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Experimental evaluation of exhaust emissions from compressed natural gas-fueled, retrofitted spark-ignited engines in Ethiopian intercity buses

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In countries with limited financial resources and access to new technologies, as well as difficult environmental conditions, renewing urban transport infrastructure is complex. An example is Africa, especially Ethiopia. Ethiopia is assessing compressed natural gas as a transport fuel for intercity buses currently powered by ageing diesel engines. This study reports a controlled before and after comparison of a single 12 m coach tested in its original Euro III diesel configuration and after replacement with a 6.7 L spark-ignited CNG engine equipped with stoichiometric control, exhaust gas recirculation, and a three-way catalyst. Chassis dynamometer tests were performed using the world harmonized transient cycle (WHTC) and a locally defined intercity cycle, followed by repeated on-road measurements on the Addis Ababa-Adama corridor using a portable emissions measurement system. Distance-based emission factors for carbon monoxide (CO), total hydrocarbons (THC), nitrogen oxides (NO_x), particulate matter (PM), and carbon dioxide (CO_2) were determined from diluted exhaust measurements. Under both cycles, the CNG configuration yielded lower NO_x, particulate, and CO_2 emissions than diesel. Hydrocarbon emissions increased under both cycles, while CO increased under the WHTC and on-road but decreased slightly under the intercity cycle. On-road measurements confirmed the same directional trends. Fuel consumption and operating cost were evaluated from measured fuel use and local retail prices. A fleet scenario was derived from the measured emission factors and stated activity assumptions. The results indicate that engine-replacement CNG conversions reduced NO_x and particulate emissions in Ethiopian intercity service, while hydrocarbon control remained the principal emission trade-off requiring improved aftertreatment calibration. All findings are based on a single test vehicle and constitute a case study of the conversion concept.

Key words: *compressed natural gas, intercity buses, emissions measurement, retrofitting*

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1. Introduction

1.1. Background

Transportation is one of the largest and fastest growing sources of energy consumption and greenhouse gas emissions. The sector accounts for approximately 25% of global carbon dioxide (CO_2) emissions and almost 50% of total oil consumption [7]. In addition to climate impacts, diesel engine exhaust contains nitrogen oxides (NO_x), particulate matter (PM) and toxic hydrocarbons that contribute to urban air pollution and pose serious health risks. Sub-Saharan African cities rely heavily on ageing diesel buses; a recent survey of public transport vehicles in Addis Ababa found that more than 67% of the vehicles exceeded opacity standards, with minibuses being the principal polluters [6, 11]. Retrofitting older diesel buses or replacing them with alternative fuel vehicles has therefore emerged as a key strategy for reducing local pollution and improving transport sustainability.

Global analyses of energy trends show that transport remains the only sector whose greenhouse gas emissions have increased relative to 1990 levels. In 2024 the sector accounted for 23.3% of global carbon dioxide emissions and 40.4% of fossil energy consumption [23]. The ten largest CO_2 emitting countries were responsible for 68% of worldwide transport emissions. Although renewable energy usage in transport reached 3.54% in 2022, it remains marginal, and many countries have yet to develop comprehensive decarbonization strategies [24]. Studies emphasize the importance of combining demand-side measures, such as modal shifts and efficiency improvements, with supply-side measures, such as alternative fuels, to achieve meaningful emission reductions. Ethiopia, like other low-income countries, faces the dual challenge of expanding mobility services while reducing environmental impacts [9]. Investing in cleaner fuels for buses can thus contribute to both economic development and climate mitigation. Ethiopia's Ogaden LNG project is projected to produce more than 111 million liters of CNG annually for industrial, transport and household use. This domestic resource base could significantly reduce fuel imports and provide a reliable supply for a national CNG bus program.

Natural gas (NG) presents a promising alternative [20]. It has a lower carbon content than diesel and gasoline and burns more completely, resulting in reduced PM and NO_x emissions [12, 13]. The European Union has promoted natural gas vehicles and set a target for alternative fuels to account for 20% of transport energy consumption by 2020 [19, 25]. Modern heavy-duty natural gas engines are spark-ignited and can employ stoichiometric combustion with exhaust gas recirculation and a three-way catalyst to achieve very low NO_x and PM levels, meeting strict Euro VI standards [2]. In developing countries, natural gas is attractive because it can be cheaper than imported diesel fuel and may reduce dependence on oil [21, 22]. Ethiopia has recently confirmed substantial natural gas reserves and plans to use compressed natural gas (CNG) to meet industrial and transport demands; one kilogram of CNG is reported to power a vehicle for approximately 34 km and is less expensive than petrol. However, the practical benefits and challenges of converting existing buses to CNG remain understudied in the Ethiopian context.

1.2. Research gap and objectives

Most emission studies on natural gas buses are based on dedicated vehicles in Europe or North America. For example, Ayala et al. [1, 3] tested a 2000 model-year Detroit Diesel Series 50G CNG bus and found that particulate matter emissions were negligible compared with diesel, although hydrocarbon emissions were higher due to the absence of oxidation after treatment. Comparisons between clean diesel and CNG buses at New York City Transit showed that diesel buses equipped with particulate filters had similar or lower PM and hydrocarbon emissions than CNG buses, while CNG buses offered lower NO_x emissions but higher variability and higher operating cost [5, 15]. Studies evaluating natural gas retrofits in African countries are scarce. European investigations based on portable emissions measurement systems document the real driving emission behavior of urban buses with diesel, hybrid, and CNG drivelines and provide reference procedures for heavy duty in service testing [4, 18]. Moreover, existing work seldom considers the operating conditions of intercity buses, which differ from urban routes in speed and load [10, 16]. Thus, there is a need for region specific data on emissions, fuel economy and cost effectiveness of CNG conversions. The central uncertainty concerns whether emissions benefits reported for dedicated, regulated CNG buses translate to engine-replacement conversions under Ethiopian intercity duty cycles, fuel supply conditions, and maintenance practices. The study tests this by pairing controlled chassis-dynamometer measurements with repeated on-road PEMS measurements on a representative corridor.

This study aims to fill that gap by performing an experimental evaluation of exhaust emissions from a diesel intercity bus retrofitted with a spark-ignited CNG engine in Ethiopia. The specific objectives are:

- to characterize the regulated emissions (CO, THC, NO_x, PM) and CO_2 from a baseline diesel bus and a retrofitted CNG bus under chassis dynamometer and on road tests
- to compare emission factors and fuel consumption between diesel and CNG configurations and assess statistical significance
- to estimate fuel costs and evaluate the economic viability of CNG retrofits
- to perform a fleet level emission reduction scenario for Ethiopia's intercity buses.

1.3. Significance and contribution

The significance of this work lies in providing the first experimental emission measurements from an Ethiopian intercity bus converted to CNG operation through complete engine replacement. Unlike previous studies that focused on dedicated CNG buses or urban cycles, the present research examines a modified spark-ignited engine operating on a representative intercity route. It integrates chassis dynamometer testing, portable emissions measurement system (PEMS) data and economic analysis to provide comprehensive evidence on the environmental and financial implications of natural gas retrofits or replacement. The findings contribute to transport policy discussions in Ethiopia and other developing nations exploring alternative fuels.

2. Materials and methods

2.1. Vehicle selection and retrofit (replacement) procedure

The test vehicle was a 12 m intercity coach built in 2010, originally equipped with a 6.7 liter turbocharged diesel engine compliant with Euro III standards as shown in Fig. 1.



Fig. 1. The tested 12 m intercity coach after conversion (a) and the installed 6.7 L spark-ignited CNG engine (b)

The bus had accumulated approximately 800,000 km. A conversion kit supplied by a local engineering company replaced the diesel engine with a spark-ignited CNG engine of similar displacement. The retrofit involved the complete replacement of the compression-ignition engine with a factory-reconditioned 6.7 L spark-ignition engine designed for compressed natural gas operation. In this article, the terms "retrofit" and "engine replacement" denote the same procedure. The CNG engine was calibrated for stoichiometric combustion with closed-loop lambda control and external exhaust gas recirculation (EGR). A three-way catalyst (TWC) was installed in the exhaust system to simultaneously control NO_x, CO, and hydrocarbons. No upstream dedicated methane oxidation catalyst was installed.

Compressed natural gas was stored in four composite cylinders mounted beneath the vehicle floor. The total geometric capacity was 640 L at a nominal storage pressure of 9 MPa. A high pressure regulator reduced the storage pressure to 0.8 MPa before injection. Safety devices, including automatic shut-off valves, pressure relief devices, and gas leak detection, were installed in accordance with UNECE Regulation 110. All mechanical and control modifications were completed by certified technicians and approved by the national road authority before testing started.

2.2. Chassis dynamometer testing

Baseline diesel testing and post-conversion CNG testing were conducted at the Ethiopian Automotive Industry Development Institute on a heavy-duty single roller chassis dynamometer with rollers of 1.2 m diameter. The equivalent inertia was set to 16,000 kg for both configurations, and the road load setting followed from coast-down measurements recorded on the test corridor. Two driving schedules were applied: the world harmonized transient cycle (WHTC) for heavy-duty vehicles and the locally defined intercity Ethiopian cycle (IEC) representing highway operation with extended cruise segments at near-80 km/h. The IEC was constructed from speed recordings on Ethiopian intercity corridors and combines cruising speeds near 80 km/h with lower-speed segments representing town transit and junction passages. Its speed profile is shown in Fig. 2. For each fuel configuration and cycle, three replicate tests were performed. Prior to each test, the vehicle was conditioned to stabilize coolant and lubricant temperatures.

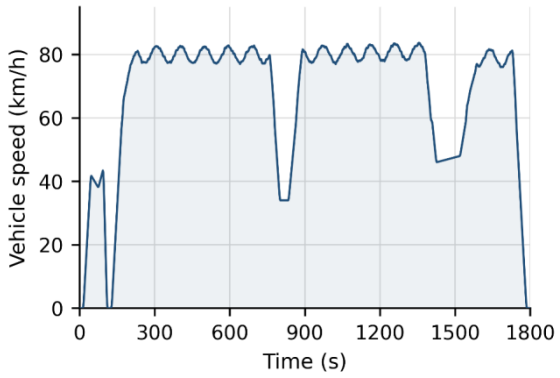


Fig. 2. Speed time profile of the intercity Ethiopian cycle with a duration of 1800 s, a mean speed of 68 km/h, and a maximum speed of 84 km/h

Exhaust gas was diluted using a full-flow constant-volume sampling system. Regulated gaseous pollutants were measured with a Horiba MEXA-7400DEGR analyzer. CO and CO_2 were determined by non-dispersive infrared detection, NO_x by chemiluminescence, and total hydrocarbons by flame ionization detection. Particulate matter was monitored using a TSI DustTrak optical instrument connected to the diluted exhaust stream. The optical instrument infers mass concentration from light scattering rather than from a gravimetric filter method, so the reported PM values are used to compare the two configurations and are not directly comparable to gravimetric type approval limits. The method's uncertainty increases at the low concentrations observed in the CNG configuration, and the corresponding results are reported as below the method's detection capability. Zero and span calibrations were performed before and after each test using certified calibration gases.

Distance-based emission factors were calculated by dividing the integrated pollutant mass over the cycle by the driven distance:

$$E_i = \frac{C_i \times Q \times T}{d} \quad (1)$$

where: E_i – emission factor of pollutant i [g/km], C_i – measured average concentration of pollutant i in the diluted exhaust [g/m³], Q – volumetric flow rate of diluted exhaust gas [m³/s], T – total test duration (s), and d – distance traveled on the chassis dynamometer (km).

For pollutant i, the emission factor E_i [g/km] was obtained from the product of the mean diluted concentration, the diluted exhaust flow rate, and the test duration, which, under constant volume sampling, equals the time integral of the instantaneous mass flow. The concentration was corrected for the background level measured in the dilution air, and the resulting pollutant mass was normalized by the chassis dynamometer distance. The formulation follows standard mass-balance procedures for measuring diluted exhaust.

2.3. On-road measurement using PEMS

Real-world operation was assessed on the Addis Ababa-Adama corridor, which is approximately 90 km in each direction. Each measurement run covered the outbound and return legs, totaling about 180 km, so each configuration accumulated roughly 540 km over the three runs. Route speed alternated between town transit and highway cruising near the 80 km/h level represented by the IEC. A portable emissions measurement system (AVL MOVE 2200) was installed at the tailpipe. CO and CO_2 were measured using non-dispersive infrared analyzers, and NO_x was measured using chemiluminescence. Total hydrocarbons were measured by a heated flame ionization detector calibrated to methane equivalence. Methane was not measured separately, and the methane-related quantities reported later rely on the premise that hydrocarbon emissions from the CNG engine consist mainly of methane. Sampling lines were maintained at 191°C to prevent hydrocarbon condensation.

A portable PM sensor was connected to the exhaust, and particle number concentrations were monitored using a condensation particle counter. Vehicle speed, position, and engine operating parameters were logged at 1 Hz. The vehicle was loaded with approximately 30 passengers and luggage to represent the typical service mass. Three repeated runs were performed for each configuration on consecutive days under ambient temperatures between 18°C and 24°C.

Daily zero and span checks were conducted. Time alignment between exhaust flow and concentration signals was verified prior to data processing. Distance-based emission factors were computed by integrating instantaneous mass rates over the route and dividing by total distance traveled.

2.4. Fuel consumption and cost analysis

Fuel consumption during chassis testing was determined gravimetrically. Diesel consumption was obtained from the mass difference of the fuel tank before and after testing and converted to volume using a density of 0.84 kg/L. CNG mass flow was measured using a Coriolis flowmeter installed in the supply line. For the intercity cycle, fuel consumption was expressed as L/100 km for diesel and kg/100 km for CNG. The reported fuel consumption values were verified against the carbon balance of the measured CO_2 emission factors. Unit fuel prices at the time of testing were 116 Ethiopian Birr per liter for diesel and 80 Birr per kilogram for CNG. Fuel cost per kilometer was calculated as

the product of measured consumption per kilometer and the respective unit price.

An economic assessment of the retrofit was performed using net present value (NPV) over a 10-year service period. Annual mileage was assumed to be 90,000 km per bus, the discount rate 7%, and the retrofit investment cost was 650,000 Ethiopian Birr. Cash flows were derived from the difference in annual fuel expenditure between diesel and CNG configurations.

2.5. Data analysis

For each pollutant and test condition, replicate emission factors were averaged and reported as mean values. Differences between diesel and CNG configurations were evaluated with two sample Welch t tests applied to the replicate emission factors at a 95% confidence level. With three replicates per condition, the tests carry limited statistical power, so the significance statements should be read as indicative. Fleet level emission scenarios were estimated by multiplying the measured emission factor differences by the assumed annual distance travelled and the number of vehicles in the national intercity fleet. All scenario calculations are derived directly from the experimentally determined emission factors and stated activity assumptions.

3. Results

3.1. Chassis dynamometer emission factors

Under the WHTC, the CNG configuration showed lower NO_x and particulate emissions than the diesel baseline. NO_x decreased from 8.5 g/km to 4.7 g/km. Particulate matter from the CNG configuration was below the reporting threshold of the applied optical measurement method, while the diesel baseline emitted 0.010 g/km. Carbon dioxide decreased from 1100 g/km to 930 g/km. Table 1 presents the mean distance based emission factors obtained from three replicate chassis dynamometer tests for each configuration and cycle. Results are reported for the World Harmonized Transient Cycle and the intercity Ethiopian cycle.

Table 1. Average emission factors (g/km) from chassis dynamometer tests, mean ± standard deviation of three replicate tests

Cycle	Fuel	CO	THC	NO_x	PM	CO_2
WHTC	Diesel	1.60 ±0.05	0.22 ±0.01	8.5 ±0.3	0.010 ±0.001	1100 ±30
WHTC	CNG	2.50 ±0.08	0.45 ±0.01	4.7 ±0.1	< 0.001	930 ±25
IEC	Diesel	1.20 ±0.04	0.18 ±0.01	7.2 ±0.2	0.015 ±0.002	1050 ±28
IEC	CNG	1.00 ±0.03	0.90 ±0.03	1.2 ±0.04	0.002 ±0.001	855 ±22

Carbon monoxide and total hydrocarbons increased after conversion under the WHTC. CO rose from 1.60 g/km to 2.50 g/km, and THC from 0.22 g/km to 0.45 g/km. Under the intercity cycle, NO_x decreased from 7.2 g/km for diesel to 1.2 g/km for CNG. Diesel particulate matter was 0.015 g/km, whereas CNG particulate mass was near the detection limit of the measurement approach. CO_2 decreased from 1050 g/km to 855 g/km. THC increased relative to diesel, while CO decreased slightly from 1.20 g/km to 1.00 g/km. The elevated THC under the intercity cycle coincided with sustained high-load cruising on grade sections, where enrichment episodes and the three-way catalyst's limited methane conversion increased methane slip. These results confirm that the CNG conversion shifted the emission profile, with reductions in NO_x and particulate emissions accompanied by higher hydrocarbon emissions. Table 1 reports the mean and standard deviation for the three replicates, with relative standard deviations below 4% for the gaseous components in both configurations. Two sample Welch t tests confirmed all diesel to CNG differences within each cycle at the 95% confidence level ($p < 0.01$).

Figure 3 compares the emission factors graphically. The large difference between NOx and PM indicates the environmental advantage of CNG, whereas the increase in CO and THC indicates the need for improved oxidation catalysis.

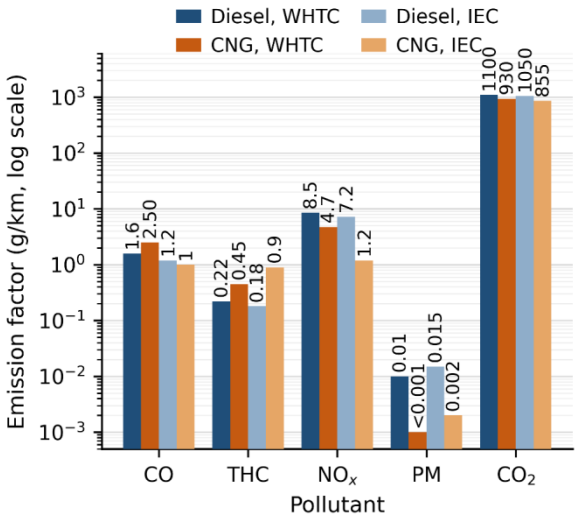


Fig. 3. Comparison of emission factors for diesel and CNG buses under WHTC and IEC cycles

3.2. On-road emission factors and driving behavior

On-road measurements along the Addis Ababa-Adama corridor yielded emission factors consistent with chassis results. Average NO_x decreased from 8.0 g/km in diesel operation to 4.8 g/km in CNG operation. CO_2 decreased from 960 g/km to 845 g/km, a reduction of approximately 12% under comparable loading conditions. Carbon monoxide increased from 1.30 g/km to 2.20 g/km, and total hydrocarbons increased from 0.20 g/km to 0.50 g/km. Instantaneous emission traces indicated that diesel NO_x peaks coincided with high-load events, such as hill climbing, whereas CNG NO_x remained comparatively stable along the route. Elevated CNG hydrocarbon emissions were associated with transient operation and load changes. Particulate emissions from the CNG configuration were consistently low under the applied measurement method, while diesel particulate signals increased during acceleration phases. Table 2 reports each mean with the standard deviation of the three runs. Run-to-run relative standard deviations stayed below 6% for the gaseous components, above the chassis dynamometer level because route grade, traffic and driver input add variability. Welch t tests confirmed the CO, THC, NO_x, and CO_2 differences at the 95% confidence level ($p < 0.01$).

Table 2. Average on-road emission factors (g/km) from PEMS measurements, mean ± standard deviation of three runs

Pollutant	Diesel	CNG	Change relative to diesel
CO	1.30 ±0.06	2.20 ±0.10	+69%
THC	0.20 ±0.01	0.50 ±0.02	+150%
NO_x	8.0 ±0.4	4.8 ±0.2	–40%
CO_2	960 ±45	845 ±40	–12%

Figure 4 illustrates the on-road emission factors, including CO_2. The data confirm that conversion to CNG offers significant NO_x reductions and consistently low particulate signals on real intercity routes, with trade-offs in CO and THC.

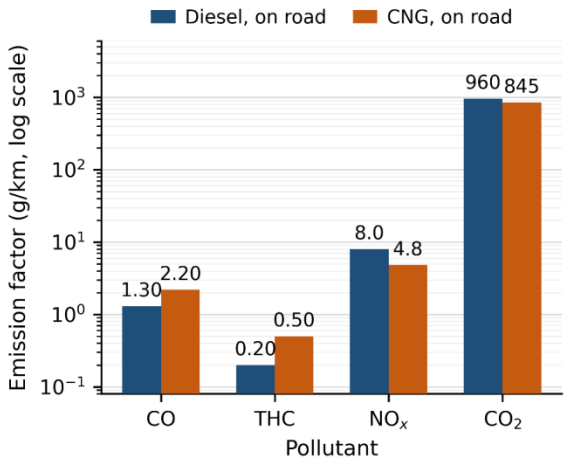


Fig. 4. PEMS on road emission factors for diesel and CNG buses

3.3. Normalized emission and energy performance under Ethiopian operating conditions

A radar chart compares the diesel and CNG configurations using the measured intercity cycle emission factors from Table 1 for CO, THC, NO_x, PM, and CO_2. The chart converts the CNG THC to methane on the stated premise that hydrocarbon emissions from the CNG engine consist mainly of methane and treats the diesel THC as non-methane hydrocarbons. Tank-to-wheel (TTW) CO_{2e} is calculated as the sum of CO_2 and 29.8 times the methane mass, using the IPCC AR6 GWP100 value for fossil methane, and reaches 1050 g/km for diesel and 882 g/km for CNG. Energy use in MJ/km is calculated from intercity cycle fuel consumption and the lower heating values of the fuels stated in Section 3.5.

The radar chart shown in Fig. 5 compares diesel and CNG buses under Ethiopian operating conditions using a 0–1 normalization for each metric, where values closer to 1 indicate the higher burden within that pollutant or energy category.

Diesel shows higher normalized CO_{2e}, NO_x, PM, and CO under the intercity cycle, indicating a stronger climate and criteria pollutant signature in these dimensions. The CNG bus presents higher normalized THC and, through the methane premise, a larger methane contribution to CO_{2e}. Energy use per kilometer, calculated from the fuel consumption and lower heating values reported in Section 3.5, reaches 15.6 MJ/km for the CNG bus against 14.1 MJ/km for diesel, about 10% higher, consistent with throttled spark ignition load control.

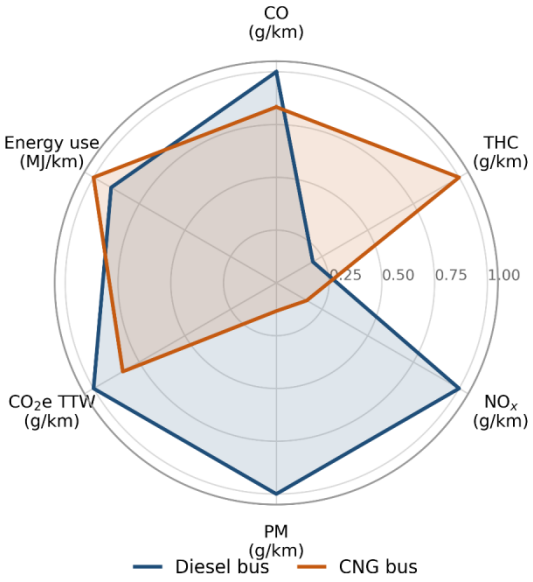


Fig. 5. Normalized comparison of emission and energy indicators for the diesel and CNG configurations under Ethiopian intercity conditions

3.4. Engine performance results

After conversion, peak power decreased from 220 kW to 205 kW and peak torque from 1100 N·m to 1020 N·m, a reduction of about 7% in both cases. Peak power, peak torque, and brake specific fuel consumption (BSFC) correspond to manufacturer certification data for the two engines, whereas the acceleration times were measured on the road with the laden vehicle. Figure 6 compares the selected performance indicators of the diesel and CNG configurations relative to the diesel baseline.

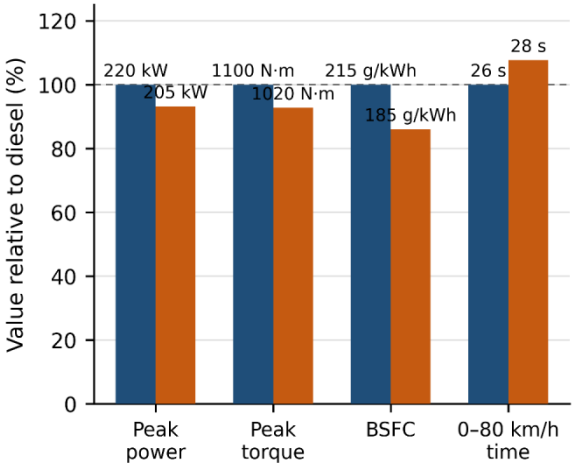


Fig. 6. Engine and performance parameters of the CNG configuration relative to the diesel baseline, based on manufacturer certification data for power, torque, and BSFC and on-road measurements for acceleration

The reduction in power is attributable to the lower volumetric energy density of the stoichiometric methane air charge and to the throttled load control of the spark-ignited engine. Brake specific fuel consumption at the rated point

was 215 g/kWh for diesel and 185 g/kWh for CNG. Because the two fuels differ in their lower heating values, these mass-based figures are not directly comparable. On an energy basis, both engines consume close to 9.2 MJ/kWh at the rated point, corresponding to a brake thermal conversion near 39%. Acceleration measurements showed a small increase in the 0-80 km/h time from 26 s to 28 s. Drivers reported no noticeable difference in drivability, although gear shifting patterns were adjusted to the modified torque curve.

These results indicate that maximum power and torque decrease slightly, while the energy conversion of the spark-ignited engine remains close to that of the replaced diesel engine, owing to methane's high knock resistance. Drivers may need to adjust shifting strategies to maintain performance on steep gradients.

3.5. Fuel consumption and cost

The diesel bus consumed 39.5 L per 100 km under the intercity cycle, while the CNG bus used 31.1 kg per 100 km, values consistent with the measured CO_2 emission factors in Table 1, as determined through the fuel carbon balance. With the stated energy contents of 35.8 MJ per liter for diesel and 50 MJ per kilogram for CNG, and the local fuel prices, the fuel cost per kilometer reached 45.8 Birr for diesel and 24.9 Birr for CNG, as shown in Fig. 7. The conversion therefore reduced the fuel cost per kilometer by approximately 46%. At the assumed annual mileage of 90,000 km, the fuel cost saving amounts to about 1.9 million Birr per year, so the conversion investment of 650,000 Birr is recovered within the first year of service, and the net present value over 10 years at a 7% discount rate reaches about 12.6 million Birr, assuming stable fuel prices.

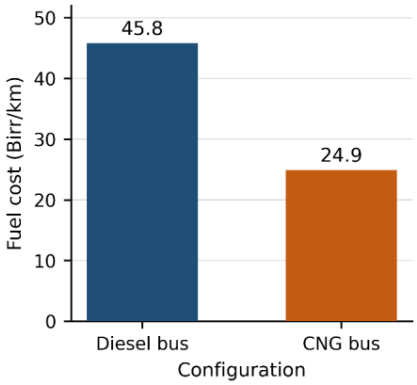


Fig. 7. Ethiopian fuel cost per kilometer for diesel and CNG buses

3.6. Fleet level emission reduction potential

A scenario analysis was conducted for Ethiopia's intercity bus fleet, assumed to comprise 2000 vehicles each travelling 90,000 km per year. Fleet annual emissions were estimated by multiplying the emission factors by the total distance. Using the WHTC emission factors, annual diesel fleet emissions amount to about 1,530 t of NO_x, 1.8 t of PM, and 198,000 t of CO_2. If all buses were converted to CNG, NO_x would decrease to about 850 t (45% reduction), PM to below 0.2 t (a reduction above 90%), and CO_2 to about 167,000 t (15% reduction). Figure 8 summarizes these results and shows that CNG conversions offer substantial reductions relative to diesel while serving as a transitional technology toward electrification.

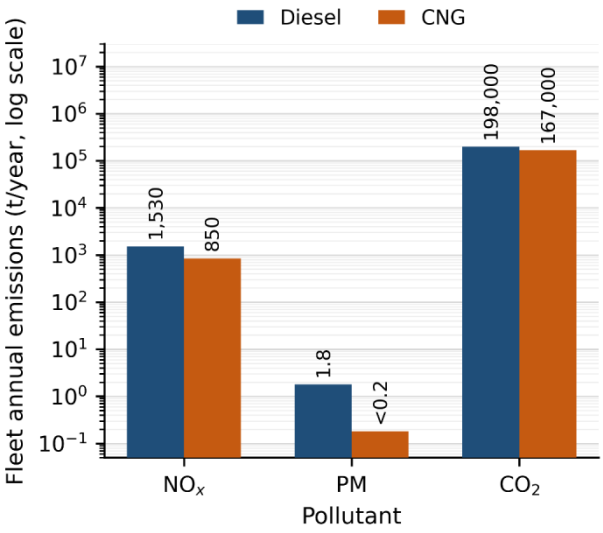


Fig. 8. Fleet level annual emissions of NO_x, PM, and CO_2 for 2000 buses at 90,000 km per year

4. Discussion

4.1. General context

Natural gas buses have been widely adopted in Europe, North America and parts of Asia. In the 1990s, the rapid diffusion of natural gas buses was driven by the need to meet stringent emission standards and reduce dependence on imported oil; early lean-burn engines produced lower NO_x and particulate emissions but sometimes sacrificed fuel efficiency. Subsequent developments introduced stoichiometric combustion with exhaust gas recirculation and three-way catalysts, allowing heavy-duty CNG engines to meet United States 2010 and Euro VI standards with more than 90% reductions in NO_x. These technological advances demonstrate that natural gas powertrains can achieve near parity with diesel engines in performance and durability.

The benefits of natural gas must be weighed against infrastructure requirements and methane slip. CNG refueling networks are dense in countries like China and India, where millions of vehicles run on natural gas, but sparse in Ethiopia. Developing refueling infrastructure requires coordinated investment in distribution pipelines, stations and safety regulation. Methane, the principal component of natural gas, is a potent greenhouse gas; unburned methane emissions from natural gas engines can offset part of the CO_2 benefit if not properly controlled. Advanced oxidation catalysts are therefore critical for minimizing methane slip and ensuring climate benefits.

Beyond CNG retrofits, other pathways for decarbonizing bus fleets include battery electric and hydrogen fuel cell technologies. Electric buses produce zero tailpipe emissions and are increasingly competitive on urban routes, although their life-cycle emissions depend on the electricity mix. Hydrogen fuel cell buses offer fast refueling and long range, but remain expensive. In the Ethiopian context, natu-

ral gas could serve as a transitional fuel while renewable electricity generation and hydrogen infrastructure expand.

4.2. Comparisons with existing studies

The observed reduction in NO_x and PM emissions with CNG retrofitting is consistent with prior research. Early lean-burn natural gas buses without aftertreatment produced lower NO_x and PM than diesel engines while delivering comparable power. Stoichiometric CNG engines equipped with EGR and three-way catalysts can reduce NO_x by more than 90% relative to lean burn engines. The 45% reduction in NO_x recorded here under the WHTC is lower than values reported for modern dedicated CNG buses, likely because the retrofit engine operated at a lower compression ratio and used a smaller three-way catalyst [27]. Under the intercity cycle, the reduction reached 83%, closer to the levels reported for stoichiometric engines with three-way catalysts. The near-zero PM emissions mirror findings by Ayala et al. [3], who measured negligible PM from a CNG bus and an 85% reduction from a diesel bus equipped with a continuously regenerating trap.

The increase in CO and THC emissions observed here aligns with previous studies indicating that CNG buses without oxidation catalysts emit higher unburned hydrocarbons and carbon monoxide. New York City Transit found that diesel buses with particulate filters had lower hydrocarbon and CO emissions than CNG buses, although CNG buses maintained lower NO_x [14]. Recent engine developments in Europe emphasize integrating oxidation catalysts upstream of three-way catalysts to oxidize methane and reduce THC [8, 17]. Future retrofits should incorporate such catalysts to mitigate hydrocarbon emissions.

The fuel economy advantage of CNG stems from the lower per-unit energy cost and the favorable local price of natural gas. The present results show a 46% reduction in fuel cost per kilometer, of the same order as the cost savings reported for natural gas bus fleets in developing countries. The investment is recovered within the first year of service, well within the remaining service life of Ethiopian intercity buses, which indicates strong economic attractiveness.

4.3. Implications for Ethiopian transport policy

The demonstration that CNG retrofits can substantially reduce NO_x and PM emissions while lowering fuel costs supports Ethiopia's strategy to exploit domestic natural gas reserves. Intercity buses operate on major corridors and contribute disproportionately to regional air pollution. Converting 2000 buses would abate approximately 680 t of NO_x and most of the PM annually. Such reductions would improve air quality and public health, particularly in densely populated areas along major highways.

The introduction of natural gas buses must be accompanied by safety regulations, training, and infrastructure. The retrofit procedure described here adhered to European (UNECE) safety standards and employed certified technicians [26]. Ethiopia should establish inspection and certification protocols, including leak detection and cylinder testing, to ensure long term safety. The government must also invest in CNG filling stations along intercity routes. Given the current limited infrastructure, a phased deployment focusing on high traffic corridors could be effective.

4.4. Limitations and future research

This study has several limitations. First, only one bus was tested; although replicate runs were performed, vehicle to vehicle variability remains unknown. Second, the retrofit engine was stoichiometric with EGR but lacked a dedicated oxidation catalyst, leading to elevated methane emissions. Third, PEMS measurements captured a single route under moderate weather conditions; different topographies or seasons may influence emissions. Fourth, particulate mass was determined with an optical method and methane was not measured separately, so the comparability of PM with gravimetric limits and the methane share of THC carry additional uncertainty. Future research should include larger vehicle samples, evaluate the impact of catalyst configurations, and explore advanced controls such as variable valve timing and delayed intake valve closing, which can reduce particle emissions by over 95%. Studies should also consider life cycle emissions and compare CNG retrofits with emerging battery electric and hydrogen fuel cell buses.

5. Conclusions

Retrofitting diesel intercity buses with spark ignited CNG engines offers a practical pathway for reducing emissions and operational costs in Ethiopia. Experimental results from the single converted vehicle showed that, compared with the baseline diesel configuration, the conversion achieved:

- A 40 to 45% reduction in NO_x emissions under the WHTC and the on-road tests, with a larger reduction of 83% recorded under the intercity cycle
- Particulate emissions below the reporting threshold of the applied optical method, indicating a substantial reduction of a key toxic pollutant within the limits of that method
- A 12 to 19% reduction in CO_2 emissions, reflecting the lower carbon content of natural gas
- A reduction of about 46% in fuel cost per kilometer, recovering the conversion investment within the first year of service.

The primary drawback observed was the increase in unburned hydrocarbons, accompanied by higher carbon monoxide under the WHTC and on-road tests, due to the absence of a dedicated oxidation catalyst. Incorporating oxidation catalysis and refining engine calibration could mitigate these emissions. A fleet level scenario indicated that converting 2000 intercity buses could avoid about 680 t of NO_x, about 1.6 t of PM, and 31,000 t of CO_2 annually. These findings support policy initiatives to deploy CNG buses as part of a broader strategy for sustainable transport transitions.

Moreover, adoption of CNG buses can stimulate local industries in cylinder manufacturing, engine maintenance and retrofitting services, creating skilled employment and fostering technological capabilities within the country.

The comparison under Ethiopian conditions indicates a trade-off rather than a uniform advantage. Diesel buses present higher burdens in CO_{2e}, NO_x, and PM, while CNG buses shift the burden toward unburned hydrocarbons and

methane. These results imply that fuel switching alone will not deliver consistent benefits unless policy and fleet actions also address methane control on CNG platforms and particulate and NO_x control on diesel platforms under local operating and maintenance realities.

This study relates to the Sustainable Development Goals (SDGs) in the area of transport engineering, in particular SDG 7 (affordable and clean energy), SDG 11 (sustainable cities and communities) and SDG 13 (climate action). It also supports the decarbonization and low-carbon transport priority of the United Nations Decade of Sustainable Transport 2026–2035, proclaimed by the General Assembly in resolution A/RES/78/148 and launched in December 2025 [27].

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Nomenclature

BSFC	brake specific fuel consumption
CNG	compressed natural gas
CO	carbon monoxide
CO_{2e}	carbon dioxide equivalent
EGR	exhaust gas recirculation
IEC	intercity Ethiopian cycle
NPV	net present value
PEMS	portable emissions measurement system
PM	particulate matter
THC	total hydrocarbon
TTW	tank to wheel
TWC	three way catalyst
UNECE	United Nations Economic Commission for Europe
WHTC	World Harmonized Transient Cycle

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