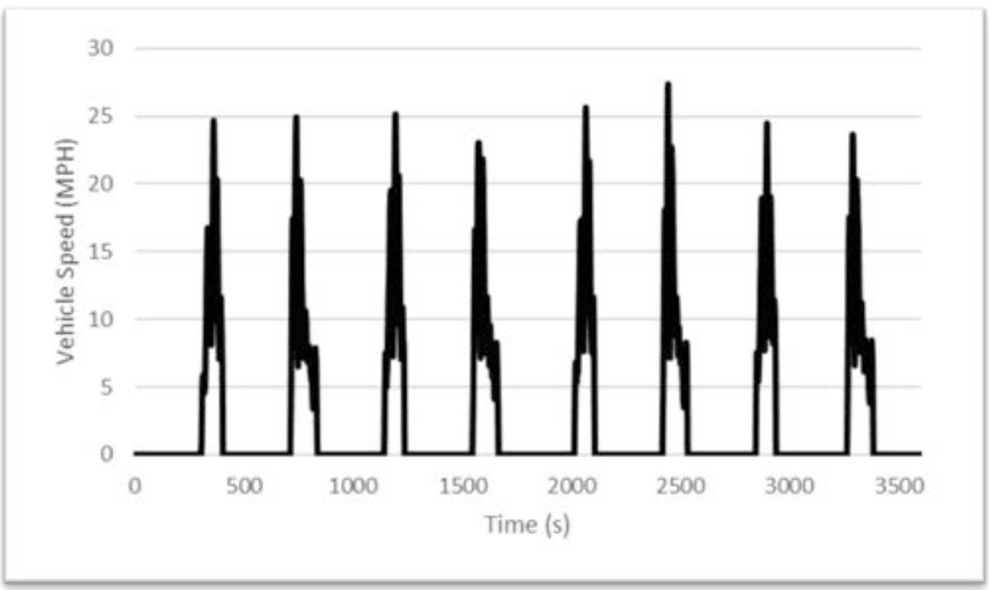


Figure 18: Characteristic Vehicle Speed Trace for the Stop and Go Route (5 Minute)

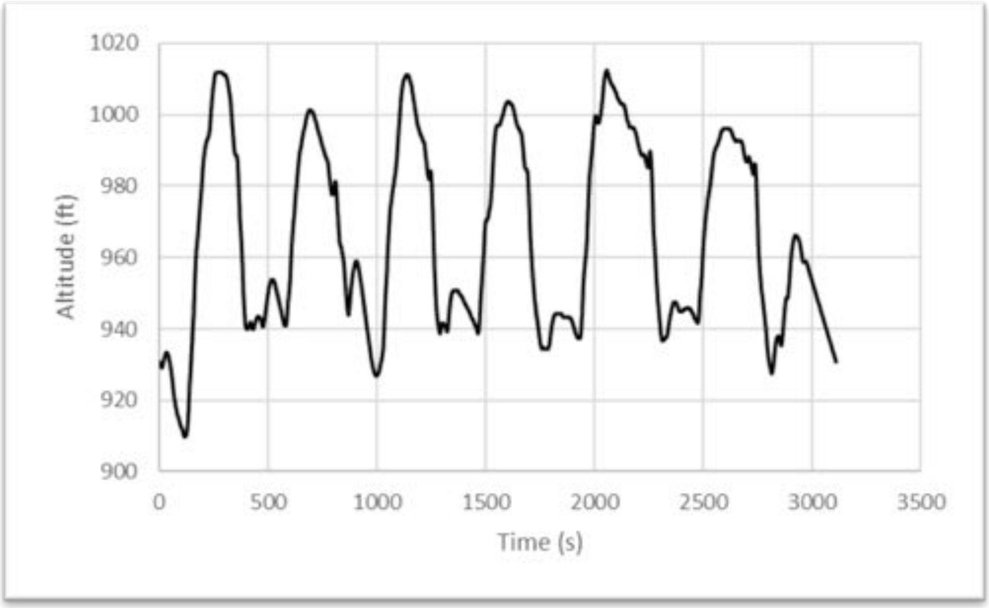
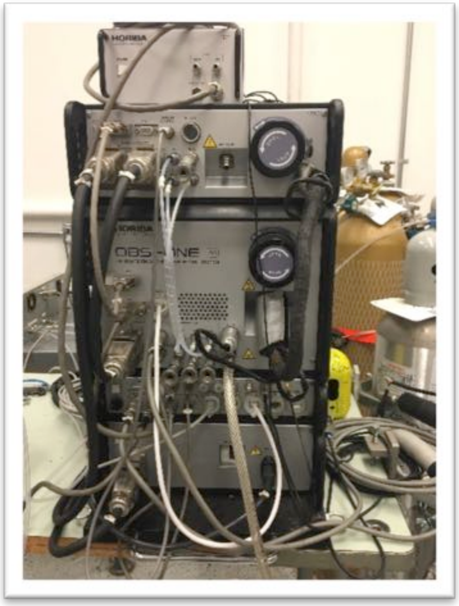


Figure 19: Plot of the Altitude Trace for the Stop and Go Route

5 Portable Emissions Measurement System

A Horiba® OBS-2200 gaseous PEMS was utilized to perform emissions measurements on the 2015 propane school bus and 2014 diesel school bus detailed in Section 3. For the testing of the 2017 propane school bus and 2017 diesel school bus a Horiba® OBS-ONE gaseous PEMS (Figure 20) was utilized. Both PEMS are equipped with a non-dispersive infrared (NDIR) analyzer that measures carbon monoxide (CO) and carbon dioxides (CO_2), a chemiluminescence (CLD) analyzer that measures oxides of nitrogen (NO_X), and a flame ionization detector (FID) analyzer that measures total hydrocarbons (THC). Both units also include OBD measurement, exhaust flow measurement, ambient temperature, pressure, and humidity measurement, and global positioning system (GPS) measurement capabilities. Both PEMS instruments are an approved device of the U.S. EPA heavy-duty in-use testing standards and complies with the EU 582/2011 in-use emissions measurement standards, as well as the procedures and guidelines set forth in Title 40 CFR, Part 1065 Subpart J - 'Field Testing and Portable Emission Measurement Systems'; *Gaseous and Particulate Exhaust Test Procedures*', European Regulation EC No. 427/2016 - '*Emissions from passenger and commercial vehicles (Euro 6)*', and EC No. 715/2007 for regulated gaseous emissions for the purposes of in-use/in-service compliance.



20: Horiba® OBS-ONE Portable Emissions Measurement System

5.1 PEMS Challenges and Sources of Variability

There are certain inherent limitations of PEMS when compared to laboratory emissions measurement systems that should be noted and considered when examining in results. These limitations emanate predominantly from the size and packaging constraints required to carry the PEMS on board a vehicles and environmental variabilities associated with in-use testing. One limitation related to packaging constraints is the approach to CO and CO_2 emissions measurement via a single NDIR analyzer. Typically, in a fixed laboratory, CO and CO_2 emissions are measured by two different NDIR analyzers because accurate measurements of low CO concentrations (below 5000 ppm) require a much longer measurement cell length than what is required for CO_2. Thus, measurements of CO and CO_2 with a single measurement cell results in a high noise to signal ratio for CO emissions at low concentrations. This can introduce additional variability into the CO emissions results. Furthermore, Horiba utilizes a wet measurement in the NDIR analyzer that is compensated for water content via a water sensor whereas laboratory grade NDIRs measure CO and CO_2 dry with the moisture removed before the analyzer by a chiller or dryer. The wet measurement of the NDIR can introduce variability due to the accuracy of the water sensor. The calibration procedure for the water sensor is only performed periodically by the manufacturer. Furthermore, the high exhaust moisture content produced from stoichiometric spark ignited engines versus compression ignition engines can exacerbate the variability introduced by the wet CO and CO_2 measurement.

Environmental variables can also introduce variability for PEMS. Ambient temperature, humidity and pressure cannot only affect the operation of the vehicle being tested but can also influence the PEMS. As noted in the following section, the testing of the 2015 propane and 2014 diesel school buses was performed at low ambient temperatures. Due to these low ambient temperatures, the relatively long exhaust system length, and high exhaust water content for stoichiometric spark-ignited engines, condensation becomes an issue for exhaust flow measurements and emissions sampling. Issues with condensation at the pitot tube exhaust flow meter were experienced during this testing, but were mitigated by installing heaters and insulation around the pitot tube pressure lines. However, heating and insulating the long exhaust system of the school buses was not feasible and thus condensation in the exhaust may have introduced variability in the emissions measurements. If water condenses out of the exhaust stream then the concentrations of the other emissions constituents can be affected. The effect on constituents at the ppm level such as NOX, THC, and sometimes CO will be minimal compared to CO_2, which is measured at percent levels.

Different ambient temperatures, pressures, and humidity can also affect the performance of a vehicle and the engine control strategies, which can also introduce variability and decrease repeatability. Traffic is also another major variable that cannot be controlled. The amount of time a vehicle idles in traffic or the number of accelerations performed due to traffic signals can directly affect the distance specific emissions. Thus, it is important to not only look at the average distance specific emissions, but also plots of the mass rate of each reported emissions constituent to get an overall profile of the emissions produced by a particular vehicle.

Despite these limitations, PEMS offer the most robust and accurate method to capture real-world emissions measurements from vehicles. When large differences are present between vehicles and multiple data points have been collected it can be assured that these results are valid and not significantly influenced by the limitations discussed herein.

6 Results - 2014/2015 School Buses

Emissions measurements presented in this section were performed on a 2015 Blue Bird propane powered school bus and 2014 Blue Bird diesel powered school bus over the routes specified in Section 4. Each route, cold Morgantown, hot Morgantown, and Stop and Go (2-minute stops), was repeated three times for each vehicle. The result is 9 total tests per vehicle. For comparison purposes the average emissions results are presented on a mass per distance basis (distance specific); grams of emissions constituent measured per mile traveled by the vehicle. The magnitude of the individual bars is equivalent to the average of the three tests performed for that route and vehicle. Error bars indicate the maximum and minimum values used to calculate the average. A sample of real time traces of mass rate (grams per second) emissions from each vehicle are also presented. Distance specific results for each individual test can be found in the Appendix, Section 9.1. It is important to note that these measurements were not performed for the purpose of certification or comparison to the emissions certification standards. Furthermore, a not-to-exceed analysis was not performed on this data set, and thus the data presented cannot be used to determine in-use emissions compliance.

6.1 Morgantown Route

Emissions measurements from the 2015 propane and 2014 diesel school buses are presented below for a cold start and hot start Morgantown route as detailed in section 4.1. All of these tests were performed in Morgantown WV, during January and February of 2018. These tests were conducted on public roads, on a predetermined route, and thus the results presented below can be influenced by external factors such as traffic, weather, and road conditions as discussed in Section 5.1. Given the inherent nature of in-use emissions testing and the time of year during which testing took place a varying range of ambient temperatures were encountered which is presented in Figure 21. It is important to note that many of the ambient temperatures encountered during this testing were below the range of temperatures specified for emissions certification testing and in-use not-to-exceed emissions testing for medium and heavy-duty engines/vehicles. Average emissions results are presented on a vehicle distance specific basis rather than an engine brake specific basis, which these engines are certified to, due to the equipment and procedures used as well as the on-board diagnostic channels available.

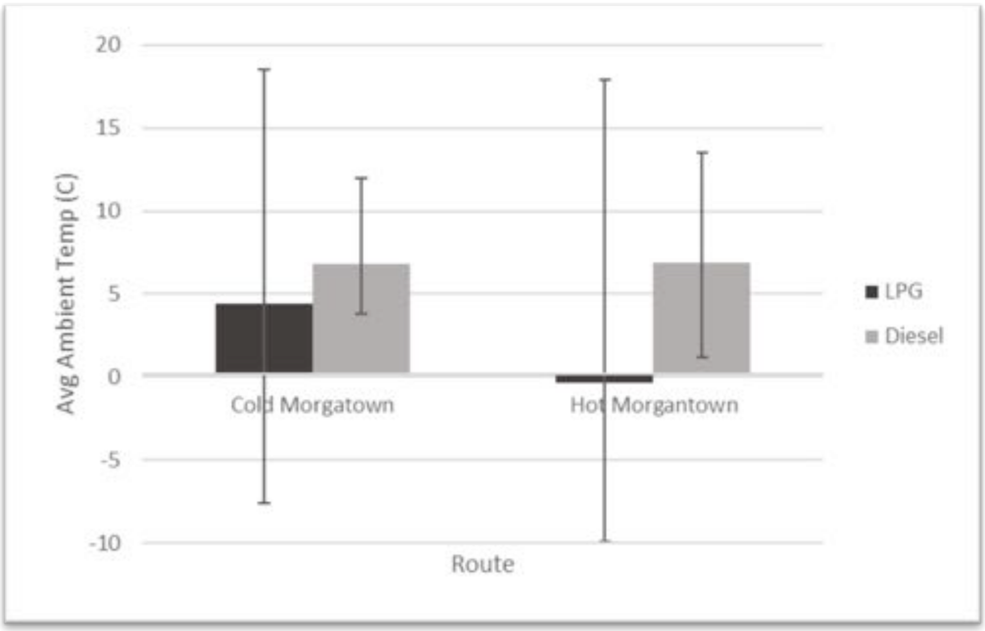


Figure 21: Average Ambient Air Temperature (°C) for Propane and Diesel School Bus

The average ambient temperatures encountered during in-use emissions testing on the Morgantown route ranged from approximately -10 degrees Celsius (°C) to 18 °C as presented in Figure 21. Note that the range of average ambient temperatures was larger for the propane school bus versus the diesel school bus.

6.1.1 Oxides of Nitrogen Emissions

NO_X emissions were quantified via the CLD analyzer in the OBS 2200 PEMS. Figure 22 presents the average distance specific NO_X emissions for the propane (LPG) and diesel school busses operated over the cold and hot Morgantown routes.

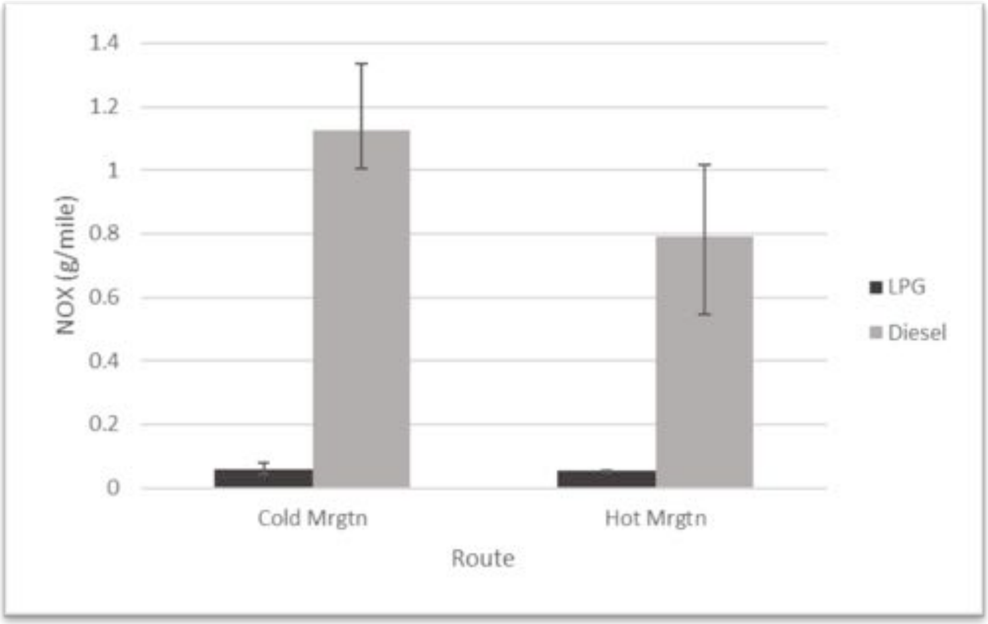


Figure 22: Average NO_X Emissions (g/mile) for Propane and Diesel School Bus

The average distance specific NO_X emissions measured from the diesel school bus were significantly higher than the propane school bus. While both vehicles are equipped with exhaust aftertreatment systems, the approaches are significantly different. As noted in Section 3, the propane bus was equipped with a TWC to simultaneously reduce CO, THC and NO_X, while the diesel school bus was equipped with a DOC to reduce CO and THC, a DPF to reduce particulate matter, and an SCR system to reduce NO_X emissions. Compared to the diesel exhaust aftertreatment system, the TWC is much smaller, has less surface area to dissipate heat, and less overall mass to maintain heat. Thus, it is easier to maintain a minimum temperature to effectively reduce NO_X emissions. For modern diesel engines thermal management strategies are often employed to increase the temperature of the SCR systems to effectively reduce NO_X emissions. Low ambient temperatures and low speed, low load activity can exacerbate this problem and make it difficult for the SCR system to reach adequate temperatures for NO_X reduction.

The mass rate traces of NO_X emissions presented in Figure 23 through Figure 26 demonstrate the elevated NO_X emissions for the diesel school bus. While the propane school bus has several spikes of NO_X emissions corresponding to acceleration events, the diesel school bus has significantly more spikes in addition to overall higher NO_X production throughout the route.

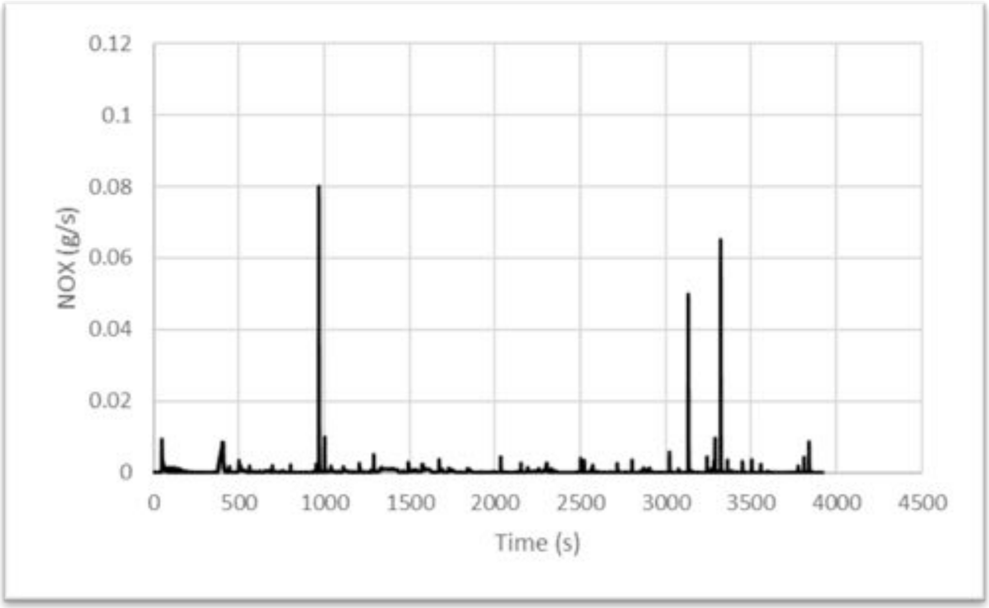


Figure 23: Mass Rate (g/s) of NO_X Emissions for Propane School Bus from Cold Morgantown Route

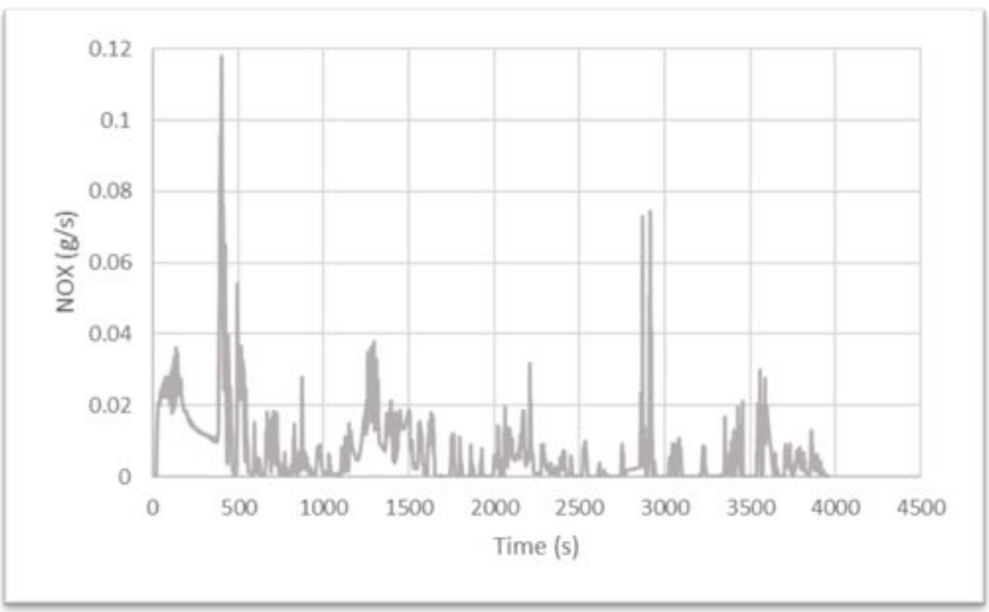


Figure 24: Mass Rate (g/s) of NO_X Emissions for Diesel School Bus from Cold Morgantown Route

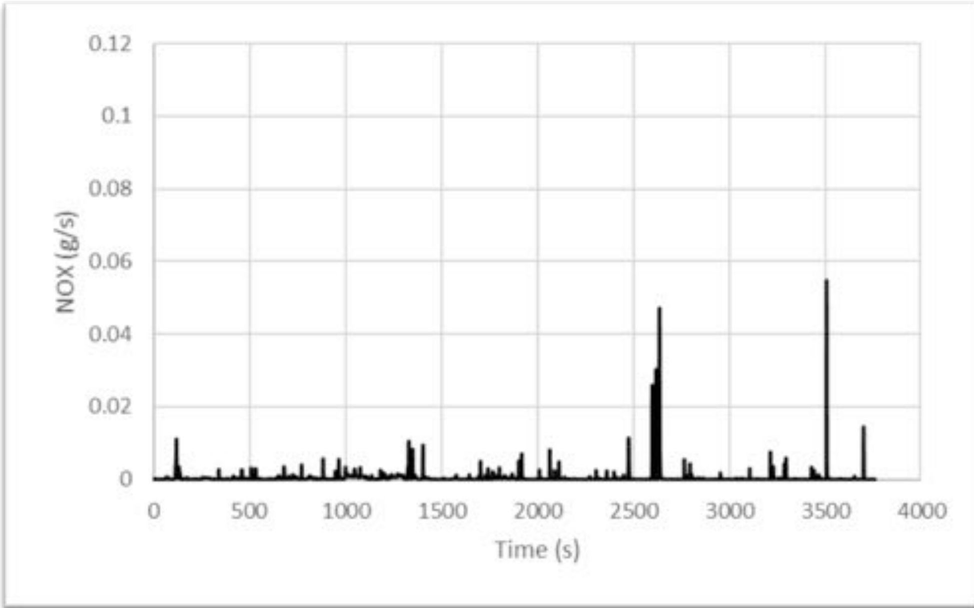


Figure 25: Mass Rate (g/s) of NO_X Emissions for Propane School Bus from Hot Morgantown Route

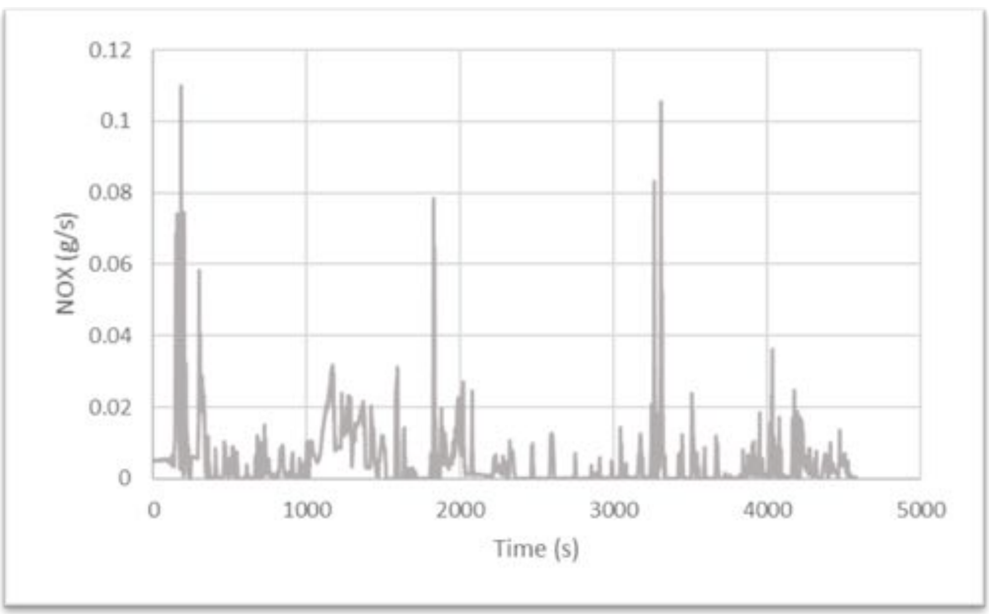


Figure 26: Mass Rate (g/s) of NO_X Emissions for Diesel School Bus from Hot Morgantown Route

6.1.2 Carbon Monoxide Emissions

CO emissions were quantified via the NDIR analyzer in the OBS 2200 PEMS. As discussed in section 5, the NDIR analyzer simultaneously measures CO and CO_2 in wet form. Figure 27 presents the average distance specific CO emissions for the propane (LPG) and diesel school busses operated over the cold and hot Morgantown routes.

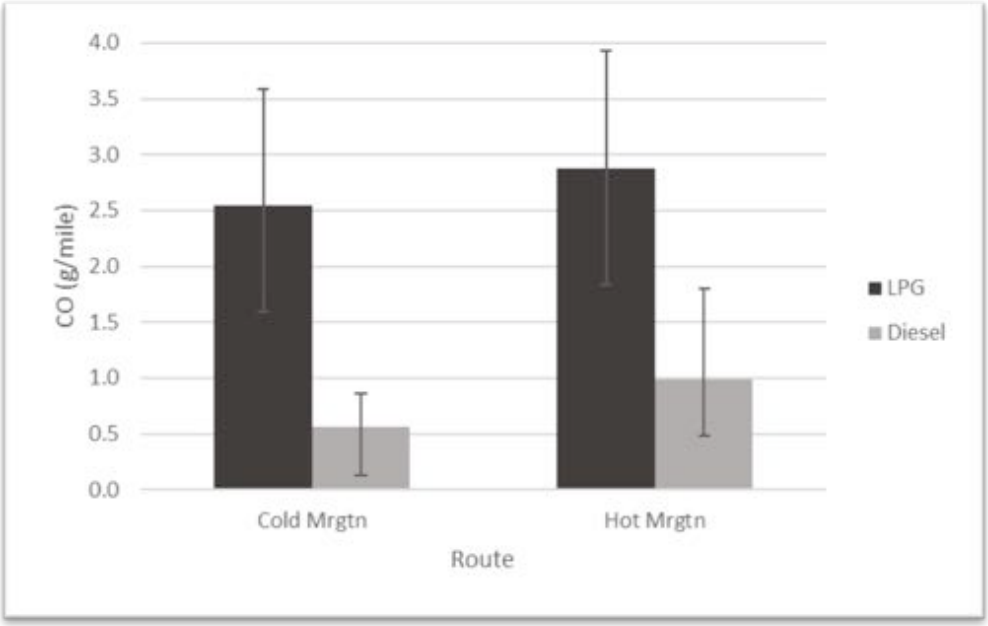


Figure 27: Average CO Emissions (g/mile) for Propane and Diesel School Bus

The propane school bus emitted higher levels of CO emissions when compared to the diesel school bus. This is an expected outcome of the testing given the operating principles of port-fuel spark-ignition engines (propane school bus) versus compression ignition engines (diesel school bus). While both vehicles were equipped with an oxidation catalyst to reduce CO, the pre-catalyst levels of CO were presumably higher for the propane bus and thus more difficult to fully oxidize. One unexpected anomaly is the higher average CO emissions reported for both propane and diesel school buses over the hot start Morgantown route versus the cold start Morgantown route. This could potentially be a result of the variability caused by ambient temperatures, wet NDIR measurements or traffic during testing.

Figure 28 through Figure 31 present a sample of the mass rate of CO emissions from both school buses and the cold and hot Morgantown routes. These plots provide further evidence of the higher CO emissions from the propane buses and show that elevated CO emissions from the propane bus can be observed in high peaks that correspond to accelerations.

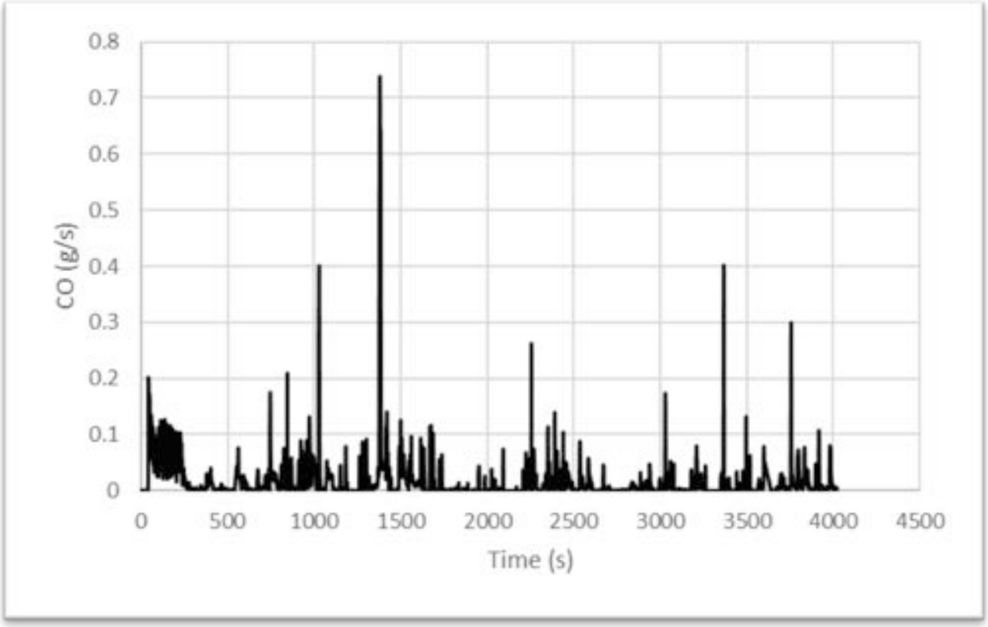


Figure 28: Mass Rate (g/s) of CO Emissions for Propane School Bus from Cold Morgantown Route

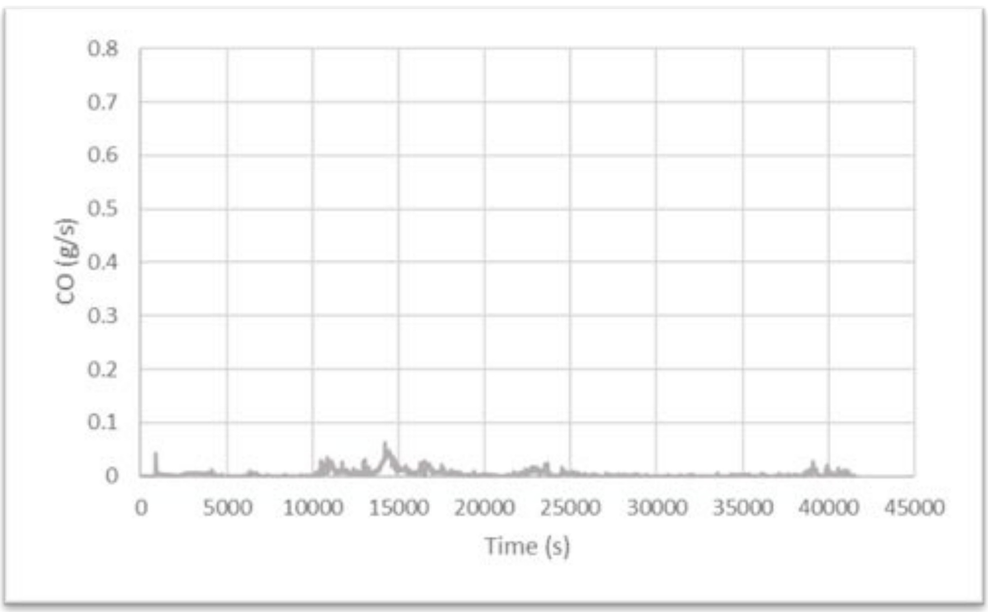


Figure 29: Mass Rate (g/s) of CO Emissions for Diesel School Bus from Cold Morgantown Route

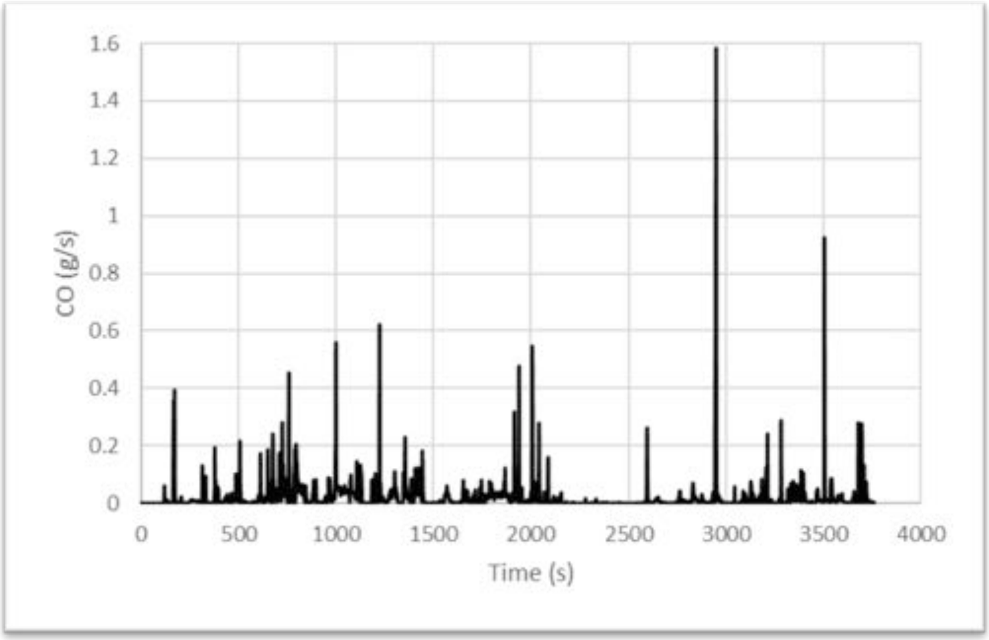


Figure 30: Mass Rate (g/s) of CO Emissions for Propane School Bus from Hot Morgantown Route

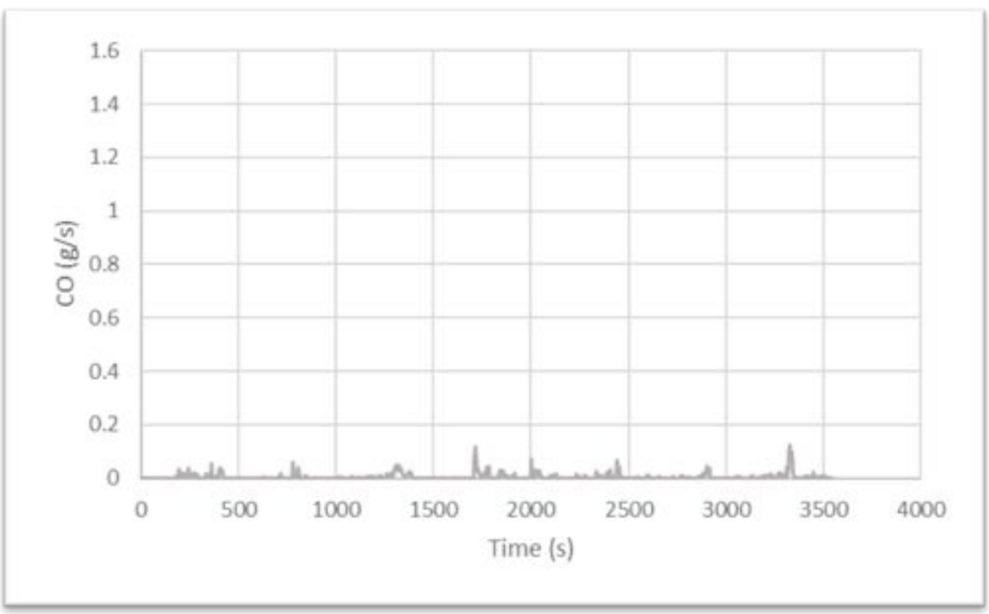


Figure 31: Mass Rate (g/s) of CO Emissions for Diesel School Bus from Hot Morgantown Route

6.1.3 Carbon Dioxide Emissions

CO_2 emissions were quantified via the NDIR analyzer in the OBS 2200 PEMS. Figure 32 presents the average distance specific CO_2 emissions for the propane (LPG) and diesel school busses operated over the cold and hot Morgantown routes.

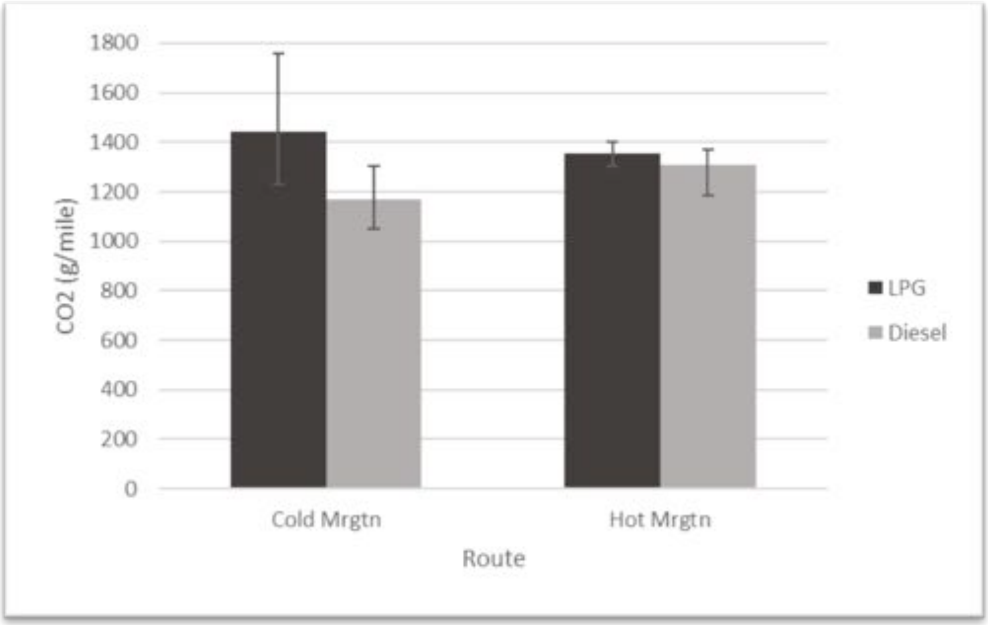


Figure 32: Average CO_2 Emissions (g/mile) for Propane and Diesel School Bus

The average CO_2 emissions were slightly higher for the propane school bus versus the diesel bus over the Morgantown routes. For the hot Morgantown route the average CO_2 was very similar with less variability compared to cold Morgantown route. The stoichiometric operation of the propane bus presents it with an inherent CO_2 disadvantage compared to the lean operation of the diesel school bus. However, the lower hydrogen-to-carbon ratio of propane helps to make up this difference. Both vehicles utilize warm-up strategies to bring the engine and aftertreatment systems up to temperature. However, the extensive aftertreatment system on the diesel school bus, particularly the SCR system, requires thermal management strategies to be employed when the aftertreatment system drops below a minimum temperature that in turn increases CO_2 emissions and fuel consumption. These strategies are often activated during periods of prolonged idling where it can be observed that exhaust flow and CO_2 emissions increase while the engine speed remains relatively constant.

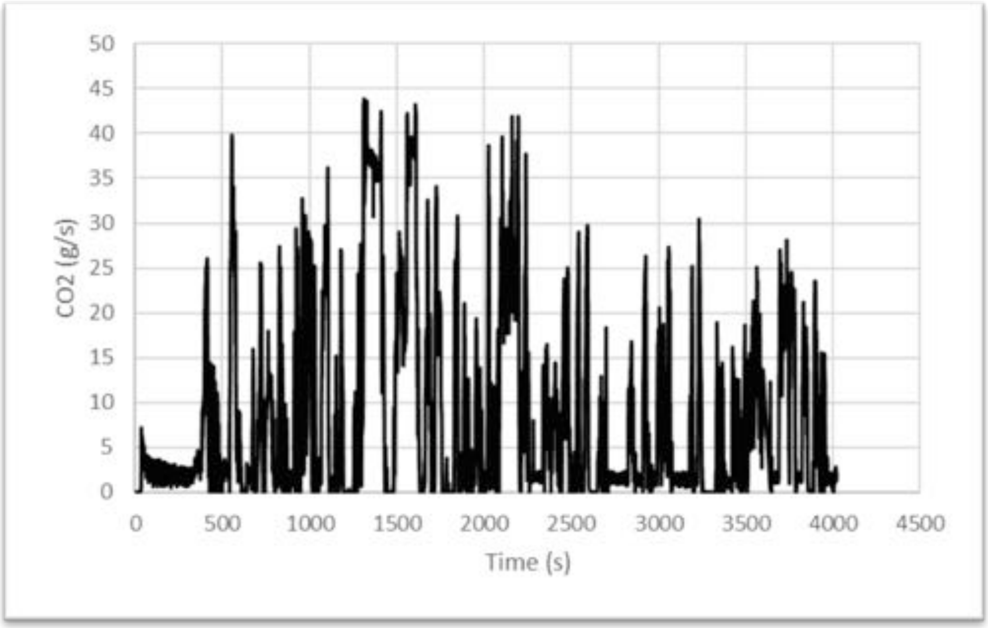


Figure 33: Mass Rate (g/s) of CO_2 Emissions for Propane School Bus from Cold Morgantown Route

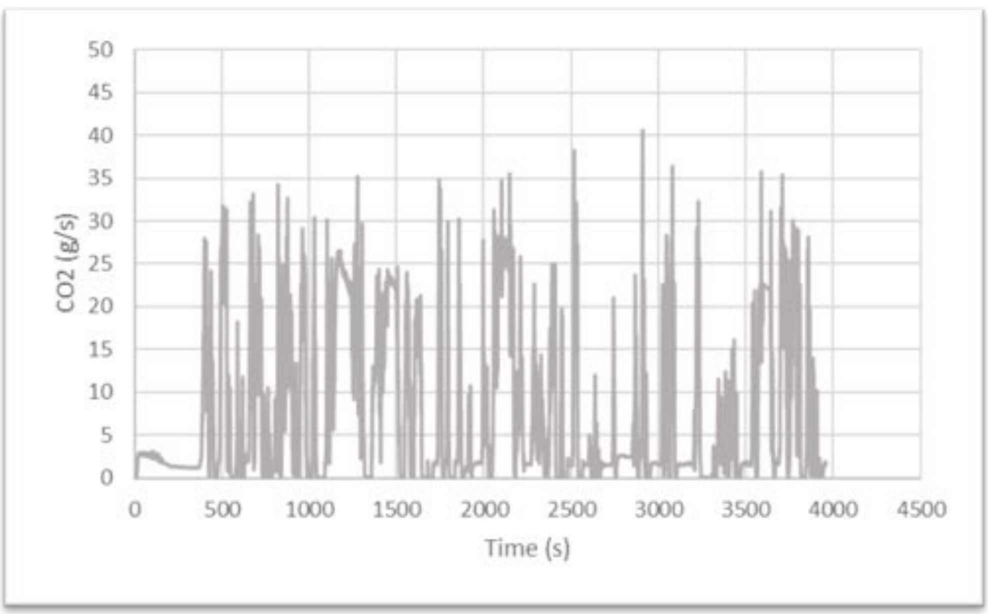


Figure 34: Mass Rate (g/s) of CO_2 Emissions for Diesel School Bus from Cold Morgantown Route

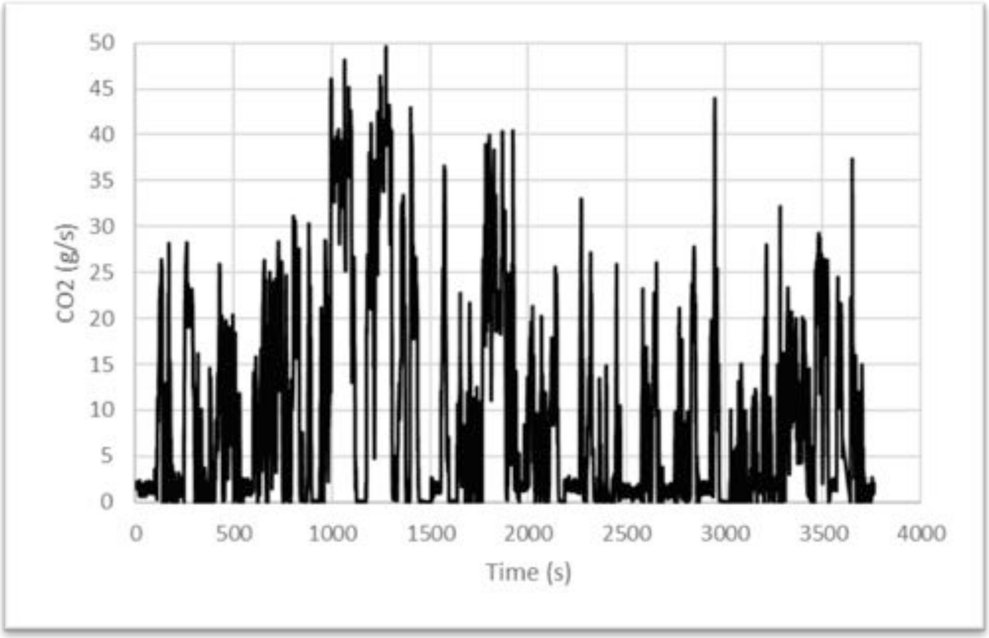


Figure 35: Mass Rate (g/s) of CO_2 Emissions for Propane School Bus from Hot Morgantown Route

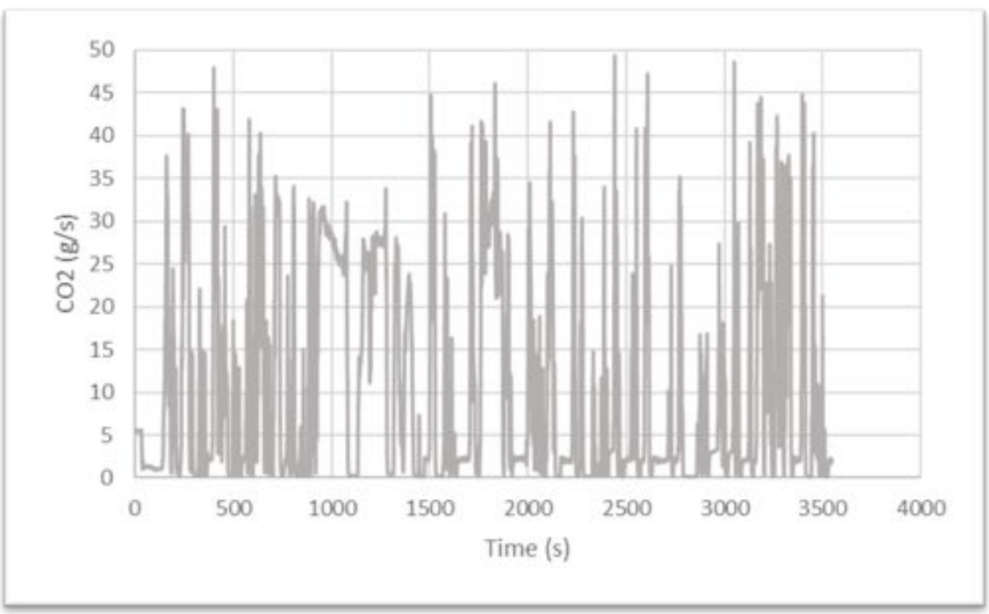


Figure 36: Mass Rate (g/s) of CO_2 Emissions for Diesel School Bus from Hot Morgantown Route

6.1.4 Total Hydrocarbon Emissions

THC emissions were quantified via the FID analyzer in the OBS 2200 PEMS. Figure 37 presents the average distance specific THC emissions for the propane (LPG) and diesel school busses operated over the cold and hot Morgantown routes.

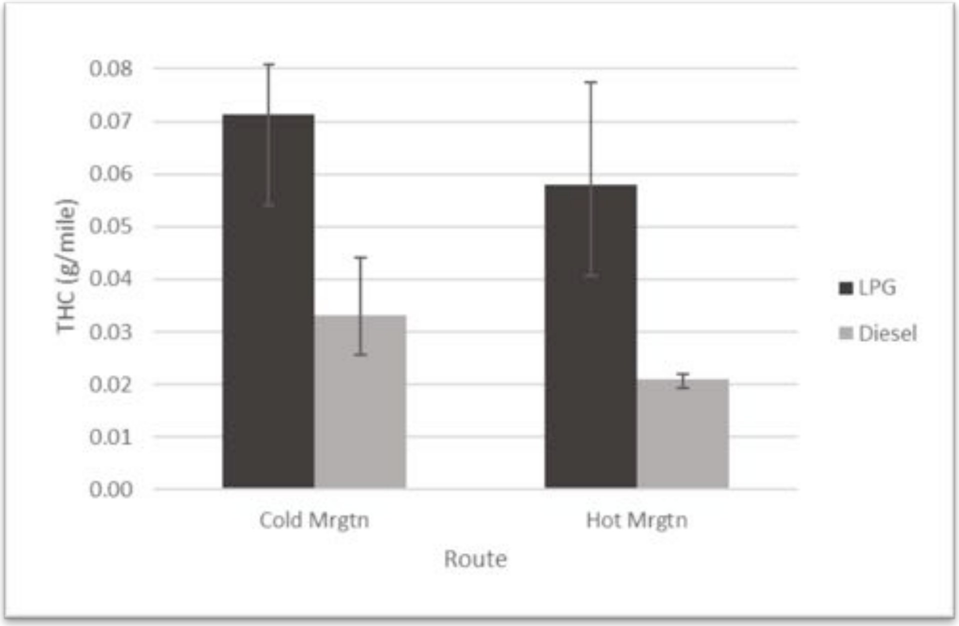


Figure 37: Average THC Emissions (g/mile) for Propane and Diesel School Bus

The average distance specific THC emissions were higher for the propane versus the diesel school bus. This result is intuitive given the stoichiometric operation of the propane school bus compared to the lean operation of the diesel school bus. However, it is important to note that the magnitude of the THC emissions is an order lower than that of the CO emissions, and both the propane and diesel school buses produced minimal THC emissions.

The mass rate traces of THC emissions Figure 38 through Figure 41 provide insight into the higher THC emissions from the propane school bus. Similar to the traces for CO emissions, spikes in THC emissions associated with acceleration events for the propane school bus are the main contributors to the higher distance specific measurements.

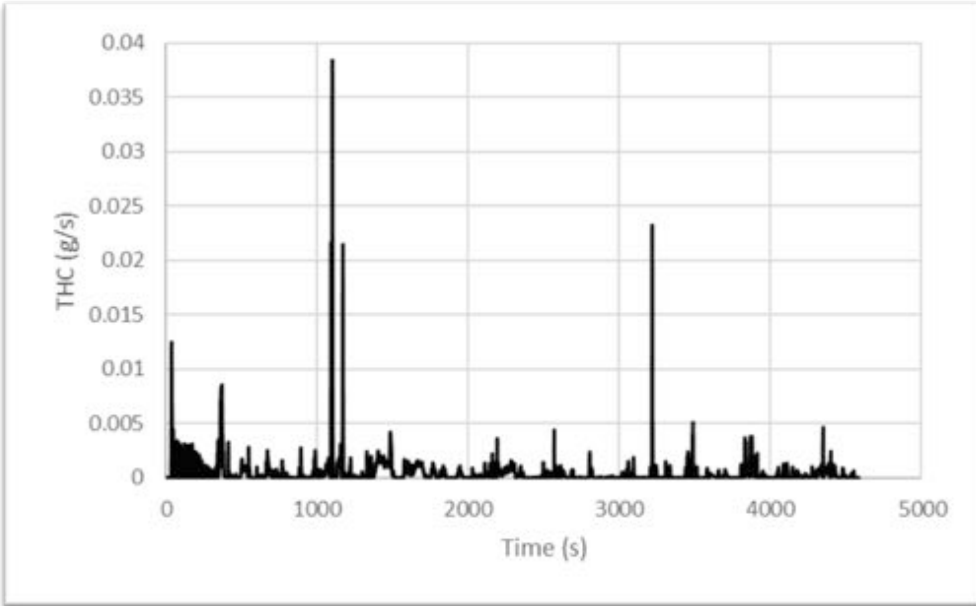


Figure 38: Mass Rate (g/s) of THC Emissions for Propane School Bus from Cold Morgantown Route

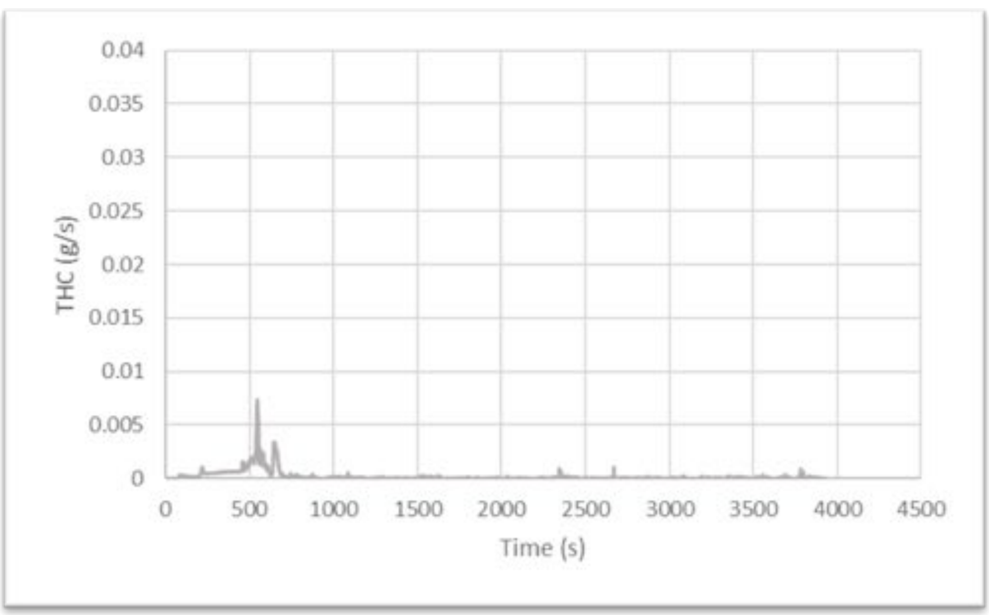


Figure 39: Mass Rate (g/s) of THC Emissions for Diesel School Bus from Cold Morgantown Route

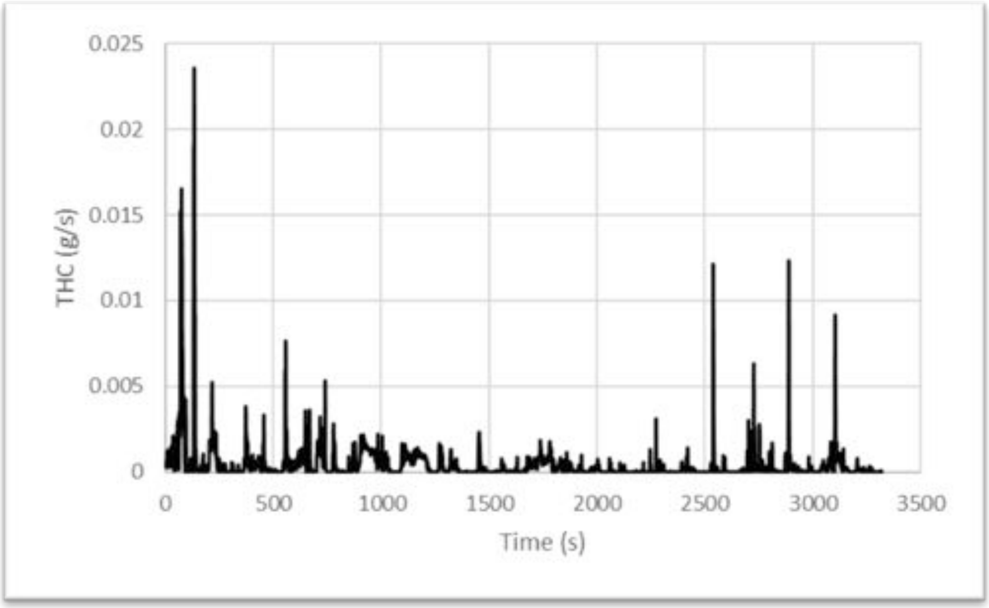


Figure 40: Mass Rate (g/s) of THC Emissions for Propane School Bus from Hot Morgantown Route

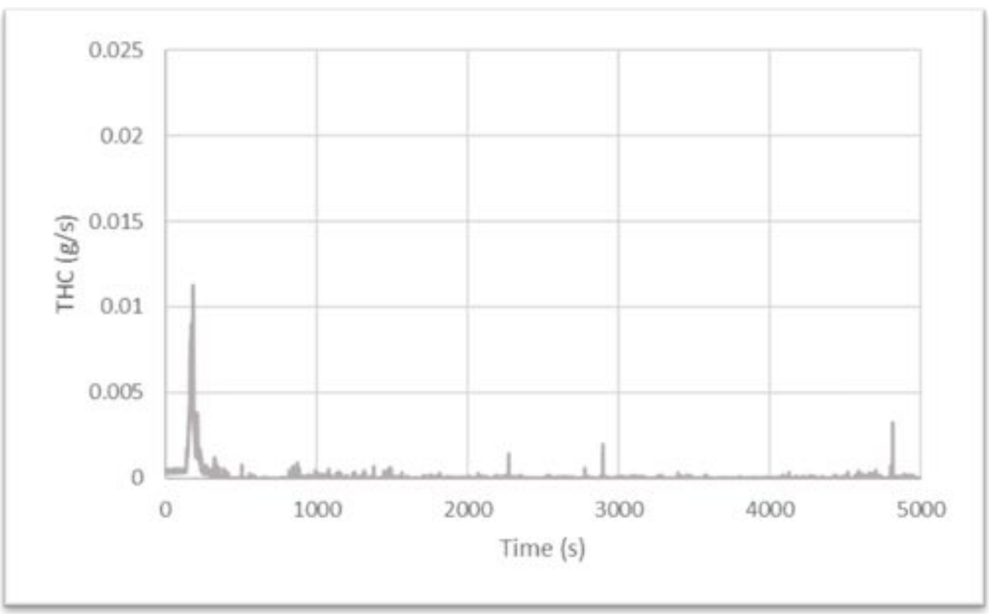


Figure 41: Mass Rate (g/s) of THC Emissions for Diesel School Bus from Hot Morgantown Route

6.2 Stop and Go Route

Emissions measurements from the diesel and propane school buses are presented below for a Stop and Go route as detailed in Section 4.2. These tests were performed in Morgantown WV, during January and February of 2018. These tests were performed on private property, on a predetermined route eliminating the variability associated with traffic on public roads. The results can still be influenced by ambient conditions and weather as discussed in Section 5.1. Given the inherent nature of in-use emissions testing and the time of year during which testing took place a varying range of ambient temperatures were encountered which is presented in Figure 42. Again, it is also important to note that many of the ambient temperatures encountered during this testing were well below the range of temperatures specified for emissions certification testing and in-use not-to-exceed emissions testing for medium and heavy-duty engines/vehicles. Average emissions results are presented on a vehicle distance specific basis rather than an engine brake specific basis, which these engines are certified to, due to the equipment and procedures used as well as the on-board diagnostic channels available.

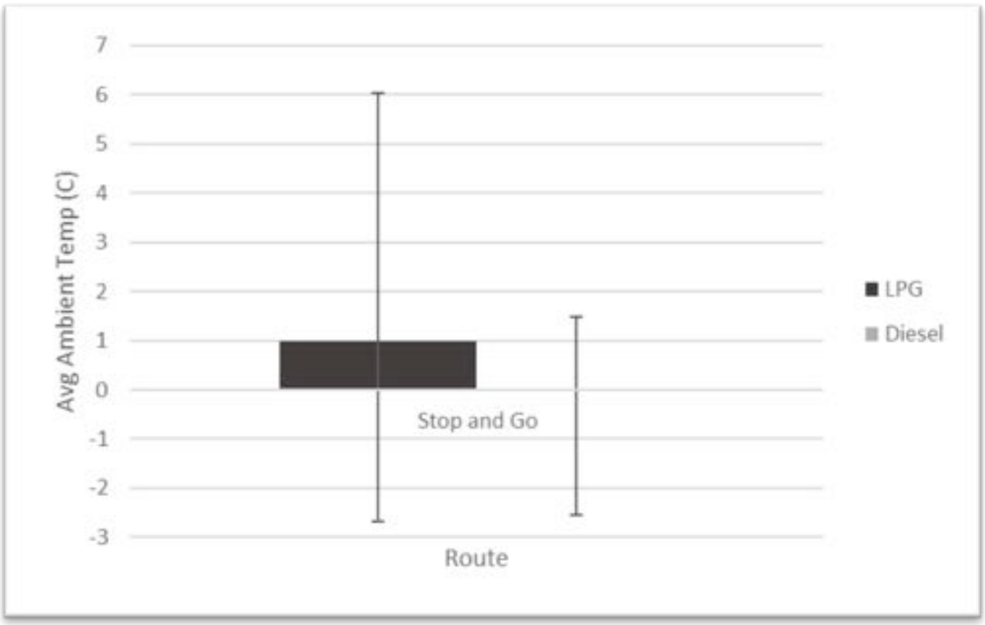


Figure 42: Average Ambient Air Temperature (°C) for Propane and Diesel School Bus

Note that the average ambient temperature for the diesel school bus was approximately 0 °C and thus the bar chart is not observable.

6.2.1 Oxides of Nitrogen Emissions

NO_X emissions for the diesel and propane school buses operated over the Stop and Go route are presented in Figure 43.

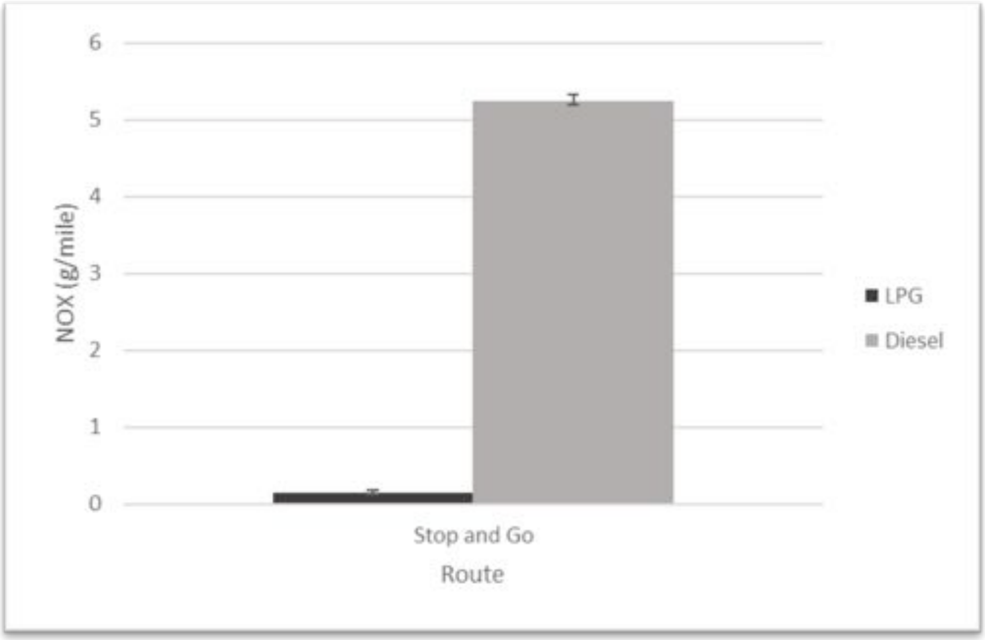


Figure 43: Average NO_X Emissions (g/mile) for Propane and Diesel School Bus

Similar to the Morgantown route NO_X emissions were substantially higher for the diesel school bus compared to the propane school bus over the Stop and Go route. Furthermore, the average NO_X emissions from the diesel school bus (5.2 g/mile) were an order of magnitude higher than the propane school bus (0.2 g/mile) and the variability in the measurements was minimal. As noted previously the exhaust aftertreatment, particularly the SCR system for diesel vehicles, can be negatively influenced by colder ambient temperatures and low speed, low load operation.

The mass rate of NO_X emissions presented in Figure 44 and Figure 45 further demonstrates the disparity in measurements between the propane and diesel school buses. The propane school bus has spikes of NO_X emissions corresponding to acceleration events, however the diesel school bus has significantly higher and longer duration spikes as well as increased NO_X emissions at idle.

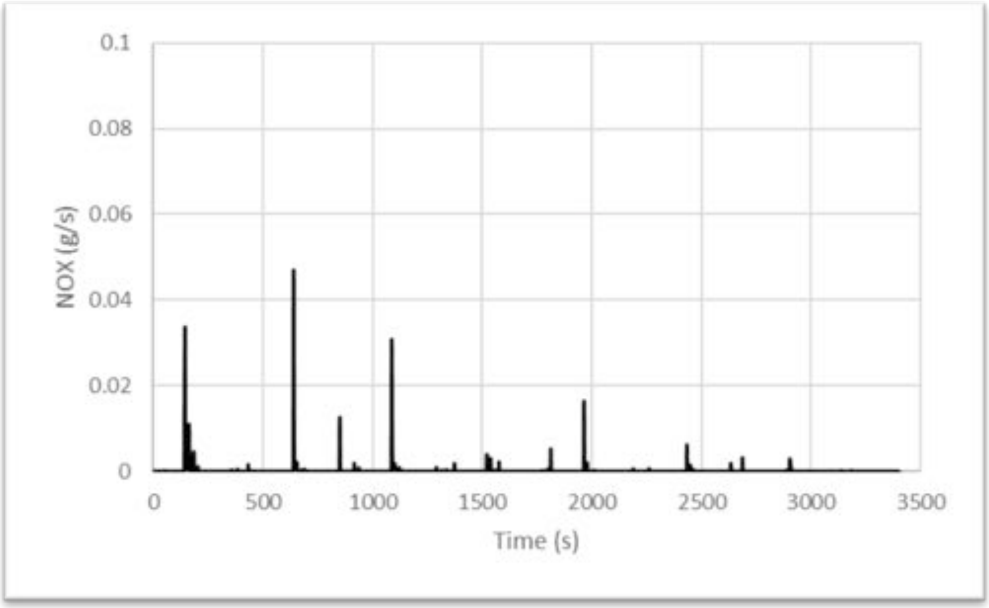


Figure 44: Mass Rate (g/s) of NO_X Emissions for Propane School Bus from Stop and Go Route

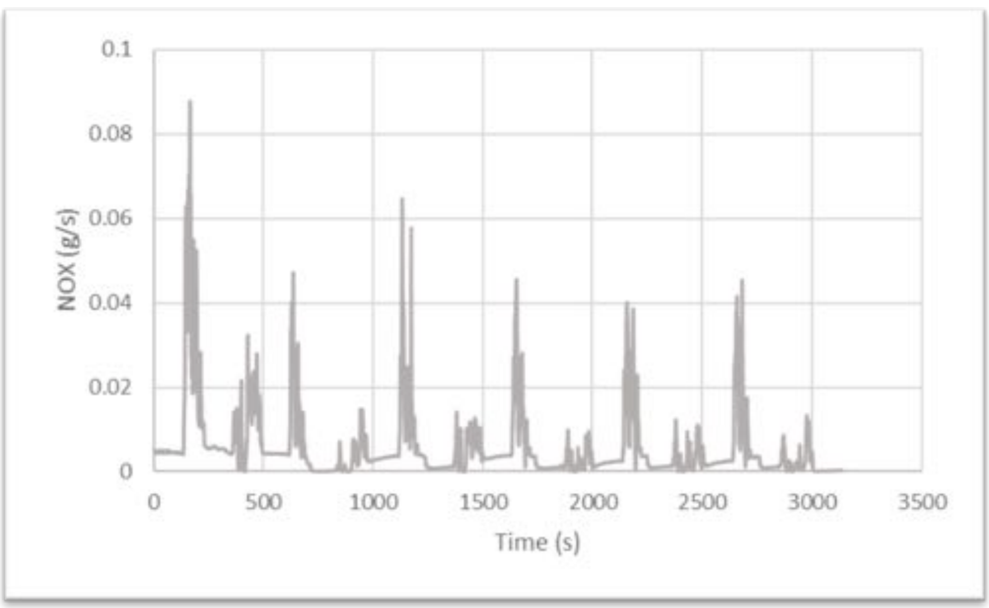


Figure 45: Mass Rate (g/s) of NO_X Emissions for Diesel School Bus from Stop and Go Route

6.2.2 Carbon Monoxide Emissions

CO emissions for the diesel and propane school buses operated over the Stop and Go route are presented in Figure 46.

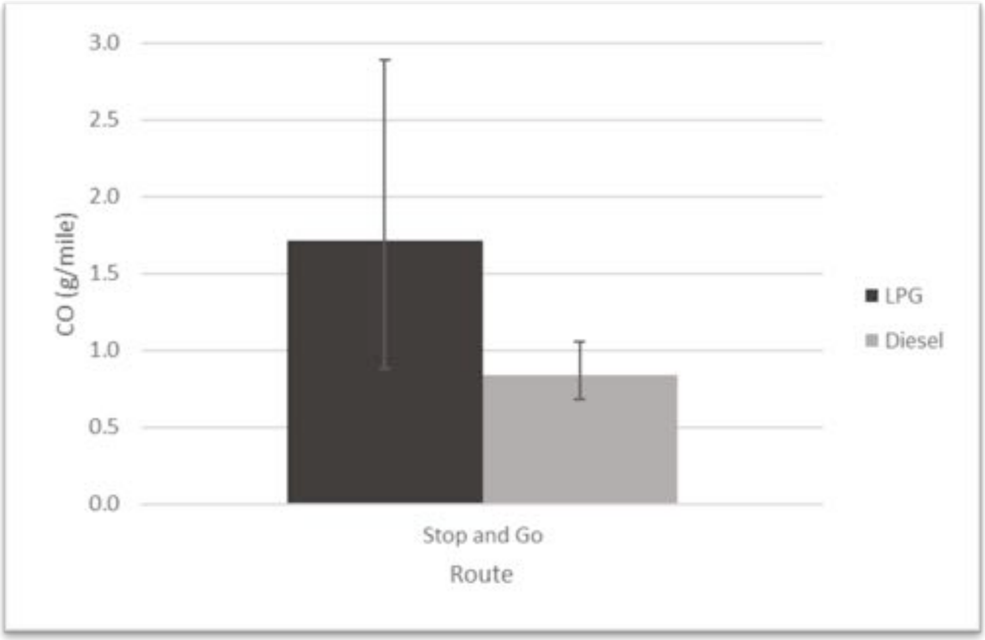


Figure 46: Average CO Emissions (g/mile) for Propane and Diesel School Bus

A trend of higher average distance specific CO emissions for the propane bus similar to the Morgantown route was observed over the Stop and Go route, however the disparity between the average of the two vehicles is not as dramatic. The variability in the CO measurements are higher for the propane school bus compared to the diesel school bus which could be related to the higher water content and its effect on the NDIR analyzer.

The mass rate of CO emissions presented in Figure 47 and Figure 48 demonstrate that while both vehicles produce spikes of CO emissions corresponding to acceleration events, the spikes from the propane school bus are much larger in magnitude.

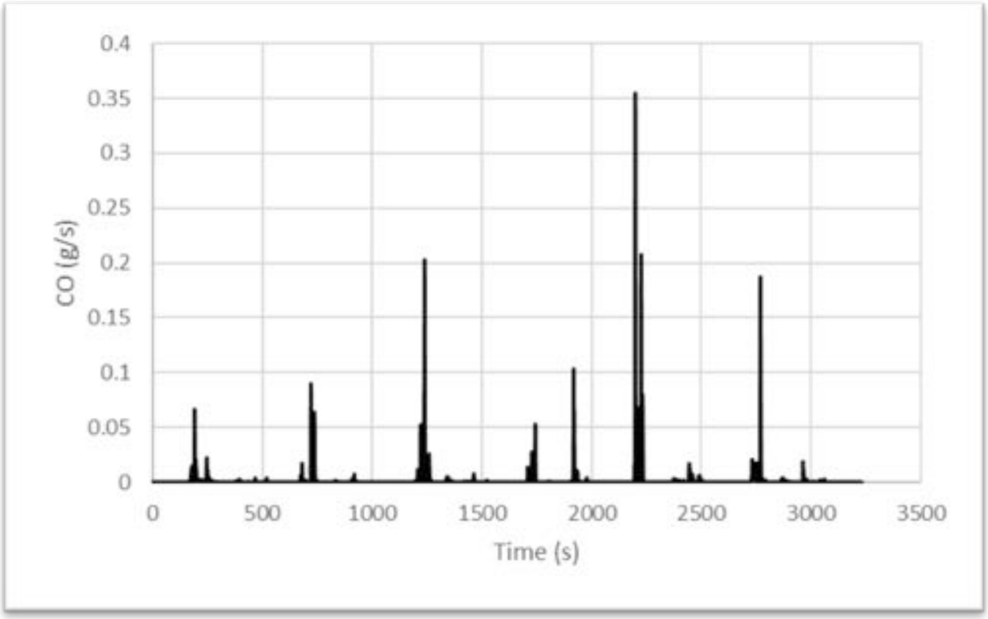


Figure 47: Mass Rate (g/s) of CO Emissions for Propane School Bus from Stop and Go Route

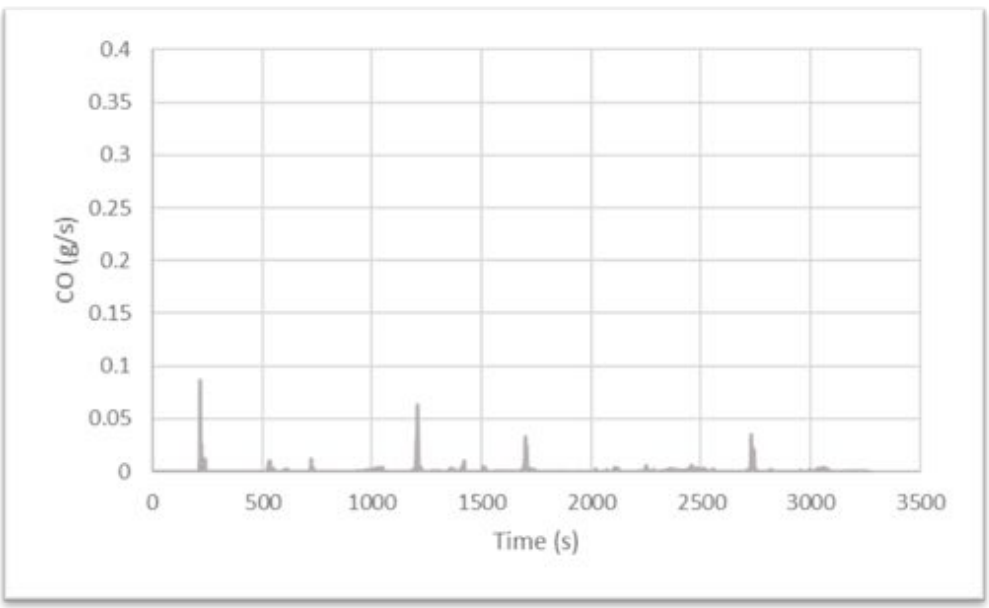


Figure 48: Mass Rate (g/s) of CO Emissions for Diesel School Bus from Stop and Go Route

6.2.3 Carbon Dioxide Emissions

CO_2 emissions for the diesel and propane school buses operated over the Stop and Go route are presented in Figure 49.

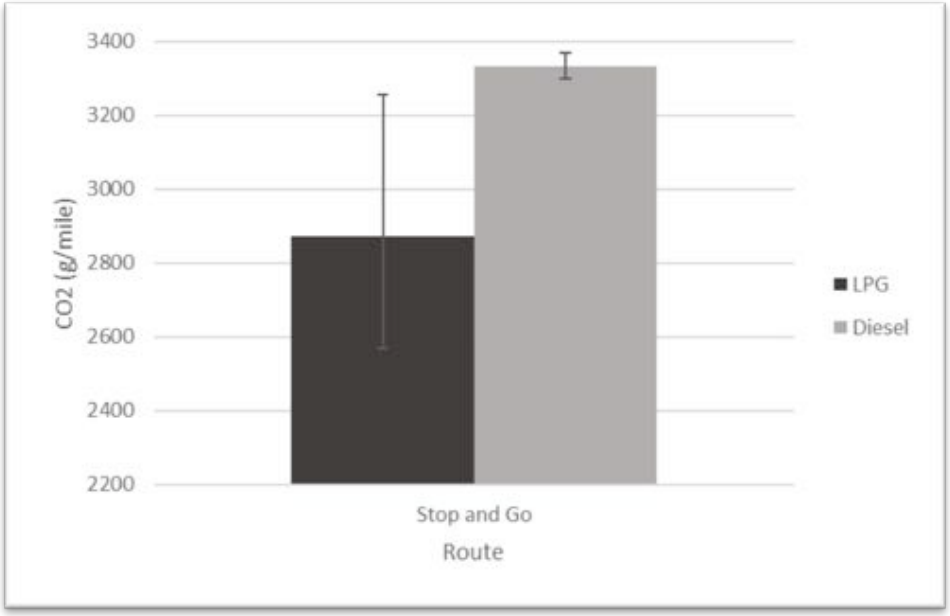


Figure 49: Average CO_2 Emissions (g/mile) for Propane and Diesel School Bus

The average CO_2 emissions produced by the diesel school bus exceeded that of the propane school bus. However, it is important to note that the variability of the CO_2 emissions from the propane bus were much higher which may be related to the elevated water content in the exhaust and its effect on the NDIR analyzer. The high distance specific CO_2 emissions from the diesel school bus may be explained by the low ambient temperatures and low speed, low load route that increases the use of thermal management strategies to maintain exhaust and SCR temperatures which also increase CO_2 emissions and fuel consumption.

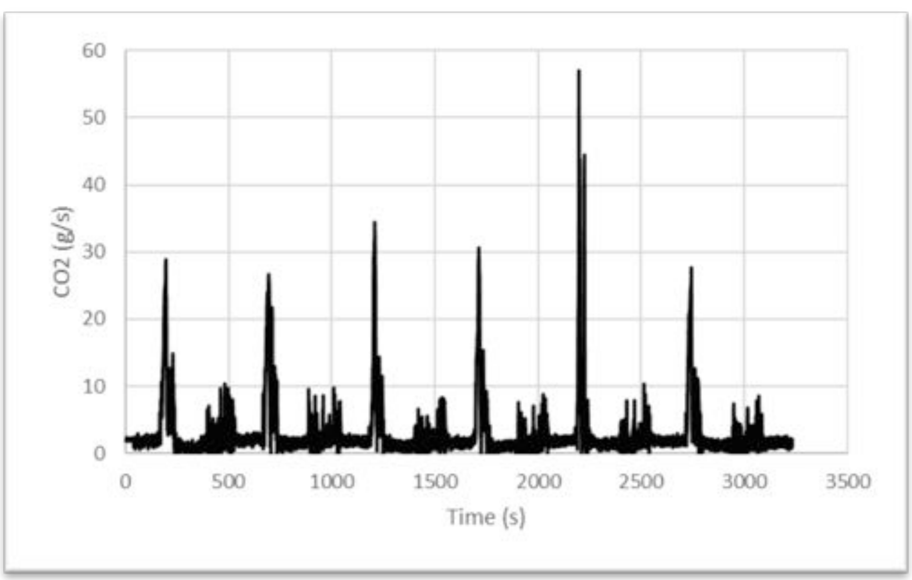


Figure 50: Mass Rate (g/s) of CO_2 Emissions for Propane School Bus from Stop and Go Route

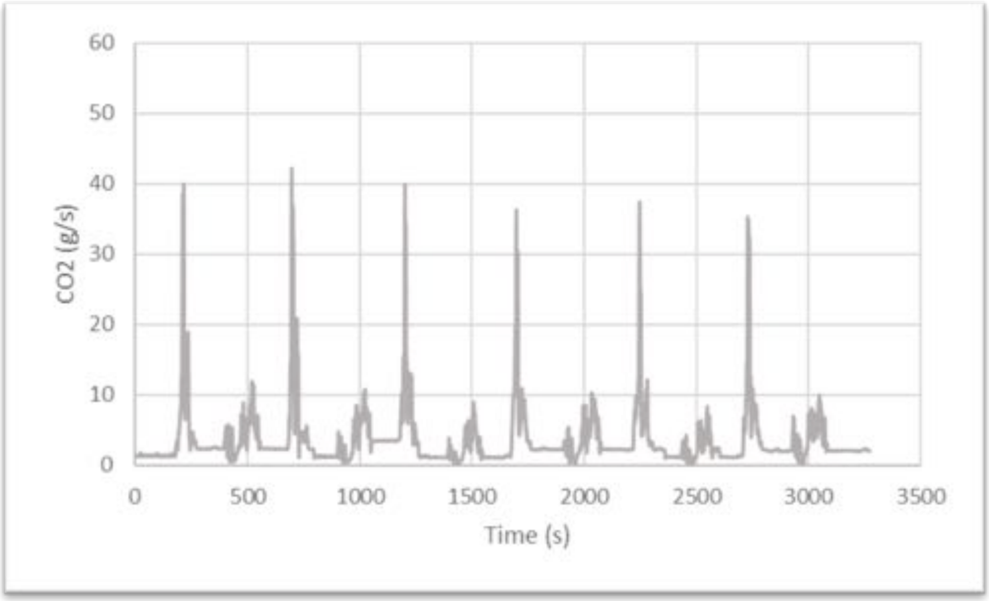


Figure 51: Mass Rate (g/s) of CO_2 Emissions for Diesel School Bus from Stop and Go Route

6.2.4 Total Hydrocarbon Emissions

THC emissions for the diesel and propane school buses operated over the Stop and Go route are presented in Figure 52.

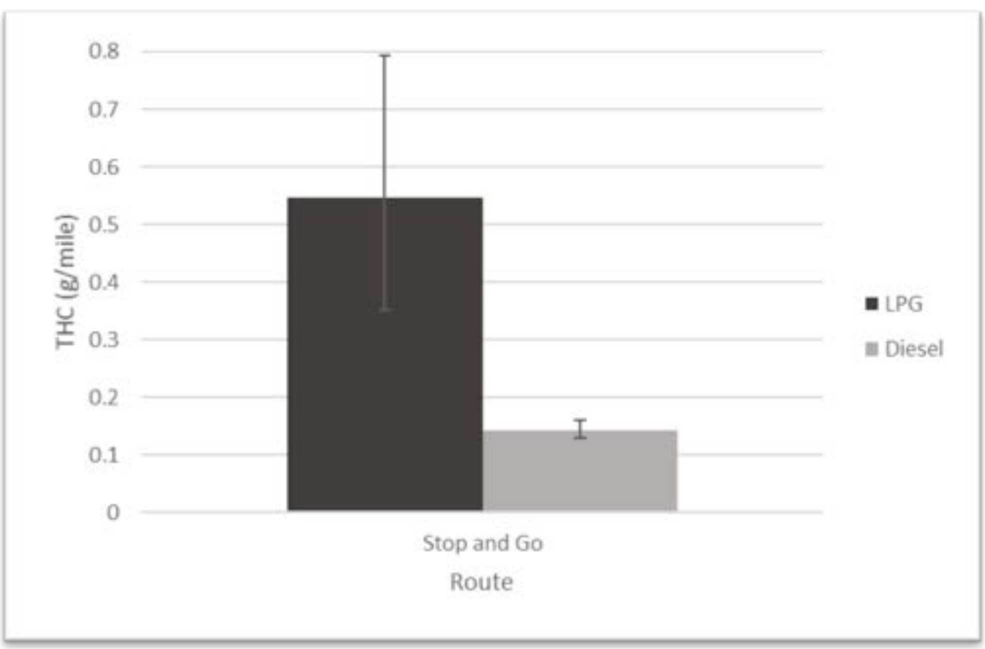


Figure 52: Average THC Emissions (g/mile) for Propane and Diesel School Bus

Similar to the CO emissions, the average distance specific THC emissions from the propane school bus were higher compared to the diesel school bus. Furthermore, both vehicles produced higher distance specific THC emissions compared to the results from the Morgantown route, presumably due to the low speed, low load nature of the route.

The mass rate of THC emissions presented in Figure 53 and Figure 54 show that the propane school bus produced spikes of THC emissions throughout the route, while the majority of the THC emissions produced from the diesel school bus were located at the beginning of the route. While the vehicles were warmed up and allowed to idle before the test, the DOC on the diesel bus may have cooled down enough to limit its performance, but quickly warmed up once the vehicle started moving.

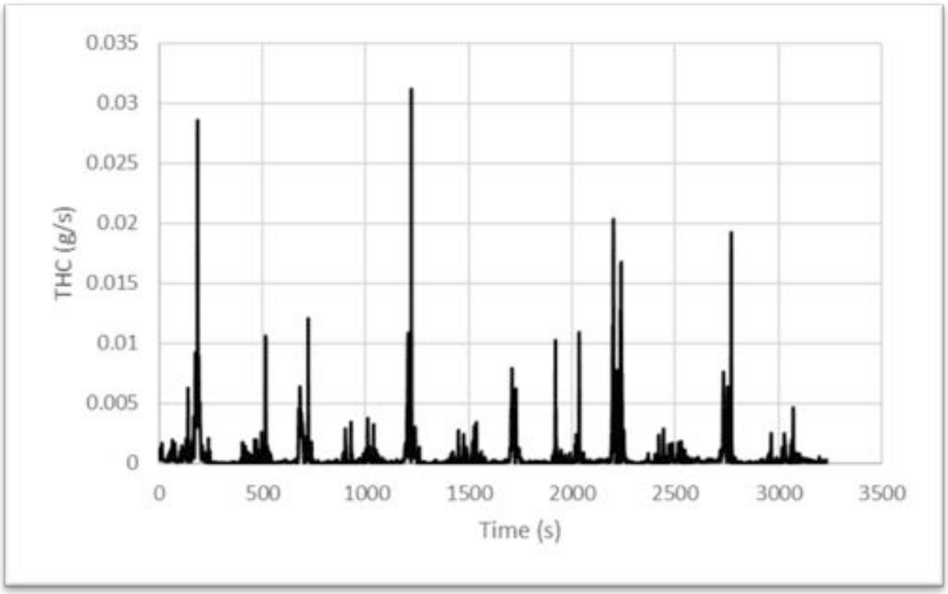


Figure 53: Mass Rate (g/s) of THC Emissions for Propane School Bus from Stop and Go Route

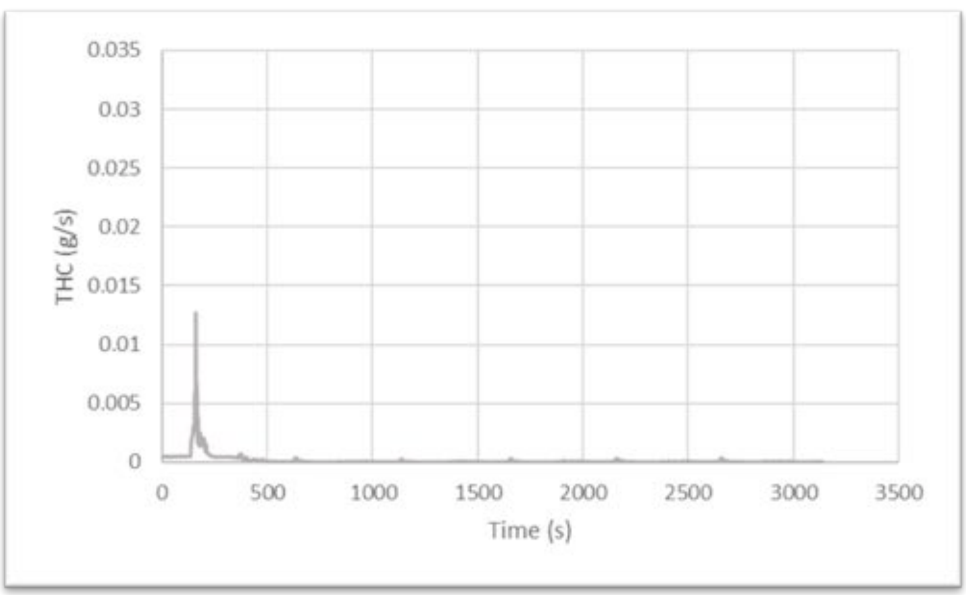


Figure 54: Mass Rate (g/s) of THC Emissions for Diesel School Bus from Stop and Go Route

7 Results - 2017 School Buses

Emissions measurements presented in this section were performed on a 2017 model year Blue Bird propane powered school bus and a 2017 model year Blue Bird diesel powered school bus over the routes specified in Section 4. Each route, Cold Morgantown, Hot Morgantown, 2-Minute Stop and Go, and 5-Minute Stop and Go was repeated three times for each vehicle. The result is 12 total tests per vehicle. For comparison purposes the average emissions results are presented on a mass per distance basis (distance specific); grams of emissions constituent measured per mile traveled by the vehicle. The magnitude of the individual bars is equivalent to the average of the three tests performed for that route and vehicle. Error bars indicate the maximum and minimum values used to calculate the average. A sample of real time traces of mass rate (grams per second) emissions from each vehicle are also presented. Distance specific results for each individual test can be found in the Appendix, Section 0. As mentioned in the previous section it is important to note that these measurements were not performed for the purpose of certification or comparison to the emissions certification standards. Furthermore, a not-to-exceed analysis was not performed on this data set, and thus the data presented cannot be used to determine in-use emissions compliance.

7.1 Morgantown Route

Emissions measurements from the 2017 propane and 2017 diesel school buses are presented below for a cold start and hot start Morgantown route as detailed in Section 4.1. All of these tests were performed in Morgantown WV, during July and August of 2018. Similar to the previous school bus testing, these tests were conducted on public roads, on a predetermined route, and thus the results presented below can be influenced by external factors such as traffic, weather, and road conditions as discussed in Section 5.1. Average emissions results are presented on a vehicle distance specific basis rather than an engine brake specific basis, which these engines are certified to, due to the equipment and procedures used as well as the on-board diagnostic channels available.

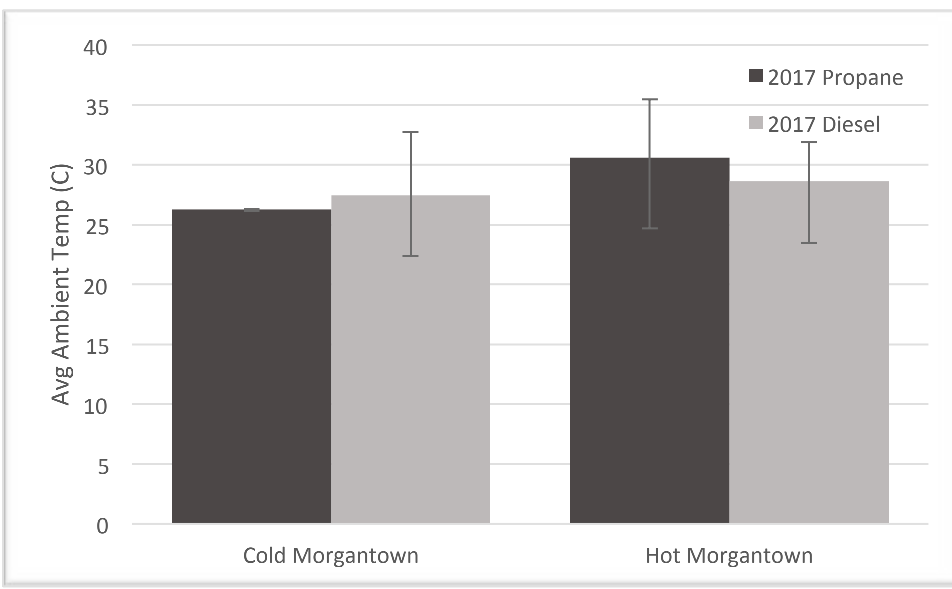


Figure 55: Average Ambient Air Temperature (°C) for Propane and Diesel School Bus

The average ambient temperatures encountered during in-use emissions testing on the Morgantown route ranged from approximately 22 degrees Celsius (°C) to 35 °C as presented in Figure . Note that the ambient temperature can be influenced by sunlight especially if the vehicle has prolonged idling such as at a stoplight.

7.1.1 Oxides of Nitrogen Emissions

NO_X emissions were quantified via the CLD analyzer in the OBS-One PEMS. Figure 56 presents the average distance specific NO_X emissions for the propane and diesel school busses operated over the cold and hot Morgantown routes.

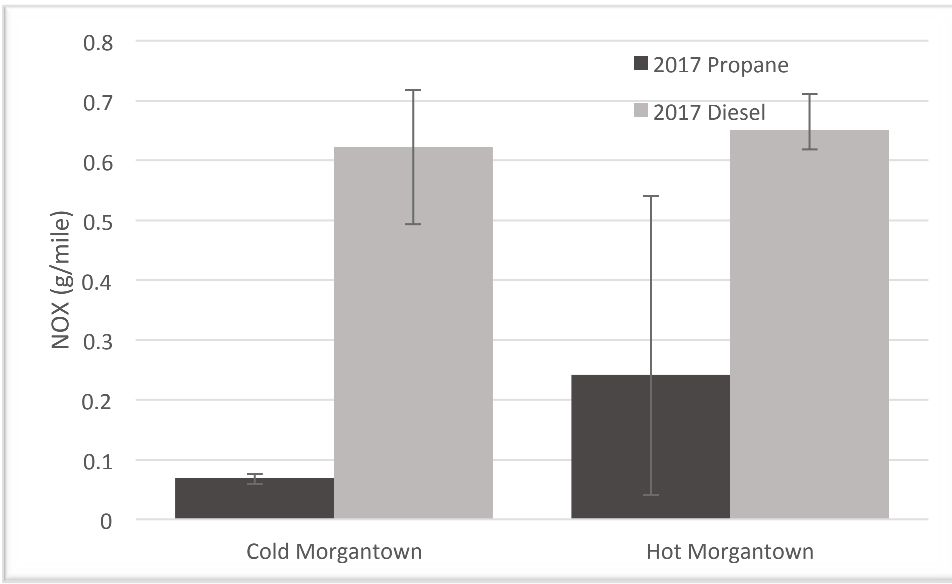


Figure 56: Average NO_X Emissions (g/mile) for 2017 Propane and 2017 Diesel School Bus

The average distance specific NO_X emissions measured from the diesel school bus were higher than the propane school bus, which follows the same trend as the previous school bus testing. With regards to the propane school bus the NO_X emissions were lower on average for the cold Morgantown route versus the hot Morgantown route. Additionally, the variability in NO_X emissions produced by the propane school bus was much greater during the hot Morgantown route than the cold Morgantown route. This is a result of a large NO_X spike event that occurred on one of the tests but not the others. This phenomenon is displayed in the mass rate traces presented in Figure 57 through Figure 60. Specifically, in Figure 59, a large spike occurs around the 1000-second mark presumably due to a lean condition in the three-way catalyst. On both routes, NO_X emissions produced by the diesel school bus had significantly more spikes in addition to overall higher NO_X production throughout the route.

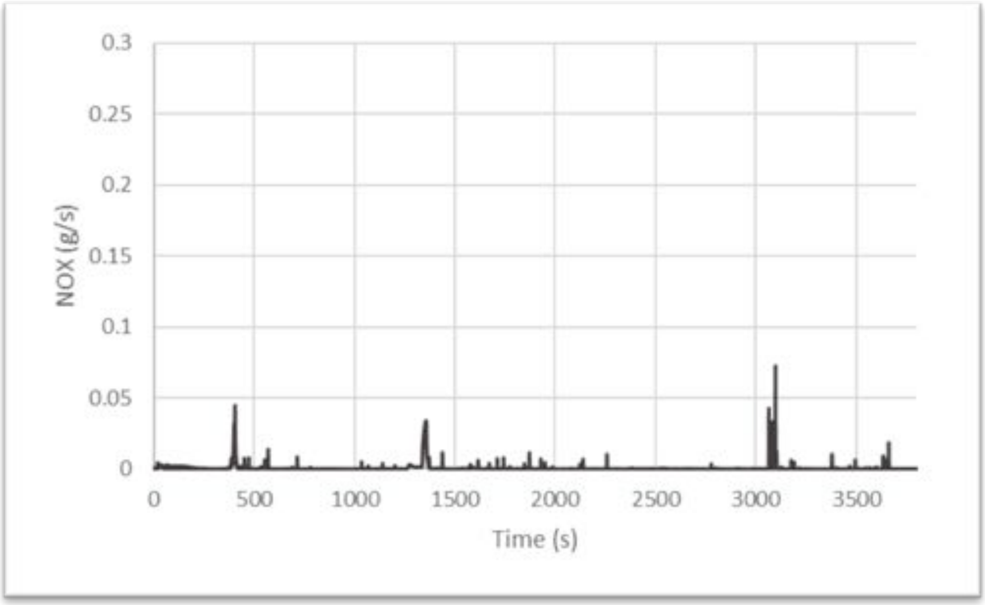


Figure 57: Mass Rate (g/s) of NO_X Emissions for 2017 Propane School Bus from Cold Morgantown Route

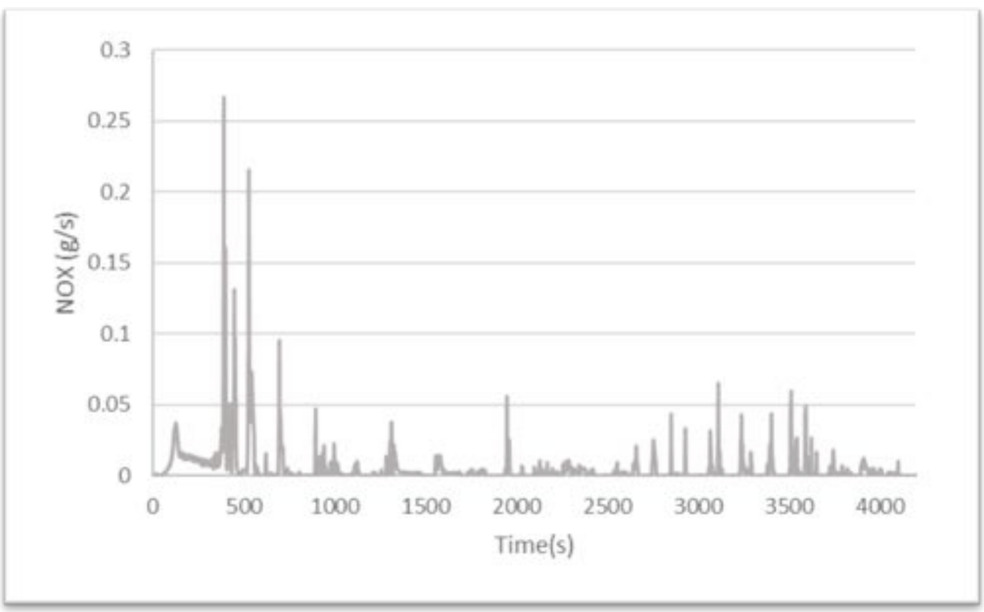


Figure 58: Mass Rate (g/s) of NO_X Emissions for 2017 Diesel School Bus from Cold Morgantown Route

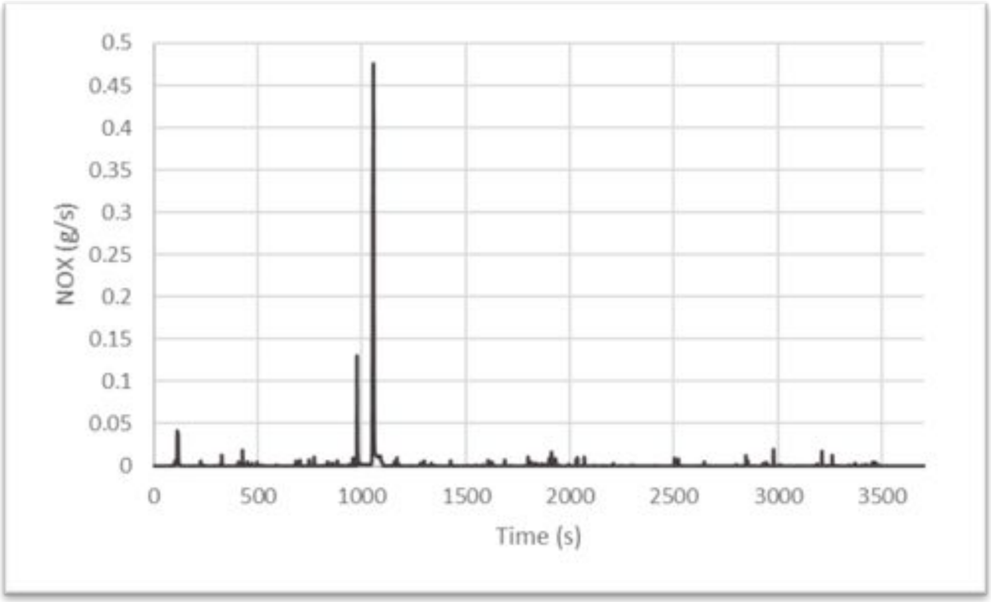


Figure 59: Mass Rate (g/s) of NO_X Emissions for 2017 Propane School Bus from Hot Morgantown Route

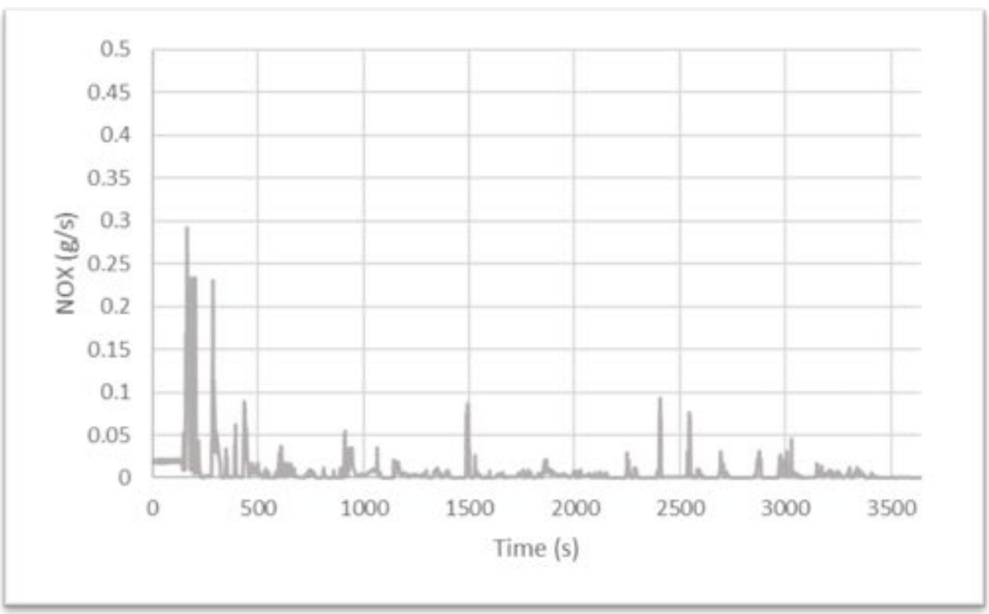


Figure 60: Mass Rate (g/s) of NO_X Emissions for 2017 Diesel School Bus from Hot Morgantown Route

7.1.2 Carbon Monoxide Emissions

CO emissions were quantified via the NDIR analyzer in the OBS-ONE PEMS. As discussed in section 5, the NDIR analyzer simultaneously measures CO and CO_2 in wet form. Figure 61 presents the average distance specific CO emissions for the propane and diesel school busses operated over the cold and hot Morgantown routes.

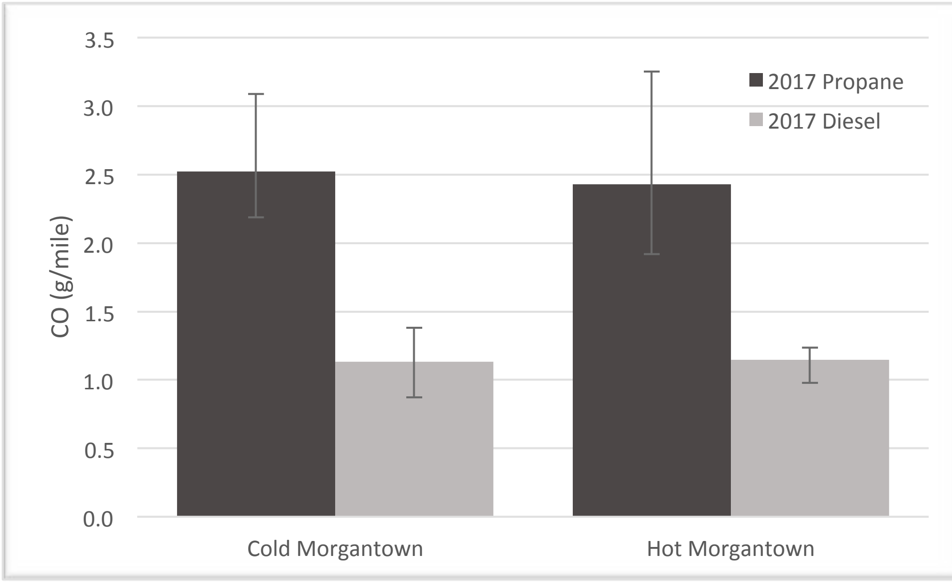


Figure 61: Average CO Emissions (g/mile) for 2017 Propane and 2017 Diesel School Bus

Synonymous with the previous school bus testing the propane school bus emitted higher levels of CO emissions when compared to the diesel school bus. CO emissions were relatively similar between the Cold and Hot Morgantown route.

Figure 62 through Figure 65 present a sample of the mass rate of CO emissions from both school buses and the cold and hot Morgantown routes. These plots provide further evidence of the higher CO emissions from the propane buses and show that elevated CO emissions from the propane bus can be observed in high peaks that correspond to accelerations. Note that the scaling of the graphs is different between the cold and hot Morgantown tests.

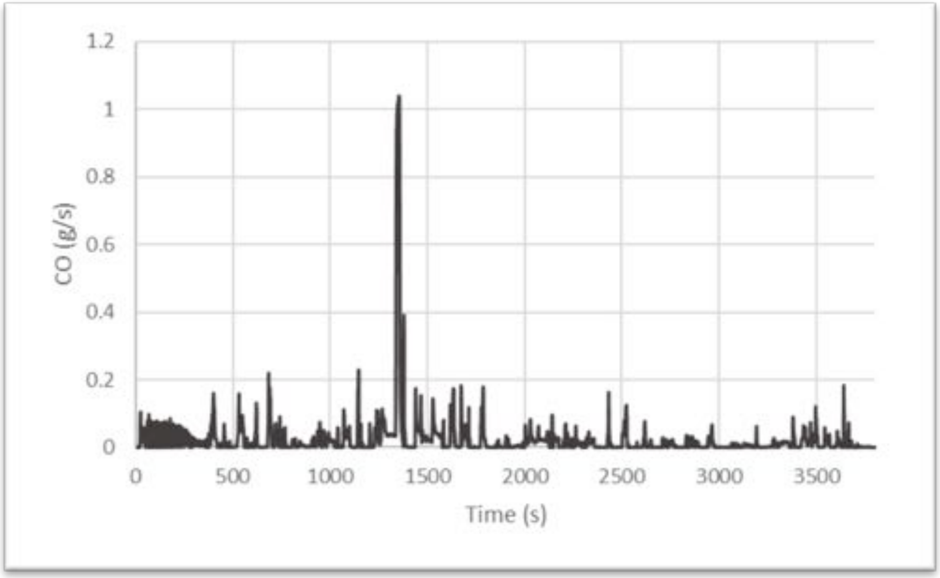


Figure 62: Mass Rate (g/s) of CO Emissions for 2017 Propane School Bus from Cold Morgantown Route

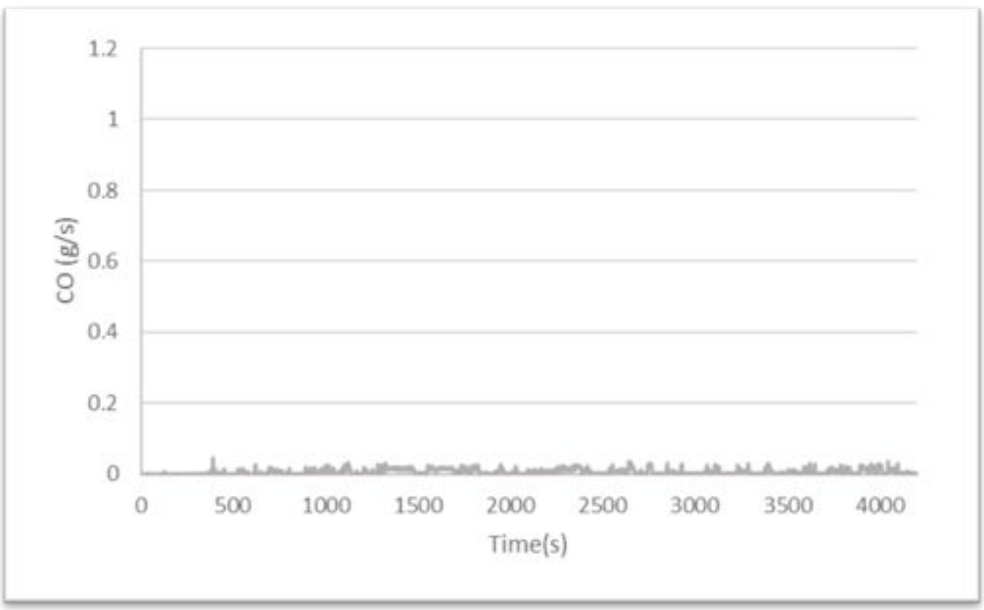


Figure 63: Mass Rate (g/s) of CO Emissions for 2017 Diesel School Bus from Cold Morgantown Route

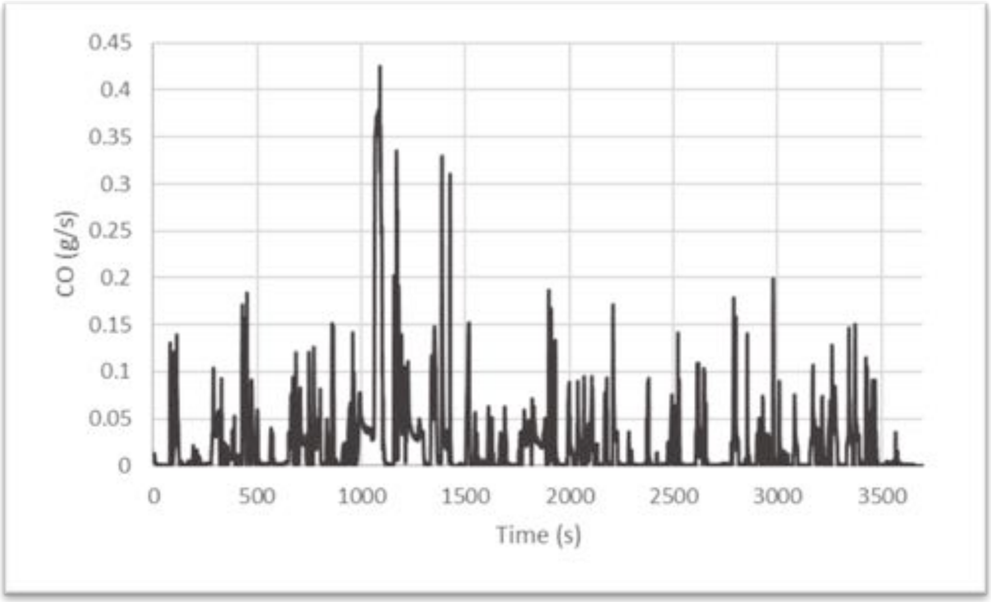


Figure 64: Mass Rate (g/s) of CO Emissions for 2017 Propane School Bus from Hot Morgantown Route

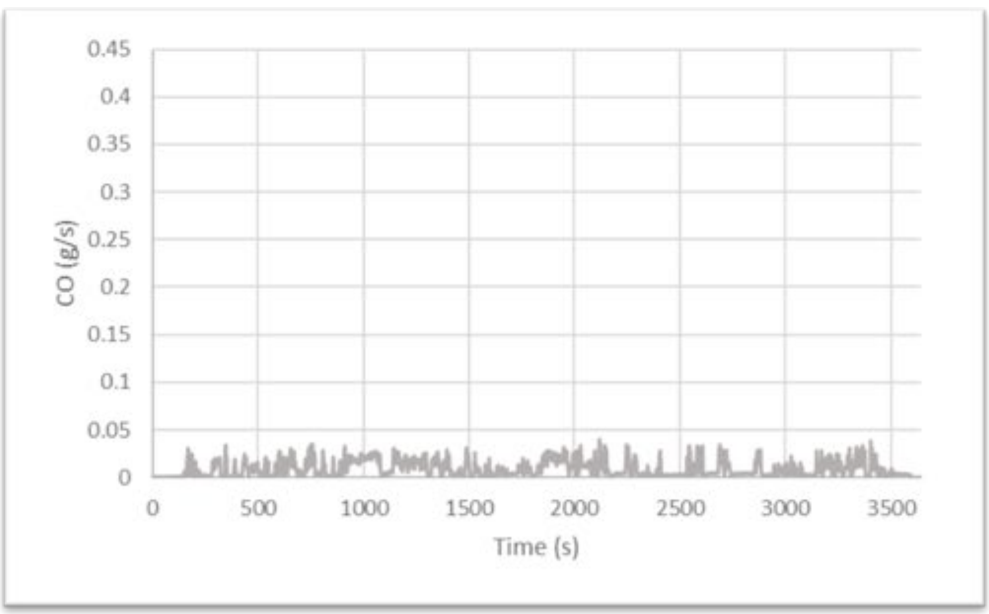


Figure 65: Mass Rate (g/s) of CO Emissions for 2017 Diesel School Bus from Hot Morgantown Route

7.1.3 Carbon Dioxide Emissions

CO_2 emissions were quantified via the NDIR analyzer in the OBS-ONE PEMS. Figure 66 presents the average distance specific CO_2 emissions for the propane and diesel school busses operated over the cold and hot Morgantown routes.

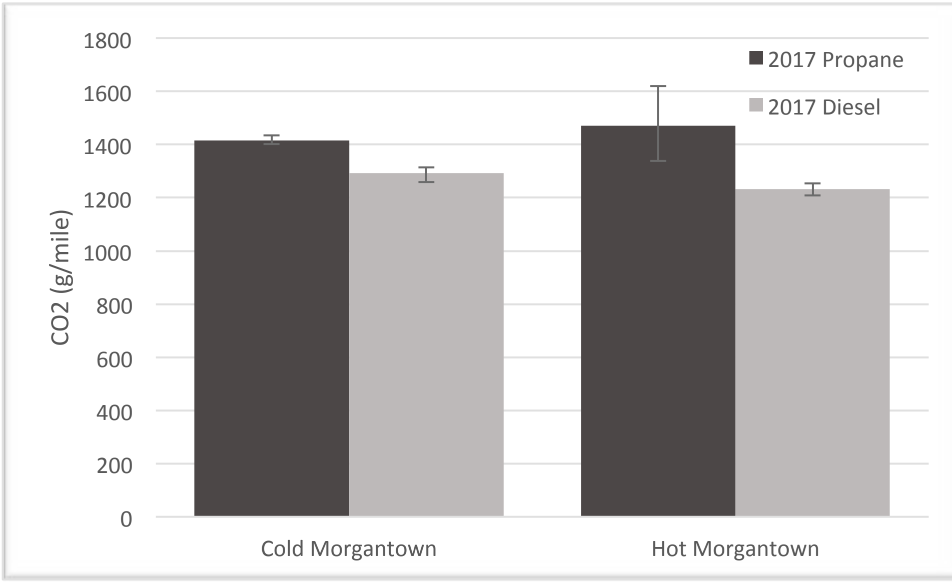


Figure 66: Average CO_2 Emissions (g/mile) for 2017 Propane and 2017 Diesel School Bus

The average CO_2 emissions were higher for the propane school bus versus the diesel school bus. The disparity between the two vehicles was less pronounced for the Cold Morgantown route versus the Hot Morgantown route. This may be related to differing technologies and the associated energy for warm-up, however CO_2 is directly related to fuel consumption, which can be influenced heavily by external factors such as traffic, acceleration events, and stoplights while operating on public roads.

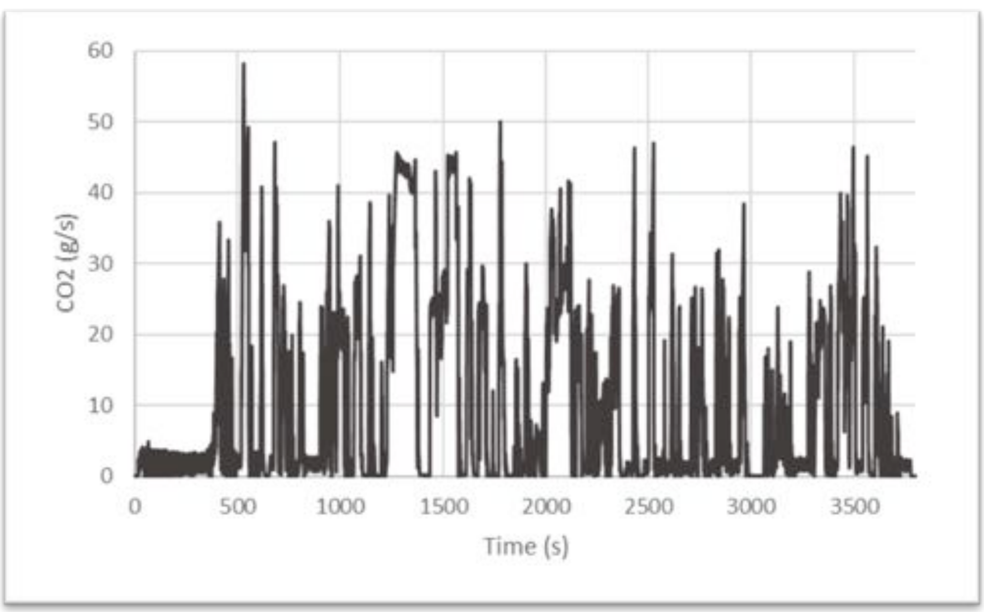


Figure 67: Mass Rate (g/s) of CO_2 Emissions for 2017 Propane School Bus from Cold Morgantown Route

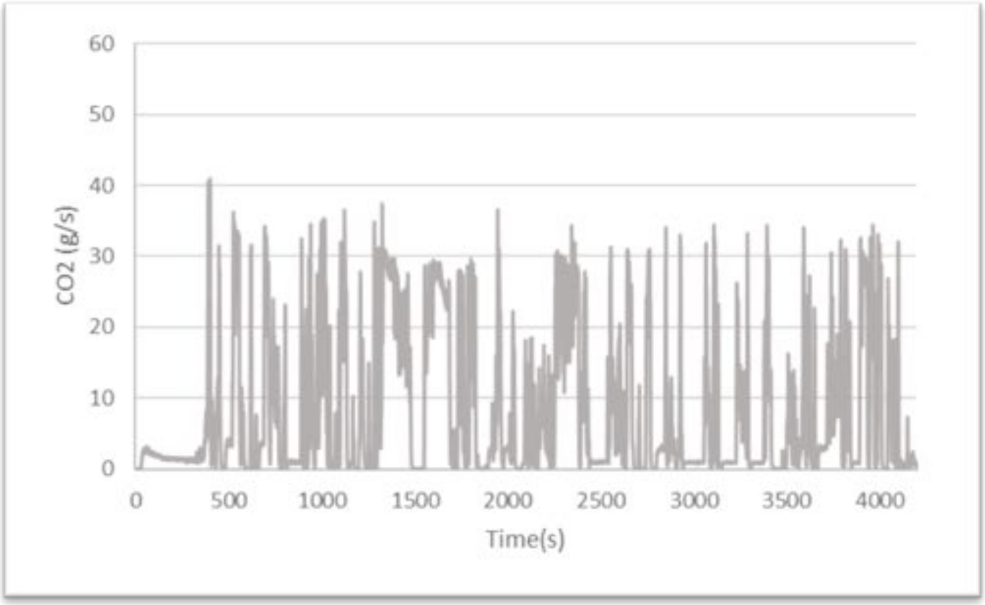


Figure 68: Mass Rate (g/s) of CO_2 Emissions for 2017 Diesel School Bus from Cold Morgantown Route

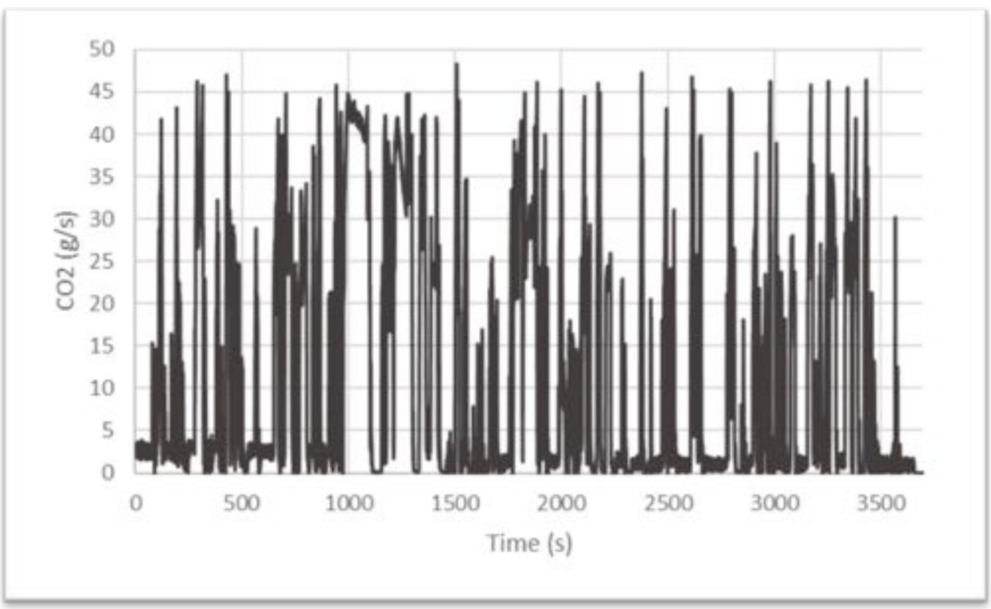


Figure 69: Mass Rate (g/s) of CO_2 Emissions for 2017 Propane School Bus from Hot Morgantown Route

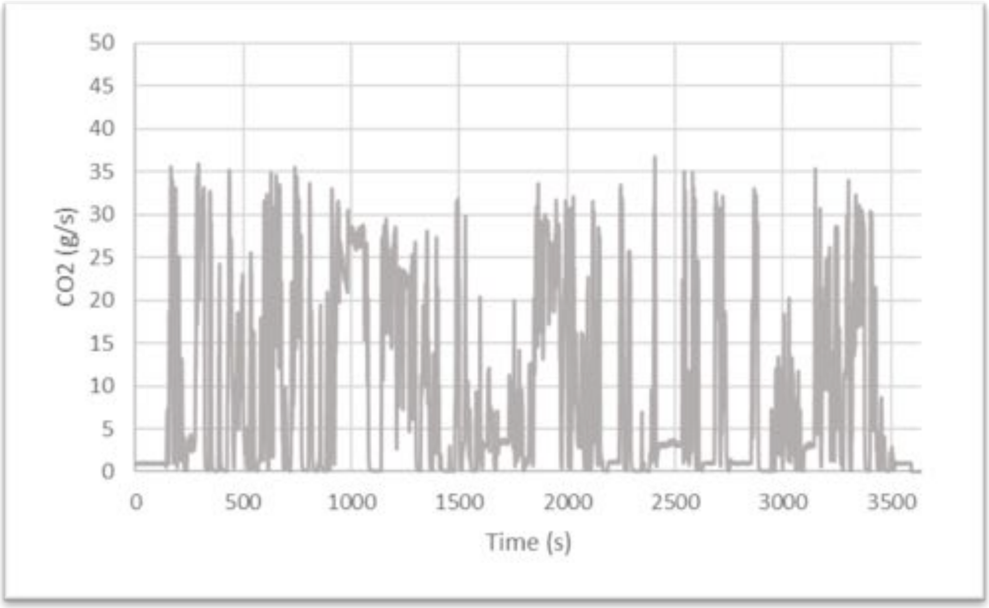


Figure 70: Mass Rate (g/s) of CO_2 Emissions for 2017 Diesel School Bus from Hot Morgantown Route

7.1.4 Total Hydrocarbon Emissions

THC emissions were quantified via the FID analyzer in the OBS-ONE PEMS. Figure 71 presents the average distance specific THC emissions for the propane (LPG) and diesel school busses operated over the cold and hot Morgantown routes.

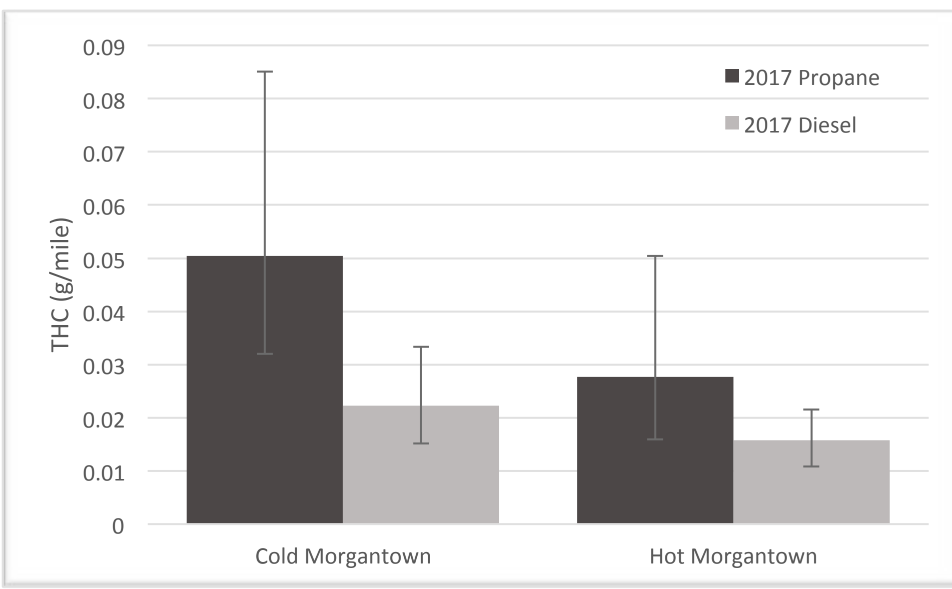


Figure 71: Average THC Emissions (g/mile) for 2017 Propane and 2017 Diesel School Bus

Similar to the previous school bus testing the average distance specific THC emissions were higher for the propane versus the diesel school bus. It is important to note that the magnitude of the THC emissions is an order lower than that of the CO emissions, and both the propane and diesel school buses produced minimal THC emissions.

The mass rate traces of THC emissions in Figure 72 through Figure 75 provide insight into the higher THC emissions from the propane school bus. Similar to the traces for CO emissions, spikes in THC emissions associated with acceleration events for the propane school bus are the main contributors to the higher distance specific measurements.

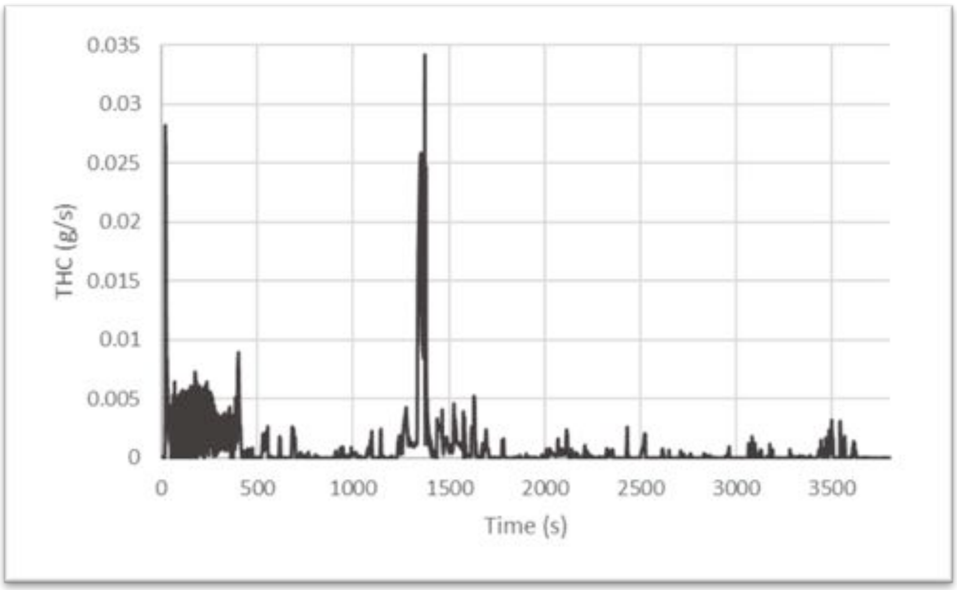


Figure 72: Mass Rate (g/s) of THC Emissions for 2017 Propane School Bus from Cold Morgantown Route

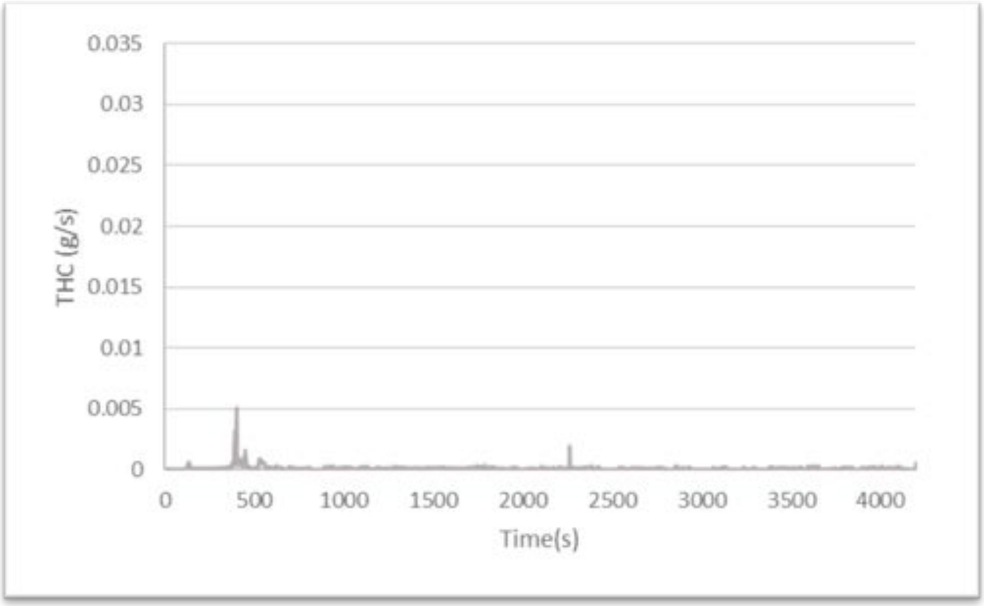


Figure 73: Mass Rate (g/s) of THC Emissions for 2017 Diesel School Bus from Cold Morgantown Route

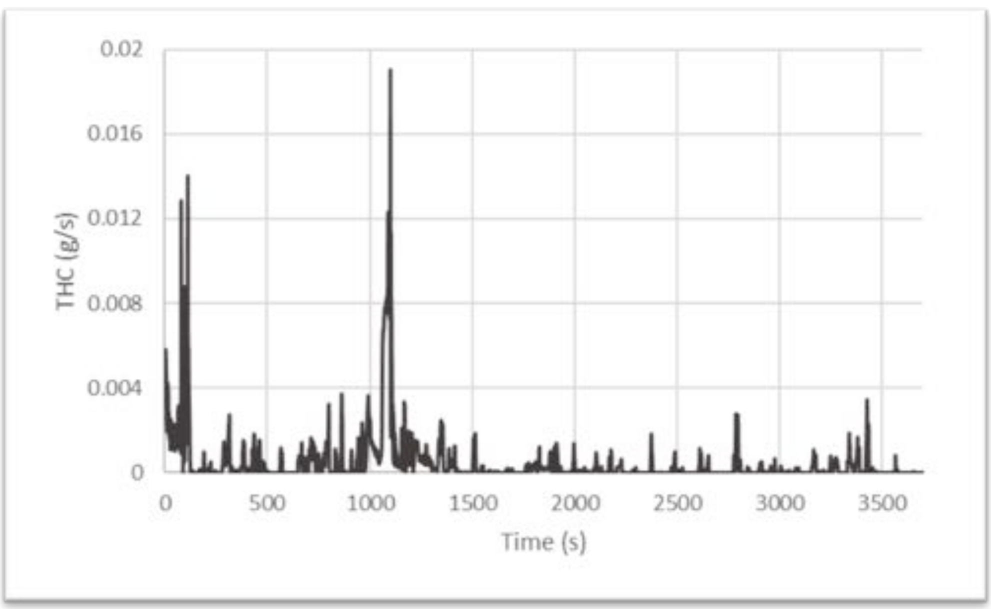


Figure 74: Mass Rate (g/s) of THC Emissions for 2017 Propane School Bus from Hot Morgantown Route

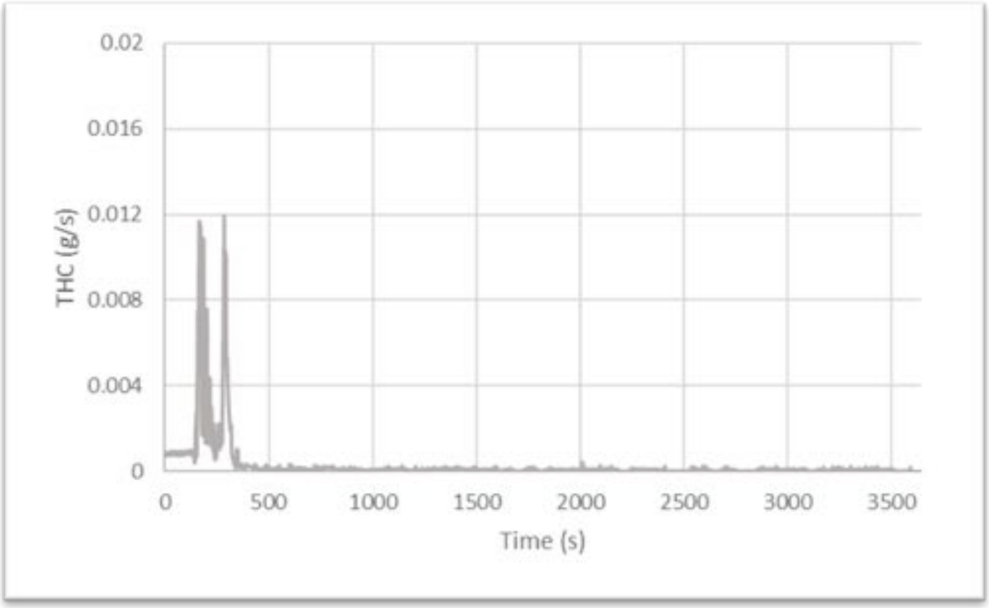


Figure 75: Mass Rate (g/s) of THC Emissions for 2017 Diesel School Bus from Hot Morgantown Route

7.2 Stop and Go Route

Emissions measurements from the 2017 diesel and 2017 propane school buses are presented below for the Stop and Go routes as detailed in Section 4.2. These tests were performed in Morgantown WV, during July and August of 2018. These tests were performed on private property, on a predetermined route eliminating the variability associated with traffic on public roads. Two different test routes are presented below. Both routes share the same driving path, however the duration of the stops is different, i.e. two minute stops versus 5-minute stops. Average emissions results are presented on a vehicle distance specific basis rather than an engine brake specific basis, which these engines are certified to, due to the equipment and procedures used as well as the on-board diagnostic channels available.

Ambient air temperature during the testing is presented in Figure 76. As mentioned previously the ambient temperature measurements can be influenced by sunlight especially when stopped.

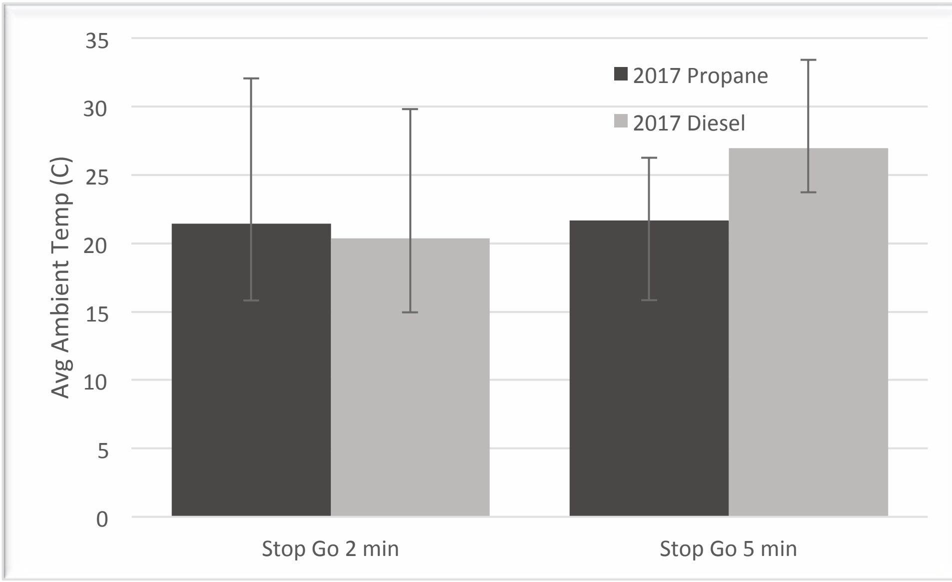


Figure 76: Average Ambient Air Temperature (°C) for 2017 Propane and 2017 Diesel School Bus

7.2.1 Oxides of Nitrogen Emissions

NO_X emissions for the diesel and propane school buses operated over the Stop and Go route are presented in Figure 77.

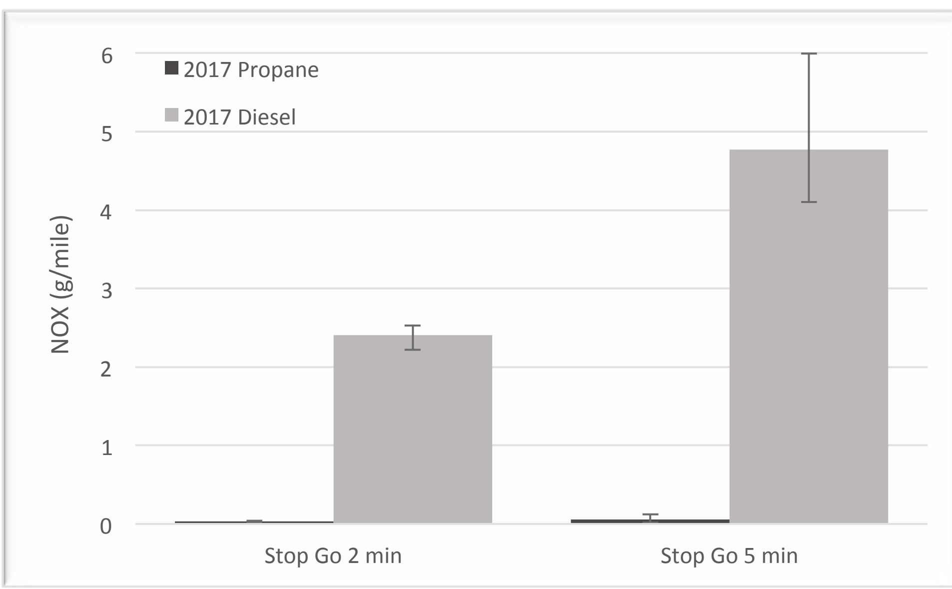


Figure 77: Average NO_X Emissions (g/mile) for 2017 Propane and 2017 Diesel School Bus

Similar to the previous school bus testing performed in January and February, NO_X emissions were substantially higher for the diesel school bus compared to the propane school bus over the Stop and Go route. As noted previously, thermal management of the aftertreatement system for the diesel school bus can be a challenge when presented with idling operation followed by short periods of accelerations.

The mass rate of NO_X emissions presented in Figure 78 through Figure 81 further demonstrates the disparity in measurements between the propane and diesel school buses. The propane school bus has minimal spikes of NO_X emissions corresponding to acceleration events, while the diesel school bus has significantly higher and longer duration spikes. OBD data collected for the diesel school bus included a channel, or per SAE J1939 terminology, a suspect parameter number (SPN) 5400 "SCR Thermal Management Active". This SPN is a boolean output (0 or 1) that indicates if the SCR thermal management strategy (first discussed in Section 6.1.1) is active (1) or inactive (0). The SCR thermal management is utilized to increase the amount of heat energy in the exhaust system. For the diesel school bus SPN 5400 "SCR Thermal Management Active" is also plotted in Figure 79 and Figure 81. The plots reveal that large NO_X emissions spikes occur when the thermal management strategy is not active, or was not previously active.

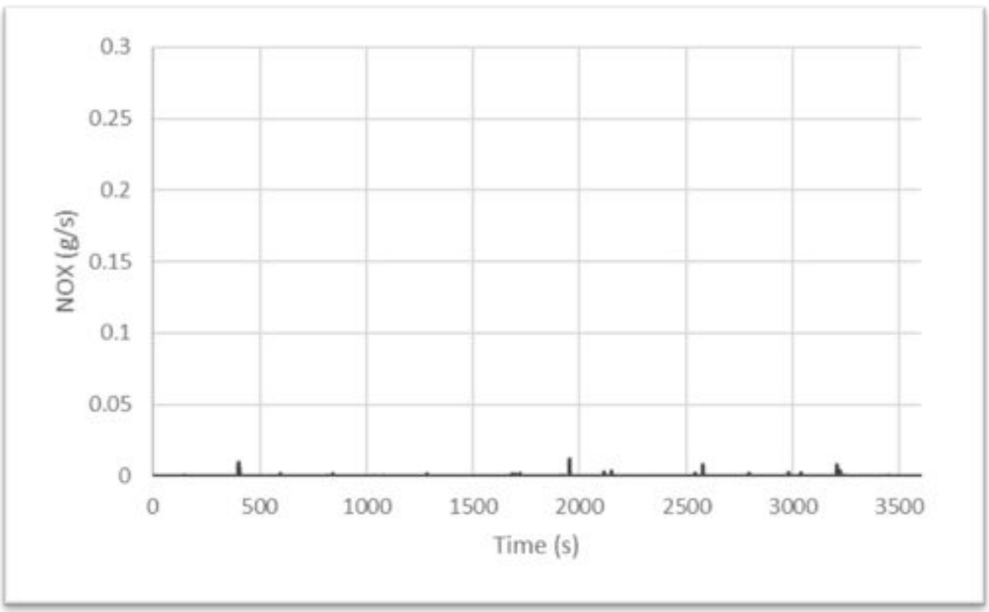


Figure 78: Mass Rate (g/s) of NO_X Emissions for 2017 Propane School Bus from 2 Minute Stop and Go Route

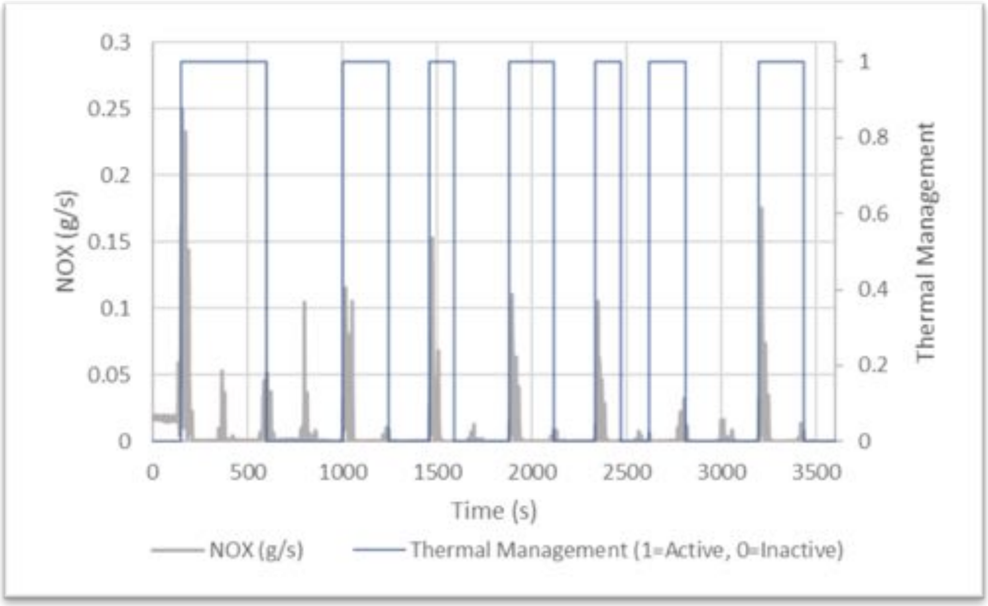


Figure 79: Mass Rate (g/s) of NO_X Emissions for 2017 Diesel School Bus from 2 Minute Stop and Go Route

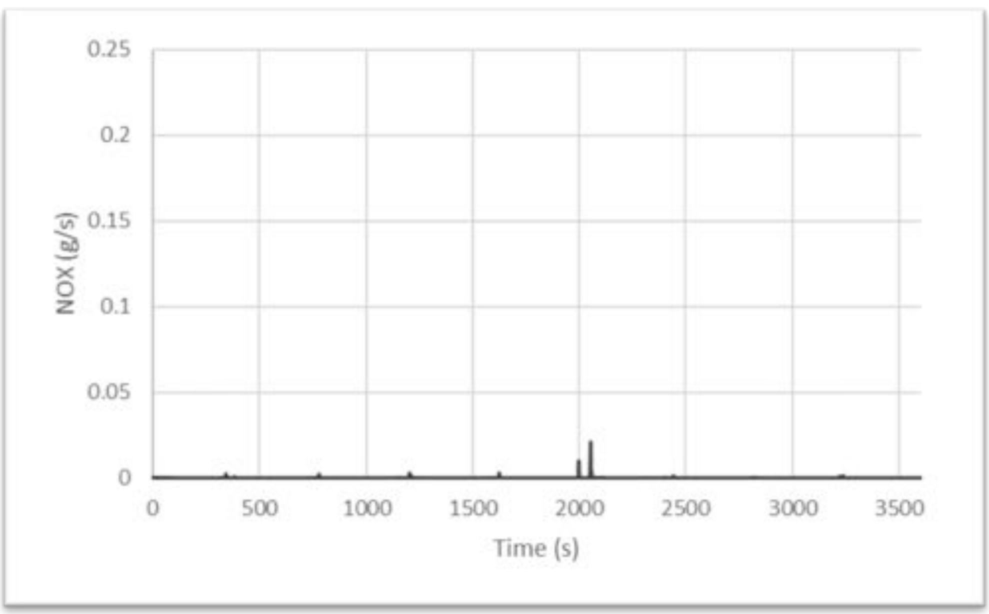


Figure 80: Mass Rate (g/s) of NOX Emissions for 2017 Propane School Bus from 5 Minute Stop and Go Route

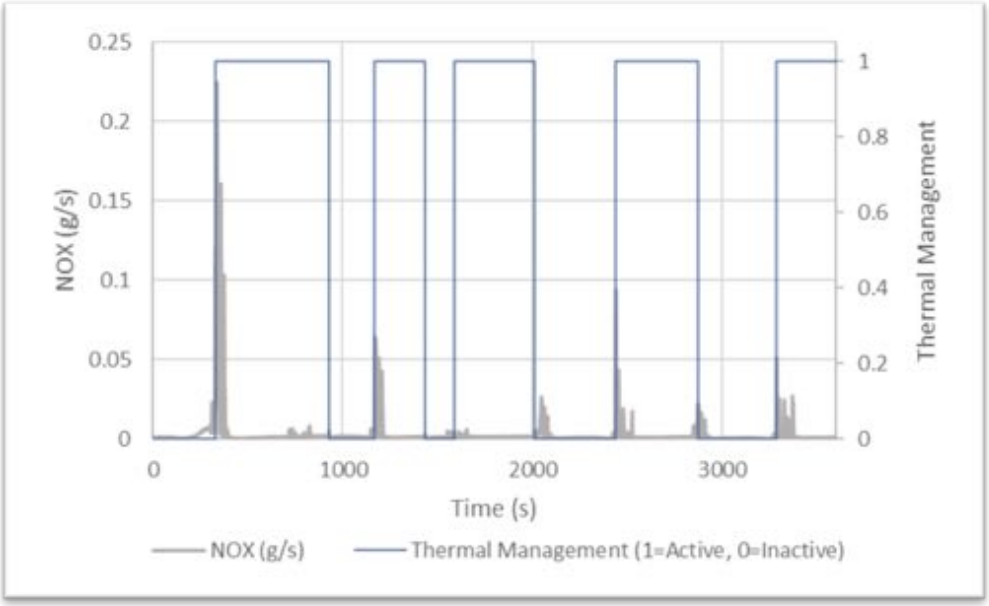


Figure 81: Mass Rate (g/s) of NOX Emissions for 2017 Diesel School Bus from 5 Minute Stop and Go Route

7.2.2 Carbon Monoxide Emissions

CO emissions for the diesel and propane school buses operated over the Stop and Go route are presented in Figure 82.

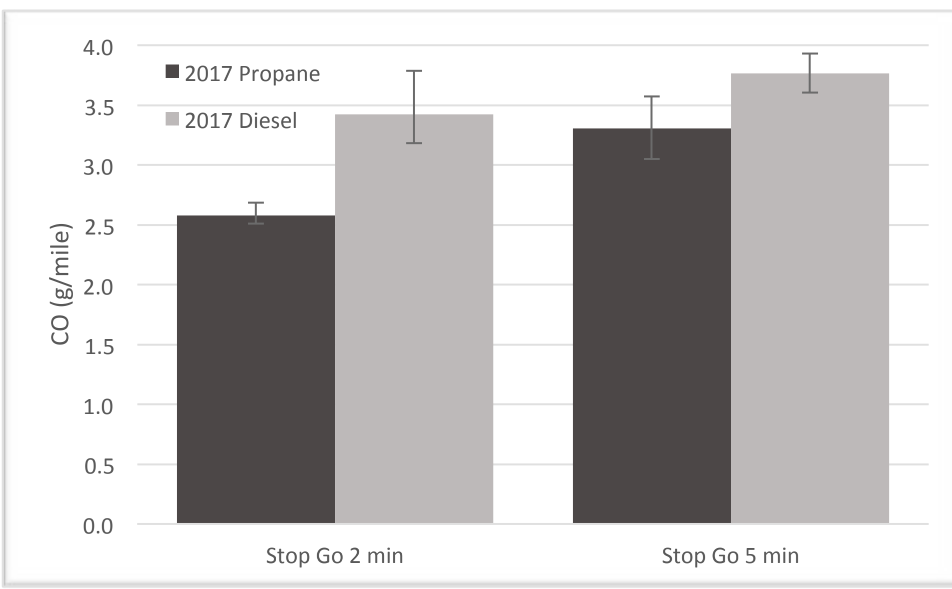


Figure 82: Average CO Emissions (g/mile) for 2017 Propane and 2017 Diesel School Bus

A trend of higher average distance specific CO emissions for the diesel school bus was observed over the Stop and Go routes. This is an opposing outcome compared to the previous school bus testing and the

Morgantown test routes for these vehicles. One hypothesis is it may be related to the higher exhaust flow rates from the diesel school bus during idling periods.

The mass rate of CO emissions presented in Figure 83 through Figure 86 demonstrates that both vehicles produced spikes of CO emissions corresponding to acceleration events. However, it is difficult to see, but during idle the diesel school bus exhibits a higher mass rate of CO emissions, which integrates into a greater overall mass of CO per distance traveled.

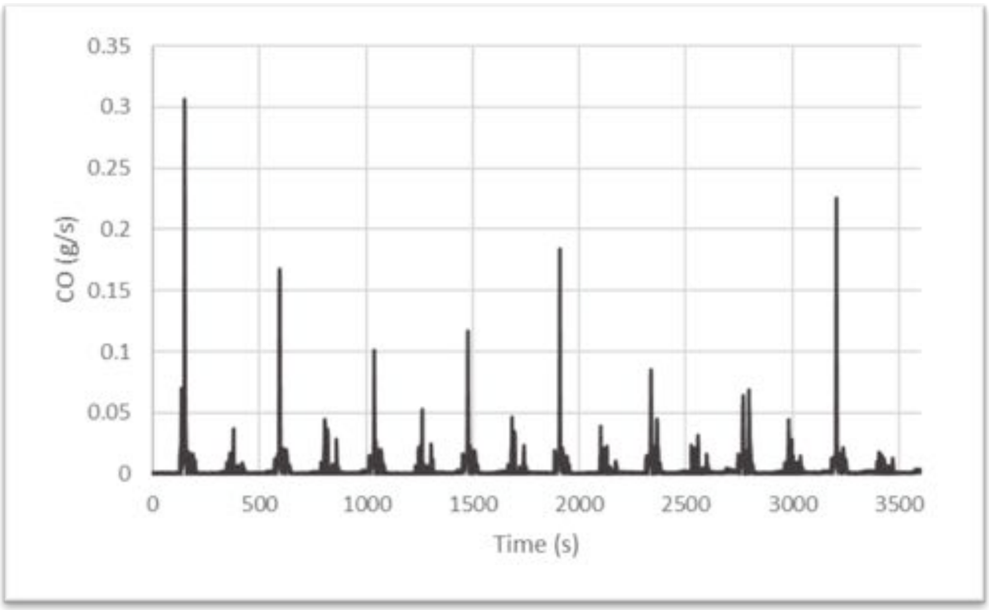


Figure 83: Mass Rate (g/s) of CO Emissions for 2017 Propane School Bus from 2 Minute Stop and Go Route

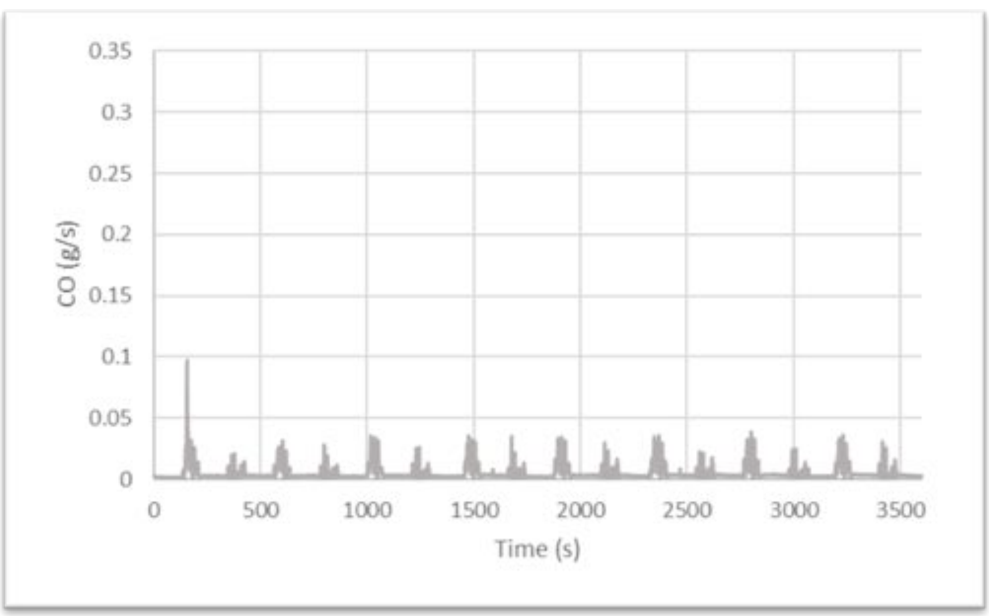


Figure 84: Mass Rate (g/s) of CO Emissions for 2017 Diesel School Bus from 2 Minute Stop and Go Route

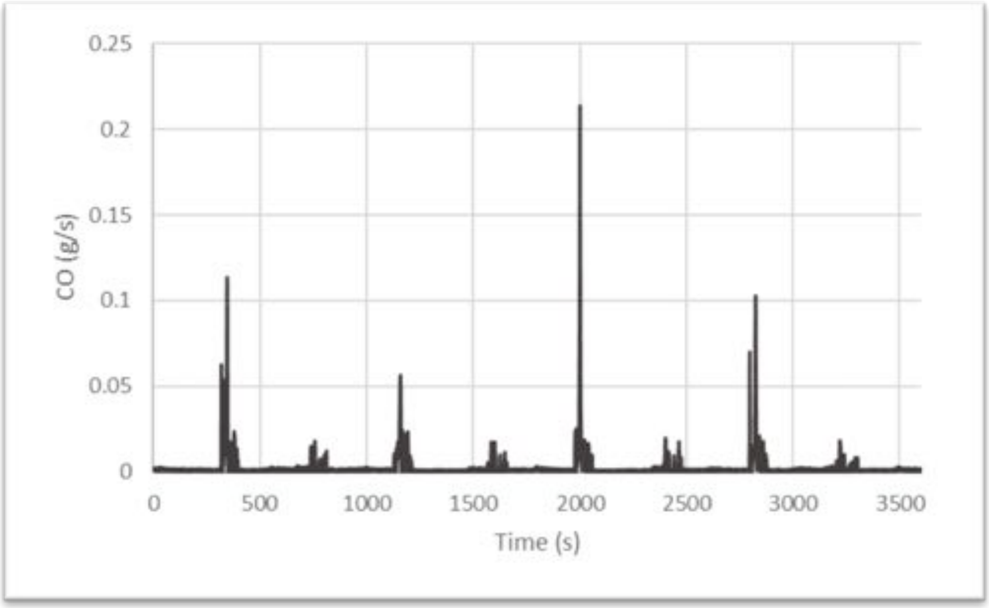


Figure 85: Mass Rate (g/s) of CO Emissions for 2017 Propane School Bus from 5 Minute Stop and Go Route

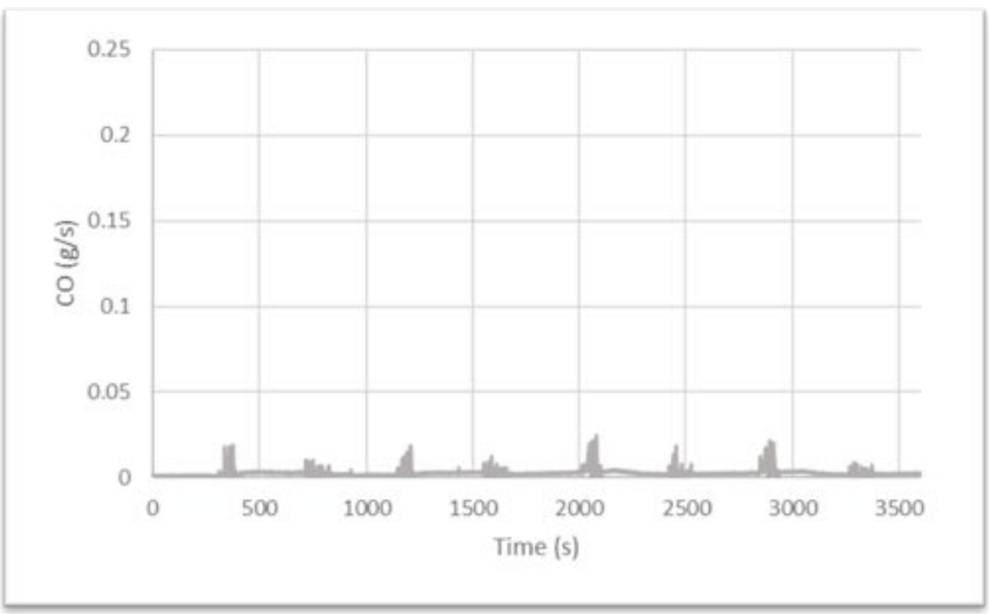


Figure 86: Mass Rate (g/s) of CO Emissions for 2017 Diesel School Bus from 5 Minute Stop and Go Route

7.2.3 Carbon Dioxide Emissions

CO_2 emissions for the diesel and propane school buses operated over the Stop and Go route are presented in Figure 87.

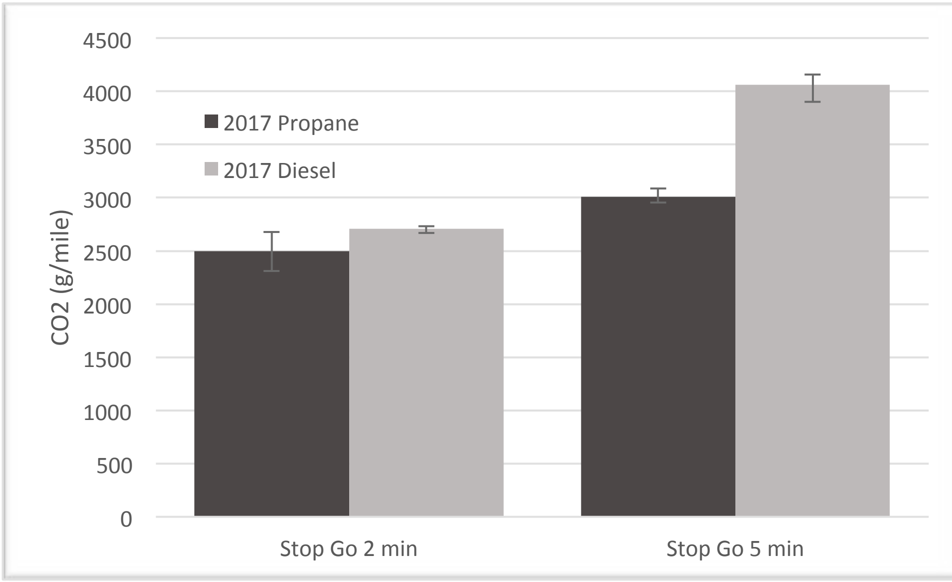


Figure 87: Average CO_2 Emissions (g/mile) for 2017 Propane and 2017 Diesel School Bus

The average CO_2 emissions produced by the diesel school bus exceeded that of the propane school bus. Similar to the previous school bus testing the higher distance specific CO_2 emissions from the diesel school bus may be explained by the use of thermal management strategies, especially at idle, to maintain exhaust and SCR temperatures, which also increase CO_2 emissions and fuel consumption. This is supported by the observation that during the 5-minute stop and go route with more idling time, the disparity in CO_2 emissions between diesel and propane school buses is larger.

Figure 88 through Figure 91 present mass rate of CO_2 emissions for both school buses during both stop and go routes. For the diesel school bus, the SCR thermal management (SPN 5400) flag is also plotted in Figure 89 and Figure 91. As previously mentioned the thermal management strategy results in a higher exhaust flow and more fuel consumption, as demonstrated by the higher mass rate of CO_2 at idle conditions when the strategy is active for the diesel school bus.

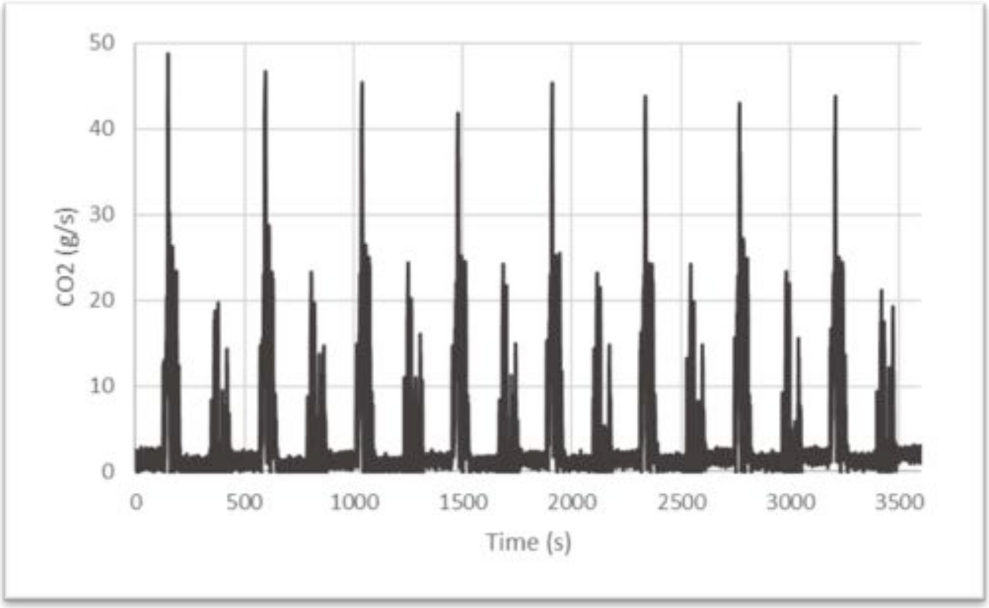


Figure 88: Mass Rate (g/s) of CO_2 Emissions for 2017 Propane School Bus from 2 Minute Stop and Go Route

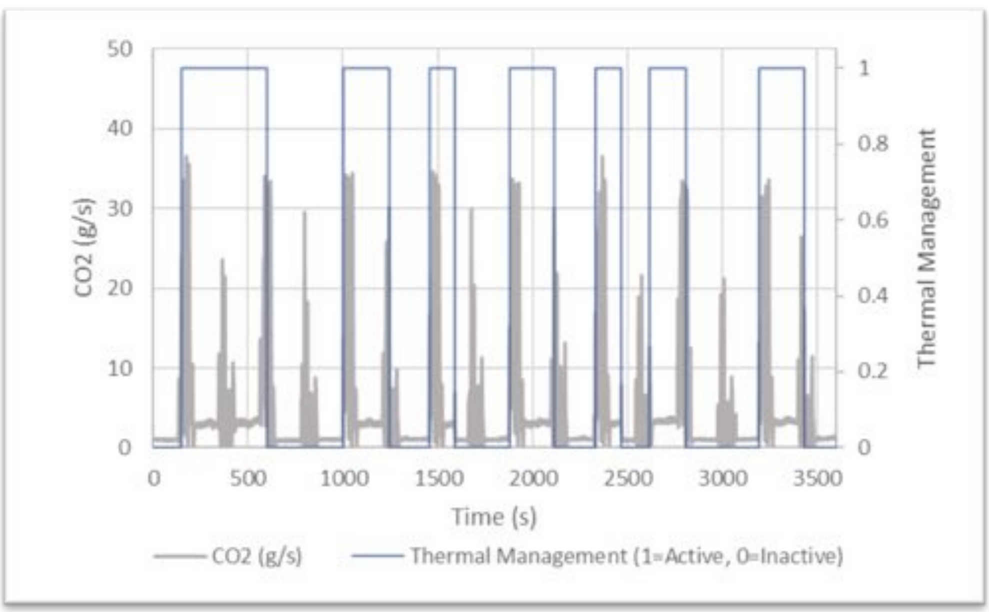


Figure 89: Mass Rate (g/s) of CO_2 Emissions for 2017 Diesel School Bus from 2 Minute Stop and Go Route

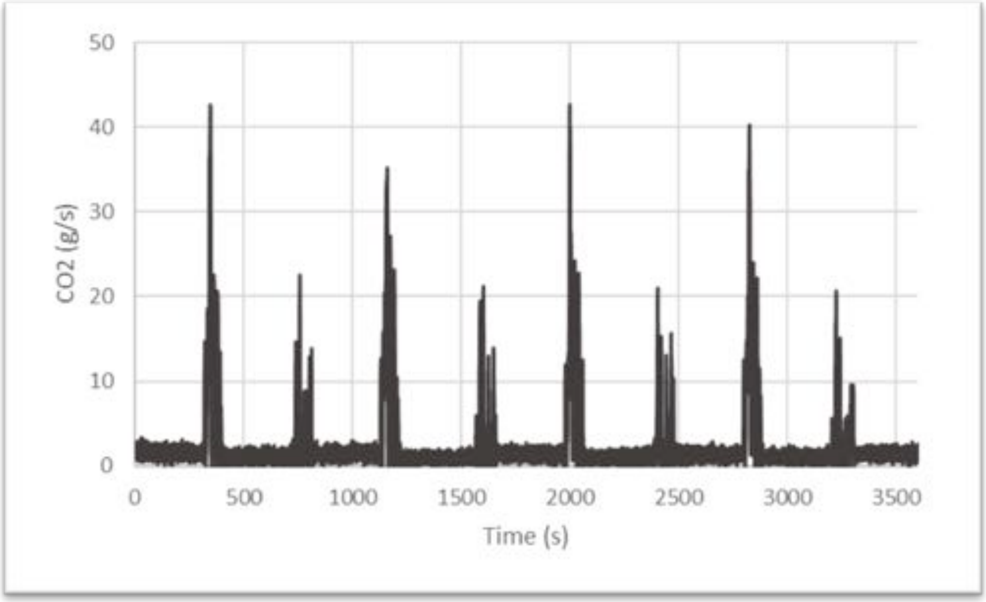


Figure 90: Mass Rate (g/s) of CO2 Emissions for 2017 Propane School Bus from 5 Minute Stop and Go Route

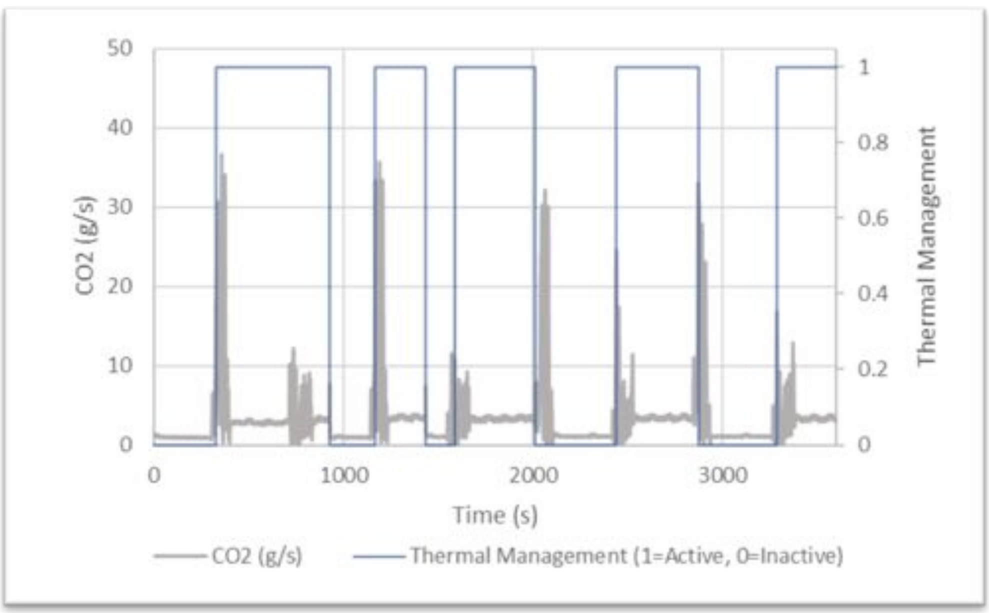


Figure 91: Mass Rate (g/s) of CO2 Emissions for 2017 Diesel School Bus from 5 Minute Stop and Go Route

7.2.4 Total Hydrocarbon Emissions

THC emissions for the diesel and propane school buses operated over the Stop and Go route are presented in Figure 92.

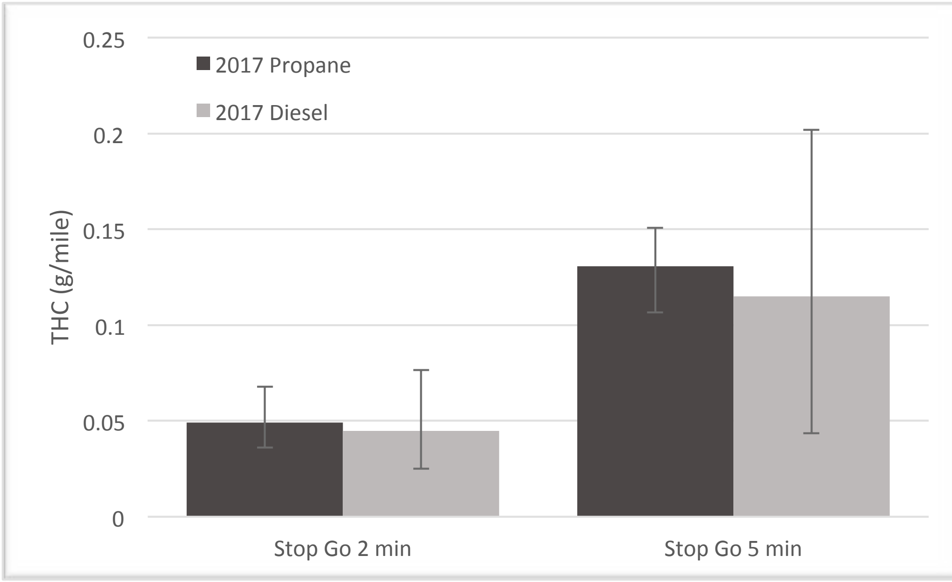


Figure 92: Average THC Emissions (g/mile) for 2017 Propane and 2017 Diesel School Bus

The distance specific THC emissions from the propane and diesel school buses were similar. The mass rate of THC emissions presented in Figure 93 through Figure 96 show that the propane school bus produced spikes of THC emissions throughout the route, while the majority of the THC emissions produced from the diesel school bus were located at the beginning of the route. While the vehicles were warmed up and allowed to idle before the test, the DOC on the diesel bus may have cooled down enough to limit its performance, but quickly warmed up once the vehicle started moving. Regardless, the magnitude of THC emissions for both school buses were very low.

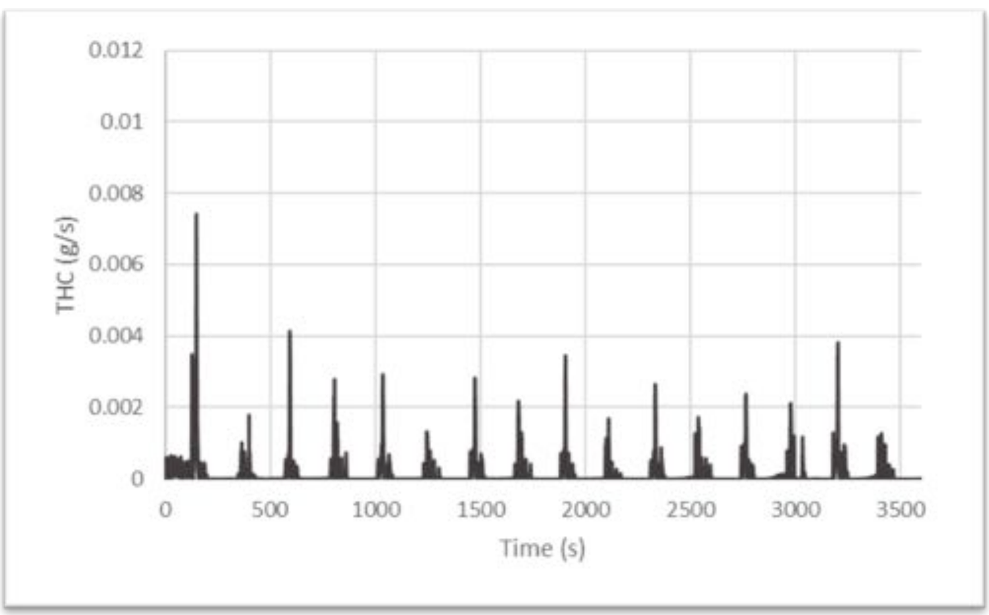


Figure 93: Mass Rate (g/s) of THC Emissions for 2017 Propane School Bus from 2 Minute Stop and Go Route

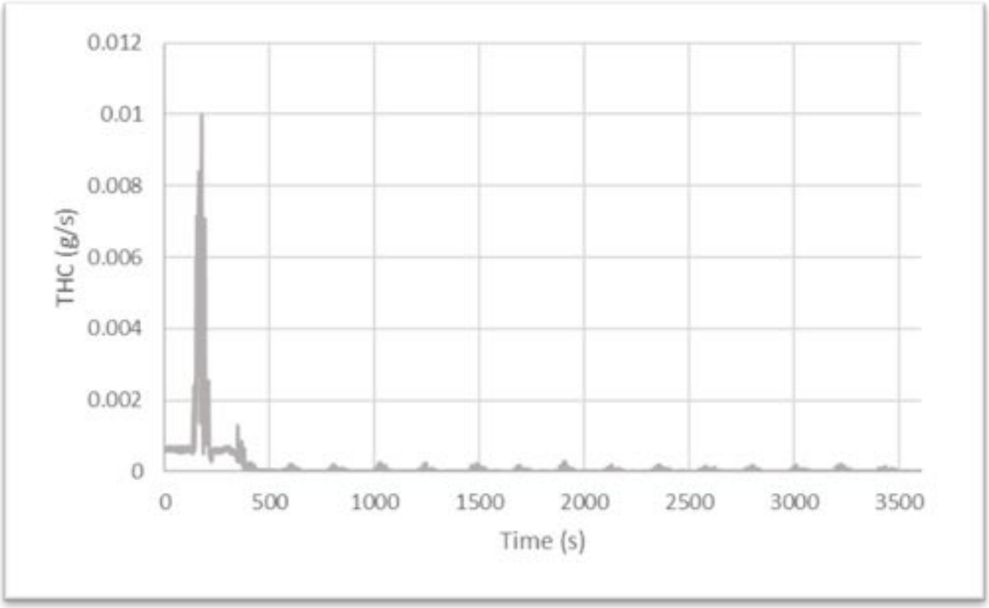


Figure 94: Mass Rate (g/s) of THC Emissions for 2017 Diesel School Bus from 2 Minute Stop and Go Route

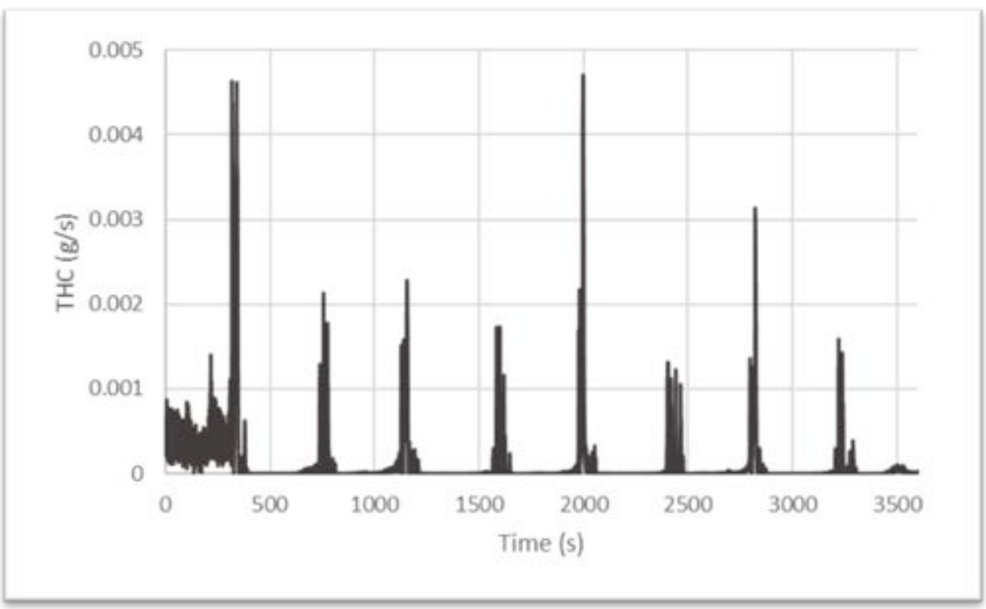


Figure 95: Mass Rate (g/s) of THC Emissions for 2017 Propane School Bus from 5 Minute Stop and Go Route

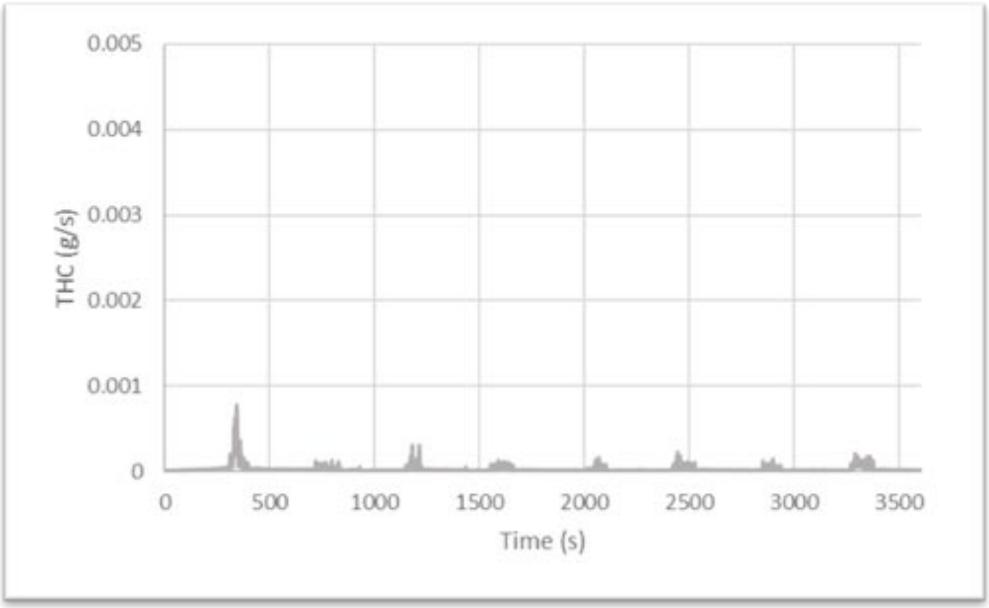


Figure 96: Mass Rate (g/s) of THC Emissions for 2017 Diesel School Bus from 5 Minute Stop and Go Route

8 Conclusions

In-use emissions measurements were performed on four Blue Bird school buses. A model year 2015 propane school bus and a model year 2014 diesel school bus were tested in January and February of 2018 over two pre-defined test routes. Three cold and three hot start Morgantown routes were performed for both vehicles in addition to three Stop and Go routes. Subsequently, a model year 2017 propane school bus and a model year 2017 diesel school bus were tested in July and August of 2018. Three cold and three hot start Morgantown routes were performed for both vehicles in addition to six Stop and Go routes; three Stop and Go routes with two-minute stops and three Stop and Go routes with five minute stops. The Morgantown route included operation on public roads and thus it should be noted that traffic, the number of acceleration events, and the amount of time spent idling can introduce variability in to the results, hence the reason for 2 repeats of each test cycle. The Stop and Go route was performed on private property eliminating the variation caused by traffic. It should also be noted that environmental factors such as ambient temperature, pressure, and humidity can affect the operation of the vehicle as well as the PEMS instrument and introduce variability into the results. Despite these inherent sources of variation PEMS offer the most robust and accurate method to capture real-world emissions measurements from vehicles. Furthermore, large differences between certain emissions constituents for each vehicle and repeated tests provide confidence in the results.

The primary conclusions during the first round of testing in January and February of 2018 were:

- Distance specific NO_X emissions measured from the diesel bus were significantly higher than those measured from the propane bus for both the Morgantown (180 to 175 percent difference) and Stop and Go (189 percent difference) routes.
- Low ambient temperatures may have exacerbated the NO_X emissions from the diesel school bus in addition to the low speed, low load operation contained in these routes and the inherent difficulties to maintain adequate temperatures in the SCR system.
- Distance specific CO emissions measured from the propane bus were greater than those measured from the diesel bus for all routes with a percent difference ranging from 68 percent (Stop and Go) to 128 percent (Cold Morgantown). However, it is important to note that since 2010 there are no longer any non-attainment areas for CO in the United States.
- THC emissions followed a similar pattern, however the magnitude of THC emissions was lower than the CO emissions, particularly for the Morgantown routes.
- Average distance specific CO_2 emissions were similar yet slightly higher for the propane school bus operated over the Morgantown route (Cold – 21 percent difference, Hot – 4 percent difference) however lower on average for the propane bus over the Stop and Go route versus the diesel school bus (15 percent difference).

Subsequent testing performed in July and August with newer model year and lower mileage propane and diesel school buses provided further confidence in many of the conclusions from the previous testing. The primary conclusions were:

- NO_X emissions were an order of magnitude greater for the diesel school bus compared to the propane school bus during the Cold Morgantown and Stop and Go routes.

- Higher variation in the NO_X emissions was observed during the Hot Morgantown route from the propane school bus due to a large NO_X emissions spike during one of the tests with the propane powered school bus, that did not occur in the other tests. This resulted in an average of the three Hot Morgantown tests that was only 40 percent lower than the diesel-powered school bus.
- During the Stop and Go routes, OBD data revealed that the largest NO_X production from the diesel school bus resulted during periods when the SCR thermal management strategy was not active or was not recently active.
- CO and THC distance specific emissions from the propane school bus were on average approximately double in magnitude compared to the diesel school bus over the Morgantown Route.
- Over the Stop and Go routes the trend reversed for CO emissions with the diesel school bus producing 20 percent more distance specific CO emissions (on a percent difference basis) over the Stop and Go routes. THC emissions were very similar and minimal for both vehicles.
- CO_2 emissions shared a similar trend with the initial round of testing; the propane school bus exhibited higher distance specific CO_2 emissions during the Morgantown routes (13 percent difference greater), yet lower CO_2 emissions over the Stop and Go routes compared to the diesel school bus (21 percent difference lower).
- OBD data from the diesel school bus revealed higher CO_2 emissions mass rates at idle when the SCR thermal management strategy is active, which led to a larger disparity in CO_2 emissions during the 5-Minute Stop and Go test versus the 2-Minute Stop and Go test.

In summary, the diesel school busses emitted less CO emissions, although there were exceptions during the Stop and Go route. However, as previously mentioned, since 2010 there are no longer any non-attainment areas for CO in the United States. THC emissions from both propane and diesel school buses were relatively minimal, but measurements from propane school buses exceeded those of the diesel school buses. CO_2 emissions were lower for the diesel school busses during city and interstate driving, however, they were lower for the propane busses during the simulated stop and go testing. In general, NO_X emissions were an order of magnitude lower from the propane school busses compared to the diesel school busses. This is significant due to the fact that NO_X and Ozone is a predominant non-attainment concern for many areas in the United States.

9 Appendix

The following sub sections provide distance specific emissions results for each in-use test of each school bus.

9.1 2014/2015 School Buses

Fuel	Test	CO (g/mile)	CO_2 (g/mile)	THC (g/mile)	NO_X (g/mile)
Propane	1	3.589	1760	0.0790	0.0779
	2	1.599	1233	0.0540	0.0573
	3	2.448	1336	0.0808	0.0420
Diesel	1	0.866	1050	0.0301	1.0036
	2	0.684	1301	0.0441	1.3345
	3	0.130	1152	0.0256	1.0400

Table 5: Cold Morgantown Route Distance Specific Emissions for 2014/2015 School Buses

Fuel	Test	CO (g/mile)	CO_2 (g/mile)	THC (g/mile)	NO_X (g/mile)
Propane	1	1.836	1402	0.0407	0.0518
	2	2.877	1359	0.0773	0.0520
	3	3.930	1302	0.0559	0.0563
Diesel	1	1.796	1370	0.0215	1.0159
	2	0.668	1367	0.0219	0.5445
	3	0.486	1182	0.0193	0.8133

Table 6: Hot Morgantown Route Distance Specific Emissions for 2014/2015 School Buses

Fuel	Test	CO (g/mile)	CO_2 (g/mile)	THC (g/mile)	NO_X (g/mile)
Propane	1	0.885	3258	0.352	0.175
	2	1.381	2788	0.498	0.134
	3	2.890	2570	0.794	0.150
Diesel	1	0.790	3299	0.141	5.207
	2	1.058	3368	0.130	5.324
	3	0.685	3332	0.161	5.196

Table 7: Stop and Go Route Distance Specific Emissions for 2014/2015 School Buses

9.2 2017 School Buses

Fuel	Test	CO (g/mile)	CO_2 (g/mile)	THC (g/mile)	NO_X (g/mile)
Propane	1	3.09	1435	0.0851	0.0759
	2	2.19	1402	0.0343	0.0588
	3	2.29	1411	0.0320	0.0734
Diesel	1	1.15	1304	0.0185	0.6566
	2	1.38	1315	0.0333	0.4927
	3	0.87	1258	0.0151	0.7178

Table 8: Cold Morgantown Route Distance Specific Emissions for 2017 School Buses

Fuel	Test	CO (g/mile)	CO_2 (g/mile)	THC (g/mile)	NO_X (g/mile)
Propane	1	3.25	1620	0.0505	0.1707
	2	2.21	1499	0.0223	0.5400
	3	1.92	1338	0.0159	0.2171
	4	2.34	1429	0.0222	0.0406
Diesel	1	0.98	1238	0.0108	0.6179
	2	1.23	1209	0.0215	0.6230
	3	1.23	1253	0.0151	0.7118

Table 9: Hot Morgantown Route Distance Specific Emissions for 2017 School Buses

Fuel	Test	CO (g/mile)	CO_2 (g/mile)	THC (g/mile)	NO_X (g/mile)
Propane	1	2.53	2311	0.0361	0.0215
	2	2.51	2677	0.0431	0.0450
	3	2.69	2498	0.0680	0.0260
Diesel	1	3.30	2669	0.0331	2.5327
	2	3.18	2718	0.0249	2.4725
	3	3.79	2734	0.0765	2.2201

Table 10: 2 Minute Stop and Go Route Distance Specific Emissions for 2017 School Buses

Fuel	Test	CO (g/mile)	CO_2 (g/mile)	THC (g/mile)	NO_X (g/mile)
Propane	1	3.57	2991	0.151	0.1240
	2	3.29	3085	0.107	0.0354
	3	3.05	2953	0.135	0.0161
Diesel	1	3.76	3902	0.100	5.9940
	2	3.93	4126	0.202	4.2174
	3	3.60	4157	0.044	4.0991

Table 11: 5 Minute Stop and Go Route Distance Specific Emissions for 2017 School Buses