South Africa flagship on green mobility: Johannesburg Metrobus

PART II: ASSESSMENT OF DIESEL DUAL-FUEL ENGINE BUS

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ICCT CONSULTING REPORT

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EXECUTIVE SUMMARY

This report evaluates the environmental and operational performance of the Metrobus Diesel Dual-Fuel (DDF) Program in Johannesburg, South Africa, and provides recommendations to improve the environmental performance of the DDF fleet. We conducted an operational assessment that focused on fuel consumption and examined 148 Euro V DDF buses deployed in the current fleet. The analysis was based on both available historical records and field data.

Additionally, we contracted with West Virginia University to measure the real-world emissions of two DDF buses to determine emission values of local pollutants and greenhouse gases (GHGs). Portable emissions measurement systems (PEMS) were used on current Metrobus routes to assess the bus emissions under representative driving conditions. Emission rates from the tested DDF buses are presented and compared with legacy and modern soot-free bus technology.

Results show that Metrobus DDF buses experience a 7% average diesel substitution rate with compressed natural gas (CNG). That is, 7% of the total fuel consumed was CNG. This rate is considered low as manufacturer data show a DDF substitution rate closer to 50%. Note that this result is highly influenced by the fact that 75% of the DDF fleet was not fueled with CNG over the reporting period. The highest substitution rate with CNG for an individual vehicle was 30%. Proximity to a CNG refueling station at Milpark Depot did not appear to increase substitution rates. Fuel consumption rates for the DDF fleet range from 51 to 56 diesel liters equivalent (DLE) per 100 kilometers.

Real-world emission test results reveal that nitrogen oxide (NO_x) emissions from DDF buses are reduced by more than 70% with respect to the legacy Metrobus fleet, which is composed of Euro 0 and Euro II technology. Unfortunately, though, DDF methane (CH_4) emissions are more than 100 times higher than any other diesel or CNG technology, legacy or modern.

Under a 20-year time frame analysis, GHG emissions from Euro V DDF buses are slightly lower than legacy Metrobus buses. Although CO_2 emissions are much lower, the warming contribution of CH_4 reduces the fuel efficiency benefit, and CH_4 emissions from DDF operation are more than 30% of the total GHGs emitted by these buses. Excess CH_4 emissions from DDF buses result in higher GHG emissions than all other technology options available today.

Results of the PEMS testing suggest that DDF can be an effective intermediate technology toward soot-free, cleaner technology, but in order to deliver long-term reductions in the air pollution and GHG emissions of the fleet, Metrobus must move beyond Euro V DDF technology.

The operational and environmental benefits of the current DDF fleet can also be improved. Key recommendations are to:

» Establish a process and implement tools for data management. The system for the recording and sharing of data about bus operations and fuel consumption, both diesel and CNG, should be digitalized and centralized. This would ensure transparency and more frequent performance feedback to not only management, but also to the maintenance team and drivers.

» Establish a training system focused on the operation of DDF technology and its benefits. Training should apply across all levels of Metrobus and be targeted toward operating staff. The maintenance and operation teams will play a key role in driving the adoption of the technology and creating a culture of continuous improvement.

» Get commitment from Metrobus managers to fund, develop, and implement the data collection, training, and other strategies and actions needed to address current system gaps and ensure optimum DDF operation.

INTRODUCTION

This is the second of two papers that develop a strategy for the adoption of soot-free bus technology in Johannesburg Metrobus. The first, *Part I: Greening the Future Fleet*, aims to identify the least-cost technology pathways for improving air quality and reducing carbon dioxide (CO_2) emissions from the Metrobus fleet. This second report, *Part II: Assessment of Diesel Dual-Fuel Engine Bus Performance*, evaluates the environmental and operational performance of the Diesel Dual-Fuel (DDF) Program implemented by Johannesburg Metrobus in 2016.

DDF technology converts a diesel engine into a dual diesel and compressed natural gas (CNG) engine (Taniguchi, Masubuchi, Kitano, & Mogi, 2012). The DDF engine retrofits a natural gas injection system to the intake manifold. It is found in niche applications in stationary machines, such as generators, but the application of this technology is not common in urban bus fleets (Wakizaka, Hara, & Fukushima, 2009). Nonetheless, DDF technology is named as part of medium-term and long-term objectives in South Africa's national Green Transport Strategy. This section therefore looks closely at DDF implementation by Johannesburg Metrobus to arrive at an assessment of this technology and the practical lessons learned from its implementation.

The first call for Metrobus to reduce its greenhouse gas (GHG) emissions came in 2011, in response to international attention on South Africa as host of the 17th meeting of the Conference of the Parties to the United Nations Framework Convention on Climate Change (COP17) held in Durban, South Africa. The city's Green Transport Initiative gave priority to reducing GHG emissions from the Metrobus fleet, and that led to an investigation of alternative energy sources. At the time, the Industrial Development Corporation (IDC), the University of Johannesburg, and the Clinton Foundation contributed an analysis of alternative fuels—biodiesel, natural gas, ethanol, and hydrogen. Engine manufacturers were opposed to diesel, as the fuel quality was not considered sufficient.

Natural gas emerged as the best option. However, concerns about infrastructure, supply, and access led to the choice of DDF as a bridge technology to manage risk. DDF also allowed Metrobus to minimize costs and revamp existing buses in the fleet. A decision was made to retrofit a Volkswagen bus with a DDF system. No report on the performance of this DDF pilot is available.

Following this pilot, a series of procurements of DDF buses were made by Johannesburg Metrobus. In the first stage, Metrobus retrofitted 30 Mercedes-Benz Euro I diesel buses using a NOVO DDF kit. An additional 90 retrofits were planned but never implemented, reportedly due to technical problems such as engine knocking.

In the second phase, Metrobus took a different approach. Management procured 150 new Euro V buses with the intent to retrofit all with DDF systems (see Figure 1.) The buses were designed, manufactured, and retrofitted by Mercedes-Benz, which today maintains the vehicles under a service contract.

Figure 1. DDF buses obtained during the second phase of procurement.

Table 1 presents the technical specifications of the DDF buses operated by Metrobus. The engine and chassis were manufactured at the Mercedes-Benz production facility in Brazil. The buses were delivered as knocked-down parts and assembled in South Africa. Once assembled, Mercedes-Benz installed an aftermarket DDF retrofit kit designed and manufactured by Bosch. The integration of the Bosch DDF kit was in accordance with engine specifications and the capacity of the buses to use CNG, as certified by the manufacturer. Presently, 148 Mercedes-Benz Euro V DDF buses remain in operation.

Table 1. Technical specifications of the DDF buses. Source: Metrobus & Mercedes-Benz

Description	Specification
Brand	Mercedes-Benz
Model	OM-926-LA.V/22
Engine size	7.2 liters (L)
Emission standard	Euro V
Passenger capacity	44 sitting, 38 standing
Fuel tank	350 L of diesel + 40 L of AdBlue 250 L diesel equivalent of CNG (top mounted)
Dimension	12 meters (m)
Power drive	188 kilowatt (kW) @ 2200 revolutions per minute (rpm)
Gross vehicle mass (GVM)	18,500 kilograms (kg)
Number of cylinders and type	6 cylinders – straight
Exhaust conversion and emission control	Selective catalytic reduction (SCR) system

National regulations mandate Euro II emission levels for new buses, but the DDF fleet uses more advanced Euro V emission control technology. These buses are fitted with a selective catalytic reduction (SCR) system to achieve NO_x emission control in accordance with Euro V emission levels. The SCR system requires the use of a urea-based additive called AdBlue. The system is not unique to DDF or Euro V technology. It is also found in Euro IV and Euro VI engines. At its maximum potential, which is dictated by the Euro VI emission certification standard, the SCR can reduce real-world NO_x emissions by up to 99%.

According to interviews with Mercedes-Benz personnel and as confirmed by Metrobus personnel, a technical evaluation of selected Euro V DDF buses was conducted prior to their commissioning. That evaluation was not available for this study. Still, the main driver behind the selection of the DDF technology was the policy-based commitment to "greening" the Metrobus fleet.

A principal benefit of DDF technology is the ability to substitute lower cost CNG fuel for the more expensive diesel. However, substitution rates are not fixed and will vary with driving conditions. Factors such as engine start, idling time, and low-speed driving serve to reduce the substitution rate. The targeted deployment of DDF technology along routes where operating conditions favor high substitution rates, such as highway routes with minimal traffic, would maximize operational performance.

PERFORMANCE ASSESSMENT OF DIESEL DUAL-FUEL TECHNOLOGY

Metrics were established to assess the performance of DDF buses on technical and environmental grounds. These metrics include fuel consumption, diesel substitution rate, fleet-to-route allocation, and average distance traveled. A research team reviewed historical records, collected field data, and conducted interviews with a range of stakeholders to perform the analysis presented here.

FUEL CONSUMPTION AND DIESEL SUBSTITUTION RATE

Historical data on fuel consumption from July 2017 to April 2019 were retrieved and reviewed as detailed in Table 2. Additional field data, including fuel consumption data, for 90 buses were collected from May 2019 to June 2019 at Milpark and Roodepoort depots. Village Main depot was excluded from field data collection due to operational constraints.

Table 2. Summary of historical data retrieved

Description	Data
Historical data retrieved	22 months – July 2017 to April 2019
Data resolution	monthly
Asset size	148 buses
Fuel type captured	diesel and CNG
Others	urea (AdBlue) for SCR operation
Depots	Milpark, Village Main, and Roodepoort

The research team faced challenges in collecting accurate fuel consumption data. Diesel fuel dispensed can be traced to each bus using anti-theft technology, but the operational use of this fuel—for example, revenue versus nonrevenue operation—cannot be traced between refueling intervals.[1] Nonrevenue operation occurs when the bus moves from the depot to the start of passenger service and fare collection. CNG consumption data was also not available from the vehicle data. Only the quantity of CNG dispensed can be recorded. Hence, it is difficult to establish revenue-generating versus nonrevenue use of the CNG. Also, diesel substitution with CNG was only established for a period of time. The buses' operational data lack CNG consumption values during a 5-month period, January 2018 to May 2018, due to unspecified technical problems with data capture.

Over the 22-month period from July 2017 through April 2019, the Euro V DDF buses were consuming on average 17 liters of diesel fuel for every 1 diesel-liter equivalent (DLE) of CNG. During this period, a total of 4,514,521 liters of diesel and 260,389 DLE of CNG was dispensed. On average, 205,205 liters of diesel and 15,316 DLE of CNG were dispensed per month (see Figure 2). Field data collected for 90 buses between May 2019 and June 2019 showed that 155,894 liters of diesel, 13,446 DLE of CNG, and 8,288 liters of AdBlue were dispensed; this represented an improved ratio of diesel-to-CNG of 12:1. The total dispensed CNG per month remains below the 45,000 DLE of CNG contracted maximum at the Milpark Depot, which is the only Metrobus depot with a CNG station.

1 Anti-theft technology has been installed at the dispensing unit at Metrobus depots. The anti-theft system involves a bus-specific magnetic reader attached to the tank of each bus that communicates to a magnetic transmitter at the nozzle of the dispensing pump. In order to verify the productive use of the dispensed diesel once the bus is placed into service, it is necessary to review the distance traveled and the estimated fuel economy between service intervals for any anomalies.

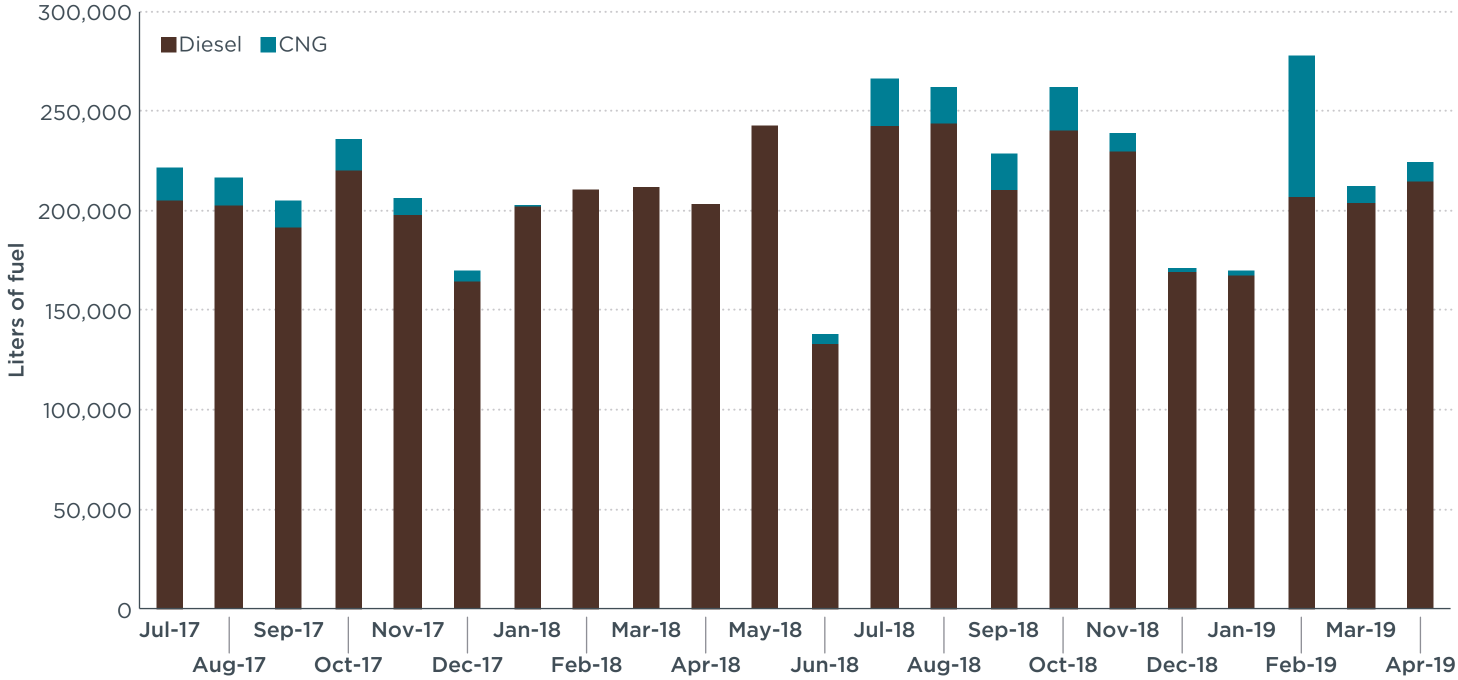

Figure 2. Monthly fuel dispensed. CNG data are missing from January 2018–May 2018.

The average diesel substitution rate across all DDF fleets over the 22-month period was 7%, compared with a 7.3% substitution rate across the 90 DDF buses evaluated during the 2-month field data collection. The monthly data show that the diesel substitution rate ranged between 1.3% and 8.8% (see Figure 3.) A substitution rate of 25.5% was realized in February 2019 for the whole fleet, but this exceptionally high rate appears to be an outlier, as the historical data show a substitution rate that was otherwise consistently less than 10% per month.

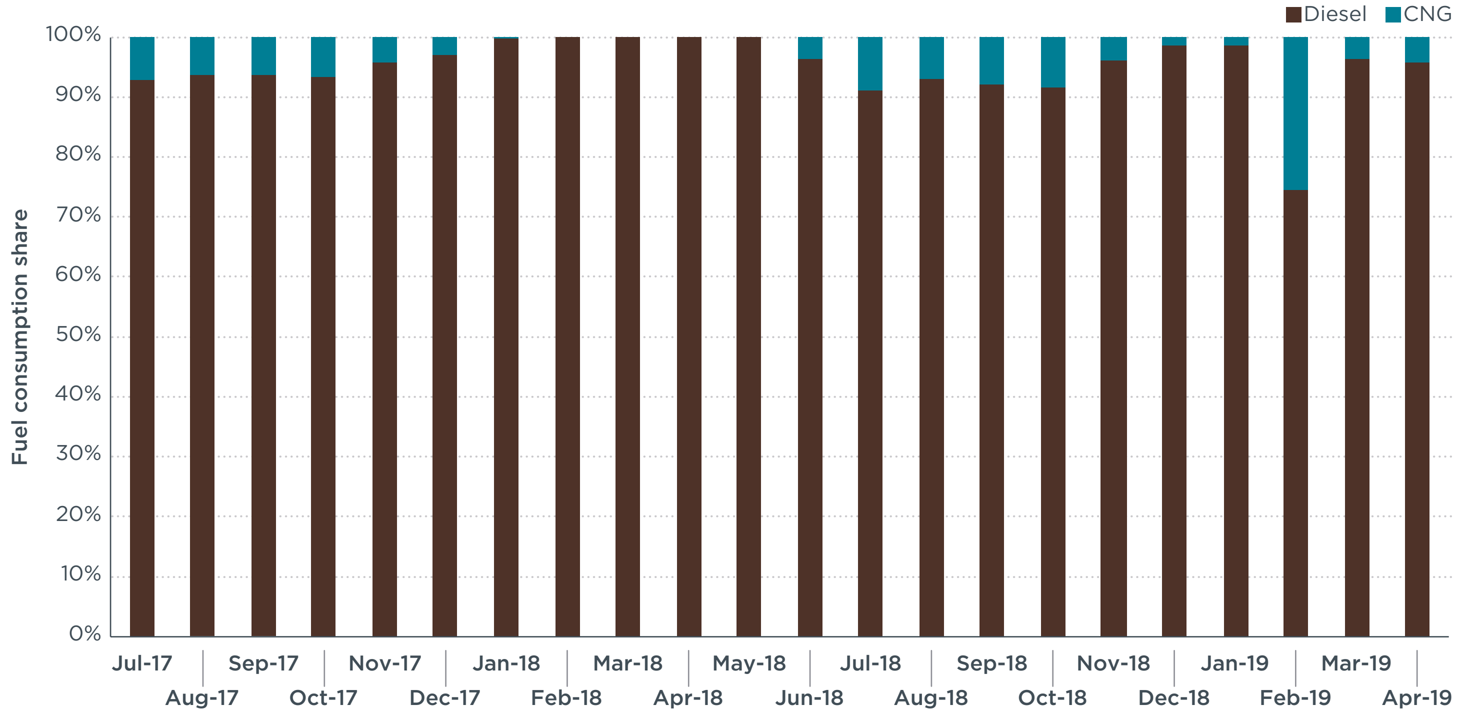

Figure 3. Monthly fuel contribution with diesel substitution rates.

Although some DDF buses in the fleet are delivering substitution rates of up to 30%, many are delivering a substitution rate of zero and that lowers the fleet average. The low average substitution rate is attributed to inconsistent CNG refueling practices. If consideration is given to the 58 buses that were fueled with both diesel and CNG during the field data collection period—recall that the field data collection focused on 90 buses—the diesel substitution rate was 12.6%.

Individual fuel depot consumption and substitution rates were also analyzed. This enabled the connection of depot-specific characteristics and routes frequently plied to fuel consumption and diesel substitution rates. The analysis showed that Village Main Depot consumed the highest amount of diesel, approximately 1.7 million liters for the 22 months covered in the study. Roodepoort Depot, with its fleets travelling the longest distance on average, consumed the least diesel at approximately 1.4 million liters. This is shown in Figure 4.

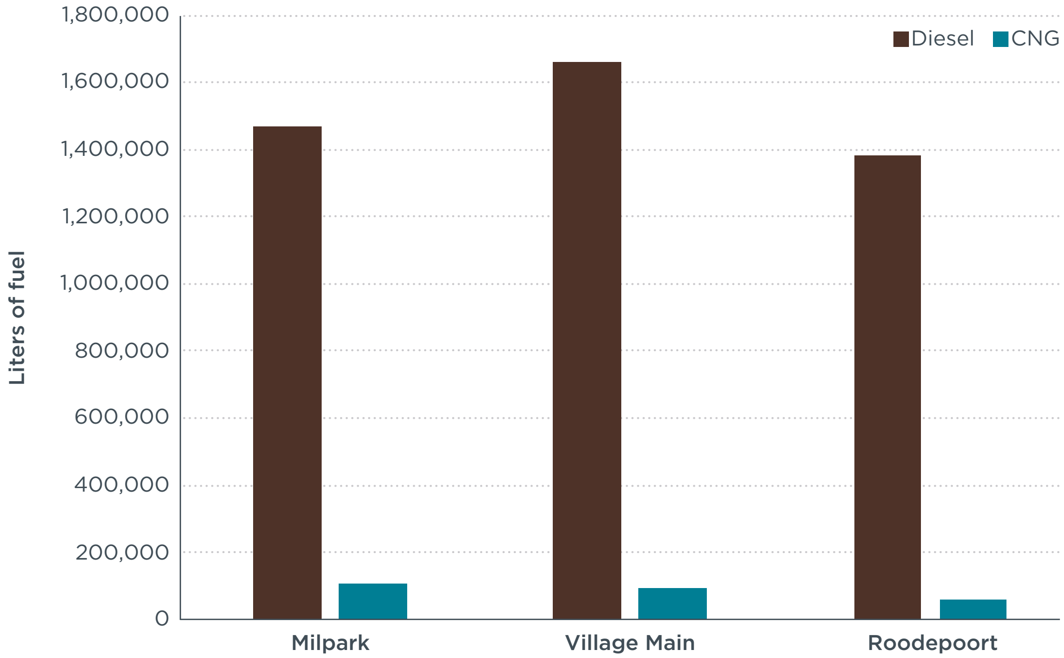

Figure 4. Depot fuel consumption from July 2017 through April 2019. CNG values are presented as diesel liter equivalent.

During the period studied, it was observed that buses at Milpark Depot consumed more gas— 109,216 DLE of CNG—than the other two depots, Village Main and Roodepoort, which consumed 92,081 and 59,091 DLE of CNG respectively. This was due to the presence of an on-site CNG filling station, otherwise called a CNG mother station, at Milpark Depot. Nonetheless, the rate of diesel substitution with CNG for the Milpark DDF fleet is still lower than anticipated, at an average of 7.14%. It was further observed that 48% of the Milpark DDF fleet had less than 5% diesel substitution rate. This performance demonstrates that a CNG mother station does not guarantee a high diesel substitution rate. Although the presence of the CNG mother station is an important factor in the uptake of CNG, other factors must also be considered when rolling out such initiatives to other depots.

AVERAGE DISTANCE TRAVELED

The monthly average distance traveled by the DDF fleet across all depots from July 2017 through April 2019 was about 436,793 kilometers (km). The field-collected data for 90 buses from the Milpark and Roodepoort depots in May and June 2019 show a total distance covered of 333,543 km. According to historical data, buses based at the Milpark depot covered on average 2,271 km per month, whereas those based at the Village Main and Roodepoort depots covered an average of 2,916, and 3,628 km per month, respectively (see Figure 5). This put the per-bus average distance traveled across the three depots at 3,045 km per month. The field data collected on the 90 DDF buses show 3,507 km per month.

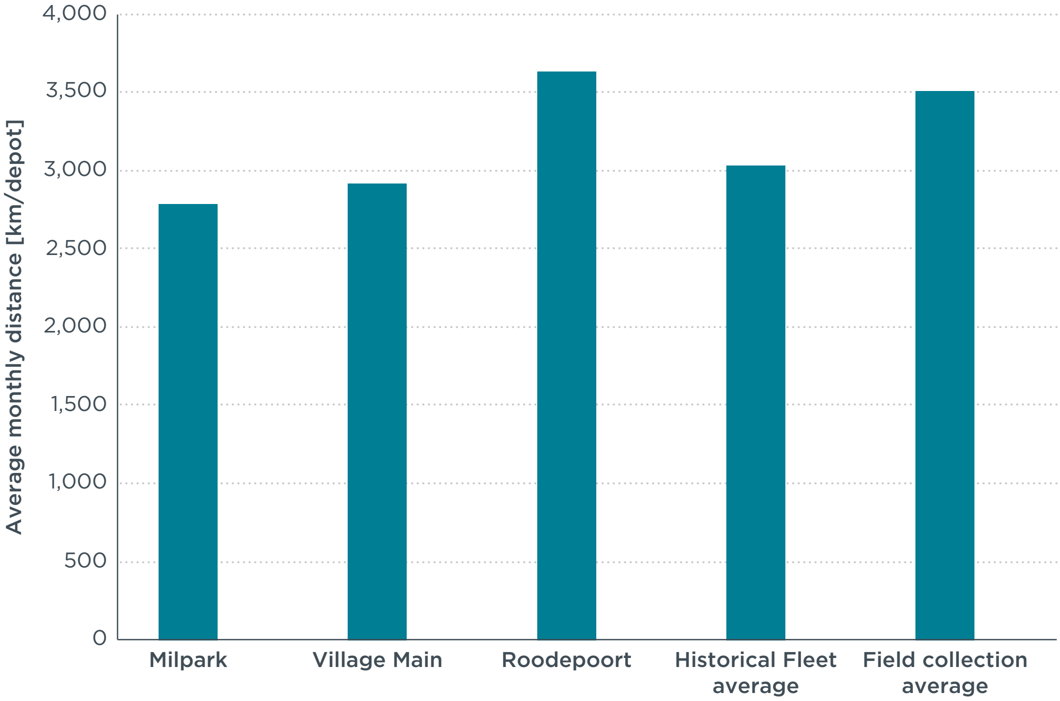

Figure 5. Average monthly distance traveled by the DDF Fleet.

AVERAGE BUS FUEL CONSUMPTION FROM HISTORICAL DATA

Historical data on average bus fuel consumption and the average distance traveled data were used as the basis for calculating average fuel consumption for both the overall fleet and per-depot fleets, expressed as the distance in kilometers per DLE. The average fuel consumption of diesel and CNG across the three depots was 56 DLE/100 km based on the 22 months of historical data. Field collected data put the average fuel consumption at 51 DLE/100 km. The field collected average fuel consumption may be lower than the historical average because of the exclusion of Village Main Depot, which hosts the buses and routes with the highest reported fuel consumption. The historical data show fuel consumption was 60, 56, and 52 DLE/100 km for the Village Main, Milpark, and Roodepoort depots, respectively. It was observed that Village Main Depot reported fuel consumption above the average and in some instances as high as 90 DLE/100 km.

The diesel-only fuel consumption was 54, 52, and 48 liters per 100 km for Village Main, Milpark, and Roodepoort depots, respectively, based on the reported historical data. The low fuel consumption for the DDF fleet resident at Roodepoort could be due to the routes usually served, which are characterized by longer drives at higher speed with fewer traffic lights compared to routes of fleets resident at Village Main Depot.

REFUELING PRACTICES

Historical data show that on average, 75% of the DDF fleet did not fuel with CNG during the 22 months reported. This is shown in Figure 6. During the field data collection period, 64% of the 90 DDF buses analyzed were fueled with CNG. Further analysis of the 22 months of reported historical data indicated that only 4% of the fleet was fueled with more than 400 DLE of CNG per month. The field data, meanwhile, show that only 11% of the 90 DDF buses were fueled with more than 400 DLE of CNG. This shows that, during the field data collection, more effort was put into fueling with CNG at the Milpark and Roodepoort depots. Despite the attempt, however, low substitution rates across the fleet account for the overall low CNG consumption.

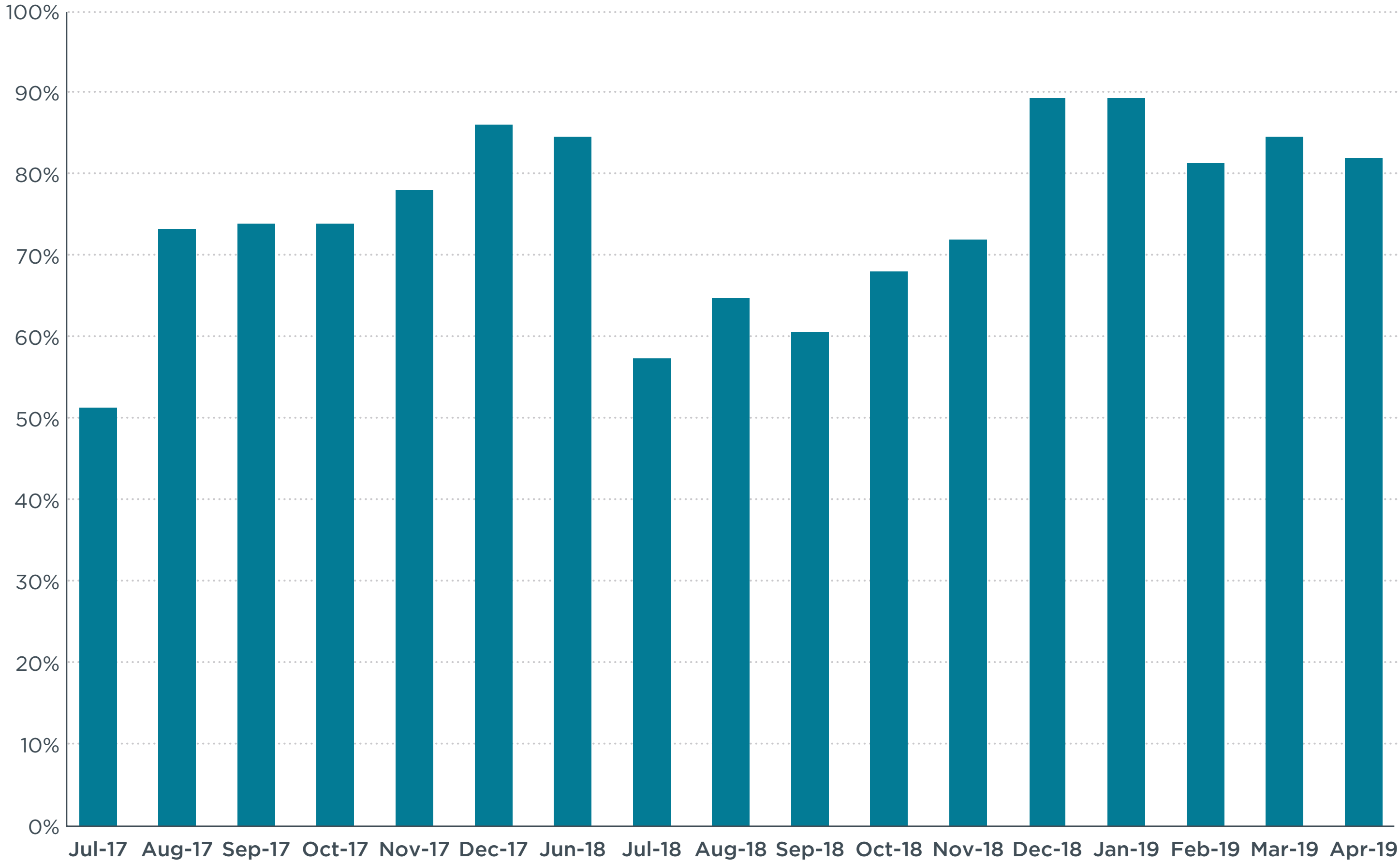

Figure 6. Monthly percentage of buses not fueled with CNG.

OPERATING COSTS AND FUEL SAVING POTENTIAL OF DDF BUSES

CNG is cheaper per liter equivalent than diesel fuel. The dispensing prices for CNG and diesel at Metrobus Milpark Depot were South African Rand (R) 8.99/DLE and R 11.39/L, respectively, at the time of data collection. These costs are lower than market rates (R 9.99/DLE and R 14.88/L for October 2019) due to infrastructure ownership by Metrobus. The cost to Metrobus for operating 100% on diesel based on fuel rates at the depot is R 1.25/km. By substituting with CNG at the average fuel substitution rate, the cost to Metrobus is R 1.19/km. Considering the variable substitution within the historical (7.0%) and field-collected data (7.3%), the fuel savings Metrobus is achieving was calculated to range between R 0.0968/km and R 0.1008/km.

As a result, the monthly savings for the whole DDF fleet range between R 44,950 and R 52,930.[2] This assumes that the 148 buses cover on average 3,045 km per month and all use CNG at the average substitution rate. The fuel-cost saving potentials are based

2 These are not the final fuel cost savings. Metrobus incurs a monthly opportunity cost for gas not consumed due to the structure of its current contract with CNG Holdings. CNG Holdings also charges a maintenance fee to Metrobus for its refueling infrastructure at Milpark Depot.

on the observed average substitution rate for the DDF buses using the dispensing fuel prices at Metrobus.

Current diesel substitution rates are not enough to quickly recover Metrobus's original investment in CNG technology. According to Metrobus, the CNG fueling infrastructure cost R 6,100,000. At current substitution rates it would take approximately 10 years of fuel savings to recover that cost. Additionally, the contribution of savings from the current level of diesel substitution to the total cost of ownership of the buses will be minimal over a 15-year operational life with a typical engine overhaul expense at about 5 years. In an interview with Metrobus, it was noted that after 12 years, the operational and maintenance costs of its buses escalate significantly.

ENVIRONMENTAL PERFORMANCE OF DDF BUSES

DDF technology is rarely found in urban bus fleets. This niche technology presented challenges to the research team in terms of evaluating environmental performance because there is no academic literature that shows tailpipe emissions from this particular application of diesel and CNG. To address this gap, ICCT and the University of Johannesburg (UJ) commissioned bus emissions testing to verify the emission levels of DDF technology under real-world driving conditions along representative Metrobus routes.

The West Virginia University (WVU) Center for Alternative Fuels Engines and Emissions (CAFEE) was contracted to procure and deploy a portable emissions measurement system (PEMS) and use vehicle testing methodologies applied for heavy-duty engine certification to measure real-world emissions performance. Such testing has been incorporated into emission certification procedures for soot-free Euro VI and EPA 2010 engines.

REAL-WORLD EMISSION MEASUREMENT METHODOLOGY

Emissions testing of two Euro V DDF Metrobus buses was carried out along three different Johannesburg service routes in November 2019. The PEMS system and additional instrumentation were calibrated at CAFEE and shipped from Morgantown, West Virginia, to Johannesburg. The WVU research team collected emissions data over a period of two weeks.

TEST DESIGN

Two Euro V DDF buses were selected from a pool of DDF buses that were deemed in the best mechanical and operating condition in Milpark Depot. Three test routes—7A, 5D, and 80D—were selected from all current service routes. Each route represents different levels of speed conditions, from low average speeds that are found in urban areas to high-speed driving routes with a large share of highway operation. Each bus-route combination was tested twice. All buses were tested with a properly functioning DDF system, which implies that the diesel and CNG share was selected by the engine fueling engine control unit (ECU) commands; an additional fueling condition was tested where the CNG valve was manually closed to simulate the findings of most DDF buses operating without CNG. The buses were operated in Metrobus service routes without passengers but with sandbags representing passenger load. Table A1 in the appendix details the test matrix for the buses tested.

INSTRUMENTATION

WVU imported into Johannesburg a state-of-the-art PEMS from AVL (Gas PEMS iX). This PEMS unit is capable of measuring nitrogen oxides (NO and NO_2), carbon monoxide (CO), CO_2, total hydrocarbons (THC), and methane (CH_4). Particulate matter data was captured but is not presented here due to reporting challenges. Additional data captured consisted of ambient weather conditions including temperature, barometric pressure, and humidity. Vehicle speed, location, and altitude were recorded using a stand-alone GPS receiver. Tailpipe exhaust flow was measured using a 4-inch exhaust flow meter (EFM). More instrumentation details are provided in the appendix.

Figures 7 and 8 show the PEMS equipment set up in a Metrobus bus. Figure 7 shows the back of the bus, where the original bus exhaust pipe was replaced with the EFM and the sampling line that carries exhaust gases to the analyzers. The sampling line was carried from the exhaust pipe to the PEMS gas analyzer through panels below the last seating row, which is shown in Figure 8.

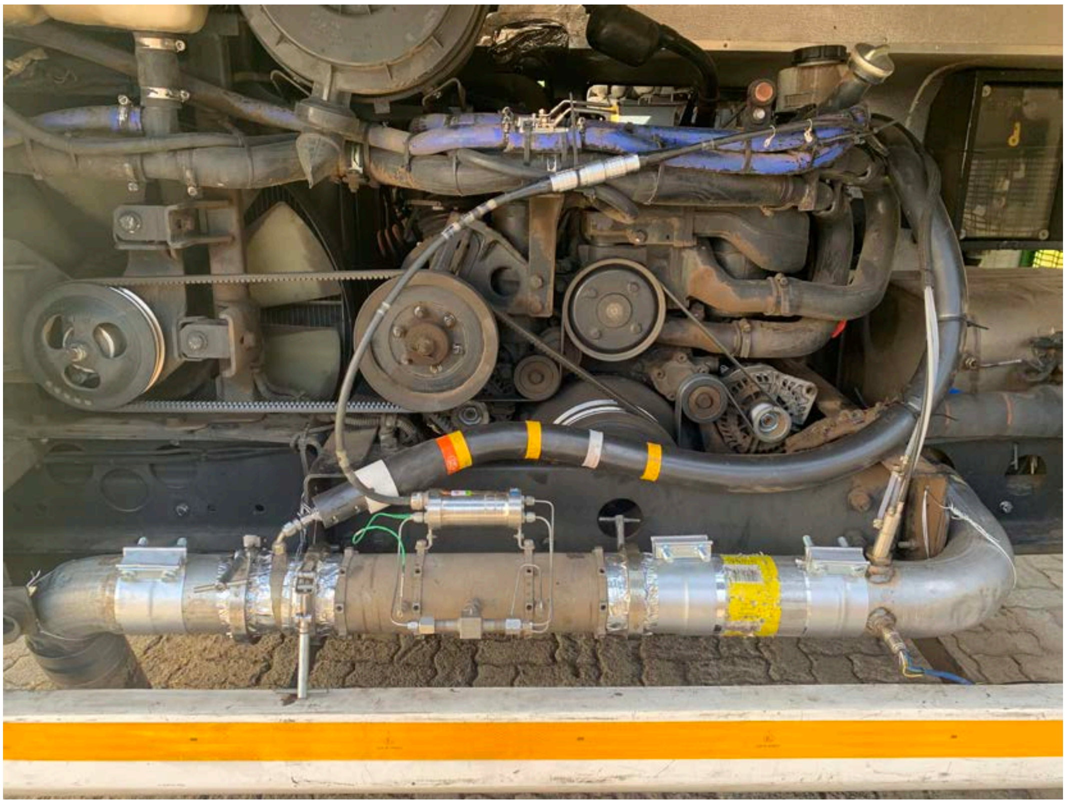

Figure 7. EFM and sampling line installed in the back of Metrobus bus # 2097. Source: WVU

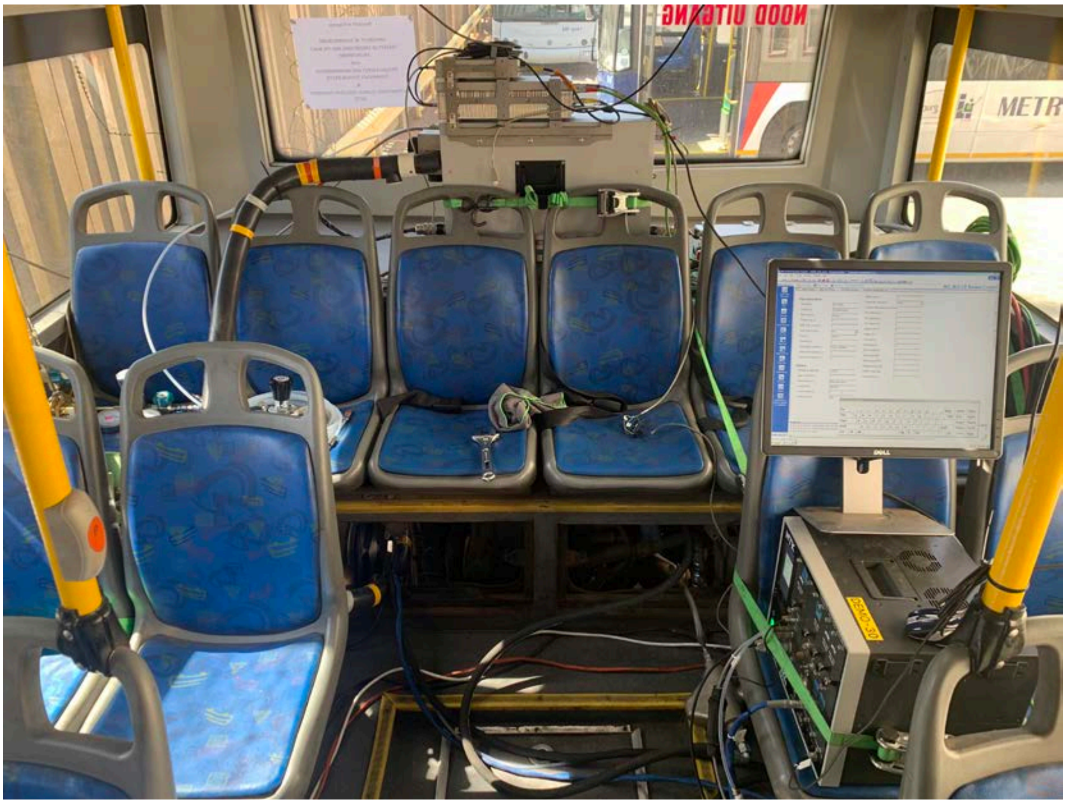

Figure 8. AVL PEMS installed in Metrobus bus # 2097. Source: WVU

TEST ROUTES

Routes for the testing were discussed with Metrobus and covered a range of characteristics: low speed, with multiple stops; medium speed, characteristic of suburban driving; and high speed, mainly highway driving. We also sought routes with both flat and hilly terrain to reflect variable loads on the engine. The selected Metrobus routes that satisfy these criteria are presented in Table 3.

Table 3. Bus testing routes in Johannesburg

Test route	Bus route code	Description	Driving mode	Distance (km)	Average duration (h)	Average speed (km/h)	Number of stops
Route 1	7A	Gandhi square to Centurion	Urban/ highway	68.9	2.1	32.3	42
Route 2	5D	Gandhi square to Sunninghill	Urban	35.2	1.7	20.8	74
Route 3	80D	Gandhi square to Fourways to Dainfern	Urban/ suburban	32.0	1.2	26.5	57

The test routes selected covered a wide range of driving conditions representative of bus driving in the city of Johannesburg and neighboring areas. Figure 9 presents the test routes on a regional map. Route 1 includes a large share of highway driving, higher average speeds, and fewer stops. Route 2 is a stop-and-go urban driving route, with low average speed and the most stops among the test routes. Route 3 combines urban and suburban driving conditions and average bus speeds.

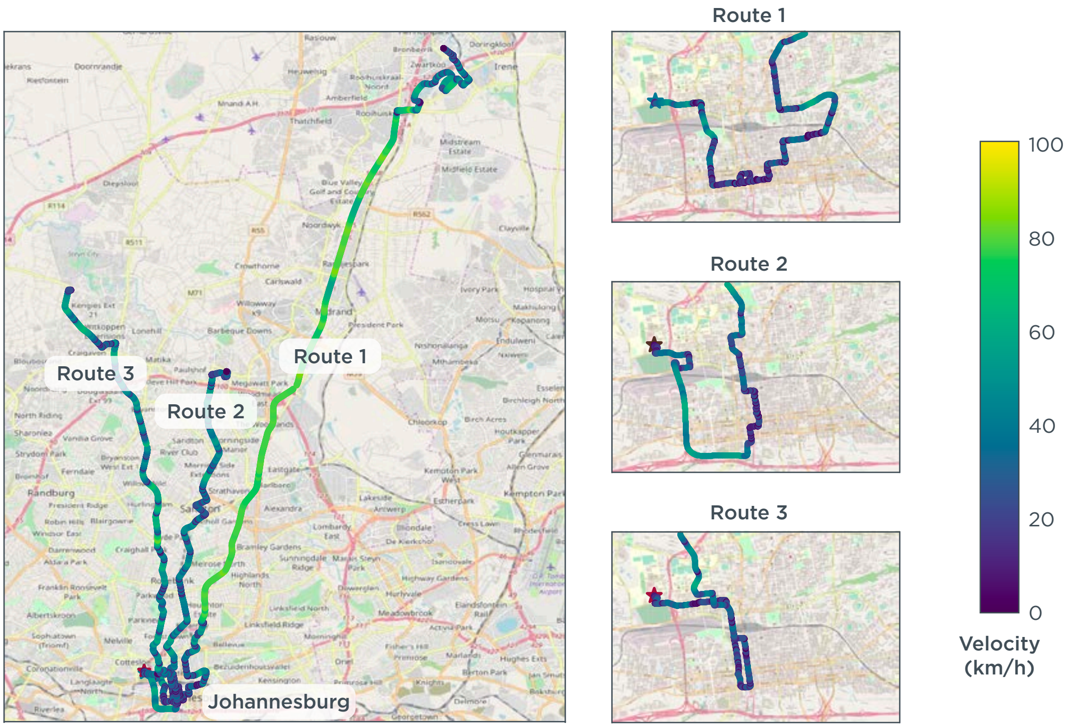

Figure 9. Test routes and speed values recorded. Boxes on the right show Johannesburg's Central Business District.

DATA ANALYSIS

Bus emission values were determined based on second-by-second data from the two Euro V DDF buses. The analysis uses data from all engine and vehicle operating conditions, including all power, torque, and engine rpm conditions, cold-start periods, and exhaust temperature conditions. This best captures the overall picture of emissions under real-world driving conditions. The key focus of our analysis was to gain an understanding of overall emissions performance of DDF vehicles under the default DDF fueling operation and under the diesel-only (no-CNG) option found during the first section of the data collection program.

In two cases PEMS data were filtered out for the purposes of our analysis:

» The "zero-check" condition, in which the PEMS instrument auto-zeros itself while the rest of the parameters remain live.

» Times when the on-board diagnostics (OBD) stream is interrupted for various reasons; this results in invalid data, with "blanks," "null," or "NA" strings in the data output.

The metrics presented here are distance-specific emissions, in grams of pollutant per distance driven. Work-specific emissions (g/kWh) were not available because the ECU data captured via OBD was not compliant with harmonized communication protocols. This is an issue common to all pre-Euro VI vehicles.

TEST RESULTS

Test results for both buses and fueling conditions are shown in Table 4 for local pollutants and in Table 5 for GHGs (CO_2 and CH_4). Results of the PEMS tests show that the DDF mode presents some emission benefits as well as some challenges. NO_x emissions were reduced under DDF operation by 4% to 20% compared to diesel-only operation. On the other hand, CO emissions increase by a factor of three under DDF operation. During DDF operation, THCs increase by two orders of magnitude compared to diesel-only operation. This increase in THC is driven by CH_4 emissions, which are at instrument detection limits under diesel-only operation and increase by 110 times when CNG is used under DDF fueling mode.

Table 4. PEMS measured tailpipe criteria pollutant emission from two Euro V DDF buses

Bus	Fueling	NO_x, g/km	CO, g/km	THC, g/km	NMHC, g/km	CH_4, g/km
1	DDF	2.91 ± 0.77	0.65 ± 0.31	5.08 ± 1.01	0.14 ± 0.1	5.15 ± 0.79
	Diesel	3.65 ± 2.28	0.2 ± 0.09	0.05 ± 0.06*	0.34 ± 0.47	0.05 ± 0.05*
2	DDF	2.55 ± 0.58	0.29 ± 0.29	4.15 ± 2.33	0.14 ± 0.07	4.11 ± 2.25
	Diesel	2.64 ± 1.38	0.1 ± 0.09	0.03 ± 0.03*	0.04 ± 0.04*	0.03 ± 0.03*
Average of bus 1 and 2	DDF	2.77 ± 0.65	0.51 ± 0.33	4.71 ± 1.46	0.14 ± 0.08	4.73 ± 1.38
	Diesel	3.15 ± 1.77	0.15 ± 0.1	0.04 ± 0.04*	0.19 ± 0.34	0.04 ± 0.04*

*Instrument detection limits

GHG emission results are presented in Table 5. The GHG emissions are presented here as CO_2 equivalent (CO_2e) emissions, or the summation of tailpipe CO_2 emissions and the product of tailpipe CH_4 emissions and its global warming potential (GWP). The 100-year and 20-year GWP factors for CH_4 were obtained from the Intergovernmental Panel on Climate Change (IPCC) Assessment Report 5 (AR5), which normalizes the climate forcing impact of methane into CO_2e. For CH_4, the 20-year GWP is 86 and the 100-year GWP is 36 (IPCC, 2013).

DDF operation provides improvements in distance-specific CO_2 emissions, but high CH_4 emissions negatively impact its GHG performance. Average distance-specific CO_2 emission values show that DDF emits about 16% to 20% less CO_2 per kilometer driven than diesel-only operation. CH_4 emissions, on the other hand, were more than 100 times higher during DDF operation than during diesel-only mode. As a result, the DDF operation's GHG emissions over a 100-year time frame are about 8% higher than the diesel operation mode. Over a 20-year time frame, the DDF operation emits 40% more GHGs than operation in diesel mode.

Table 5. PEMS measured tailpipe greenhouse gas emission results for two Euro V DDF buses in Johannesburg

Bus	Fueling	CO_2, g/km	CH_4, g/km	gCO_2e/km 20 years GWP	gCO_2e/km 100 years GWP
1	DDF	979 ± 326	5.15 ± 0.79	1422 ± 394	1113 ± 347
	Diesel	1163 ± 18	0.05 ± 0.05*	1167 ± 21	1164 ± 19
2	DDF	646 ± 209	4.11 ± 2.25	999 ± 402	753 ± 268
	Diesel	803 ± 180	0.03 ± 0.03*	806 ± 178	804 ± 179
Average of bus 1 and 2	DDF	846 ± 312	4.73 ± 1.38	1388 ± 329	1071 ± 296
	Diesel	983 ± 228	0.04 ± 0.04*	986 ± 228	984 ± 228

*Instrument detection limits

Comparisons of Euro V DDF buses adopted by Metrobus against other bus types run with diesel and CNG can provide an idea of the relative benefit and challenges of this type of novel technology. We compared emissions from Metrobus Euro V DDF buses against legacy Metrobus diesel Euro 0 to Euro II buses (labeled here as non-DDF), and Euro V and Euro VI diesel and CNG buses. Euro VI bus data are included here as a benchmark for what is possible with soot-free buses running with fossil fuels.

Focus is placed on three pollutants: NO_x, nonmethane hydrocarbons (NMHC), and CH_4. The first two are ground-level ozone (O_3) precursors and can cause breathing problems, asthma, reduced lung function, and lung disease (World Health Organization, 2013). CH_4 is of interest for comparison because PEMS test data show excessive CH_4 from DDF operation on a distance-specific basis, and CH_4 is a potent GHG. The emission values for non-DDF diesel buses, and Euro V and Euro VI buses, were obtained from average emission factors sourced from the Handbook Emission Factors for Road Transport (HBEFA), a European emission factor model used widely in emissions inventory development applications (INFRAS, 2019).

The metric used for comparing the PEMS data from DDF buses with HBEFA data from European buses is grams of pollutant per kilogram of CO_2 emitted. This CO_2 specific metric is useful for comparing across testing methods and loading conditions. It removes the effect of the vehicle load—the combined weight of bus chassis and passengers, which is not known—from the resulting emission value.

Compared to legacy Metrobus buses, Euro V DDF buses provide significant benefits by reducing the ozone precursors NO_x and NMHC. As Figure 10 shows, DDF buses provide a 70% reduction in NO_x emissions and a 62% reduction in NMHC emissions.

In comparing Euro V DDF buses against similar Euro V buses, we see mixed results. NO_x emissions from Euro V DDF buses are 33% lower than Euro V diesel bus emissions, but also about 1.8 times higher than dedicated Euro V CNG buses. NMHC emissions from DDF buses are 4 to 6 times above the average values of Euro V diesel and CNG buses.

Compared to soot-free Euro VI bus technology, DDF buses emit NO_x and NMHC at levels 10 to 100 times higher. This highlights how DDF is an excellent intermediate technology in the move toward soot-free, cleaner technology, but an eventual transition to Euro VI is needed to reach air quality and decarbonization goals.

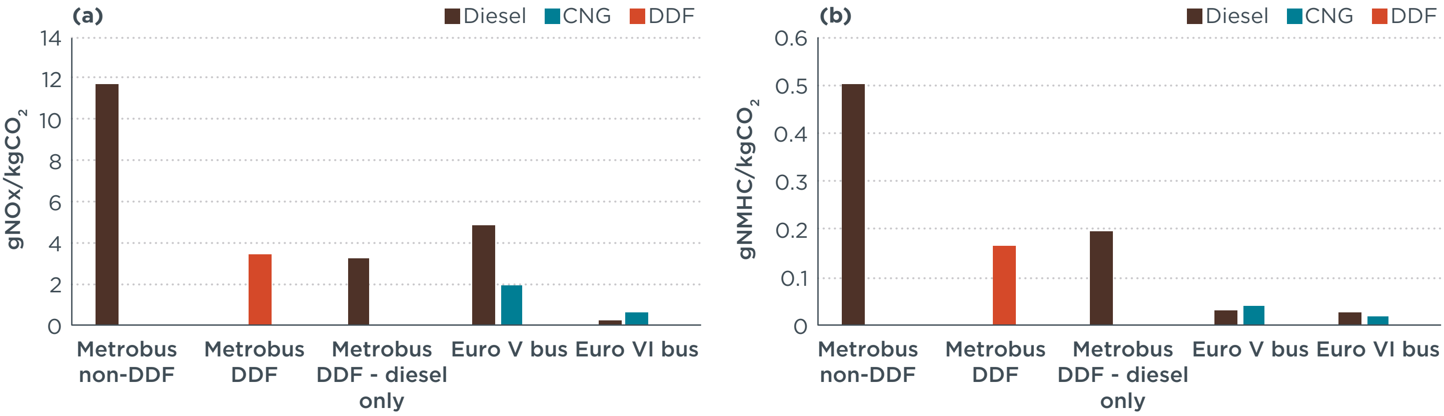

Figure 10. Comparison of CO_2-specific NO_x (a) and NMHC (b) emissions from DDF (dual and diesel-only mode) and other bus technologies.

Figure 11 compares CO_2-specific emissions of CH_4 from DDF buses and other select technologies. Metrobus Euro V DDF buses operating under the dual-fuel mode with diesel and CNG emit 12 times more CH_4 per gram of CO_2 emitted than dedicated CNG Euro V buses. This indicates that sizable amounts of CH_4 are not ignited in the engine cylinder during DDF mode and are not being oxidized in the aftertreatment system.

This suggests that the Euro V DDF engine may have not been properly certified to meet the Euro V emission standard for CH_4, which applies to CNG dedicated engines. Diesel engines are not required to meet CH_4 emission limits during Euro V engine certification. One issue that was not explored during the PEMS testing was the potential for CH_4 bypass through the piston rings and into the crankcase, which would add to crankcase emissions of CH_4 that go undetected.

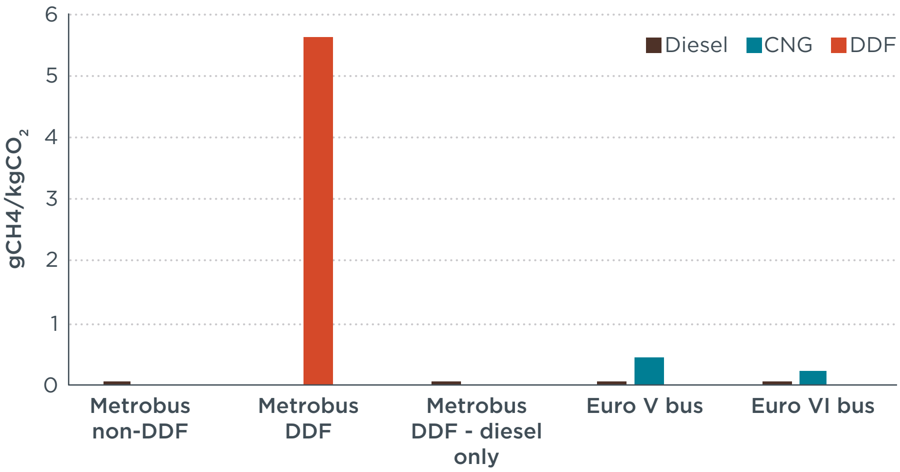

Figure 11. Comparison of CO_2-specific CH_4 emissions from DDF, dual and diesel-only mode, and other bus technologies.

The tailpipe emissions of GHGs from the DDF buses tested are compared against other similar buses in Figure 12 over a 20-year and 100-year time frame. GHG emissions here include CO_2 and the global warming potential of CH_4. The metric used is grams emitted per distance driven. Over a 20-year time frame, GHG emissions from Euro V DDF buses are slightly lower than legacy Metrobus buses. Although CO_2 emissions are much lower, the warming contribution of CH_4 reduces the fuel efficiency benefit, and CH_4 emissions from DDF operation are more than 30% of the total GHGs emitted by these buses. Excessive CH_4 emissions from DDF buses result in higher GHG emissions over 20 years than all other technology options available today in global markets. Over a 100-year time frame, GHG emissions from DDF buses tend to be more in line with advanced technologies.

It should be noted that a 20-year time frame analysis better reflects the urgency of reducing GHGs to reduce global warming, as well as the timelines to meet goals for 2030 and 2040 set by the Republic of South Africa and the city of Johannesburg, respectively. This time frame is also more representative of the useful life of a bus in an urban fleet.

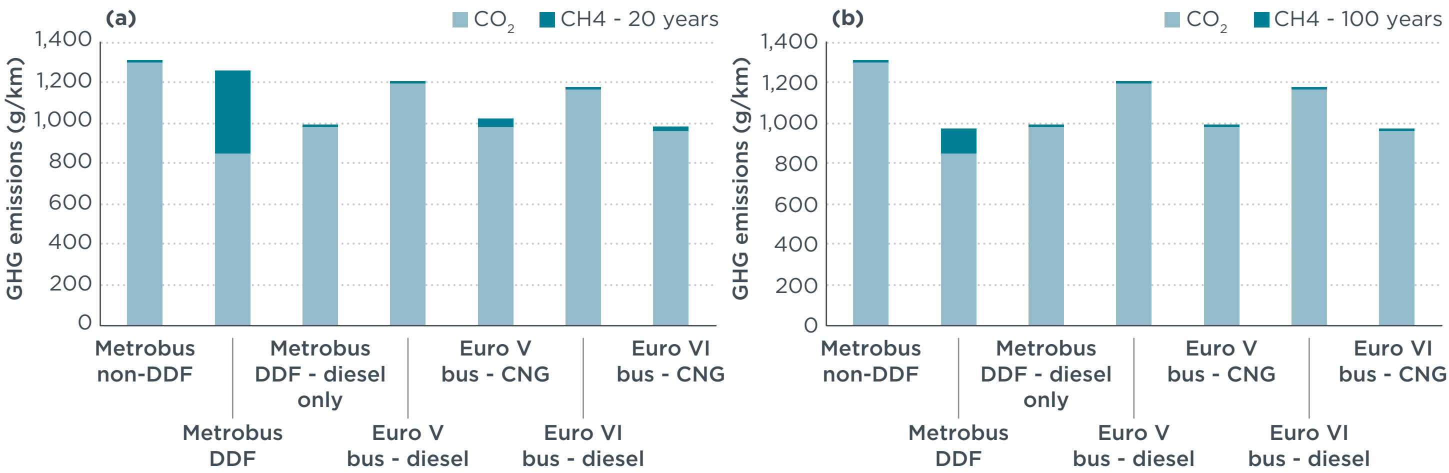

Figure 12. Comparison of distance-specific GHG emissions from DDF, dual and diesel-only mode, and other bus technologies, with (a) showing 20-year time frame results and (b) showing 100-year time frame results.

GUIDELINES FOR PERFORMANCE IMPROVEMENT OF DDF BUSES

This section focuses on understanding the barriers to adoption of the DDF technology and presents guidelines for Metrobus to achieve the full environmental and economic potential of DDF. A gap analysis that looks at challenges related to DDF fleet operation is presented first, followed by suggestions for addressing those gaps. The gap analysis was carried out by direct, on-the-ground interviews with Metrobus staff at the management and operations levels. The guidelines and proposed solutions are DDF bus fleet improvement strategies and are based on the observed gaps in the technical, operational, and knowledge areas. A change management strategy is also outlined to guide Metrobus management and staff toward successful DDF fleet operation.

GAP ANALYSIS

TECHNICAL GAPS

Technical barriers of interest are those that stem from CNG refueling practices and infrastructure, and the DDF bus technology itself.

CNG USE

During the data collection phase, it was identified that DDF buses were operated below maximum possible substitution rates. Possible causes for the low substitution rate of diesel with CNG were:

- Closing off the CNG valves that supply CNG to the combustion chamber from the bus tanks
- Complaints of repeated loss of power during low-speed driving conditions
- Refueling problems went unreported or were not sufficiently documented, which made it difficult to implement corrective actions
- The lag time between when a fault is noted on the bus's CNG system and when it is rectified. The DDF bus CNG system is divided into two sections, low- and high-pressure. Each section is maintained under different contracting practices: Mercedes-Benz technicians address problems on the low-pressure side and CNG Holdings technicians address problems on the high-pressure side and certify the CNG system is safe to use.
- Potential leakage of CNG. Interviews with Mercedes-Benz technicians showed that they have noticed lack of pressure with CNG on the buses quite often despite refueling attempts. Hence, both high CNG dispensed to the buses and high diesel dispensed were noted in some of the buses. Note that there were limited opportunities and instruments to explore and measure this claim.
- Lack of confidence in the CNG system. During interviews, repetitive technical problems with CNG systems were reported. These included false pressure reading, faulty valves that restrict CNG from being used by the bus, and lack of an on-site technician to check that the CNG system is working.

CNG INFRASTRUCTURE

There is only one Metrobus depot with a CNG refueling station (Milpark Depot). This creates challenges for supplying CNG to buses not housed in that depot.

- Depending on the route and bus utilization, DDF buses usually operate for 2–5 days before refueling CNG. However, such frequency is not possible for buses housed at depots without a CNG refueling station because that requires nearly 44 km of dead mileage to refuel.

- The above suggests that all DDF buses must be housed exclusively in Milpark Depot and that additional CNG fueling stations need be built to accommodate additional future DDF buses. This is key to avoiding deadhead or nonrevenue operation, which results in excess emissions, fuel consumption, and loss of revenue.
- In the long term, installing a CNG refueling station at each depot should be a priority if there is to be an increase in the number of DDF buses in the fleet.

BUSES

Part of the change management process is demonstrating management's commitment to understanding the ground-level challenges and addressing them with proper methods.

- Feedback from the drivers is that the DDF fleet was not performing as well as the standard diesel buses. Drivers are experiencing problems including loss of power, specifically when driving uphill, and there are complaints of overheating.
- The data confirm that most DDF buses are not being refueled with CNG.
- The maintenance team indicated that the drivers were not aligned with the technology changes. This may indicate a gap in training to operate DDF technology.
- Bus overheating was also reported, especially in the summer season. This problem may not be particular to the DDF buses and requires further investigation.
- In an interview with Metrobus staff, it was noted that there was no prior study of the fleet-route allocation strategy for the purposes of optimizing the deployment of the DDF buses and promoting increased diesel substitution with CNG.

PROCESS GAPS

Regular feedback loops are very important in driving continuous improvement. Information flow and reporting processes within Metrobus were investigated with regard to diesel and CNG consumption.

- The current bus performance and fuel consumption data collection process does not allow for effective and efficient processing. There are different control points and data collection points related to fuel and CNG consumption as well as distance traveled. The technical team first records the diesel pumped and CNG and odometer readings per asset number daily on a sheet of paper. Thereafter, data are transferred onto an electronic spreadsheet. These data are collated into monthly management reports and fuel consumption per 100 km traveled is calculated. Although the reports are shared with management, the information is not reaching the ground-level employees. The reporting period is generally a month and the feedback loop is too long.
- When evaluating the recorded data, it was observed that there were many data capture errors, specifically pertaining to the date, diesel amount, and odometer reading fields. The spreadsheet is split into individual monthly sheets, making annual trends difficult to calculate. The data also are not mass balanced and correlated to the diesel and CNG purchased. The errors found on the electronic spreadsheets suggest that the procedure used to verify and reconcile manually recorded values needs improvement.
- The data collected by Metrobus showed evidence of outliers in some buses' fuel consumption. The management of Metrobus should investigate these cases of outliers in fuel consumption data in more depth to reduce and eliminate inefficiencies in bus refueling practices or in data acquisition methods.

KNOWLEDGE GAPS

The key to maximizing the economic and environmental benefits of new technology lies in the technology itself and in the hands of those who are using it on a daily basis. The following knowledge gaps were identified:

- The benefits of DDF technology are known by those in upper and middle management at Metrobus, but there is a gap in knowledge transfer to drivers and ground operations.
- At the ground level, the bus drivers do not understand the reason for changing to the dual-fuel system. Some drivers interviewed could not explain satisfactorily the benefits of CNG or the function of AdBlue for NO_x control and SCR operation. It was observed that the DDF bus performance feedback information is also not reaching the ground-level employees.
- Loss of power during DDF operation was noted both by drivers and by the vehicle supplier, Mercedes-Benz. A gear lock mechanism on the vehicle will automatically switch to low gear, but drivers may not be aware of how to disengage this feature. Training on appropriate use of the gear lock mechanism is necessary, as is the tracking and investigation of any power loss incidents on DDF buses.

CHANGE MANAGEMENT INTERVENTION

Change management is defined as the process by which an organization leads its staff through a shift in behaviors necessary to successfully transition to new systems, including technology changes (Hayes, 2018). Organizations from all sectors embark on different approaches to change management to better their performance and promote success and growth. One classic example of change management is Toyota's Production System, which helped make Toyota the top vehicle manufacturer in the world (Takeuchi et al., 2008). Adopting such an approach would be helpful for Metrobus.

After the initial evaluation of the challenges facing Metrobus and taking into consideration the willingness of management to participate in an improvement program, the following practical and executable solutions have been identified.

TECHNOLOGY SOLUTIONS

- A review of overheating and loss of power incidents with respect to DDF and non-DDF buses should be conducted. The findings of the review and strategies for mitigation should be discussed with and presented to bus drivers and maintenance staff.
- Conformity of compliance (COC) of DDF buses should be a priority for management and maintenance staff, and vehicles should be monitored periodically for COC validity according to South African CNG vehicle safety protocols. Safety checks should be scheduled and executed, and the results reported to managers and maintenance and drivers.
- The availability, functionality, and prompt replacement, when necessary, of gas safety sensors should be prioritized. This way, drivers can be sure that the vehicle's safety systems are operating at all times.
- The Metrobus maintenance team and the Mercedes-Benz technicians should evaluate all buses to establish the operational state of the installed CNG systems. That translates into providing evidence of updated COC certificates, maintenance work, and the condition of the CNG systems, specifically tanks and fuel lines. Sharing this information would help reduce the resistance to operating the DDF system.
- Lag time between fault identification and repairs should be minimized. This would address staff concerns. The perceptions of the drivers and members of the maintenance team need to be considered; when issues are reported, a technical analysis should be carried out to confirm the issue, find the root causes, and correct them.

SOLUTIONS FOR PROCESS GAPS

It is recommended that Metrobus adopt an integrated fleet management tool to not only optimize the performance of the DDF fleet but also to control fuel consumption and provide a guide for the drivers and maintenance teams so that they can continuously improve their performance. Specific recommendations are:

- Develop and implement a digital and centralized fuel consumption and performance reporting system. The current bus operation and fuel use data capture system, which consists of separate electronic spreadsheets, is not an effective management tool. Both diesel and gas consumption should be documented.
- A real-time bus management system should include real-time recording of diesel and CNG consumption and kilometers traveled, as well as a logging system to report errors and driver behavior. This will help gauge the performance of DDF technology under different operating conditions and optimize the system.
- This system should be integrated with fueling station data with a mass balance capability to capture deviations between purchase and consumption of diesel, CNG, and AdBlue.
- Periodic tracking of depot fuel consumption, total distance traveled, fuel consumption, and diesel substitution should become standard practice. Data should be reported by route and driver. This information should be shared with drivers and the maintenance crew at least monthly.
- There is currently no indicator inside the bus that shows the ratio of CNG to diesel usage during driving. Drivers indicated that if they had some form of display on the dashboard of the bus, it could assist with awareness and enhance their ability to understand bus performance. The bus manufacturer and CNG provider should be approached to build an indicator onto the dashboard of the bus. This information could be recorded electronically to enable real-time analysis of the performance of the buses by route.
- The data can further be utilized to build prediction models and route optimization strategies. This would allow management to reallocate some of the buses to routes more favorable to DDF performance.
- During a session with management, the benefits of being more transparent and creating feedback loops to the drivers and maintenance teams was discussed. These discussions also included continuous improvement that is possible from engagement with a cycle of Plan, Do, Study, and Act. This further highlighted the importance of regular feedback for not only the management staff but also the ground-level staff.

SOLUTIONS FOR KNOWLEDGE GAPS

The lack of awareness of the benefits of CNG at the driver level was identified as the main barrier to a collective acceptance of the DDF bus technology. Training and retraining sessions are recommended for the drivers.

- A process must be established for developing and implementing strategies for training and management of communications in order to reap the benefits of investing in the DDF technology.
- Knowledge sharing should be facilitated by Metrobus management and led by the internal maintenance team and Mercedes-Benz personnel. The focus should be on all ground-level personnel. Training for DDF bus drivers can be developed to increase exposure to and operational experience with the technology and its potential. Developing the needed skill set among drivers will increase their ability to overcome operational and technical challenges and can lead to overall higher skill development within the driver pool.

- Improve the communication links between the maintenance and operations departments. To ensure a good interface between ground-level staff and top management personnel, a transparent communication mechanism is needed. Feedback sessions with supervisors and drivers must be arranged where specific cases can be discussed, and this can also be a platform to discuss ongoing challenges. Currently, there are daily logs in which the drivers record problems experienced. A direct engagement between the maintenance team and the driver to explain the cause of the problem and the solution to it will improve the confidence of the drivers in the DDF technology.
- Improve engagement and communication with bus drivers. Maintenance personnel, operations supervisors, and the refuelers at the fueling station could all play a key role in creating awareness and motivating drivers to embrace the technology. If a computer station is installed at the fueling station, the refueler could call up the specific asset or bus driver information from the online dashboard system and discuss the results with the driver while the bus is being fueled. Similarly, workstations can be installed for supervisors where they can access the dashboards and discuss the results with their team. Awareness and online training videos could be incorporated into the system, as could a logging system to capture complaints and suggestions. The latter would give direct feedback to the maintenance and technical teams as well as the management staff, enhancing transparency and giving the ground-level operators a channel to voice their suggestions and challenges.

Developing and implementing these recommendations will require commitment from Metrobus managers and allocation of sufficient funds to accomplish the needed changes. Doing so will address current system gaps, ensure optimum DDF operation, and achieve the expected economic and environmental goals.

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APPENDIX

PEMS TESTING DETAILS

TEST MATRIX

The PEMS test matrix for Metrobus buses and routes is presented in Table A1.

Table A1. Test matrix for two Metrobus DDF buses in Johannesburg service

Bus No	Test #	Route #	Route type	Fuel*
1 MP 2097	1	Route 1	Highway	Dual-fuel
	2	Route 1	Highway	Diesel
	3	Route 2	Urban	Diesel
	4	Route 2	Urban	Dual-fuel
	5	Route 3	Urban/Rural	Dual-fuel
	6	Route 3	Urban/Rural	Diesel
2 MP 2093	1	Route 3	Urban/Rural	Diesel
	2	Route 3	Urban/Rural	Dual-fuel
	3	Route 1	Highway	Diesel
	4	Route 1	Highway	Dual-fuel
	5	Route 2	Urban	Dual-fuel
	6	Route 2	Urban	Diesel

*Dual-fuel means DDF (diesel and CNG) operation.

INSTRUMENTATION

The AVL Gas PEMS iX unit is CFR Title 40 Part 1065 compliant and was developed for heavy-duty in-use emissions measurements according to U.S. and European regulations. This PEMS unit is capable of measuring NO and NO_2 via a non-dispersive ultraviolet (NDUV) spectroscopy analyzer; CO and CO_2 via a non-dispersive infrared (NDIR) analyzer; and THC and CH_4 via a dual flame ionization detector (FID) in conjunction with a nonmethane cutter (NMC) that is used for the CH_4 FID. Particulate matter data were captured but not reported here due to technical challenges that we expect to address in future publications.

Ambient weather conditions including temperature, barometric pressure, and humidity were measured with a stand-alone weather probe from Vaisala and via the weather probe that is part of the AVL Gas PEMS. Similarly, vehicle speed, location and altitude were measured using a stand-alone GPS receiver and the PEMS integrated GPS receiver. In addition, altitude was calculated based on barometric pressure measurements such as from the weather probe because this approach has shown to be more accurate for road grade calculation than GPS data.

Tailpipe exhaust flow was measured using a 4-inch exhaust flow meter (EFM) tube from Sensors Inc. The EFM is operated using stand-alone software and provides exhaust mass flow rates, standardized volumetric flow rate, and exhaust gas temperature measurements on a continuous basis, for example at 10Hz frequency.

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