2024-01-5011 Published 01 Feb 2024

Diesel Fuel-Fired Heater Emissions from a Battery Electric Transit Bus in Real-World Conditions

Kieran Humphries, Hussein Rashid, and Fadi Araji Environment and Climate Change Canada

Citation: Humphries, K., Rashid, H., and Araji, F., "Diesel Fuel-Fired Heater Emissions from a Battery Electric Transit Bus in Real-World Conditions," SAE Technical Paper 2024-01-5011, 2024, doi:10.4271/2024-01-5011.

Received: 07 Jul 2023 Revised: 18 Aug 2023 Accepted: 28 Dec 2023

Abstract

Battery electric transit buses sold in Canada generally include a fuel-fired diesel auxiliary heater for cabin heating in cold weather. This report details a test project, performed in collaboration with OC Transpo, to capture and quantify the emissions from such a fuel-fired heater (FFH) installed on a New Flyer XE40 battery electric transit bus from OC Transpo's fleet in Ottawa, Canada. The FFH was tested while the bus was both stationary and being driven on-road in cold conditions. The results include the emissions rates of carbon dioxide, carbon monoxide, nitrogen oxides, hydrocarbons and methane, and soot. Additionally, total particulate matter results were obtained during stationary testing. The results of stationary testing were compared to the California Air Resources Board and European Union standards for FFH emissions, even though these standards do not apply directly to buses operated outside of these jurisdictions. During stationary testing, average emissions of carbon monoxide and non-methane organic gases (hydrocarbons) were 0.069 g/mi and 0.035 g/mi, respectively, which are both within their respective regulated limits for FFH emissions in California. However, the California nitrogen oxide limit was exceeded during stationary testing with an average value of 0.337 g/mi. In addition, momentary exceedances of the concentration limits for carbon monoxide and hydrocarbons set in European Union Regulation 122 were detected during stationary testing, but these were very short-lived.

Keywords

Battery, Electric, Bus, Transit, Heater, Fuel-fired, Diesel, Emissions

Introduction

Transit buses in OC Transpo's Ottawa fleet regularly operate in sub-freezing temperatures during the winter months, and a significant amount of heat energy is required to maintain a comfortable cabin temperature for both the vehicle operator and passengers. Diesel fuel-fired heater (FFH) units are equipped on the majority of the transit buses in the OC Transpo fleet, irrespective of drivetrain type (both internal combustion and battery electric), to provide cabin heat during the winter season. This report focuses on the emissions from a diesel FFH equipped on a battery electric transit bus, specifically a 40-foot New Flyer XE40. This bus is one of four battery electric buses of the same type, which OC Transpo has been testing on various transit routes across the city in preparation for the upcoming purchase of up to 350 battery electric city buses, which are intended to begin transitioning the City of Ottawa's bus fleet to primarily "zero-emission" vehicles (ZEVs) in order to reduce greenhouse gas (GHG) emissions from city operations.

Background Information

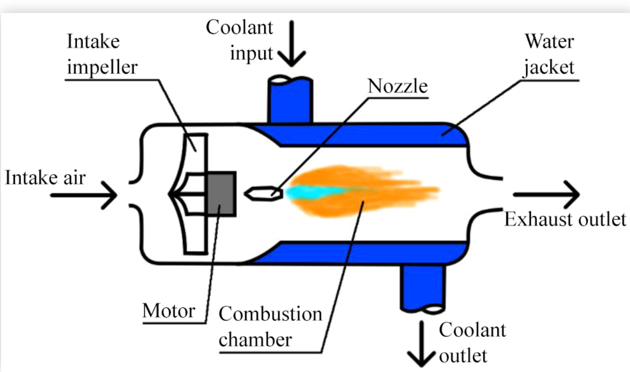
FFHs have been used in vehicles for decades, both for cabin heating and/or engine pre-heating. The basic operation of the FFH is that fuel is burned in a combustion chamber and the resulting heat is either transferred to a circulating coolant (which can preheat the engine or be used in fan-coil systems to heat the cabin) or to the cabin air directly. The type of FFH used on this bus is a "hydronic" heater, meaning that an intermediate coolant fluid is heated rather than the cabin air being heated directly. The circulating coolant in such systems is generally a mixture of water and anti-freeze such as glycol (to avoid freezing during cold temperature).

A simplified schematic of a FFH, which heats a circulating coolant is shown in Figure 1. On startup, the intake impeller (powered by a small electric motor) begins drawing intake air through the combustion chamber and pushes it out the exhaust pipe. When a sufficient air flow rate has been reached, the system begins to inject diesel fuel into the combustion chamber using the nozzle and the air/fuel mixture is ignited by an ignition electrode (located in the combustion chamber, not shown in Figure 1). While the fuel is burning in the combustion chamber, the intake impeller continues to provide intake air and more fuel is pumped through the nozzle, sustaining the flame. Coolant is pumped through the water jacket surrounding the combustion chamber and is heated by the time it exits the coolant outlet. This coolant circulates through the engine (for ICE vehicle preheat) and/or to the heating system for cabin heating. In this case, since the vehicle uses electrical propulsion, the hot coolant is only used to heat the cabin.

Alternative approaches to diesel FFH cabin heating for electric transit buses include fuel-fired heaters using alternative fuels (such as natural gas or hydrogen), heat pumps (which use electricity but consume less energy than typical electric heaters because they can capture heat energy from the ambient air), and even fuel cell heating [1]. Additional design improvements such as increased insulation, driver-specific climate zones, and heated seats could also further reduce the heating demand for electric buses [1]. None of these solutions are utilized on the test vehicle.

The test bus is factory-equipped with a high-voltage DC electric heater and a diesel fuel-fired heater, both of which are capable of heating the coolant that circulates to heat the cabin of the bus. The FFH is limited via software to operate only when the outdoor temperature is below 5°C, and solely the electric heater is used when temperatures are milder than this limit. In Canada, it is common to equip battery electric buses (both transit buses and school buses) with diesel FFHs to avoid the significant driving range loss in cold temperatures associated with electric heater usage.

FIGURE 1 Schematic of a basic fuel-fired heater.



The FFH on this bus is a Valeo/Spheros Thermo 230, which is the latest iteration of a long line of popular FFHs sold worldwide. The Thermo 230 heater has a peak output of 23.0 kW (about 80,000 BTU/h) and uses up to 2.5 kg of fuel per hour according to the heater's specifications. Most of OC Transpo's buses with FFHs use a variation of this heater type, with diesel buses generally using the slightly larger, 30 kW, version. The heater manufacturer claims to have sold over 450,000 FFHs over four decades in business [1].

In North America, FFHs do not need to conform to any current emissions standards, except in the State of California where rules are set by the California Air Resources Board (CARB) [1]. Since Canada's regulations are mainly harmonized with those of the United States Environmental Protection Agency (US EPA), there is no current Canadian standard for FFH emissions. Therefore, emissions from FFHs are essentially unregulated for transit use in Canada. In addition to CARB standards, there are European Union standards for FFHs [2]. However, the limits in the EU regulations use different measurements, and so are not directly comparable to CARB's regulations.

Previous studies have been conducted on FFH systems, mostly in Europe. A study from Finland found that auxiliary FFHs installed on recent light-duty vehicles (LDVs) had particle number (PN) emissions that were up to three orders of magnitude higher than the corresponding vehicle's engine tailpipe emissions during idling, raising questions about the suitability of FFHs for the intended purpose of reducing overall emissions and for their use on BEVs [3]. The Euro 5- and Euro 6-compliant diesel vehicles in this study were each equipped with a diesel particulate filter (DPF), which significantly reduces the particulate emissions from the engine tailpipe, but not from the auxiliary FFH (as the FFH tailpipe was separate and did not include any aftertreatment systems). A more recent report about this research by some of the same authors reached a similar conclusion in that FFH particle number emissions could be much higher than engine emissions for these LDVs [4].

A study investigating the effect of using different fuel blends and alternative fuels was conducted by FORCE Technology for Movia Public Transport in Denmark [5]. This study compared the emissions of two heaters using B7 diesel fuel (diesel with 7% biodiesel by volume), hydrogenated vegetable oil (HVO), and biodiesel made from fatty acid methyl esters (FAME). The study showed minor differences in NO_x, CO, and CO_2 emissions when running on the different fuels, and large differences in particle number and particle mass between fuels and between the two different types of heaters. On B7 diesel, the Spheros Thermo 300 heater emitted 1.2 mg/h PM (which is equivalent to

0.06 mg/mi PM using the CARB FFH test calculations) whereas the Stroco 3500 emitted 40 mg/h PM (2.0 mg/mi as per CARB calculations). Also using B7, the Spheros heater emitted 8.0 g/h NO_x (0.40 g/mi NO_x as per CARB) and 6.0 g/h CO (0.30 g/mi CO as per CARB).

Motivation and Contribution

Since the aforementioned studies of LDVs with FFHs in Europe showed high levels of particle number emissions from diesel FFHs [3, 4], it was deemed important to investigate the emissions of the larger type of FFHs in use on electric buses in North America. This larger type of heater is commonly used on electric buses intended to transition fleets to low GHG operation. In addition, the FORCE Technologies study showed a large variation in exhaust emissions (specifically PM) between different makes of FFH [5] and this was also deemed worthy of further investigation. This report therefore attempts to quantify the emissions from a typical FFH used on electric transit buses while in-use in ambient, real-world conditions in Canada (rather than in a lab setting) to inform regulators of the levels of pollutants that these systems can emit, including their greenhouse gas (GHG) emissions. Aside from the GHG considerations when burning diesel fuel for heating, various pollutants that are harmful to human health can be present in diesel exhaust. Such components include carbon monoxide (CO), nitrogen oxides (NO_x, which is made up of NO and NO_2), hydrocarbons (HC) including methane (CH_4), and particulate matter (PM, which includes soot emissions). Therefore, the effectiveness of electric buses to reduce GHG emissions and provide cleaner air for cities depends significantly on the emissions performance of the FFH.

Test personnel used portable emissions measurement systems (PEMS) to measure the concentrations and mass emission rates of each of the previously mentioned pollutants while the FFH was in operation. Testing was split into stationary "idle" tests and "on-road" tests while the bus was driven along a set route (specifically on the OC Transpo Transitway, which is a bus-only rapid transit corridor in the City of Ottawa). Further testing details are introduced in the Methods section.

Methods

Vehicle Specifications

Selected specifications for the test vehicle are listed in Table 1. The New Flyer XE40 is currently the only BEV bus in use by OC Transpo, but other makes of battery electric bus are expected to be included in the OC Transpo fleet in the future (Figure 2). BEV buses are intended to reduce GHG emissions from transit operation by removing the typical tailpipe emissions from a diesel-powered bus. However, like its diesel counterparts in the OC Transpo fleet, the BEV bus in this study uses a diesel FFH for cabin heating. A large 525 kWh battery pack is used on this version of the XE40 to give it sufficient range for all-season operation in Ottawa. The battery pack was made using cells with a lithium nickel manganese cobalt oxide (NMC) cathode chemistry.

TABLE 1 Vehicle specifications.

Parameter	Value
Vehicle ID number	2104
Vehicle mileage (km) (approx.)	60,675
Make	New Flyer
Model	XE40
Curb weight (kg)	15,227
GVWR (kg)	19,960
Drivetrain	Rear wheel drive
Cabin heating type	Separate electric and diesel-fired auxiliary heaters
Battery description	Li-ion, NMC chemistry
Battery energy, rated gross (kWh)	525
Vehicle length (m)	12.48
Vehicle height (m)	3.37
Vehicle width, no mirrors (m)	2.58

FIGURE 2 Test vehicle, the New Flyer XE40 electric bus in OC Transpo livery.

FFH Emissions Regulations Overview

CARB Regulations The CARB specifies that FFHs used for heating vehicle cabins must conform to the emissions limits in Table 2 when tested in an applicable manner [1]. These limits are based on the CARB LEV II ULEV Standards for LDVs [6]. The compounds that are regulated include carbon monoxide (CO), nitrogen oxides (NO_x), non-methane organic gases (NMOG), and formaldehyde (HCHO).

TABLE 2 CARB FFH regulated emissions limits.

Species	CO [g/mi]	NO_x [g/mi]	NMOG [g/mi]	HCHO [g/mi]
Limit	1.7	0.05	0.040	0.008

The CARB test procedure specifies a full-power, 20-minute bench test of the heater unit, with a cold-start ambient temperature of between 20°C and 30°C [7]. The emissions from such tests are generally captured using a constant volume sampling (CVS) system in a lab setting. The resulting emissions from this 20-minute procedure are collected in mass units (grams). CARB uses the rule of thumb that a vocational vehicle of the type to use such a FFH will travel 1 mile every 3 minutes (which equates to an average speed of 20 mph). Therefore, the collected mass of each regulated chemical species is divided by 20 (to obtain a mass emissions per minute value in g/min) and then multiplied by 3.0 (to obtain the emissions on a mass per distance basis in g/mi) [7]. The results are then compared to the regulated limits in Table 2 to determine whether the FFH conforms to the regulation.

European Regulations The European R122 regulations for FFHs are different than those created by CARB and are not directly comparable. The European test procedure is similar to CARB's but includes a one-hour test duration rather than 20 minutes [2]. In addition, instead of regulating the emissions on a mass per distance basis, the European regulations limit the instantaneous tailpipe concentration of CO, NO_x, and hydrocarbons (HC) (all values are "dry" concentrations); and a smoke opacity number on the Bacharach scale is used for PM [2]. The R122 regulated limits are shown in Table 3 [1, 2].

United States EPA and Canadian Regulations There are currently no applicable FFH criteria emissions regulations from either the United States Environmental Protection Agency (US EPA) or from any Canadian regulator (federal or provincial). This means that FFH criteria emissions are essentially unregulated in Canada and most of the United States. Heaters that are sold in these locations may meet the CARB or EU regulations discussed in the previous sections, but this is up to the discretion of the manufacturer.

Instrumentation

The primary instruments for this test program were a Sensors Inc. Semtech LDV PEMS with an exhaust flow meter (EFM) and an AVL PM-PEMS unit (Figure 3). The Semtech LDV PEMS recorded emissions of CO, CO_2, NO, NO_2, HC, and CH_4, and the exhaust flow rate in kg/h. The

TABLE 3 European R122 standard regulated emissions limits.

Species	CO [ppm]	NO_x [ppm]	HC [ppm]	PM [Bacharach]
Limit	1000	200	100	4

FIGURE 3 Rear of test vehicle, showing the exhaust flow meter attached to the tailpipe, along with heated sample lines for on-board instrumentation (Semtech LDV and AVL PM-PEMS).

TABLE 4 Semtech LDV and AVL PM-PEMS measurement specifications.

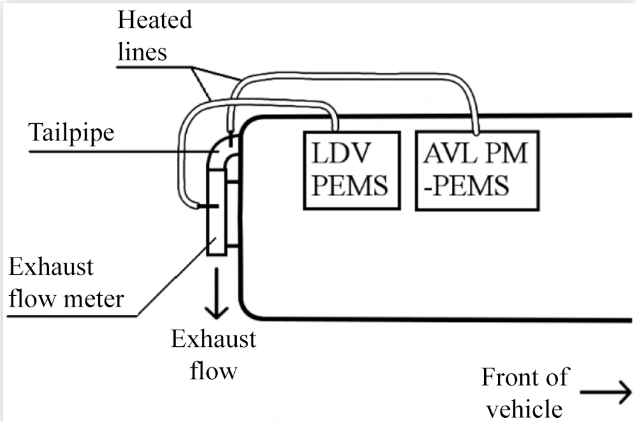
Species	Measurement ranges
CO	8% vol.
CO_2	18% vol.
NO	3000 ppm
NO_2	1000 ppm
HC	10,000 ppmC_1 (selected range)
CH_4	10,000 ppmC_1 (selected range)
Soot (AVL PM-PEMS)	0.001–50 mg/m³

AVL PM-PEMS instrument is focused on PM emissions and captured total particulate matter (TPM) emissions on Teflon filters during the stationary tests, and second-by-second soot emissions during both stationary and on-road tests (soot is one component of TPM). Both instruments used probes installed in the exhaust system to sample the exhaust and heated lines to deliver the small exhaust samples to the instruments. Details of the instrument capabilities are included in Table 4 and a schematic of the instrument installation is shown in Figure 4. All instrumentation was powered by portable lithium ion-based battery packs for the duration of testing.

Test Procedures

Stationary Idle Test The test procedures for this program can be grouped into stationary "idle" testing and on-road testing types. Stationary testing was modeled on the CARB procedures explained in previous sections. However, CARB test procedures specify a bench test with the FFH in a lab setting, whereas testing for this report was conducted while the FFH was installed on the test vehicle. This difference in testing procedure may have caused

FIGURE 4 Equipment setup for bus testing.



significant differences in test results, along with the fact that CARB testing is conducted between 20 and 30°C ambient temperatures while our testing was conducted at <5°C. The following paragraphs explain the test procedure used in this study in more detail.

Overnight, prior to a test, the vehicle was left indoors at the OC Transpo garage, hooked up to a DC fast charger or simply parked (if sufficient battery charge was available for the next day's test). The temperature set point inside the garage facility is 18°C and this is typically where BEV buses are stored overnight prior to operation. This means that the FFH was essentially soaked at 18°C overnight prior to testing.

In the morning, the bus was driven (without starting the FFH) from the indoor garage to the BEV maintenance bay and the bus was parked outdoors next to the maintenance bay doors. This meant that the bus was subjected to ambient conditions during testing. This was necessary since the vehicle's FFH will not operate unless the bus detects an ambient temperature of less than 5°C. Above this set point, the fully electric auxiliary heater is used instead of the FFH to provide cabin heating, meaning no tailpipe emissions would be produced.

Calibration was then performed on the PEMS instruments, which took between 20 minutes and an hour, while the bus was turned off and parked outdoors. Then the instruments were set to capture the emissions data throughout the test.

Finally, a test began when the bus was turned on and "heat" mode was selected on the operator's HVAC control dial to keep the FFH active for a total of 20 minutes ("auto" heat mode was not used for stationary testing in order to keep the heater on for the entire test). After the 20-minute test time was reached, both the heat mode and the vehicle itself were turned off.

On-Road Test The on-road test procedure began immediately after the conclusion of the stationary test procedure. The test instrumentation was the same between these tests (except no TPM filter collection was done on-road), and a new test file was started on each instrument prior to on-road testing. The PEMS units did not require recalibration prior to the on-road test because they had already been calibrated prior to the stationary test. The purpose of the on-road test was to monitor the FFH operation and emissions in real-world conditions encountered by the BEV bus when in use in the field. The cabin heating "auto" setting was used for the duration of the on-road test (instead of the "heat" setting). This setting controls the interior temperature of the bus to a set point of 21°C. This is the default set point of the XE40 bus control system.

The on-road route consisted of two "laps" of the Ottawa Transitway between Hurdman Station and the Hunt Club Loop roundabout (just after the South Keys Stop, at the southern end of the Transitway). Short portions of driving from the OC Transpo garage to Hurdman station at the start of the test, and back to the OC Transpo garage from Hurdman station at the end of the test, were also included in the results. The duration of an on-road test varied slightly but was generally about one hour in total.

Data Analysis

Stationary Test Mass Emissions Rate Calculations As mentioned in the Regulations Section, CARB uses the rule of thumb that a heavy vehicle travels approximately 1 mile every 3 minutes [7]. Therefore, the mass emissions rates for stationary tests in grams per mile were calculated using the total emissions (in grams) for each chemical species ($m_{species}$) and converting that via Equation 1, as defined by CARB [7].

$$\text{Mass emission rate}_{species} = \frac{m_{species}}{20} \cdot 3.0 \qquad \text{Eq. (1)}$$

Fuel Consumption Calculations

The amount of diesel fuel used by the FFH during testing was calculated based on the amounts of carbon-containing compounds in the exhaust emissions from the FFH. The three species involved in this calculation were CO, CO_2, and HC. The standard molar masses of carbon, M_C (12.011 g/mol), CO, M_{CO} (28.0101 g/mol), and CO_2, M_{CO_2} (44.0095 g/mol), were used in these calculations, along with the molar mass of hydrocarbons, M_{HC} (13.875389 g/mol), found in exhaust as specified in the United States Code of Federal Regulations, specifically 40 CFR §1065.1005(f)(2). In addition, a fuel fraction carbon (FFC) of 0.8641 and fuel density (ρ_{fuel}) of 827.6 kg/m³ were determined via laboratory analysis of test fuel samples taken during the test program. These fuel specifications and physical characteristics were used to calculate the mass of fuel consumed, m_{fuel}, by conducting a basic carbon-balance procedure using the mass of each measured carbon-containing exhaust compound (m_{CO}, m_{CO_2}, and m_{HC}), as shown in Equations 2, 3, and 4. These equations were derived from first principles, as documented in an archived EPA report [8], but were modified from the equations shown in the report to express fuel consumed on a mass basis rather than in miles per gallon. The summation of all the masses determined using Equations 2, 3, and 4 equals the final mass of fuel, as shown in Equation 5. Finally, the volume of fuel consumed, V_{fuel}, was determined via the total mass of fuel from Equation 5 and the density of fuel as shown in Equation 6, and then converted to liters. The fuel consumption was also determined by dividing the fuel volume by the GPS-captured distance driven.

$$m_{fuel\_CO} = m_{CO} \cdot \frac{M_C}{M_{CO}} \cdot \frac{1}{FFC} \quad \text{Eq. (2)}$$

$$m_{fuel\_CO2} = m_{CO2} \cdot \frac{M_C}{M_{CO2}} \cdot \frac{1}{FFC} \quad \text{Eq. (3)}$$

$$m_{fuel\_HC} = m_{HC} \cdot \frac{M_C}{M_{HC}} \cdot \frac{1}{FFC} \quad \text{Eq. (4)}$$

$$m_{fuel} = m_{fuel\_CO} + m_{fuel\_CO2} + m_{fuel\_HC} \quad \text{Eq. (5)}$$

$$V_{fuel} = \frac{m_{fuel}}{\rho_{fuel}} \quad \text{Eq. (6)}$$

TPM Calculations Unlike the other types of exhaust emissions data collected during this test program, which could be collected on a second-by-second basis, TPM emissions could only be collected as a single value per test. The gravimetric module of the AVL PM-PEMS system flows diluted exhaust through a Teflon filter at a specific rate during the entire test segment, and the resulting mass deposited on the filter is determined by weighing the filter before and after the test. For practicality, TPM was only collected during stationary testing for this program.

Since the exhaust sample that flows through the filter is diluted and is only a small portion of the total exhaust flow from the heater, detailed calculations are required to convert the mass value from the filter to a complete TPM value for the test. All calculations used for this purpose were adapted from the ISO 8178-1:2006 standard for measuring exhaust emissions including particulate [9].

Initially, the raw filter weight, m_f, in µg was corrected using a humidity correction factor, K_p, giving a corrected filter weight, m_{fc}, as shown in Equation 7.

$$m_{fc} = m_f \cdot K_p \quad \text{Eq. (7)}$$

To calculate K_p, the average absolute humidity during the test, denoted H_a, in [gH_2O/kg dry air] was used via Equation 8.

$$K_p = \frac{1}{1 + \left(0.0133 \cdot \left(H_a - 10.71\right)\right)} \quad \text{Eq. (8)}$$

Then, the particle mass flow rate, q_{mPT}, in g/h was calculated using the corrected filter weight m_{fc} in µg, the calculated mass of exhaust passed through the filter m_{sep} in kg (estimated using a density of 1.1 kg/m³ for diluted exhaust), the average mass flow rate of wet exhaust q_{mew} in kg/h, and the average dilution ratio (DR), via Equation 9.

$$q_{mPT} = m_{fc} / 10^6 \cdot \frac{q_{mew}}{m_{sep}} \cdot DR \quad \text{Eq. (9)}$$

Finally, this result was multiplied by the filter loading time $t_{loading}$ in seconds to get a final TPM mass value m_{TPM} in mg via Equation 10.

$$m_{TPM} = q_{mPT} \cdot \frac{t_{loading}}{3.6} \quad \text{Eq. (10)}$$

This TPM mass result for stationary tests was also modified via the CARB method in Equation 1 to obtain a mass emission rate per unit distance where applicable.

Results and Discussion

Stationary Test Results

The stationary testing results are included in Tables 5 and 6. Table 5 shows the total mass results for each measured compound, as well as the average temperature during the test and the calculated volume of fuel consumed. Table 6 shows the mass emissions per unit distance for the measured compounds, as well as the average test temperature and the calculated equivalent fuel consumption (assuming the vehicle travels 1 mile every 3 minutes for this stationary test).

Three stationary tests were scheduled in the test plan; however, only two test days were sufficiently cold to keep the FFH running while stationary (during other test attempts, the heater would run only intermittently

TABLE 5 Stationary test totals.

Date	Avg. temp. [°C]	CO_2 [g]	CO [g]	NO [g]	NO_2 [g]	HC [g]	CH_4 [g]	NMHC [g]	Soot [mg]	TPM [mg]	Fuel [L]
2023-03-28	3.5	2515.9	0.36	2.13	0.12	0.03	0.00	0.03	4.78	105.7	0.96
2023-03-30	−5.5	2546.8	0.56	2.10	0.14	0.04	0.00	0.04	4.80	19.6	0.97

TABLE 6 Stationary test CARB method calculated results.

Date	Avg. temp. [°C]	CO_2 [g/mi]	CO [g/mi]	NO [g/mi]	NO_2 [g/mi]	HC [g/mi]	CH_4 [g/mi]	NMHC [g/mi]	Soot [mg/mi]	TPM [mg/mi]	Fuel cons. [L/100 km]
2023-03-28	3.5	377	0.054	0.320	0.017	0.004	0.000	0.004	0.718	15.9	9.0
2023-03-30	−5.5	382	0.083	0.315	0.021	0.005	0.000	0.005	0.720	2.9	9.1

and so these tests were considered incomplete and their results are not shown).

Comparing the values in Table 6 to the regulated FFH emissions regulations in California, the results show that CO emissions levels were well below the limit, whereas NO_x (NO + NO_2) values were above the limit. This higher NO_x result may be due to the testing conditions being non-standard for this project, as outdoor temperatures were needed for the control system to allow the heater to operate, whereas typical CARB testing is done in a climate-controlled test chamber between 20 and 30°C.

Since the FFH uses diesel fuel, non-methane hydrocarbon (NMHC) emissions, determined by subtracting the CH_4 emissions from the HC emissions, can be considered equivalent to non-methane organic gas (NMOG) emissions (which are regulated for FFHs by CARB), according to the US EPA 40 CFR §1066.635(e). When this conversion is done, the NMHC results obtained during testing are significantly lower than the NMOG limit imposed by CARB.

Formaldehyde, which is regulated by CARB, could not be measured by the portable emissions equipment used during this test program, so the values of this component of the FFH emissions are currently unknown. In future studies, formaldehyde could be measured using in-lab instruments, or a customized portable measurement system could be fabricated.

Soot emissions and TPM are currently unregulated under CARB's FFH rules. However, light-duty passenger vehicles have limits on their PM emissions. The current US EPA Tier 3 standard for passenger vehicle PM emissions is 3 mg/mi of TPM, and the current CARB standards are as low as 1 mg/mi TPM for certain vehicle classes. The proposed US EPA standard for model years 2027 and later is 0.5 mg/mi PM [10]. The measured FFH soot mass emission rates during stationary testing were slightly above the 0.5 mg/mi level at approximately 0.72 mg/mi in both successful tests; however, the TPM emissions, to which these standards apply, were significantly higher since soot is generally only a fraction of TPM. In addition, there was high variability in the TPM results and only two test runs were successfully completed (due to temperature limitations during testing). Further testing of FFH emissions is recommended to obtain more representative TPM results.

In addition to the CARB-style results, EU-style maximum concentration results are shown in Table 7. The instantaneous dry concentrations of CO and HC exceeded EU limits momentarily on both valid tests. However, exceedances were on the order of one or two seconds, while the concentrations for the rest of the test were below the maximums. Testing for EU R122 compliance is typically completed at warm temperatures, and this could explain the higher initial concentrations captured during outdoor testing. NO_x concentrations did not exceed the regulated EU R122 limit of 200 ppm during stationary testing. Unlike the CO and HC concentrations, the NO_x concentration was relatively consistent whenever the heater was operational. Figure 5 shows a visual representation of the concentration results for a single idle test over the entire duration of the test. In this example, CO concentration peaks as soon as the FFH is started by the vehicle, then quickly tapers down to very low values as the heater is running consistently throughout the test time. Hydrocarbon concentrations show a similar pattern, with a short-lived peak and tapering off to nearly zero for the rest of the test. NO_x, on the other hand, is more consistent throughout the time that the heater is running, with tailpipe concentrations of nearly 90 ppm throughout the test.

On-Road Test Results

On-Road Route Statistics Several general route statistics from on-road testing are shown in Table 8. These include the total distance traveled while testing, the average ambient temperature during the test, the average kinetic intensity (which is a measurement of the aggressiveness of a driving cycle using speed and acceleration rates [11]), the average speed, the average driving speed (omitting any stops), the average and maximum acceleration rates, the average and maximum deceleration rates, and the percentage of idle time (when the vehicle was stopped) during the test. Since testing was conducted mostly on the Transitway, which is closed to private vehicle traffic, average speeds were relatively high for a transit bus and there were few stops. This type of driving is representative of bus rapid transit (BRT)-style operation, but not of routes where buses would mix with regular traffic.

On-Road Total Mass and Emission Rate Results The emissions results from on-road testing are shown in Tables 9 and 10. The results in Table 9 show the total mass of emissions (and volume of fuel used) over the

TABLE 7 Instantaneous maximum concentrations for EU R122 comparison.

Date	Average temperature [°C]	Maximum CO (dry) [ppm]	Maximum NO_x (dry) [ppm]	Maximum HC (dry) [ppm]
2023-03-28	3.5	1601	96	488
2023-03-30	−5.5	1683	92	527

FIGURE 5 Stationary test exhaust concentrations for R122 comparison (test date: 2023-03-30).

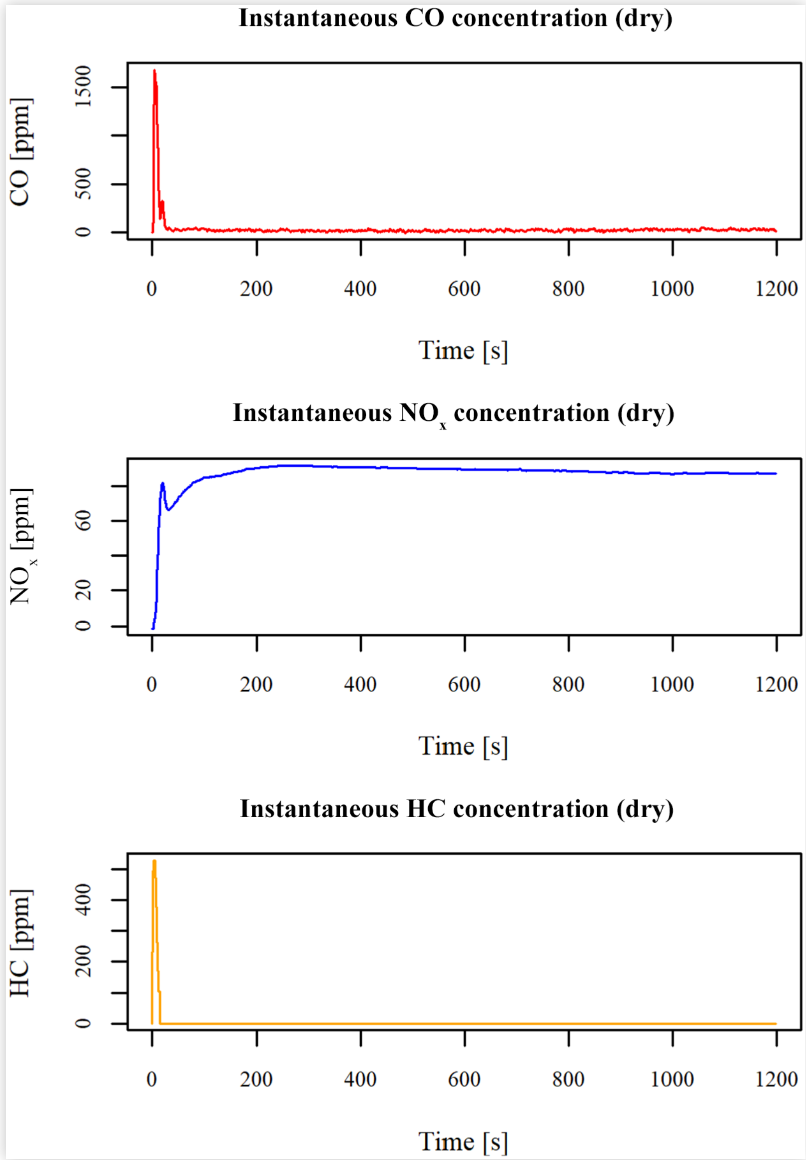


TABLE 8 Route statistics—on-road.

Date	Dist. [km]	Avg. temp. [°C]	Kinetic intensity [1/km]	Avg. speed [km/h]	Avg. driving speed [km/h]	Avg. accel. [m/s²]	Max. accel. [m/s²]	Avg. decel. [m/s²]	Max. decel. [m/s²]	Idle time [%]
2023-03-28	39.7	3.4	0.723	39.4	42.5	0.31	2.26	−0.32	−2.21	7.4
2023-03-20	40.1	6.2	0.817	39.7	42.8	0.36	2.95	−0.38	−2.01	7.2
2023-03-30	39.8	−1.5	0.707	39.7	43.8	0.33	2.95	−0.35	−2.35	9.5

TABLE 9 On-road test total results.

Date	Avg. temp. [°C]	CO_2 mass [g]	CO mass [g]	NO mass [g]	NO_2 mass [g]	HC mass [g]	CH_4 mass [g]	NMHC mass [g]	Soot mass [mg]	Fuel [L]
2023-03-28	3.4	4689	0.99	3.55	0.30	0.07	0.01	0.06	20.88	1.79
2023-03-29	6.2	4273	1.03	3.30	0.26	0.08	0.00	0.08	16.13	1.63
2023-03-30	−1.5	5233	1.90	3.90	0.31	0.04	0.00	0.04	21.72	2.00

TABLE 10 On-road test distance-based results.

Date	Avg. temp. [°C]	CO_2 [g/mi]	CO [g/mi]	NO [g/mi]	NO_2 [g/mi]	HC [g/mi]	CH_4 [g/mi]	NMHC [g/mi]	Soot [mg/mi]	Fuel cons. [L/100 km]
2023-03-28	3.4	190	0.040	0.144	0.012	0.003	0.000	0.003	0.847	4.5
2023-03-29	6.2	171	0.041	0.132	0.010	0.003	0.000	0.003	0.647	4.1
2023-03-30	−1.5	211	0.077	0.157	0.013	0.002	0.000	0.002	0.877	5.0

entire test, while the distance-based results shown in Table 10 take into account the GPS-based distance. Note that TPM results are unavailable for on-road testing as gravimetric filters were only used on stationary tests.

As shown in Table 10, the CO_2 emissions rates (and fuel consumption) were lower on-road when compared to those calculated during stationary testing (Table 6). This is partly due to the higher average speed of the test cycle (the stationary test assumes a speed of 32 km/h whereas the on-road test average speeds were closer to 40 km/h), as well as the fact that the heater did not run all the time during the on-road tests. When the cabin was sufficiently warm, the heater turned off for short periods of time until it was needed again. CO and NO_x emissions per unit distance were also slightly lower for on-road testing, likely for the same reasons.

HC and CH_4 emissions were very low in both stationary and on-road testing, leading to low NMHC results as well. Small amounts of hydrocarbon emissions were measured on each restart of the heater but levels were undetectable when the FFH was running consistently.

Finally, soot emissions per unit distance on-road were slightly higher than those calculated during stationary testing on two of three occasions. Peak soot emissions during startup of the FFH during on-road testing also reached higher levels on-road than during stationary testing. This could be due to the airflow around the heater and other operating condition differences attributable to the vehicle being in motion.

Conclusions

Stationary and on-road testing of the diesel FFH installed on an OC Transpo New Flyer XE40 BEV bus was completed in moderately cold weather in Ottawa, Canada, in late March 2023. The results showed that during stationary testing, the heater met CARB's regulated emissions levels for CO and NMOG emissions (NMHC was considered to be equivalent to NMOG for this test), but that NO_x emissions levels were higher than the CARB standard. However, these high NO_x emissions could have been the result of non-standard test conditions (ambient temperatures were colder than the 20 to 30°C recommended range for bench testing, and the FFH was installed on a vehicle instead of a test bench). TPM levels varied significantly between the two successful stationary test runs and were higher than the latest proposed 0.5 mg/mi standard for passenger vehicles, but there is no official CARB FFH PM standard that currently applies to FFH units. Comparing the test results to EU Standard R122 for FFHs, the concentrations of CO and HC momentarily exceeded their respective limits; however, the test was performed at ambient temperatures lower than those recommended by this standard as well, and the spikes in values were very short-lived (i.e., on startup of the FFH only). NO_x values were below the EU R122 upper limit.

On-road testing showed that during one hour of operation on the Ottawa Transitway between Hurdman and South Keys stations, the emissions levels of most measured compounds were lower on a mass per distance basis than their respective results during stationary testing, except for soot. This is likely due to the high-speed nature of the Transitway test cycle operation causing lower values due to the higher distance per unit time, as well as the fact that the heater turned off for short periods when the cabin temperature reached its set point. For soot, the on-road emissions values point to increased soot emission rates while the vehicle was moving, perhaps due to different conditions caused by the vehicle's operation.

Stationary Testing Summary

- Stationary tests at <5°C ambient temperatures showed levels of CO_2 emissions from 377 g/mi to 382 g/mi based on CARB calculations, and corresponding diesel fuel consumption values around 9 L/100 km.
- Stationary CO emissions rates were between 0.054 g/mi and 0.083 g/mi using CARB calculations, which is lower than the 1.7 g/mi CARB limit.
- Stationary NO_x emissions rates were approximately 0.34 g/mi based on CARB calculations, which is higher than the CARB standard of 0.05 g/mi; however, the test procedure was conducted at <5°C rather than the lab test standard of 20 to 30°C, which could have affected the results along with the fact that this testing was completed with the FFH mounted on the vehicle rather than on a test bench.
- Stationary test levels of NMHC were between 4 mg/mi and 5 mg/mi based on CARB calculations, which is below the NMOG limit of 40 mg/mi.
- Soot emissions were about 0.72 mg/mi for each stationary test, according to CARB calculations.
- TPM emissions levels were highly variable, with one test showing 3 mg/mi and another showing 16 mg/mi.
- When compared to the EU R122 regulations, CO and HC spikes momentarily exceeded the dry concentration limits for these species, whereas NO_x was below its limit for the entire test duration.

On-Road Testing Summary

- CO_2 emissions and fuel consumption were approximately 200 g/mi and 4.5 L/100 km, respectively, during on-road testing. These levels are comparable to the emissions from an efficient light-duty passenger vehicle, equating to significant GHG benefits when the overall electric bus emissions are compared to those of a typical diesel transit bus (not including the GHG intensity of the grid electricity used).
- During on-road testing, CO emissions were between 0.040 g/mi and 0.077 g/mi.
- NO_x emissions were between 0.14 g/mi and 0.17 g/mi.
- NMHC emissions were between 2 mg/mi and 3 mg/mi.
- Soot emissions were between 0.65 mg/mi and 0.88 mg/mi, two of three on-road tests showed soot levels higher than those emitted during stationary testing on a g/mi basis.
- No TPM data was available for on-road tests.

Recommendations and Future Work

Further testing could potentially be conducted on FFH units on various vehicles to determine whether the high NO_x concentrations are a consistent issue when operating in cold weather, and to determine whether emissions vary significantly within a fleet of buses using FFHs. Additionally, testing of ICE vehicles with FFHs could be undertaken to analyze the current state of emissions from transit fleets, as the operation of the FFH may be more intermittent when waste heat from a diesel engine is also available for cabin heating. Regular maintenance of FFH units is recommended by their manufacturers, and this could also potentially reduce the levels of pollutants emitted when FFHs are used on transit vehicles.

Maintaining enough electric driving range in winter while heating the cabin sufficiently for passenger comfort without additional criteria emissions remains a challenge for electric transit vehicles. Heat pump and all-electric options may not maintain enough range for some situations or cold climates. Therefore, FFHs will likely remain the preferred solution for cabin heating in Canada for the immediate future unless alternative solutions such as on-route charging or different routes for electric buses are explored. Additional emissions controls for FFH units and alternative fuels for FFHs may provide short-term emissions benefits, and these topics should also be explored by researchers.

Acknowledgments

The authors would like to thank OC Transpo and its employees for both the permission to test their vehicle and their assistance during testing. Special thanks to Jasjeet Singh, Jeremy Morton, Jonathan Lewis, and Kevin Sauriol! Thanks as well to the staff of the Emissions Research and Measurement Section of Environment and Climate Change Canada, including but not limited to David Buote, Gilles Marcotte, Justin Wilson, Wayne Baas, Aaron Loiselle-Lapointe, Debbie Rosenblatt, and Norman Meyer.

Contact Information

Kieran Humphries
Emissions Research and Measurement Section
Environment and Climate Change Canada
kieran.humphries@ec.gc.ca

List of Abbreviations

Abbreviation	Definition
BEV	Battery Electric Vehicle
BRT	Bus Rapid Transit
BTU	British Thermal Unit
°C	Degrees Celsius
C_1	Single Carbon-Containing Molecules
CARB	California Air Resources Board
CFR	United States Code of Federal Regulations
CH_4	Methane
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CVS	Constant Volume Sampling
DC	Direct Current
DPF	Diesel Particulate Filter
DR	Dilution Ratio
ECE	Economic Commission for Europe
EPA	United States Environmental Protection Agency
EU	European Union
FAME	Fatty Acid Methyl Ester
FFC	Fuel Fraction Carbon
FFH	Fuel-Fired Heater
gH_2O/kg dry air	Absolute Humidity in Grams of Water Vapor per kg of Dry Air
GHG	Greenhouse Gas
GPS	Global Positioning System
GVWR	Gross Vehicle Weight Rating
H_2O	Water
HC	Hydrocarbon
HCHO	Formaldehyde
HVAC	Heating, Ventilation, and Air Conditioning
HVO	Hydrogenated Vegetable Oil

ID	Identification
ISO	International Organization for Standardization
LDV	Light-Duty Vehicle
LEV	Low Emissions Vehicle
NMC	Lithium Nickel Manganese Cobalt Oxides
NMHC	Non-Methane Hydrocarbon
NMOG	Non-Methane Organic Gases
NO	Nitrogen Oxide
NO_2	Nitrogen Dioxide
NO_x	Nitrogen Oxides (sum of NO and NO_2)
OC Transpo	Ottawa-Carleton Regional Transit Commission
PEMS	Portable Emissions Measurement System
PM	Particulate Matter
PN	Particle Number
ppm	Parts Per Million
R122	Regulation No. 122 of the Economic Commission for Europe
SAE	Society of Automotive Engineers
TPM	Total Particulate Matter
ULEV	Ultra-Low Emissions Vehicle
UN	United Nations
US	United States of America
ZEV	Zero Emissions Vehicle

References

1. Sutton, K., Jokinen, K., and Silver, F., "Fuel-Fired Heaters: Emissions, Fuel Utilization, and Regulations in Battery Electric Transit Buses," CALSTART, Pasadena, 2021.
2. Economic Commission for Europe of the United Nations, "Regulation No 122 of the Economic Commission for Europe of the United Nations (UN/ECE)—Uniform Technical Prescriptions Concerning the Approval of Vehicles of Categories M, N and O With Regard to Their Heating Systems," *Official Journal L* 53, no. 164 (2010): 231-251.
3. Karjalainen, P., Nikka, M., Olin, M., Martikainen, S. et al., "Fuel-Operated Auxiliary Heaters Are a Major Additional Source of Vehicular Particulate Emissions in Cold Regions," *Atmosphere* 12, no. 9 (2021): 1105.
4. Oikarinen, H., Olin, M., Martikainen, S., Leinonen, V. et al., "Particle Number, Mass, and Black Carbon Emissions from Fuel-Operated Auxiliary Heaters in Real Vehicle Use," *Atmospheric Environment: X* 16, no. 2022 (2022): 100189.
5. Bræstrup, F., "Measurement of Emissions from Diesel Fired Heaters for Buses," FORCE Technologies, Brøndby, 2018.
6. California Air Resources Board, "California 2001 through 2014 Model Criteria Pollutant Exhaust Emission Standards and Test Procedures and 2009 through 2016 Model Greenhouse Gas Exhaust Emissions Standards and Test Procedures for Passenger Cars, Light-Duty Trucks, and Medium-Duty Vehicles," August 5, 1999, accessed June 22, 2023, https://ww2.arb.ca.gov/sites/default/files/2020-07/ldtps_2001_2014_cp_or_2016_ghg_my_clean_complete_lev_iii_12_12_ac.pdf.
7. California Air Resources Board, "California Exhaust Emission Standards and Test Procedures for 2005 through 2008 Model Zero-Emission Vehicles, and 2001 through 2008 Model Hybrid Electric Vehicles, in the Passenger Car, Light-Duty Truck and Medium-Duty Vehicle Classes," December 2, 2009, accessed July 13, 2023, https://ww2.arb.ca.gov/sites/default/files/2020-07/clean_2005_2008_my_hev_tps_12_09_ac.pdf.
8. Lawrence, R., "Fuel Economy Measurement Carbon Balance Method," United States Environmental Protection Agency, Washington, DC, 1981.
9. International Organization for Standardization (ISO), "ISO 8178-1:2006, Reciprocating Internal Combustion Engines—Exhaust Emission Measurement—Part 1: Test-Bed Measurement of Gaseous and Particulate Exhaust Emissions," ISO, 2006.
10. United States Environmental Protection Agency, "Multi-Pollutant Emissions Standards for Model Years 2027 and Later Light-Duty and Medium-Duty Vehicles—Proposed Rules," May 5, 2023, accessed June 16, 2023, https://www.govinfo.gov/content/pkg/FR-2023-05-05/pdf/2023-07974.pdf.
11. O'Keefe, M., Simpson, A., and Kelly, K., "Duty Cycle Characterization and Evaluation towards Heavy Hybrid Vehicle Applications," SAE Technical Paper 2007-01-0302 (2007), doi:https://doi.org/10.4271/2007-01-0302.

ISSN 0148-7191