Article

Testing Method for Electric Bus Auxiliary Heater Emissions

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Abstract: Auxiliary diesel heaters are commonly used in all types of vehicles in cold climates and conditions around the world. Electric buses used in public transport utilise diesel-burning auxiliary heaters to provide thermal comfort for passengers under cold weather conditions while maintaining the operational range otherwise reduced by electric heating. However, the downside of utilising diesel burners is that they cause similar exhaust pollutants to conventional diesel vehicles. Because the emission control for auxiliary heaters is lax, the diesel burners typically lack any exhaust aftertreatment (EAT), resulting in potentially high local emissions. As the public transport sectors around the world seem to transit from traditional internal combustion engine-vehicles to battery electric applications, the significance of the emissions caused by diesel auxiliary heaters is continuously increasing. EVs are generally considered zero-emission vehicles but the implementation of diesel burners is evidently conflicting with this concept. Nevertheless, publicly available experimental results from studies around this topic are surprisingly limited. The data of the few available publications are not directly comparable because there is no direct procedure or protocol for determining the exhaust pollutants from auxiliary heaters in real-world conditions at present. As a result, assessing the direct effect of the pollutants caused by electric vehicles utilising auxiliary heaters in the public transport is challenging. This study addresses this problem by introducing two methods for measuring auxiliary heater emissions; first, a field-test method that is applicable for a quick screening of the emissions of multiple heater units; secondly, a laboratory test method for a more detailed emission characterisation in a simulated real-world operation environment. In these experiments, the primarily objective was to study the emissions of the auxiliary heaters, including CO₂, CO, NOₓ and soot. The heater operation was found to be cyclic with numerous start-ups during its typical operation. The cyclic operation resulted in concurrent emission peaks in CO and soot. Measurements of actual operation showed auxiliary heater utilisation rates similar to the controlled measurements, although the whole temperature range of the controlled measurements was not reached in real-world conditions. The measurements conducted during the field screening revealed high variations between emissions of individual units. A further screening of auxiliary heaters would provide a better outlook for the mitigation of their emissions.

Keywords: auxiliary heaters; exhaust emissions; electric bus; public transport

1. Introduction

The emission-free propulsion of electric buses makes them a viable solution in the quest for clean road transport. Consequently, electric buses have recently been adopted in urban area public transportation at an increasing rate. In Europe, the stock of electric buses almost doubled, from 4800 units in 2019 to 8400 units in 2021 [1]. Fuel-powered auxiliary heaters are commonly applied in city buses, as well as in battery electric applications. The primary reason for this is that the volume of a bus cabin is large; thus, energy demand, especially at sub-zero ambient temperatures, is relatively high. The current emission regulation is somewhat contradictory, because only vehicle propulsion systems are included in the specification of zero-emission heavy-duty vehicles in the Clean Vehicles Directive (CVD) of the European Commission [2]. The emissions of other systems, such as the auxiliary...
heaters, are not incorporated as a part of this directive [3]. Similarly, zero-emission vehicles equipped with fuel-powered auxiliary heaters retain their zero-emission status in the cold regions of the US [4]. However, California, as well as 15 other states, restrict funding if fuel-powered heaters are installed in a zero-emission vehicle [5].

In cold environments, cabin heating contributes a significant portion of the total energy consumption of city buses. In the most challenging conditions, cabin heating may even match the energy consumption of the average propulsion energy, effectively doubling the total energy consumption [6]. As the energy consumption of auxiliary heaters is often not recorded in detail, there is significant uncertainty in terms of both total energy use and the produced emissions. Cities and public transport authorities in Europe have become increasingly aware of the emissions caused by auxiliary heaters used for cabin heating in battery electric buses (BEBs). The auxiliary heaters typically operate on diesel fuels, but renewable fuels may be used to reduce the greenhouse gas (GHG) emissions. Regardless of the fuel type, auxiliary heaters generate harmful local emissions.

The intense energy demands of cabin heating is primarily due to the large cabin volume. Additionally, buses used for public transport often require frequent operation of their passenger doors, resulting in remarkable and continuous heat losses. The heating demand, therefore, is present throughout the typical bus trip. The need for heating is greater in colder climates and areas with lower average temperatures (e.g., Oslo +5.9 °C, Helsinki +6.1 °C, Tallinn +6.5 °C, Stockholm +7.3 °C), but heating may also be required during the coldest winter months in warmer areas.

In the context of electric buses, all-electric cabin heating poses a significant challenge due to the limited on-board energy capacity. Od the available fully electric heating systems, heat pumps are the most common solutions due to their high-performance efficiency if the temperature differential between the cabin and the outdoor environment is relatively small [7]. In such cases, the energy demand for heating is low and can usually be supplied by the same battery system used for propulsion. However, in colder environments, the temperature gradient between the cabin and ambient conditions increases, which leads to a drop in heat pump efficiency, increasing the heating demand. To preserve energy for the primary use of the vehicle, i.e., propulsion, auxiliary heaters powered by secondary energy sources (most commonly diesel) are usually utilised in electric city buses.

Even as the deployment of electric buses is proceeding, studies on the usage and emissions of auxiliary heaters are limited. However, the need for and interest in increasing the awareness around this topic is continuously increasing, especially among public transport operators (PTOs). The greatest concern is that buses equipped with diesel burners operate around crowded city centres, which emit harmful exhaust pollutants close to pedestrians and residents [8]. Some studies related to passenger car auxiliary heaters exist: in these publications, the focus has been optimising the control of auxiliary heaters regarding passenger comfort and fuel economy [9], which indirectly impacts emissions through the reduced fuel consumption. More recently, an auxiliary heater manufacturer has presented significant potential for emission reductions by use of a catalytic converters and alternative fuels, or the combination of both. These options showed a significant reduction in CO, NOx and soot emissions [10]. Moreover, measurements of the particle emissions caused by auxiliary heaters have shown that the particle emissions caused by auxiliary heaters may even be higher than those generated by a typical vehicle with internal combustion engines (ICE). However, this study only considered cases with idling vehicles and not the actual driving conditions [11]. Emission studies on bus auxiliary heaters have been conducted under both laboratory and field conditions. The tests performed under laboratory conditions present a test procedure for a detached heater unit in a test bench, with results from two heaters and three different fuels showing very little variation in CO and NOx emissions and some particle emission reductions from using hydrotreated vegetable oil (HVO) and fatty acid methyl ester (FAME) fuels [12]. Measurements performed on two buses have recorded a wide scale of different emission types [13], but only for a single ambient temperature and use-case. The extensive measurements conducted on 64 buses show little variation in NOx.
but significant variation in CO emissions, while particle emissions are lower with HVO fuel compared to their fossil counterpart [14]; however, these measurements were also only performed at a single ambient temperature point and use-case, and do not provide an accurate baseline for the actual usage and emissions in varying ambient conditions. This paper proposes to fill this gap in the literature by proposing more sophisticated testing methods for auxiliary heaters in buses for both field and controlled environments to account for and accurately measure the emissions caused by the heaters. The measurements described in this paper were conducted both in the form of larger-scale field tests with multiple buses and for one bus under laboratory conditions. The vehicles used in the tests are used by one of many operators acting under the Helsinki Region Transport (HSL) contracts.

Cabin Heating System of Electric Buses

The configuration of the heating systems used in electric city buses may vary depending on the vehicle brand and bus size. The heating configuration of the test vehicles described in this article comprised three different systems, all of which can operate separately from each other: (1) drive-battery-powered resistive heater equipped with a fan for the driver compartment, (2) drive-battery-powered air-to-air heat pump for the passenger compartment and (3) diesel-operated auxiliary heater connected to a coolant circuit distributing heat to the passenger compartment via radiators equipped with fans. The main focus of this study was to test system no. 3, the “diesel auxiliary heating system”. However, it must be noted that heating systems (1) and (2) may also affect the cabin temperatures as they are crucial parts of the overall cabin thermal management system and operate parallel to the diesel-powered auxiliary heater. Thus, the auxiliary heater operation may also be indirectly affected by the other heating systems.

The rated net peak heating power output of the auxiliary diesel heaters studied in this case was 35 kW, which corresponds to a fuel consumption of 3.6 kg/h. These figures were generally specified by the heater manufacturer for diesel fuels. Based on this information, the efficiency of the heater was estimated as ca. 82%. The manufacturer claimed that their diesel heaters were suitable for operation with alternative fuels according to DIN EN 15940, which includes HVO. HSL requires all operators to use 100% HVO in the auxiliary heaters of their fleet; thus, HVO was also used in this case with the auxiliary heaters.

The operation scheme of the heater was based solely on an “on/off” principle, where the heater is operated in cycles, either being completely inactive or operating with peak power without any possibility of varying the power output (unless manipulating the hardware). The fuel/air mixture may be controlled by influencing the intake airflow (configuring the intake fan rotor speed) with a dedicated service tool. The typical heater operation strategy is to activate the heater at full power until a certain coolant temperature threshold is reached, after which the heater is shut off, leading to cyclic start-stop sequences with a variable heater cooling time between the active periods. The heater is activated again when the coolant temperature falls below a lower temperature threshold defined by the vehicle operator. The temperature thresholds can vary on a case-by-case basis, and even according to the different ambient temperatures. In this case, the (lower) diesel heater activation threshold was 67 °C and (higher) deactivation threshold was 77 °C. The length of each active heating sequence was dependent on the heating system’s heat capacity and the energy transfer rate from the coolant system to vehicle cabin. The longest burn time, therefore, is during the initial cold start where the cooling media is close to ambient temperature; after this, the interval of the cyclic operation depends on the cabin heating requirements.

2. Materials and Methods

2.1. Field Tests (Pre-Screening)

The pre-screening tests were performed outdoors during November 2021 in Helsinki, Finland. During the pre-screening, nine vehicles in total were measured in actual field conditions. All vehicle/heater combinations were identical to each other. The buses were
two-axle, two-door, low-floor battery electric city buses provided by a common commercial bus manufacturer. All the measured buses had been in operation for up to two years prior to the tests and had been in daily use by the operator to serve in the public transport network of Helsinki region.

In the pre-screening phase, the gaseous emissions characteristics of multiple auxiliary heaters were studied. The measurement layout for the pre-screening is illustrated in Figure 1. The emission measurements were performed on-site using a portable Fourier transform infrared (FTIR) analyser from A&D (Figure 1, I.). The exhaust mass flow rate was measured using a 3” pitot tube exhaust mass flow meter (EFM) provided by AVL (Figure 1, II.). The fuel consumption was calculated based on the recorded CO$_2$ emissions and the known fuel carbon balance according to the method described in ISO 178-4:2020 [15]. Finally, the gross heating power was determined from the calculated fuel consumption and known fuel lower heating value (LHV), while the net heating power was based on the calculated theoretical efficiency, which was 82% of the gross heating power. The heater efficiency (82%) was derived from the data in the user manual provided by the device manufacturer.

![Figure 1. An illustrative example of the test layout used in the pre-screening. Extension tube with I. EFM and II. FTIR measurement devices connected to the exhaust outlet of the auxiliary heater.](image)

The measurements for each heater used a cold start, which meant that the auxiliary heater had not been used recently, and the cabin heating system’s coolant was close to the ambient temperature (coolant varied between +7 °C to +11.5 °C). The procedure outlined in Figure 2 was used to evaluate each vehicle with the following steps. First, the test equipment was installed. Second, the heater was activated and operated in a forced continuous mode until the upper temperature threshold was reached, at which point the heater was deactivated. Typically, the heaters ran for about 8–11 min. Third, the data were processed. The resulting emission and power consumption recordings were divided into two phases: cold start and steady state, as the heater’s emission profile initially differs when the heater unit is cold (cold start) and after the temperature and combustion in the heater have stabilised. In this case, the emission peak of the cold start occurred within the first 30 s after combustion began, followed by a settled period. The transition time between cold start and steady-state operation modes may vary between individual heater units and vehicles, depending on the ambient conditions and initial state of the vehicle heating system.
2.2. Laboratory Tests

The laboratory tests were performed in a climate-controlled chamber specifically designed for testing large-scale objects. The chamber temperature can be controlled accurately between temperatures of −40 °C and +55 °C. The chamber was equipped with fans that mix the air inside the entire chamber, ensuring more homogenous conditions throughout the chamber. Furthermore, to improve the blending of air at the crevices near the vehicle, additional fans were placed in each corner of the chamber. Both ambient and vehicle-interior temperatures were recorded during the measurements in the climate chamber. Ambient temperature was measured to ensure proper environmental conditions and interior temperatures to confirm the heating system’s operation and performance.

In the laboratory tests, the temperature gradually decreased in steps of 10 °C in the following order: +10 °C, 0 °C, −10 °C and −20 °C. In each condition, the exhaust emissions of the auxiliary heater were recorded by measuring the gaseous exhaust pollutants directly from the tail pipe of the heater. The concentration of the gaseous exhaust pollutants was recorded with a FTIR from A&D and the soot concentration was recorded using a microsoot sensor (MSS) manufactured by AVL. The exhaust mass emissions were calculated from the exhaust mass recorded by a 3" EFM from AVL. The instantaneous fuel consumption was calculated based on the CO₂ emissions as performed in the field tests. Prior to the active measurements at each temperature, the vehicle was conditioned for one hour to ensure that the environment and vehicle were settled for each condition. During the tests, two test cycles were used:

1. Opening and closing all cabin doors in a sequence representing an average door-opening sequence of an operating bus service—test time: 30 min.
2. Doors were opened for 15 s every 75 s (baseline formed from HSL bus line 23, operating within the central area of Helsinki).
3. Measurements were repeated with doors closed to represent the minimum thermal loss of the vehicle (best-case scenario)—test time: 30 min.

It should be pointed out that while the opening and closing of the bus doors as described above can address heat loss through the free convection of warm air to the colder ambient temperature upon opening the doors, the method is not able to address the additional effects of forced convection through the open doors. Heat loss by forced
convection may be created by passengers moving in and out through the open doors, as well as pressure differences and wind conditions next to the vehicle at the bus stop. To assess the impact of forced convection, computational fluid dynamics should be employed, which is beyond the scope of the present paper.

Figure 3 depicts the measurement points for ambient and cabin temperatures. Ambient temperature was measured from all four corners at 1.5 m from the floor in the climate chamber. Regarding the vehicle’s cabin, there were three measurement points inside the passenger compartment (rear, middle and front) at about one meter from the floor and one measurement point in the cockpit at driver’s head level. All temperature sensors were installed at least 20 centimetres from the attached surface and heat-conductive metal parts of the sensors had no direct contact with any surface. The temperature measurement system comprised thermocouples connected to Graphtec GL240 data logger.

![Figure 3. Bus auxiliary heating system layout and temperature measurement points (top view).](image)

### 2.3. Utilisation Monitoring

The utilisation of auxiliary heaters was recorded for two months while the bus was used in normal commercial city bus operation in Helsinki. The utilisation rate in this context refers to the share of time the auxiliary heater was in active heating mode of the total bus operation time, formulated as:

\[
\text{Utilisation rate} \ (\%) = \frac{t_{AH\ active}}{t_{bus\ operated}} \times 100\%
\]

where \(t_{AH\ active}\) is the cumulative time duration for the auxiliary heater combustion and \(t_{bus\ operated}\) is the time duration when the bus is transferred between the operating line and bus depot.

Exhaust temperature was found to be a clear indicator of heater operation due to the cyclic “on/off” style operation. According to the device’s service manual, the exhaust gas temperature can reach over 400 °C. High exhaust temperatures were also expected at the end of the exhaust pipe because of the short length between the auxiliary heater combustion chamber and exhaust outlet. Thus, the aim was to register the heater burning operation from the temperature at the tip of the exhaust pipe. A simple thermocouple was deemed suitable to detect the heater operation as there would be a high difference between ambient and exhaust fume temperatures. A thermocouple with a thin head was chosen to ensure short reaction times to changes in temperature. The setup was tested and confirmed to work as intended; the thermocouple was quick to react to both the start and the end of burner action.

The exhaust pipe thermocouple was connected to a Grant 2020 series data logger, which, in turn, was powered by the 24 V auxiliary power circuit of the measured vehicle. Thus, the logger was active whenever the main power of the bus was turned on. A logging frequency of 0.5 Hz was used in the monitoring.

Heater activity can be deduced from the logged exhaust gas temperature. A simple algorithm was utilised to detect activity from exhaust temperature (Figure 4). The algorithm...
Figure 5. Result of applying the heater combustion detection algorithm to exhaust temperature data.

In this way, the combustion is not considered active during the cooldown period after combustion when the temperature at the end of the exhaust pipe is still relatively high. This can be seen in Figure 5 between 1330–1500 s and 1900–2100 s.

Figure 4. A step-by-step diagram of the algorithm used to detect heater combustion activity from exhaust temperature data.

- If the exhaust temperature is higher than in the previous timestep and exceeds 100 °C, active combustion is deduced.
- If the exhaust temperature is lower than in the previous timestep, but still exceeds 300 °C, active combustion is deduced.
- In all other cases, combustion is deduced to be not active.

This can be seen in Figure 5 between 1330–1500 s and 1900–2100 s.

Figure 5. Result of applying the heater combustion detection algorithm to exhaust temperature data.
3. Results
3.1. Pre-Screening in Field Conditions

Figure 6 illustrates mass-based CO$_2$ (Figure 6a), CO (Figure 6b) and NO$_x$ (Figure 6c) emissions and calculated fuel consumption (Figure 6d) for all nine measured heater devices under testing (DUT). Each figure shows the average value obtained from the first 30 s after the start of the heater, together with the corresponding results acquired in steady-state operation. Table 1 shows the calculated heater gross and net power outputs during the steady-state phase. On average, the variation in CO$_2$ emissions and fuel consumption (also net power) was found to be in the range from −12% to 9%. However, one unit (DUT #2) was found to be especially deviant in terms of net power; hence, the measured CO$_2$ and thus fuel consumption values were ca. 10% lower compared to the rest of the test group. It was later found out during discussions with the bus operator that during the service of that particular heater (DUT #2), the original 35 kW fuel injector was replaced with a 30 kW variant, explaining the deviant power output.

![Figure 6](image-url)

**Figure 6.** Gaseous emissions during cold start and during steady operation for all auxiliary heaters measured in the field tests (together with average fuel consumption).

The pre-screening results suggests that the characteristics of CO emission significantly depend on the heater combustion chamber temperature, as the CO emissions emitted during the initial 30 s of the operation are notably greater compared to the steady-state operation. Initially, the recorded CO emissions were between 27 and 230 times higher than the values measured in the steady-state condition. Overall, CO emissions caused by the heater in steady state varied between 0.6 and 9.4 g/h, with an average of 4 g/h. Surprisingly,
no remarkable difference in CO was found between the 30 kW and the 35 kW versions. The characteristics of the NOx emissions were found to be opposite to the CO emissions, because the NOx emissions typically increase over time as the temperature in the combustion and combustion chamber rises. This is generally a well-known phenomenon, because the NOx formation is typically most dependent on combustion temperature [16]. The least NOx emissions were produced by the heater equipped with the 30 kW specification injector, which is in line with the relation between combustion temperature (heater power) and NOx formation.

Table 1. Calculated DUT gross and net power from the recorded fuel consumptions.

<table>
<thead>
<tr>
<th>DUT</th>
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<th>DUT</th>
<th>DUT</th>
<th>DUT</th>
<th>DUT</th>
<th>DUT</th>
<th>DUT</th>
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<tr>
<td>#1</td>
<td>#2</td>
<td>#3</td>
<td>#4</td>
<td>#5</td>
<td>#6</td>
<td>#7</td>
<td>#8</td>
<td>#9</td>
<td></td>
</tr>
<tr>
<td>Gross Power (avg) kW</td>
<td>43.1</td>
<td>34.7</td>
<td>39.4</td>
<td>38.6</td>
<td>40.5</td>
<td>42.6</td>
<td>38.0</td>
<td>39.5</td>
<td>40.4</td>
</tr>
<tr>
<td>Net Power (avg) kW</td>
<td>35.3</td>
<td>28.5</td>
<td>32.3</td>
<td>31.6</td>
<td>33.2</td>
<td>34.9</td>
<td>31.1</td>
<td>32.4</td>
<td>33.1</td>
</tr>
</tbody>
</table>

From the nine tested heaters, one unit was selected for further experiments conducted in the climate chamber. Based on the results obtained in the field tests, DUT #6 was concluded to best represent the average performance of a typical auxiliary heater in terms of performance and emissions characteristics.

3.2. Laboratory Tests
3.2.1. Ambient Conditions and Interior Temperatures

The recorded temperature data are visualised in Figure 7, which highlights the active measurement period as well as the transition periods when the ambient temperature in the climate chamber was lowered. As seen in the graph, the vehicle was mostly able to keep the cabin temperatures at comfortable levels even when doors were operated at −10 °C ambient temperature. However, the temperature in parts of the cabin started to decrease when doors were operated at −20 °C ambient; the lowest temperatures of 6 °C were recorded in the middle parts of the cabin. The temperatures started rising again after the door operation ceased, although the cabin middle part was not able to reach comfortable levels during the 30 min measurement period when doors remained closed.

Variations in the temperature at different parts of the vehicle cabin were discovered. The driver compartment and rear part of the passenger compartment were observed to be warmest during the tests, while the middle of the cabin was the coldest. Door operation affected the cabin middle and front parts the most, which is presumably because these parts of the cabin are closest to the doors. The temperature at the rear of the cabin and the driver compartment stayed over +20 °C in all tested ambient temperatures, even at −20 °C ambient temperature, whereas the cabin middle and front compartments saw some decreases at −10 °C and −20 °C ambient temperatures when doors were operated. Interestingly, at −10 °C, the vehicle was able to keep all cabin compartments warm in the middle part of the cabin when doors were operated. At the beginning and end of the test, the interior temperature decreased to about +10 °C in the cabin’s middle and front parts. It appears that the heating capacity is generally sufficient, but some periods exist when the heating capacity is reduced. At −20 °C, a notable increase in heating requirements was observed. The heating system was not able to keep the middle and front parts of the cabin warm while doors were operated; the temperature in these parts fluctuated between +7 °C and +15 °C and kept on decreasing throughout this testing phase. In the next stage of the measurement, at −20 °C, when doors were kept shut, the cabin interior temperature started to increase but the gradient was clearly more moderate when compared to the previous ambient testing points with doors kept closed. The temperature in the front of the cabin reached target levels during the measurement period, while the temperature in the middle of the cabin could only reach +14 °C at the end. The measured temperature mid-cabin
was operated during periods outside the combustion period, although the specific reason,
in turn, control the operation frequency of the auxiliary heater. Typically, simple
phases when the measurement system was kept active but the results from these parts of the
tests were not used in the emission characterisation.

Figure 7. Ambient and vehicle interior temperatures. Ambient temperature is a mean value between all ambient temperature measurement points. Light grey bars resemble the active measurements when doors were operated, while darker grey bars resemble the second part of the measurements when doors were kept shut. The white regions between the grey-scaled bars show the pre-conditioning phases when the measurement system was kept active but the results from these parts of the tests were not used in the emission characterisation.

3.2.2. Auxiliary Heater Emissions

The recordings of the laboratory measurements confirmed that the normal operation of the auxiliary heater is based on an “on/off” principle. The need for heater operation is, therefore, dependent on energy demand when heating the cabin (cabin temperature set-point), cabin heat losses (structural/isolation losses, as well as air convection and mixing due to door operation) and heat system threshold limits. The cabin heater system is typically configured according to the operator demands (cabin temperature set points), which, in turn, control the operation frequency of the auxiliary heater. Typically, simple rules are followed; the heater is activated once the heating fluid temperature decreases below the lower threshold and is deactivated when the upper temperature threshold is exceeded. However, it was found that the blower feeding air to the combustion chamber was operated during periods outside the combustion period, although the specific reason for this remains unclear. It was assumed that the heater is operated with a standby function for an improved response time. The timeout time for the blower operation after combustion stopped was around 120 s.

Figures 8–11 illustrate examples of the heater operation and its corresponding emission characteristics in −10 °C ambient conditions (emissions concentrations and exhaust mass flow in relation test time). The CO₂ trace shown in Figure 8 indicates that the heater was
periodically operated on full power for the time required to fulfil the heat transfer criteria configured for the vehicle model. Correspondingly, the exhaust mass flow during operation was kept virtually constant, or aimed at a constant condition, during the period in which combustion occurs. A small spike at the start of the combustion was observed for both the exhaust mass flow and CO$_2$ as the initiation (and ignition delay) of the combustion caused some fluctuations in the flow dynamics (Figure 8). Similarly, a sudden peak (up to ca. 2000 ppm) in CO emissions occurred during the start of combustion, due to an initially cold/cool-down combustion chamber (Figure 9). However, the CO concentration was typically rapidly reduced after the start and, after the first 60 s, the concentration settled to between 40 and 75 ppm depending on the operation time. Similarly, as found during the pre-screening, NO$_x$ concentration trends ascended over time as the temperature of the combustion event and combustion chamber temperature increased (Figure 10). Typically, the NO$_x$ concentrations increased in this case from ca. 40 to 60 ppm during one heating event. Significant soot concentrations were mainly formed during the heater start-up, similarly to CO emissions, producing a rapid, high soot peak right after ignition (Figure 11). When the combustion proceeded further, the soot concentration rapidly decreased. The soot is suspected to mainly form due to the poorer combustion in the cooler combustion chamber, where the fuel evaporation rate remains low.

![Figure 8. An example of CO$_2$ concentrations and exhaust mass flow in relation to test time (at −10 °C).](image)

In order to define the exhaust mass-based pollutants of an auxiliary heater and to compare the results from different conditions, the exhaust characteristics for the tested auxiliary heater are expressed as average results over the two test sequences. Moreover, a cumulative exhaust mass was produced in relation to the operation time. Figure 12 illustrate the emitted CO$_2$ emissions (thus simultaneously representing operation frequency and operation time), Figure 13 presents the emitted CO emissions, Figure 14 presents the emitted NO$_x$ emissions and Figure 15 presents the soot emissions over all test conditions. In the cumulative result figures, the left side depicts the emissions of the test sequence with
the doors operated and the right side presents results when the doors were kept shut. The summary of the exhaust results is shown in Table 2.

**Figure 9.** An example of CO concentration and exhaust mass flow in relation to test time (at −10 °C).

**Figure 10.** An example of NO\textsubscript{x} concentration and exhaust mass flow in relation to test time (at −10 °C).

**Figure 11.** An example of exhaust soot concentration and exhaust mass flow in relation to test time (at −10 °C).
Figure 11. An example of exhaust soot concentration and exhaust mass flow in relation to test time (at −10 °C).

Figure 12. Cumulative CO\textsubscript{2} emissions in the climate chamber tests for both test cycles.
As a general observation, the auxiliary heater remained inactive in ambient temperatures above 0 °C and was automatically activated after the ambient temperature reached 0 °C or below. This setpoint depends on the vehicle thermal control strategy and, in this case, when the ambient temperature is below 0 °C, the battery-powered HVAC system and the auxiliary heater run in parallel. Based on the measured high-voltage battery power consumption, the utilisation of an electric HVAC unit decreased at 0 °C, but ramped up in the subsequent, low-ambient-temperature points.
Figure 15. Cumulative soot emissions in the climate chamber tests for both test cycles.

Because the auxiliary heater was only active below sub-zero conditions, the ambient conditions above 0 °C were excluded from the emission analysis. Additionally, the initial start of the heater in 0 °C took place ca. 8 min after the test sequence started where the doors were operated, and no activity prior to that moment was observed. The results indicate that the heater activity rate, CO₂ and NOₓ emission characteristics in −10 °C and −20 °C, when the doors were operated, are relatively similar (within 8% of each other), while the operation rate and CO₂ and NOₓ emissions in 0 °C remained lower. The reason for this is that the turnover rate of the air mass inside the cabin has a significant influence on the heating requirement, as opening the doors will mix the existing cabin air mass with colder, ambient air that exceeded or remained close to the limit of the heater system potential.

Based on the heater activity recorded during both −10 °C and −20 °C ambient temperatures with the doors opened, the maximum limit of heat transfer for the heater configuration was reached somewhere before −10 °C, and further decreased, as the ambient temperature increased the heater activity rate only a little (3%-units). This also explains the non-linear behaviour of the heater activity under higher ambient temperatures (0 °C), as the required heat transfer of the air mass with warmer ambient temperatures is lower in relation to the maximum system heat transfer potential. It was also found that the time of the initial operation at 0 °C was longer compared to the other conditions, as this was the moment where the first heating of the day occurred. The higher energy demand for the initial start was caused by the lower initial thermal energy state in the heating system compared to typical operating temperatures. Hence, more energy needed to be transferred to the heating fluid to heat it up to operation temperatures. Therefore, the first heater operation caused some bias in the results as no corresponding behaviours for other conditions were taking place. Despite the effect of the initial start, the test data also indicate that when the coolant medium reached its typical operation conditions, the operation for the 0 °C condition settled and resulted a somewhat similar frequency of heater operation compared to other ambient conditions. Based on these tests, it is unclear if a longer test time with the doors being operated would have settled the behaviour to the advantage of the 0 °C condition. For the 0 °C operation, a heater activity of 43% was recorded, which was correspondingly 60% for −10 °C and 63% for −20 °C ambient temperatures.
Table 2. A summary of the performance of the vehicle heating system in relation to ambient temperatures recorded in laboratory conditions.

<table>
<thead>
<tr>
<th>Amb</th>
<th>Condition</th>
<th>Utilisation Rate</th>
<th>Gross Power</th>
<th>Net Power</th>
<th>Fuel Consumption</th>
<th>CO₂</th>
<th>CO</th>
<th>NOₓ</th>
<th>Soot</th>
<th>Avg. Battery Power</th>
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<tbody>
<tr>
<td></td>
<td></td>
<td>%</td>
<td>kW</td>
<td>kW</td>
<td>kg/h</td>
<td>g/h</td>
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<td>g/h</td>
<td>kW</td>
</tr>
<tr>
<td>10</td>
<td>Doors operated</td>
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<td>0</td>
<td>0</td>
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<td>0</td>
<td>0</td>
<td>6.8</td>
</tr>
<tr>
<td></td>
<td>Doors closed</td>
<td>0%</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>6.1</td>
</tr>
<tr>
<td></td>
<td>Average</td>
<td>0%</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>6.4</td>
</tr>
<tr>
<td>0</td>
<td>Doors operated</td>
<td>33.7%</td>
<td>14.4</td>
<td>11.8</td>
<td>1.2</td>
<td>3.7</td>
<td>2.3</td>
<td>2.6</td>
<td>0.019</td>
<td>5.1</td>
</tr>
<tr>
<td></td>
<td>Doors closed</td>
<td>13.5%</td>
<td>5.7</td>
<td>4.7</td>
<td>0.5</td>
<td>1.5</td>
<td>1.9</td>
<td>0.9</td>
<td>0.004</td>
<td>4.4</td>
</tr>
<tr>
<td></td>
<td>Average</td>
<td>23.6%</td>
<td>10.0</td>
<td>8.2</td>
<td>0.8</td>
<td>2.6</td>
<td>2.1</td>
<td>1.7</td>
<td>0.012</td>
<td>4.8</td>
</tr>
<tr>
<td>−10</td>
<td>Doors operated</td>
<td>52.2%</td>
<td>22.2</td>
<td>18.2</td>
<td>1.8</td>
<td>5.7</td>
<td>5.0</td>
<td>3.9</td>
<td>0.040</td>
<td>4.7</td>
</tr>
<tr>
<td></td>
<td>Doors closed</td>
<td>10.2%</td>
<td>4.3</td>
<td>3.6</td>
<td>0.4</td>
<td>1.1</td>
<td>1.2</td>
<td>0.8</td>
<td>0.005</td>
<td>7.4</td>
</tr>
<tr>
<td></td>
<td>Average</td>
<td>31.2%</td>
<td>13.3</td>
<td>10.9</td>
<td>1.1</td>
<td>3.4</td>
<td>3.1</td>
<td>2.3</td>
<td>0.022</td>
<td>6.1</td>
</tr>
<tr>
<td>−20</td>
<td>Doors operated</td>
<td>61.5%</td>
<td>26.2</td>
<td>21.5</td>
<td>2.2</td>
<td>6.7</td>
<td>7.9</td>
<td>4.8</td>
<td>0.132</td>
<td>7.4</td>
</tr>
<tr>
<td></td>
<td>Doors closed</td>
<td>47.0%</td>
<td>20.0</td>
<td>16.4</td>
<td>1.6</td>
<td>5.1</td>
<td>7.1</td>
<td>3.6</td>
<td>0.128</td>
<td>6.9</td>
</tr>
<tr>
<td></td>
<td>Average</td>
<td>54.3%</td>
<td>23.1</td>
<td>18.9</td>
<td>1.9</td>
<td>5.9</td>
<td>7.5</td>
<td>4.2</td>
<td>0.130</td>
<td>7.2</td>
</tr>
</tbody>
</table>
The average results calculated from both test sequences (doors operated and doors shut) account for fewer variables in the heater thermal state hysteresis, as the controlling of the heater system is automatic. Thus, the heater would be forced to maintain the targeted temperature even with doors shut. In practice, if the difference in the initial thermal state occurs the moment the doors are kept shut, the heater system would need to compensate for the previous sequence in any case during the doors-shut period. This effect neglects, for example, the biased deviation occurring between 0 °C and −10 °C, as the average activity accounts for the transition activity between the two sequences (Figure 16). Because of this, the average results between each condition were seen to be a more accurate and representative comparison of the heater performance in relation to ambient conditions. The average results indicate that the transition between −10 °C and −20 °C was significantly larger compared to the transition from 0 °C to −10 °C, which was mostly affected by the difference in heater behaviour with the tests conducted with doors shut. The differences in exhaust emissions were more comparable between the conditions for 0 °C and −10 °C, but roughly doubled when the temperature was decreased from −10 °C to −20 °C (Figure 17). The main reason for this is the high activity rate of the heater at −20 °C both with and without the doors being operated, while the heater activity decreased drastically for the other conditions when the doors were kept closed.

Figure 16. Heater utilisation with two test sequences (doors operated and doors shut), together with the average calculated average utilisation rate.
3.2.3. Utilisation Monitoring

The operation of an auxiliary heater in a similar bus (that was used in the emission measurements) was monitored from 4 February to 13 April 2022 in the Helsinki region. In the monitoring phase, only the exhaust temperature trace of the auxiliary heater was recorded. The activity of the auxiliary heater was determined with the algorithm presented in Figure 4. The vehicle operator provided line operation times of the monitored bus for each monitored day. Auxiliary heater utilisation rate was calculated with Equation (1) based on the bus and auxiliary heater operation times. Moreover, ambient temperatures for the operation times were extracted from the database of Finnish Meteorological Institute measured in Kaisaniemi weather station in Helsinki.

Under ambient conditions, the foremost ambient temperature was rather volatile during the long-term monitoring, and stable conditions with regard to ambient temperature were rare. In addition, ambient temperature differed notably between day and night; daytime temperatures exceeded 0 °C almost daily, while conditions below −5 °C were only recorded during night-time. Moreover, the bus was never operated continuously for the entire day because there were occasional pauses between operation. Thus, any periods where the ambient temperature was constant were separated from the long-term monitoring data. Only operation periods during which the average ambient was clearly below 0 °C and remained within ±1 °C of the ambient were selected. Twenty-two periods in total were identified and separated from the long-term monitoring data (Table 3). The longest duration of continuous operation was 7 h 20 min. In most cases, the period was significantly shorter, as the median for the periods was 1 h 46 min. The average ambient temperatures fell between −7.5 °C and −1.8 °C for the selected periods. Utilisation rates were set between 20.7% and 54.6%, with an average utilisation rate of 34.4% for all the selected periods.
Table 3. Separated periods from the long-term monitoring data when ambient temperature was below 0 °C and did not alter more than ±1 °C.

<table>
<thead>
<tr>
<th>Period</th>
<th>Duration</th>
<th>Utilisation Rate</th>
<th>Average Temperature</th>
<th>Minimum Temperature</th>
<th>Maximum Temperature</th>
</tr>
</thead>
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<tr>
<td></td>
<td>hh:mm</td>
<td>%</td>
<td>°C</td>
<td>°C</td>
<td>°C</td>
</tr>
<tr>
<td>1</td>
<td>0:35</td>
<td>54.6%</td>
<td>-7.5</td>
<td>-8.5</td>
<td>-6.5</td>
</tr>
<tr>
<td>2</td>
<td>0:49</td>
<td>49.0%</td>
<td>-4.0</td>
<td>-4.1</td>
<td>-3.9</td>
</tr>
<tr>
<td>3</td>
<td>1:05</td>
<td>47.1%</td>
<td>-6.2</td>
<td>-6.4</td>
<td>-5.9</td>
</tr>
<tr>
<td>4</td>
<td>1:20</td>
<td>42.7%</td>
<td>-3.9</td>
<td>-4.2</td>
<td>-3.6</td>
</tr>
<tr>
<td>5</td>
<td>2:10</td>
<td>41.8%</td>
<td>-2.8</td>
<td>-3.4</td>
<td>-2.5</td>
</tr>
<tr>
<td>6</td>
<td>1:17</td>
<td>39.3%</td>
<td>-3.2</td>
<td>-3.3</td>
<td>-3.0</td>
</tr>
<tr>
<td>7</td>
<td>2:02</td>
<td>38.8%</td>
<td>-5.2</td>
<td>-5.6</td>
<td>-4.4</td>
</tr>
<tr>
<td>8</td>
<td>1:10</td>
<td>36.4%</td>
<td>-5.1</td>
<td>-5.4</td>
<td>-4.8</td>
</tr>
<tr>
<td>9</td>
<td>2:45</td>
<td>36.4%</td>
<td>-1.8</td>
<td>-2.0</td>
<td>-1.7</td>
</tr>
<tr>
<td>10</td>
<td>1:40</td>
<td>35.6%</td>
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<td>-4.8</td>
<td>-4.3</td>
</tr>
<tr>
<td>11</td>
<td>2:00</td>
<td>34.4%</td>
<td>-6.1</td>
<td>-6.5</td>
<td>-5.3</td>
</tr>
<tr>
<td>12</td>
<td>2:27</td>
<td>33.8%</td>
<td>-3.7</td>
<td>-4.5</td>
<td>-3.1</td>
</tr>
<tr>
<td>13</td>
<td>0:35</td>
<td>31.5%</td>
<td>-4.4</td>
<td>-4.8</td>
<td>-3.9</td>
</tr>
<tr>
<td>14</td>
<td>2:08</td>
<td>29.8%</td>
<td>-5.7</td>
<td>-6.3</td>
<td>-5.2</td>
</tr>
<tr>
<td>15</td>
<td>7:20</td>
<td>29.8%</td>
<td>-3.0</td>
<td>-3.5</td>
<td>-2.6</td>
</tr>
<tr>
<td>16</td>
<td>2:45</td>
<td>28.6%</td>
<td>-4.0</td>
<td>-4.5</td>
<td>-3.4</td>
</tr>
<tr>
<td>17</td>
<td>1:38</td>
<td>27.9%</td>
<td>-1.9</td>
<td>-2.0</td>
<td>-1.8</td>
</tr>
<tr>
<td>18</td>
<td>2:02</td>
<td>27.2%</td>
<td>-4.3</td>
<td>-4.6</td>
<td>-3.7</td>
</tr>
<tr>
<td>19</td>
<td>0:25</td>
<td>25.1%</td>
<td>-2.9</td>
<td>-3.0</td>
<td>-2.9</td>
</tr>
<tr>
<td>20</td>
<td>3:50</td>
<td>24.8%</td>
<td>-4.4</td>
<td>-4.9</td>
<td>-3.9</td>
</tr>
<tr>
<td>21</td>
<td>1:52</td>
<td>22.1%</td>
<td>-4.1</td>
<td>-4.2</td>
<td>-3.9</td>
</tr>
<tr>
<td>22</td>
<td>0:54</td>
<td>20.7%</td>
<td>-4.8</td>
<td>-5.0</td>
<td>-4.6</td>
</tr>
</tbody>
</table>

3.3. Comparison against Real World Data

The validation of the laboratory method proposed in this study was performed by a comparison between auxiliary heater utilisation rates in laboratory and real-world use. Figure 18 shows the auxiliary heater utilisation rates plotted against average ambient temperature for both laboratory measurements and long-term monitoring data from real bus operation.

Figure 18. Comparison of auxiliary heater utilisation rates measured in laboratory and long-term monitoring.
Linear regression was used to describe the average monitoring results. On average, the results of the analysis revealed that the utilisation rates observed from real-world uses were mostly within the range of the maximum and average utilisation rates obtained from laboratory measurements. Figure 19 depicts the utilisation rate difference between the laboratory results and the linear regression of the monitored results at the temperature points of the monitored results. Overall, the laboratory measurements with the doors operated resulted in the closest match to the monitored results, although this exceeded the monitoring results by from 6 to 8% points. The difference between the two sets of measurements remained almost constant over the range of ambient temperatures recorded during the monitoring. The average of the two laboratory measurement methods (doors operated and doors shut) resulted in a slightly higher deviation from the monitored results when compared to the doors-operated method. However, the average results ranged from −3 to −12% points lower than the monitored result regression. In contrast, the results obtained from the doors-closed laboratory method were furthest from the monitoring results, from −15 to −30% points lower. It is important to note that the doors-closed method was not intended to replicate real-world operation but rather to provide a baseline for the minimum auxiliary heater utilisation rate at various low ambient temperatures.

![Figure 19](image_url)

**Figure 19.** The absolute utilisation rate difference of laboratory measurements to the linear regression of long-term monitoring results.

4. Discussion

The operation of auxiliary diesel heaters and, consequently, its emission characteristics are affected by a variety of factors. Some of this variety originates from the heater unit itself, as variance was discovered between heaters of the same make and model, while some of the variety stems indirectly from the vehicle operation and ambient conditions. Some of this variation is difficult to replicate in laboratory conditions, such as the heating effect of solar radiation or heat emitted from the passengers.

The direct emission characteristics of the auxiliary heaters tested in this study were found to be highly reliant on the direct combustion characteristics in combination with the utilisation rate and the frequency of the operation cycles alone. The emissions produced by each combustion event was concluded as trade-off between CO, NOx, and soot as a function of time. Short operational times produce less NOx emissions due to the cold start characteristics but create penalties in terms of CO and soot emissions. However, longer combustion durations would reduce the average CO and soot emissions while promoting NOx emissions.
The heater activity recorded with the vehicle used in this study indicated that the utilisation rate of the auxiliary heater seldom exceeds 60%. This corresponds to an average power of ca. 21 kW. Additionally, findings from the pre-screenings suggests that utilizing smaller injectors in auxiliary heaters would typically decrease NO\textsubscript{x} emissions. By optimizing the injector size, the exhaust pollutants could possibly be reduced by increasing the utilisation rate and prolonging the required combustion events. This could potentially reduce both CO and NO\textsubscript{x} emissions simultaneously as the occurrence of fewer cold start events will lower combustion temperatures even during continuous operation.

Previous studies published by Eberspächer indicate that using an integrated wire mesh catalyst could potentially suppress CO and NO\textsubscript{x} emissions [10]. The paper, however, suggests that the catalyst was unable to reach its full potential immediately around the start-up period before the catalyst light-off temperature is reached. Nevertheless, the peak CO concentration was reduced by roughly 50%. This means that, despite the significant emission reduction that may be achieved with wire mesh catalysts, similar issues, but to a lesser extent, still exist with heater systems operating in rapid and frequent cycles. These findings also indicate that the emission reductions of auxiliary heaters could be maximized by combining a wire mesh catalyst optimization of heater injector size.

To consider the variation in auxiliary heater units, this study proposed a lightweight gaseous emission measurement method to “pre-screen” several units before laboratory studies. This helped to improve the understanding of the average performance of auxiliary heaters and confirmed that the selected unit was operating as intended. However, the number of sampled auxiliary heater units was still rather low, and as publicly available information on auxiliary heater emissions is scarce, further auxiliary heater screenings are recommended. Due to the time limitations, no repetitions of cold-start tests during the pre-screening phase were possible. This means that the day-to-day variance remained unfortunately unknown. Further screening studies could be used to form aggregated information on auxiliary heater performance and emissions and provide guidance on what kind of unit emission levels are acceptable and to be expected. Additionally, a comparison with this sort of reference could also be used to detect malfunctions and anomalies in auxiliary heater operation, as the emission characteristics of a heater unit without a baseline to compare against may not be sufficient to determine whether an auxiliary heater is working correctly. Reports from the field also claim poorly performing auxiliary heaters can lead to a build-up of soot and other flammable by-products of combustion in the auxiliary heater, leading to safety hazards.

The analysis of the monitoring data revealed a high degree of variance, with some observations showing a variability of nearly 30% units at the same average temperature. Furthermore, some individual data points from the monitoring dataset exceeded the laboratory results, while following a similar trendline. These findings highlight the highly variable nature of auxiliary heater utilisation rates under similar ambient temperature conditions, as demonstrated by the monitoring results. For example, door-opening frequency has a great effect on the auxiliary heater utilisation rate, which was 2.5 times higher when the doors were opened at 0 \degree C ambient and 5.2 times higher at −10 \degree C ambient temperature when compared to when the test doors were kept shut. In the utilisation monitoring, such variables were not recorded.

Some shortcomings were noted in the data to form a definitive comparison. First and foremost, the amount of stable cold periods during the long-term monitoring was limited. The coldest monitored period had an average temperature of −7.5 \degree C; however, most of the datapoints were recorded at an average ambient temperature of −4 \degree C. A comparison of utilisation rates in colder conditions was not possible with the data recorded in this study. It is also possible that some unrecorded factor, such as solar radiation or passenger heat emission, reduces the energy demand to heat the passenger cabin, and thus reduces the auxiliary heater utilisation rate. Due to the large amount of uncertainty behind the auxiliary heater utilisation rates recorded from real bus operation during monitoring, more operation data would be required to form aggregated knowledge. Thus, the validation for
the laboratory testing method performed in this study can be considered indicative at best and further auxiliary heater operation recordings during bus operation are recommended. Vehicle-mounted temperature monitoring is also suggested in further auxiliary heater monitoring as the ambient temperature in close proximity to the vehicle may differ from the temperature measured at a fixed weather station. Nevertheless, the validation shows that the auxiliary heater utilisation rates obtained with the auxiliary heater laboratory measurement method can produce results that resemble auxiliary heater utilisation in actual city bus operation.

This research generated an emission profile for diesel-powered cabin heating in electric buses under various realistic conditions. The emission profile can be used in subsequent studies to provide specific information regarding the emissions from heater operation in buses. Specifically, it can help to determine the cumulative impact of the auxiliary heaters in a full fleet of vehicles regarding local emissions generation. Moreover, to obtain a further understanding of the magnitude of the emissions emitted by auxiliary heaters, the results of this study could be compared with other diesel-powered emission sources that are relevant, such as engines of the same vehicle class. The ultimate goal for future emission studies and emission source comparisons should be setting up a regulation scheme for auxiliary devices, comparable to the European emission standards already in place for vehicles such as Euro VI and upcoming Euro VII. Whether zero-emission vehicles with such auxiliary heaters can actually be considered zero-emission, and whether auxiliary heaters should nonetheless be allowed as an interim solution while thermal management technologies mature, should also be discussed.

5. Conclusions

Due to the nature of heater operation, auxiliary heater emissions are typically dependent on two main factors: the frequency of heater activation cycle and the total operation time. The frequency of the cycling is reliant on the heat system configuration (such as the heat system’s medium volume and rate of heat transfer) and the threshold temperatures (at which heat system temperatures the shut off and start).

In order to define the heater characteristics in relation to these parameters, two different conditions were compared: doors being operated and doors shut. These two sequences represent conditions on the opposite ends of the spectrum required to heat the cabin. The “doors operated” sequence represents a situation where the cabin air mass frequently changes from heated cabin air to a mixture of ambient and cabin air, cooling down the cabin during the time doors are open. Hence, a higher heater operation time is required to maintain the cabin temperature at the given set-point. The “doors shut” sequence represents a situation where the required net heating power is solely dependent on the amount of heat transferred from the cabin through the vehicle structure to the ambient environment, hypothetically representing the vehicle operation between the bus stops. As the auxiliary heater operation frequency is automatically controlled and system hysteresis affects the operation, average measurements over both test types (doors operated and doors shut) account for various conditions but fewer uncertainties in terms of heater behaviour.

Additionally, it was noted that the battery power consumption varied with the various ambient conditions. Two of the vehicles’ three cabin thermal management systems were operated by the high-voltage battery of the vehicle, namely, the driving compartment heater and the HVAC unit. At +10 °C ambient temperature, fully electric heating was utilised as per the requirements of the public transport authority in the region. At this temperature point, the heat pump of the electric HVAC unit operates at high efficiency, resulting in relatively moderate overall heating energy consumption. At 0 °C, the auxiliary heater started operating. Although the electric HVAC power consumption reduced, the overall heating power consumption increased. At lower ambient temperatures, both the auxiliary heater and HVAC power consumption increased. The average overall gross heating power consumption more than doubled at −20 °C when compared to 0 °C ambient temperature.
The results acquired from the scenario with doors shut were somewhat affected by the initial state of the heat system compared to the doors-operated scenario, as thermal hysteresis affected the initial coolant temperature. However, the doors-shut sequence offered important information regarding the general vehicle isolation efficiency, as the cabin air mass turnover rate was completely neglected. For instance, the effect may be witnessed by observing the cumulative CO$_2$ trend at 0 °C and −10 °C ambient conditions: soon after the doors-shut period started, the frequency of the heater activity was clearly decreasing in function regarding ambient temperature, dropping to 10–15%. For these two conditions, the heater was activated only once or twice during the total 30 min test time. Interestingly, this was not the case for the −20 °C condition, as the heater maintained the same operating frequency as experienced for the test with doors operated and the activity rate remained relatively high, ca. 56%. This observation suggests that the heat conduction through the vehicle structure was high and required frequent heater activity even with no cabin air mixing with ambient air. As a general conclusion, the difference in emissions behaviour compared to the doors-operated sequence was observed for all cases directly in proportion to the change in activity rate.

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**Data Availability Statement:** Restrictions apply to the availability of the data. Data are proprietary to HSL and are available from the authors with the permission of HSL.

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**Conflicts of Interest:** The authors declare no conflict of interest.

**References**


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