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Usage of Compressed Natural Gas-Diesel Dual-Fuel Engines for Optimization of Fuel Consumption

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Abstract

Transportation is one of the sectors that contribute to Greenhouse Gases (GHGs) emissions. In recent years, many efforts have been made to reduce Carbon Footprint (CF), particulate emissions, and cost of operation. Dual fuel technology has proven to be a viable technology since Compressed Natural Gas (CNG) becomes largely available. Nowadays, CNG is the best fuel alternative for the automotive industry, specifically for marine engines, heavy machinery, trucks, and buses for public transportation. This paper describes a novel approach to fuel consumption reduction and the optimization of the cost of operation after dual-fuel CNG-Diesel conversion for a fleet of 39 buses. A reduction in carbon Dioxide (CO_2), emissions are reported with a reduction in smoke emission and Particulate Matter (PM) by equipping buses with an active PDF catalyst system whereby oxides of nitrogen (NOx), Hydrocarbons (HC), and Carbon monooxide (CO) emissions were 10% lower than the limits set by Japan's current emission standard (JP05). Results were focused on the mixed fuel economy optimization using the best configuration of the CNG ratio map to be loaded in the Electronic Control Unit. Moreover, the range of the buses was increased, hence reducing stall time at pump stations. Finally, the study shows the financial advantages of diesel-engine conversion to the CNG-Diesel dual-fuel engine.

Keywords: Engine Conversion • Optimization • Fuel Economy • Diesel • Compressed Natural Gas (CNG) • Exhaust Gases

Introduction

Carbon Footprint (CF) is widely used to measure the impact of human activities on global warming and the environment [1-3]. Usage of cars, buses, trucks, and heavy traffic is increasing in the United Arab Emirates at a constant rate. PM releases have diverse effects on health and the environment [4,5]. The United Arab Emirates is one of the leading countries progressing towards a greener economy with a clear overview of the government's plan by reviewing the development of tools and activities supporting and monitoring the implementation, showcasing leading innovation initiatives, and compiling the country's latest results of the forty-one Green Key Performance Indicators [6]. One of the initial tasks in this strategy involved the changeover of Abu Dhabi's entire taxis fleet to natural gas and to refurbish existing refueling stations enabling them to supply natural gas to vehicles. In this context, the project is an attempt to reduce Carbon Footprint, GHG emissions, and hence fuel consumption by converting the Petroleum Institute's (PI) diesel-operated bus fleet into a dual-fuel system. This reduction is expected to be significant since the institute operates a fleet of 39 buses. The dual-fuel system on conventional diesel vehicles heavily depends on retrofitting kits [7] and is usually restricted by many factors including engine geometry, fuel delivery system, and safety issues. The conversion of buses was initiated at dedicated technical centers to call out for globally recognized conversion companies and open conversion centers within Abu Dhabi. Furthermore, these conversion centers started the first phase of converting gasoline-operated cars and are now moving towards a second phase of converting diesel-operated buses and trucks. The conversion of the bus fleet to dual-fuel has been successfully implemented and tested for emission and fuel consumption. Proposals given by these companies, which also relate to their experience, are used to analyze the benefits related to mixed fuel conversion within the institute as soon as the product was made available in the market.

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CNG in the automotive industry is widely used due to its availability, low cost, and low carbon emission footprint. Compression-Ignition (CI) dual-fuel engines use diesel fuel for the pilot ignition of the natural gas. Table 1 depicts a comparison of fuel specifications for both CNG and Diesel. As shown CNG has a very low cetane number and high auto-ignition temperature of 650°C, requiring a minimum quantity of diesel to be injected into the combustion chamber to ignite the combustion [8].

Table 1. Fuel specifications.

Parameter	Diesel	Compressed Natural Gases (CNG)
Cetane number	51	0
Methane number	-	82
Research octane number	15–25	110–130
Density at 1 atm and 15°C (kg/m^3)	840	0.72–0.76
Auto-ignition temperature (°C)	180–230	650
Stoichiometric air-fuel ratio	14.6	17.05
2.855	2.855	2.855
2.855	2.855	2.855
2.855	2.855	2.855

There are few issues related to Compressed Natural Gas storage and applications, such as onboard storage due to low energy volume ratio, knock at high loads, and high emission of methane and carbon monoxide at low loads. However, these can be overcome by proper design, fuel management, and exhaust treatment techniques. Also, CNG exhibits significant potential for the reduction of gaseous and particle emissions as well as improvements in energy security, and in toxicity [9-11].

It was also shown statistically in that the use of gas cylinders is safer than gasoline reservoir tanks. It is mainly due to the high safety standards and regulations concerning the use of gas cylinders. Industry standards test cylinders far beyond normal environmental and service damage risks. The cylinders are designed for a specific lifetime from 15 up to 25 years and are required to be inspected every 3 years or 36,000 miles. In the same study, statistics showed that Natural Gas as fuel had 37% fewer injuries than gasoline operated vehicles for over 178.3 million miles of cumulative travel. Also, CNG has less density and less flammability compared to Diesel, therefore gas leaks from cylinders diffuse faster into the atmosphere with practically no gas accumulation under the vehicle compared to gasoline and diesel tanks. A substantial reduction of CO_2 emission from CNG fuel compared to Diesel due to lower carbon proportion in CNG as compared to diesel was observed in (8). Thus engine operation with CNG could be considered as eco-friendly operations. The lowest CO, CO_2, and VOC (Volatile Organic Compounds) emissions were attributed to CNG regardless of the route, terrain, and location of the transporting buses. However, NOx emissions were the highest in all configurations. In this project, the dual fuel conversion kit is designed to allow the conversion of all diesel buses into dual-fuel systems without major modifications. The objective is to generate, for each trip, fuel consumption profile calculated from the average speed and engine load with the correcponding mixed fuel and CNG ratio data. This procedure will allow the determination of CNG and Diesel quantities consumed per month for the bus fleet servicing different geographic locations. The novelty of this research resides in the optimization of the mixed fuel burnt for each trip by finding the best configuration of the CNG ratio map that minimizes fuel consumption.

Methodology

Data collection and vehicle specification

Data obtained from the transportation and logistics department at the institute includes the bus model, the number of buses in service, their range, routes, the number of roundtrips per day, the diesel fuel expenditure per month, and the mixed fuel expenditure per month after conversion. The model of buses used is Fuso Rosa 29, manufactured by Mitsubishi, the vehicle specification can be found in Table 2.

The large fleet of 39 buses operates between the Petroleum Institute located in Abu Dhabi and the northern emirates. Buses are split into groups to serve different destinations: On campus, Abu Dhabi city, Bani-Yas Area, and Ras Al Khaimah. Three buses are used to circulate between different buildings on campus from 7:00 AM to 4:00 PM at intervals of fifteen minutes. In summary, different routes with the number of allocated buses, the number of roundtrips, the distance in km per roundtrip, and diesel fuel consumption are shown in Table 3.

At the time of writing this paper, the cost per month of fuel based on diesel market price was 2.9 dirhams per liter and 1.6 dirhams per liter of CNG.

Dual fuel kit components

The parts required to convert buses into dual-fuel mode are the electronic fuel injector; the CNG pressure regulator which reduces and regulates the gas pressure before delivery to the injector, which in turn is connected to a high-pressure shut-off Solenoid valve for safety requirement; the electronic throttle body; the low-pressure gas train with a gauge; the special long-life spark plugs for CNG Engines with Iridium-Yttrium electrodes that are guaranteed to be the longest-lasting spark plugs in CNG vehicle applications; the high-performance ignition coil; sensors for coolant temperature, intake air, and exhaust temperatures; the Electronic Control Unit (ECU) controlling time, pressure, and quantity of both diesel-CNG injections into the combustion chamber thus triggering the combustion of the preheated mixtures. All equipment (such as fittings, valves, and gas tubes) of the CNG fuel system are in 316 stainless steel and can support easily 5000 psi of gas pressure. The cost of the kit is 8000 dirhams (AED) for a four-cylinder turbocharged engine with 100 L tank capacity. The conversion of a bus to dual-fuel mode required 8 hours. ADNOC centers offered installation of the conversion kit and testing charges for free. The majority of gas stations in the country are now well equipped with NGV fueling stations. All buses were equipped with an active PDF catalyst system whereby NOx, HC, and CO emissions were 10% lower than the limits set by Japan's current emission standard (JP05), which has been in effect since 2010.

Tuning the Electronic Control Unit (ECU)

After the calibration of components such as accelerator pedal positions, pressure, and temperature sensors as well as the spark ignition system, software activates the ECU to set up the dual-fuel system by setting the dual-fuel map as shown in Table 4. The map is used to control the ratio of injected CNG to Diesel depending on engine load and speed conditions. At high load with large throttle opening, more Diesel is required with increasing engine speed to generate more engine power, whereas at low load more CNG is injected in the intake manifold. The optimal mixed fuel map setting depends on many conditions, such as the engine power, gearbox, different routes, climatic conditions, all sources of frictions, and the driving style. In general, the quantity of CNG gas injected into the intake manifold should be maximized to optimize fuel economy and gas emissions.

A programmable standalone data acquisition module (DI-2108 USB, 16-bit resolution, 20 Khz sampling frequency, Data Acquisition System (DAQ)) was connected to the ECU to collect in real-time the engine rotational speed and fuel injection sensor and records averaged data at regular intervals of ten seconds. A mini-program written in C was used to collect and store the data from the DAQ system to a computer for data processing.

Table 2. Bus specification.

Engine		**Variable Geometry Turbocharger (VGT) with Intercooler, Exhaust Gas Recirculation (EGR)**
Capacity	mm	2,998
Number of cylinders	4	In-line 4-Cylinder, 4P10 Diesel DOHC 16 Valve
Max. output	PS/rpm	175/2,860~3,500
Max. torque	kg-m/rpm	43.8/1,600~2,860
Compression ratio	-	17.5:1
Emission	-	Emission control silicon carbide and catalytic converter emission
		Level 80/03-JP05
Fuel tank capacity	Liter	100
Urea tank capacity	Liter	12

Table 3. Bus activity description.

Category	Destinations	Buses	Roundtrips per month (per bus)	Distance traveled in km per roundtrip	Fuel expenditure per month (before conversion) [AED]
1	On campus	3	198	6	14,500
2	Abu Dhabi City	7	22	53	4860
3	Bani-Yas areas	12	22	73.6	5,600
4	Northern Emirates (Ras Al Khaimah)	17	22	494	81,232
Net per month		39			106,192

Table 4. Total mass flow rate of mixed fuel in (g/s) versus engine rotational speed (rpm) and torque (Nm).

Torque (Nm)	Engine rotational speed (rpm)					
	500	**1000**	**1500**	**2000**	**2500**	**3000**
400	2	3.4	5	6.3	7.64	9.1
350	1.84	3.11	4.08	5.22	6.55	7.9
300	1.54	2.48	3.41	4.01	5.77	7.19
250	1.33	2.01	3.2	3.67	5.2	6.5
200	0.97	1.86	2.7	3.51	4.5	5.7
150	0.72	1.42	2.21	3.23	3.86	5
100	0.69	1.02	1.76	2.72	3.2	4.3
50	0.58	0.63	1.3	2.21	2.55	3.5
25	0.4	0.45	0.84	1.7	1.89	2.8
10	0.23	0.27	0.38	1.19	1.39	2.1
5	0.1	0.12	0.24	0.58	0.84	1.01

Results and Discussions

The map of the mixed fuel consumption with an average mass flow rate (g/s) and CNG ratio $r = \left(\frac{\dot{m}_{CNG}}{\dot{m}_f}\right)$ in percent, depending on engine rotational speed and torque are shown in Tables 4 and 5 respectively.

Data collected during the test were split into four categories according to the bus destination. The first group consists of 3 buses circulating on campus. These buses serve all stations between campuses, at intervals of 15 minutes. The speed limit on campus is restricted to 20 km/h. The 3 km trip from the main bus station to the farthest point on campus (Arzanah) takes 15 minutes including shortstops of about one minute at each station. Figure 1 depicts the engine rotational speed and torque during the trip of one particular bus used for this study.

Both mass flow rates of CNG and Diesel could be calculated from Figures 1 and 2 according to the equations in (1):

$\dot{m}_f = \dot{m}_{Diesel} + \dot{m}_{CNG}$ and $\dot{m}_{CNG} = r \times \dot{m}_f$ ....(1)

The mixed fuel consumption during the trip could be calculated, as per the following :

$$C_{CNG} = \sum_{t=1s}^{t=880s} \frac{r_{i,j} \times \dot{m}_{i,j;f}}{dG} \times CG \text{ .... (2)}$$

And

$$C_{Diesel} = \sum_{t=1s}^{t=880s} \frac{\dot{m}_{i,j;f} - \dot{m}_{i,j;CNG}}{dD} \times CD \text{ .... (3)}$$

Where ri,j is the ratio of CNG for a given load (i) and a given engine rotational speed (j) at any instant t, $\dot{m}_{i,j;f}$ and $\dot{m}_{i,j;CNG}$ are mass flow rates of mixed fuel and CNG for a given load (i) and a given engine rotational speed (j) at any instant t, dG, and dD are respectively densities of CNG and Diesel, and represent respectively the cost per liter of CNG and Diesel as outlined previously in section Data collection and vehicle specification.

Taking into account the number of roundtrips and the number of buses serving on campus, the total fuel cost per month is calculated according to :

$NFP = (C_{CNG} + C_{Diesel}) \times RT \times NB \times DM$ ....(4)

Where NFP is the Net Fuel Price in (AED), RT is the number of roundtrips performed per day, NB is the number of buses in service for a given destination or category, and DM is the number of service days in a month. The Net Fuel Price in (AED) calculated per month is 10,175. Compared to the Diesel expenditure from Table 2, a net fuel economy of 29.8% is achieved on the monthly fuel bill.

The second category of buses serves Abu Dhabi city, the trip starts at 6:00 AM, takes around 30 minutes to collect faculty. The roundtrip to the main bus station takes practically the same time due to the low-traffic conditions early in the morning. Figure 2 shows the engine rotational speed and torque during the trip of one particular bus in this category.

Using equation 4, the estimated cost of fuel consumption for category 2 amounts to 3,830 with an economy of 29.8 % on the monthly bill. In reality, only 24.1% was recorded.

Figures 3 and 4 show the engine rotational speed and torque for categories 3 (Banyas area) and 4 (Ras Al Khaimah) with an estimated fuel economy of 24.1% and 36.0% respectively. The estimated fuel economy were slightly better than the recorded expenditure.

In summary, the average fuel economy made in all of the four categories exceeds by 30% the Diesel fuel expenditure before conversion. The details are summarized in Table 6.

Table 5. CNG ratio in % versus engine rotational speed (rpm) and torque (Nm).

Torque (Nm)	Engine rotational speed (rpm)					
	500	**1000**	**1500**	**2000**	**2500**	**3000**
400	30.00%	30.00%	20.00%	10.00%	10.00%	10.00%
350	40.00%	30.00%	30.00%	20.00%	10.00%	10.00%
300	50.00%	40.00%	40.00%	30.00%	20.00%	10.00%
250	60.00%	60.00%	50.00%	40.00%	30.00%	20.00%
200	70.00%	60.00%	60.00%	50.00%	50.00%	30.00%
150	80.00%	70.00%	60.00%	60.00%	50.00%	40.00%
100	90.00%	80.00%	70.00%	60.00%	50.00%	40.00%
50	90.00%	90.00%	80.00%	70.00%	60.00%	50.00%
25	100.00%	90.00%	90.00%	80.00%	70.00%	60.00%
10	100.00%	100.00%	90.00%	90.00%	80.00%	70.00%
5	100.00%	100.00%	100.00%	90.00%	90.00%	80.00%

Table 6. Fuel consumption and economy per bus category.

Category	Destination	Diesel fuel expenditure per month (before conversion) [AED]	Calculated cost of mixed fuel from eq 4 (after conversion) [AED]	Mixed fuel expenditure per month (after conversion) [AED]	Fuel economy in %
1	On campus	14,500	10,175	11,005	24.1
2	Abu Dhabi City	4860	3,830	3,989	17.9
3	Bani-Yas areas	5,600	4,249	4,344	22.4
4	Northern Emirates (Ras Al Khaimah)	81,232	51,980	52,128	35.8
Net per month		106,192	70,234	71,466	32.7

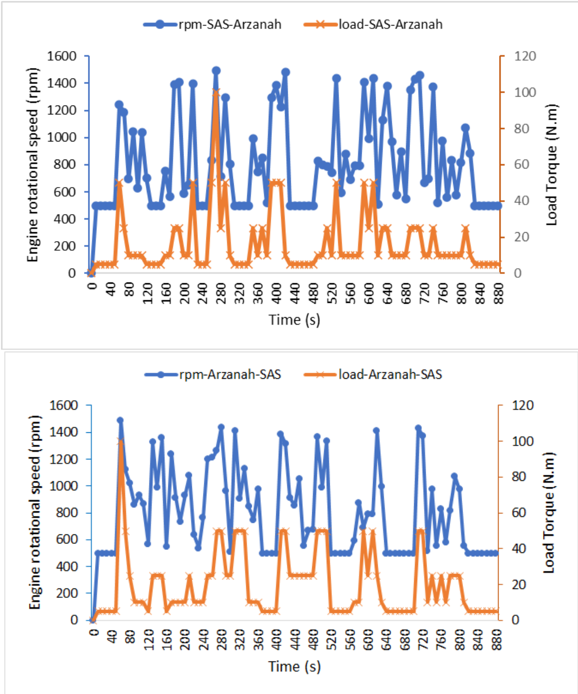

Figure 1. Engine rotational speed and torque of one particular bus from category 1.

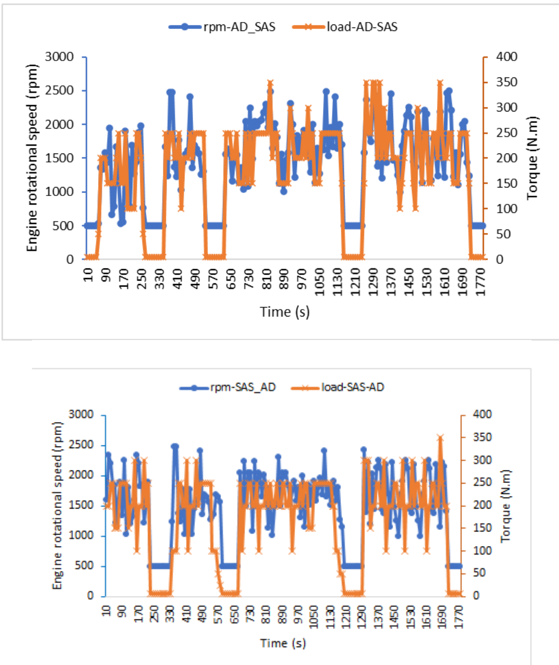

Figure 2. Engine rotational speed and torque of one particular bus from category 2.

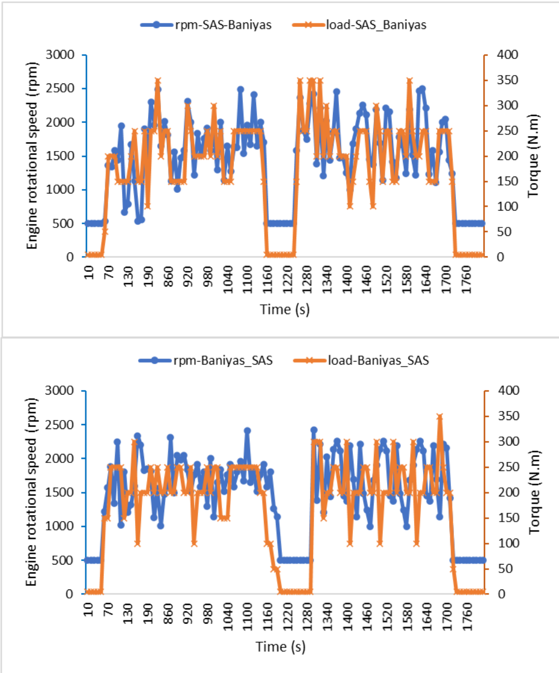

Figure 3. Engine rotational speed and torque of one particular bus from category 3.

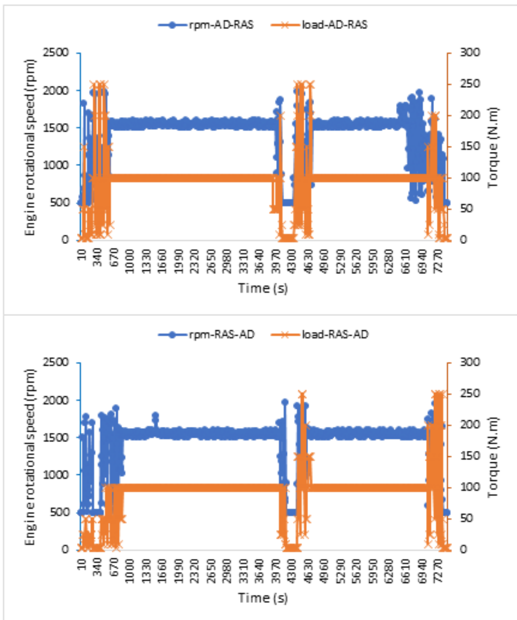

Figure 4. Engine rotational speed and torque of one particular bus from category 4.

Unmatching data obtained between the calculated cost from equation 4 and the real expenditure of mixed fuel arise from many sources. It is worth noting, that only one bus from each category was selected for the test and all other buses, in the same category, are assumed to have the same fuel consumption pattern. This assumption is not accurate since each bus might have been working in different mechanical conditions such as engine efficiency, rolling, aerodynamic drag, driving styles, mass load, idle running time, varying time spent at each station, time of service during the day related to traffic conditions, geographic and meteorological conditions.

Optimization of fuel consumption

For a given load, the air intake flow rate is increased with the engine speed due to larger throttle opening, larger vacuum suction is initiated inside the engine cylinder increasing the volume of air-fuel mixture leading to an increase in the fuel consumption. Under lower engine operating temperatures and at low-intermediate loads, the oxides of nitrogen (NOx) emissions reduce however hydrocarbon (HC) and carbon monoxide (CO) emissions are significantly increased. The increase of mixed fuel mass flow rate is countered by a slight decrease of CNG gas mass flow rate and an increase in Diesel to generate more engine power as shown in Table 4. To optimize the fuel consumption without affecting the engine performance, the CNG mass flow rate map must be regenerated for each category of buses by selecting the CNG mass flow rate best configuration that minimizes the fuel cost.

The quantity to be minimized is the NFP in (equation 4), in particular, the sum (C_{CNG}+C_{Diesel}). The total cost of mixed fuel which requires the recreation of all the 66 values in Table 4. The data in categories 1 and 2 exhibit a maximum of 2000 rotational speed and 200 Nm torque throughout the trip due to the speed limit on campus and in Abu Dhabi city. For exceptionally low torque situations, the fuel used is mainly CNG which is twice as less costly than Diesel. Consequently, the values to be recreated in the array map are reduced to (4 rpm values) × 5(load values)=20. Since each element in the array could have values 30%, 40%,50%, 60%, 70%, 80% and 90%, the space of configuration for all generated different possible maps would be 7^{20}. Also, the acceptable consecutive values in the array map must be within a 20% difference to avoid engine knocking or sudden change of engine power, especially at high loads. The space of configuration is consequently reduced to $2^{20/2}$. The algorithm takes each of these configurations, recalculates the cost of mixed fuel, and selects the configuration that yields the minimum fuel cost as illustrated in the flowchart of Figure 5.

The best configuration of CNG ratio map will be the optimal for the selected trip, the return trip will have a different configuration. The optimal map could be loaded into the ECU for a selected destination to guarantee minimum fuel consumption. An example of optimized maps only for the first category is shown in Table 7. The optimized fuel consumption is detailed in Table 8.

The optimized map loaded to the ECU was tested on the bus of the first category with a fuel cost of 10,112 AED which is slightly greater than the optimized one calculated in Table 8. The discrepancy arises from the different driving styles as it is impossible to reproduce the trip exactly, also the shortstops at the stations could be different for each trip.

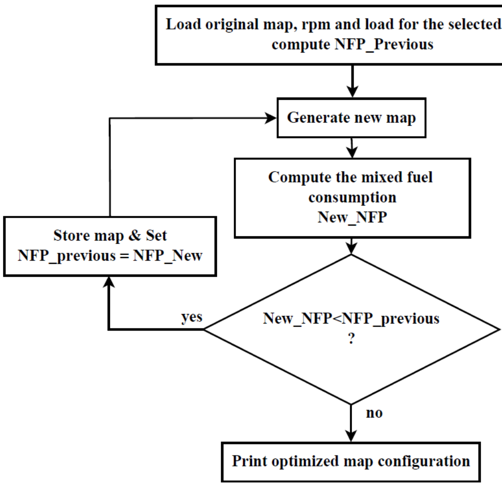

Figure 5. Flowchart for the optimized configuration map of Compressed Natural Gas (CNG) ratio.

Table 7. Optimized map of CNG ratio for category 1: from the main station to Arzanah campus; From Arzanah campus to the main station.

Torque (Nm)	**Engine rotational speed (rpm)**					
	500	**1000**	**1500**	**2000**	**2500**	**3000**
From the main station to Arzanah campus						
400	30%	30%	20%	10%	10%	10%
350	40%	30%	30%	20%	10%	10%
300	50%	40%	40%	30%	20%	10%
250	70%	60%	60%	50%	30%	20%
200	70%	60%	60%	50%	50%	30%
150	90%	80%	80%	70%	50%	40%
100	90%	80%	70%	60%	50%	40%
50	100%	100%	90%	80%	60%	50%
25	100%	90%	90%	80%	70%	60%
10	100%	100%	90%	90%	80%	70%
5	100%	100%	100%	90%	90%	80%
From Arzanah campus to the main station						
400	30%	30%	20%	10%	10%	10%
350	40%	30%	30%	20%	10%	10%
300	50%	40%	40%	30%	20%	10%

250	70%	60%	60%	50%	30%	20%
200	80%	70%	60%	50%	50%	30%
150	90%	80%	80%	70%	50%	40%
100	100%	90%	80%	60%	50%	40%
50	100%	100%	90%	80%	60%	50%
25	100%	90%	90%	80%	70%	60%
10	100%	100%	90%	90%	80%	70%
5	100%	100%	100%	90%	90%	80%

Table 8. Optimized fuel consumptions for all categories.

Category	Destination	calculated cost of mixed fuel per month (after conversion) [AED]	Optimized mixed fuel cost per month (after conversion) [AED]	The cost difference [AED]
1	On campus	10,175	10,008	167
2	Abu Dhabi City	3,830	3,681	149
3	Bani-Yas areas	4,249	4,178	71
4	Northern Emirates (Ras Al Khaimah)	51,980	51,599	381
Net per month		70,234	69,466	768

Conclusion

It was pointed out in this paper that emissions would be greatly reduced by using CNG as an alternative fuel for the bus fleet. The level of emissions was 10% lower than the limits set by Japan's current emission standard (JP05). In diesel-operated vehicles, complete substitution of Diesel is not preferable due to knocking and shortage of power engine at high loads. Thus, conversion companies have retrofitted the diesel engines to operate using a dual fuel mechanism. The conversion into a dual fuel system is a reversible process. The conversion of the diesel-operated buses within the institute has impacted tremendously emission reduction and fuel cost. Consequently, the conversion increased the range of buses.

A computational novel approach of optimizing the CNG ratio map by selecting the best configuration that minimizes mixed fuel cost is implemented. This map depends mainly on the route selected and the driving styles.

As a future perspective, these calculations could be done in real-time and using optimization procedures, as the one implemented in this paper, for a given route to select the best CNG ratio configuration to be stored and loaded automatically in the ECU unit.

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