Natural gas as a promising alternative fuel for passenger cars

Alia A. Shakour, Ahmed A. El-Abssawy* and Yasser H. Ibrahim

Air Pollution Research Department, National Research Center, Cairo, Egypt
E-mail: elabssawy@hotmail.com
E-mail: alishakour@hotmail.com
E-mail: yasser49@hotmail.com
*Corresponding author

Abstract: The present work (as a field study) investigated the role of compressed natural gas (CNG), as an automotive fuel in CO, HC and CO_2 emissions in vehicle exhaust. Besides evaluating the influence of the fuel-feed systems into their cylinders on a vehicular emission level, two different systems were examined; electronic fuel-injection and well-carburetted engines. The chosen vehicles were already in service without catalytic converters and alternately operating on either petrol or CNG fuel. Their equivalence ratios were very near to the integer unit ($\phi \simeq 1$) and they were of the same model and capacity (1800 cc) but differed in their manufacturing date. CO, HC and CO_2 concentrations were determined by using the exhaust analyser (SNAP). The output results illustrated that, compared to petrol, CNG has a vital potential to reduce CO, HC and CO_2 concentrations in exhaust released from the electronic fuel-injection and well-carburetted engines by an average of 73% and 66%, 39% and 31% and 21% and 19%, respectively. Furthermore, compared to the well-carburetted engine's emissions, the use of vehicles with the electronic fuel-injection system reduced the concentrations of the same investigated pollutants in CNG and petrol exhausts by an average of 78% and 70%, 52% and 45% and 17% and 12%, respectively. The results confirmed that auto exhaust air pollutant levels could be reduced by replacing conventional petrol by CNG and using vehicles with electronic fuel-injection systems in all activities.

Keywords: Vehicle exhaust; petrol; CNG; emissions reductions; Cairo.

Reference to this paper should be made as follows: Shakour, A.A. El-Abssawy, A.A. and Ibrahim, Y.H. (2003) 'Natural gas as a promising alternative fuel for passenger cars', *Int. J. Environment and Sustainable Development*, Vol. 2, No. 2, pp.184-196.

Biographical notes: Prof. Dr. Alia Abdel Shakour works on a variety of environmental pollution topics including atmospheric chemistry; indoor air and urban monitoring; heavy metals and organic compounds; exhaust emission studies; urban profiles of oxides; and environmental impact assessment (EIA) and air quality management.

Dr. A.A. El-Abssawy is a staff member of the Air Pollution Research Department, National Research Center, Cairo, Egypt

Mr. Y.H. Ibrahim is a staff member of the Air Pollution Research Department, National Research Center, Cairo, Egypt.

1 Introduction

Due to the continuous increase in energy consumption, environmental pollution problems have reached global proportions, particularly in developing countries, which have tended to place less emphasis on environmental issues as they have promoted economic growth and development. For instance, in Egypt, the consumption rate of all fuel types increased dramatically between the 1970s and 1990s [1]. Accordingly, pollution levels increased; the mean concentration of SO_2 increased by 90% over five years (1979-1984) in an industrial area in north Cairo [2]. The transport sector accounts for a significant and growing proportion of atmospheric pollution [1,3,4].

Undoubtedly, avoiding air pollution in the first place is cheaper and more effective than trying to control and remedy its impacts. Thus, the focus of automotive emission reductions must be shifted to better control of engine exhaust emissions. Therefore, extensive studies had been performed on alternative fuels such as alcohols, ethers and gaseous fuels and Liquefied Petroleum Gas (LPG) [3]. One of the promising alternative fuels is natural gas. This fuel has many advantages. Its octane number is high (130), thereby improving combustion efficiency. The power loss due to the relatively lower stoichiometric energy density of CNG is about 10% less than that of petrol [4]. Compared to petrol, CNG has the advantages of superior anti-knock characteristics, more stable lean combustion and lower emissions [5]. Moreover, operational safety is equal to, if not higher, than petrol, whilst engine life is increased. The low cost of CNG, its availability and the reassuring extrapolations on its availability in the coming decades also make it an attractive option [6]. The use of CNG as an alternative fuel for internal combustion engines has been demonstrated to be a feasible solution to comply with environmental regulations and requirements [7,8]. Conversion of petrol engines to CNG operation has been documented for decades. However, the technology of control systems for such engines has lagged behind those for petrol and diesel engines [9].

The current study analysed the effect of replacing petrol fuel by CNG on vehicle exhaust emissions (mainly, CO, HC and CO_2) and its effect on the air quality in Cairo, as well as evaluating the influence of engine fuel-feed systems on vehicular emission levels.

2 Material and methods

2.1 Investigated fuel properties

The composition of natural gas is not constant and can vary from one site to another and also at the same site at different times. Natural gas is a mixture of several gases, the main component of which is methane, which exists in concentrations of 80-99% by volume [3]. The investigated natural gas is obtained from three principal sources in Egypt (Abu Ghardig, Abu Madi and Abu Quir). It consists of a mixture of hydrocarbons. Their percentages are: 84.88, 92.77 and 93.85% methane, 9.16, 4.12 and 3.23 % ethane, 1.89, 1.21 and 1.22% propane, 0.59,0.39 and 0.17% nitrogen and 3.42, 0.69 and 0.53% CO2, respectively [10]. Petrol is also a mixture of hydrocarbons, distilled from petroleum. Saturated hydrocarbons are the dominant components of petrol and sulphur compounds are a constituent in fuel oil as a contaminant [11].

2.2 Experimental work

Fifty-five vehicles, with two different fuel-feed systems, were selected from the Gulf of Suez Petroleum Company (GUPCO) fleet. Twenty-eight vehicles were operating with electronic fuel-injection systems (electronic injection engines) whilst the others vehicles had well-carburetted engines (carburettor engines). They had been prepared and modified to operate alternately on either petrol or CNG fuel. The chosen vehicles were already in service without catalytic converters and had the best equivalence ratios ($\phi \simeq 1$) and the same model and capacity (1800 cc) but different manufactured dates.

Carbon monoxide (CO), carbon dioxide (CO_2) and unburnt hydrocarbons (HC) were the investigated pollutants during the current work and their concentrations were detected in exhaust gases emitted from the exhaust pipe using the exhaust analyser (SNAP). The reduction percentages in CO, HC and CO_2 concentrations using the CNG version (R%), compared to their concentrations using the petrol version for the same engine, were calculated according to equation (1). The reduction percentages related to using electronic injection engine ($R^/\%$), compared to carburettor engines' emissions released using the same fuel combustion were calculated according to equation (2).

$$R\% = ((C_1 - C_2) / C_1) \text{ X } 100 \quad (1)$$

$$R^/\% = ((C_3 - C_4) / C_3) \text{ X } 100 \quad (2)$$

Where,

C_1 and C_2 represent the same pollutant concentrations detected in petrol and CNG exhausts, respectively for the same engine kind.

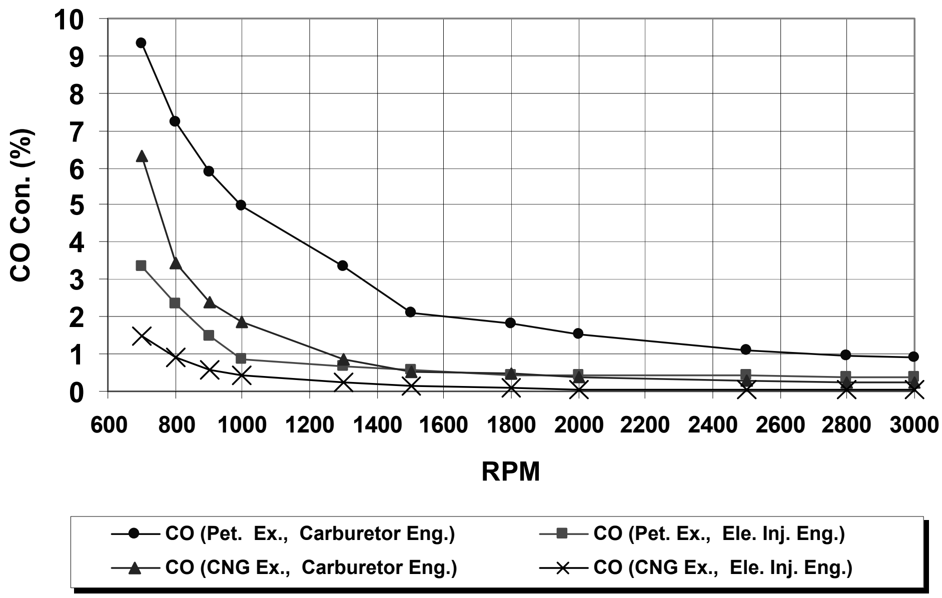
C_3 and C_4 represent the same pollutant concentrations detected in carburettor and fuel-injection engines exhausts, respectively, released due to the combustion of the same fuel type.

3 Results and discussions

3.1 Carbon monoxide (CO)

The average CO concentrations (in per cent) detected in petrol and CNG exhaust for the electronic fuel-injection and carburettor engines at different engine speeds are given in Figure 1. It demonstrates that CO concentrations determined in both engine types' exhaust were generally inversely proportional to the engine speed. CO concentrations were higher at the lower speed than at the higher speed up to 2500 rpm and insignificant variation in CO concentrations was observed after that in the four exhaust emissions. Regarding the carburettor engines, the average CO concentrations detected in petrol and CNG exhaust decreased from 9.3% and 6.3% at 700 rpm to 0.9% and 0.3% at 3000 rpm, respectively. For electronic fuel-injection engines, the corresponding CO concentration percentages in petrol and CNG exhaust decreased from 3.4% and 1.5% to 0.4% and 0.1%, respectively at the same rpm values. As was expected, the maximum concentrations of CO in petrol and CNG exhausts for both engine types were found at the start of the operating conditions (idling conditions) whilst the minimum concentrations were found at the end of the operating conditions (accelerating conditions).

Figure 1 CO concentrations (%) detected in petrol and CNG exhaust for the electronic fuel-injection and carburettor engines at different rpm



It was found that the average CO concentrations detected in petrol exhaust for the electronic fuel-injection and carburettor engines were 2.8 and 2.3 times higher, respectively, than those found in CNG exhaust. Figures 2A and 2B illustrate that compared to CO concentrations detected in petrol exhaust, CNG has the potential to reduce CO concentrations in the two types of engine exhaust. The reduction percentages were higher at the higher speed than at the lower speed. For carburettor engines the reduction percentages in CO concentrations (R_3) gradually increased from 32% at 700 rpm to 75% at 2500 rpm and decreased to 73% at 3000 rpm, with an average of 66%. The highest and lowest reduction percentages, 75% and 32% were found where CO concentrations in petrol exhaust were higher (4.0 and 1.5 times, respectively) than that in CNG exhaust (Figure 2A). With respect to the electronic fuel-injection engines, the corresponding reduction percentages in CO concentrations (R_6) increased from 56% to 88% at 2500 rpm (and still constant after that where no variation in CO concentrations was observed) with a relative higher average reduction of 73% (Figure 2B).

Figure 2A Reduction (%) of CO_2, HC and CO concentrations in carburettor engines exhaust due to CNG version at different rpm

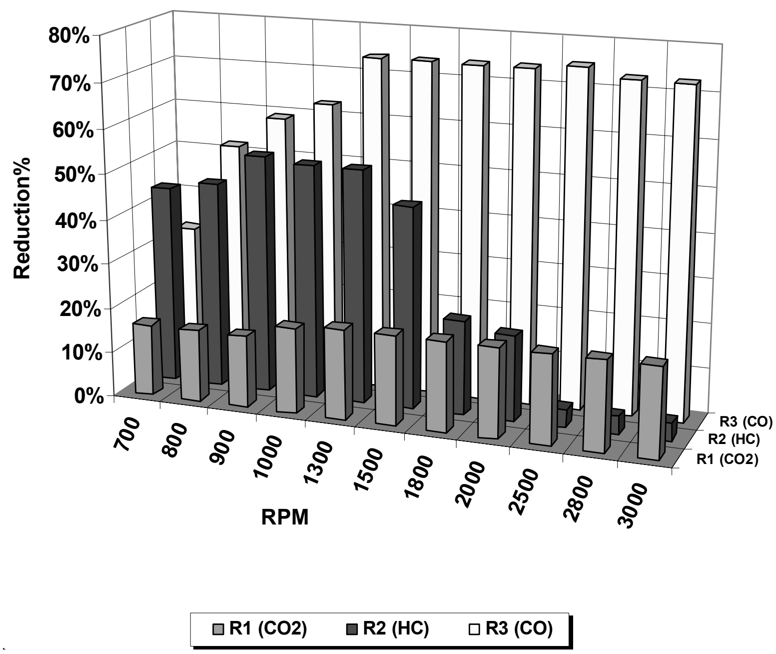
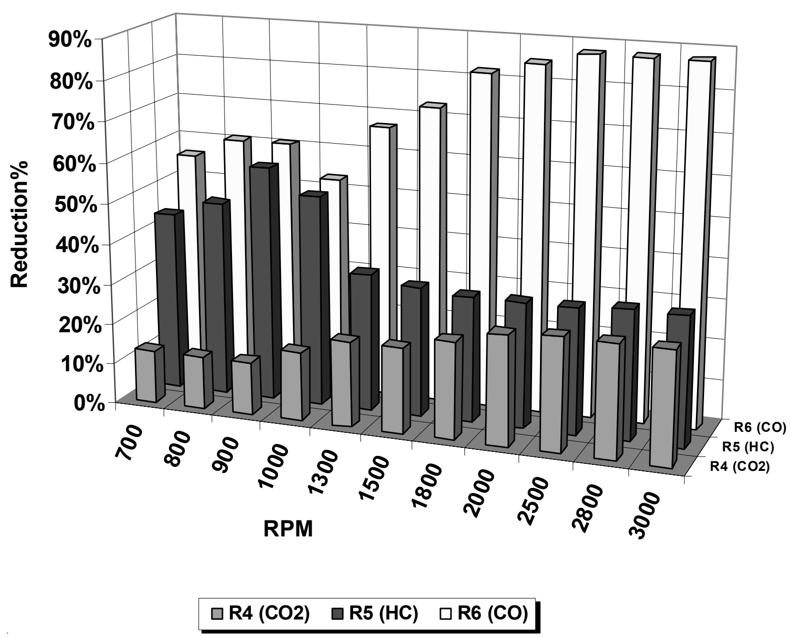


Figure 2B Reduction (%) of CO_2, HC and CO concentrations in electronic fuel-injection engines exhaust due to CNG version at different rpm



Compared to CO concentrations in carburettor engine exhausts, the use of electronic fuel-injection engines reduced CO concentrations in exhaust emissions for the two fuels as shown in Figures (3A and 3B). It is clear that for the petrol version, the reduction percentages in CO concentrations ($R^{\backslash}_{3}$) increased from 64% to 82% at 1000 rpm (which represented the highest reduction) and decreased to 57% at 3000 rpm, with an average of 70% (Figure 3A). Whilst for CNG, the corresponding reduction percentages ($R^{\backslash}_{6}$) were relatively higher at the higher speed where their average was 78% and the minimum and maximum reduction percentages were 73% and 82%, respectively (Figure 3B).

Figure 3A Reduction (%) of CO_2, HC and CO concentrations in petrol exhaust due to using the electronic fuel-injection engines at different rpm

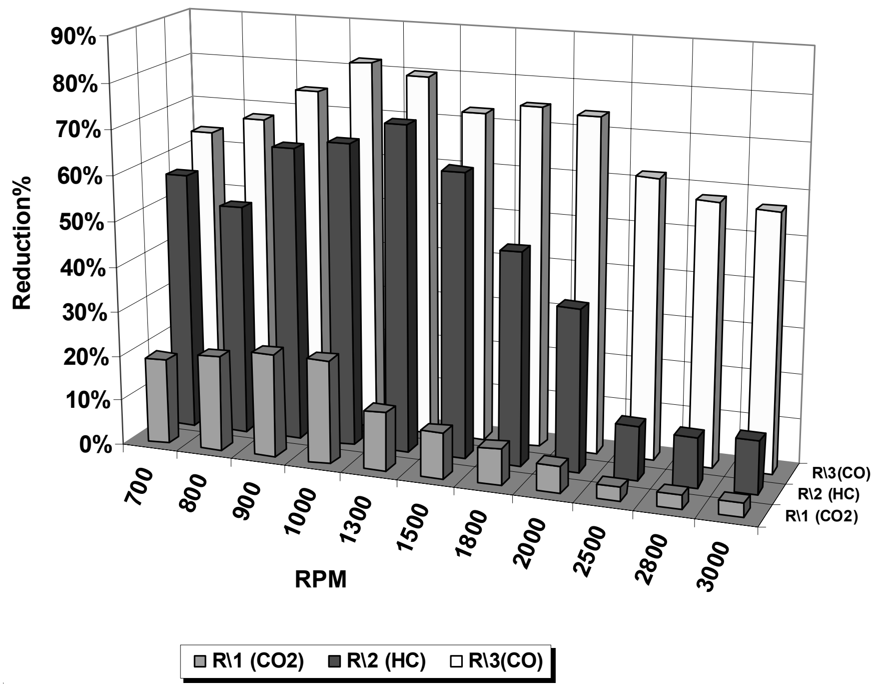
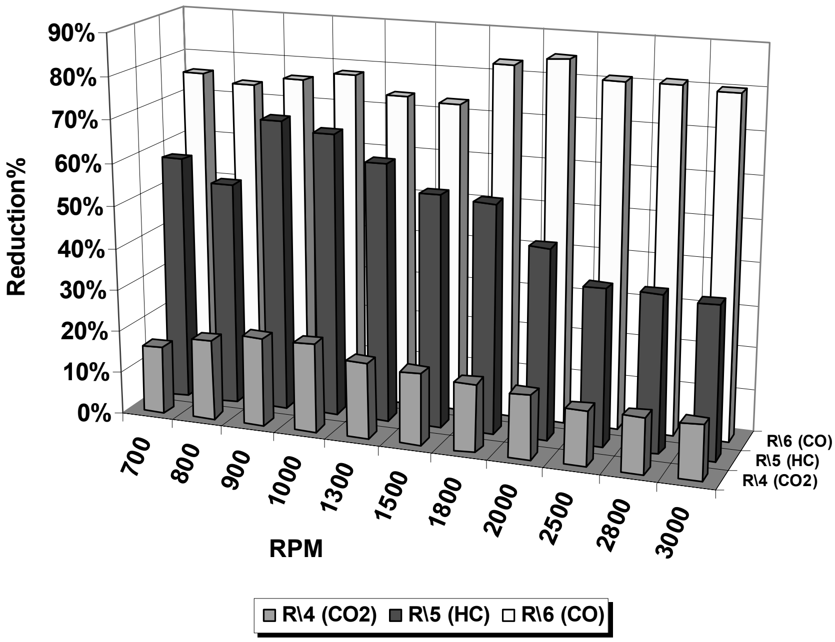


Figure 3B Reduction (%) of CO_2, HC and CO concentrations in CNG exhaust due to using the electronic fuel-injection engines at different rpm

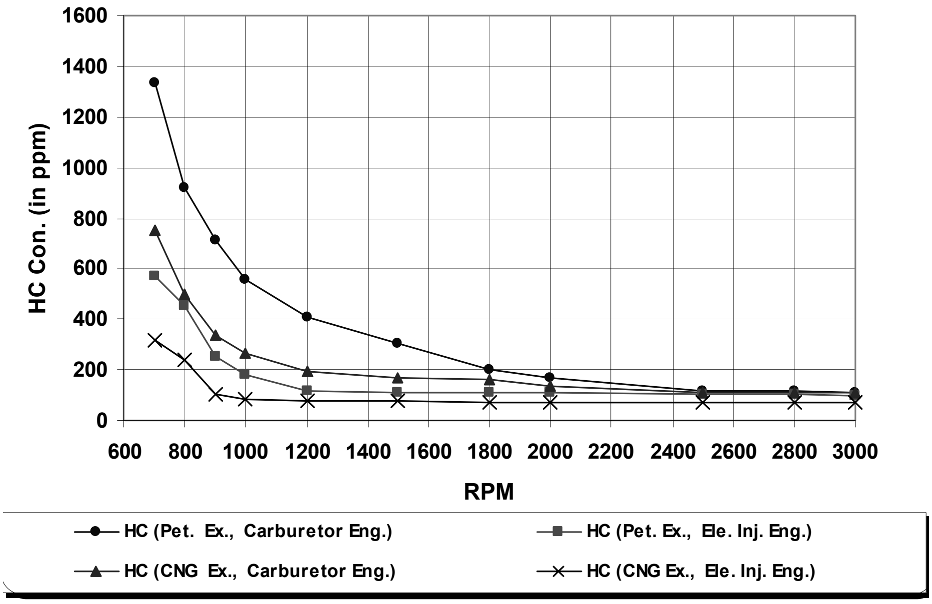


Finally, the average concentration of CO (in percent) detected in petrol exhausts for electronic fuel-injection engines is lower than the corresponding regulatory limit for CO after 1986 (4.5%) in Japan, South Korea (for old cars), Italy, Greece, Austria, Hungary and Czechoslovakia. Furthermore, average concentrations of CO (in percent) detected in CNG exhaust for electronic fuel-injection engines is lower than the corresponding limit of CO for LPG (4.5%) in the Netherlands and also for new model LPG cars in South Korea (1.2%) [12]. In addition, CO average concentration detected in petrol exhaust for the electronic fuel-injection and carburettor engines are lower (0.15 and 0.51 times, respectively) than that reported by the investigators [13-15].

3.2 Unburned Hydrocarbons (HC)

Figure 4 presents the average concentrations of HC (in ppm) detected in petrol and CNG exhaust released from the two types of engines at different rpm values. As with the pattern of CO concentrations, HC concentrations detected in the two fuels' exhaust for both engine types were inversely proportional to the engine speed. With respect to the carburettored engines, HC concentrations determined in petrol and CNG exhaust decreased from 1337 and 751 ppm at 700 rpm to 113 and 108 ppm at 3000 rpm, respectively. For electronic fuel-injection engines, the corresponding HC concentrations detected in petrol and CNG exhaust decreased from 570 and 318 ppm at 700 rpm to 99 and 70 ppm at 3000 rpm, respectively. Figure 4 also shows that the maximum concentration of HC was found at the start of every operating condition, whilst the minimum concentration was recorded at the latter stages of the cycle.

Figure 4 HC concentrations (in ppm) detected in petrol and CNG exhaust for the electronic fuel-injection and carburettor engines at different rpm



The average HC concentrations detected in petrol exhaust for electronic fuel-injection and carburettor engines were found to be higher (1.8 times) than the corresponding figures for CNG. Figure 2A shows the reduction percentages in HC concentrations for the CNG version of the carburettor engines (R_2), compared to their concentrations in petrol exhaust. It was relatively higher, between 44% and 53%, at the lower engine speeds
(700-1500 rpm) than at higher speeds at which it decreased only 4% at 2500 rpm. It remained constant after that and the associated average was found to be 31%. The same trend was also seen for the electronic injection engines (Figure 2B) where the corresponding reduction percentages in HC concentrations (R_5) were between 44% and 58% at the lower speeds (700-1000 rpm) and 32% at 2800 and 3000 rpm with an average reduction of 39%. The maximum reduction percentages for the two engine types were recorded at 900 rpm, at which HC concentrations in petrol exhaust were higher (2.4 and 2.1 times) than those found in CNG exhaust for electronic fuel-injection and carburettor engines, respectively.

Compared to carburettor engine emissions, the reduction percentages in HC concentrations resulting from using electronic fuel-injection showed the same trend for both petrol and CNG versions and the reductions were higher at the lower rpm than at the higher rpm (Figures 3A and 3B). For the petrol version, the reductions in HC concentrations (R'_2) were higher, between 51% and 72%, at between 700-1300 rpm. They decreased to 12% at 3000 rpm, with an average in the order of 45% (Figure 3A). For the CNG version, the corresponding emission reductions were the highest, 69%, at 900 rpm and they then gradually decreased to 36% at 3000 rpm. The average reduction was 52% (Figure 3B).

The average concentration of HC (in ppm) detected in petrol exhausts for electronic fuel-injection engines is lower than the corresponding regulatory limit for HC (in ppm) introduced after 1986 in countries such as Czechoslovakia (800 ppm), Finland (600 ppm), Greece (500 ppm) and South Korea (1200 ppm for old cars). Moreover, the average concentration of HC in ppm detected in CNG exhaust for electronic fuel-injection engines is lower than the corresponding limit for HC (in ppm) for the new model LPG cars in South Korea (400 ppm) [12]. Besides, the average HC concentrations detected in petrol exhaust emissions for the electronic fuel-injection and carburettor engines are lower (0.25 and 0.55 times, respectively) than those reported elsewhere [13,14] and also are lower (0.13 and 0.28 times, respectively) than those reported by [15].

The high quantities of CO and HC in petrol exhaust emissions, particularly at lower rpms, are caused by the incomplete combustion of the fuel in the idling operating condition. With cold engines at the start, emissions are substantially higher than with a hot engine and engines take some time to reach the normal operating temperature. Moreover, during the cold start period, use of the choke is required to make the air-fuel ratio rich and, thus compensate for the low vapour pressure of cold petrol [16]. At higher engine speeds the spark time will also be advanced and subsequently the combustion condition will be advanced too. The composition of the exhaust, therefore, depends largely on the acceleration rate, the overall accelerating time and the change in the gear ratio. Furthermore, the increase in engine speed improves the combustion process within the cylinder by increasing turbulent mixing and eddy diffusion. Increased exhaust port turbulence at higher speeds promotes exhaust system oxidation reactions through better mixing. Consequently, those conditions that promote or enhance complete combustion tend to reduce the quantities of CO and HC in the exhaust gases [11,17,18]. These findings are in agreement with those reported in [19].

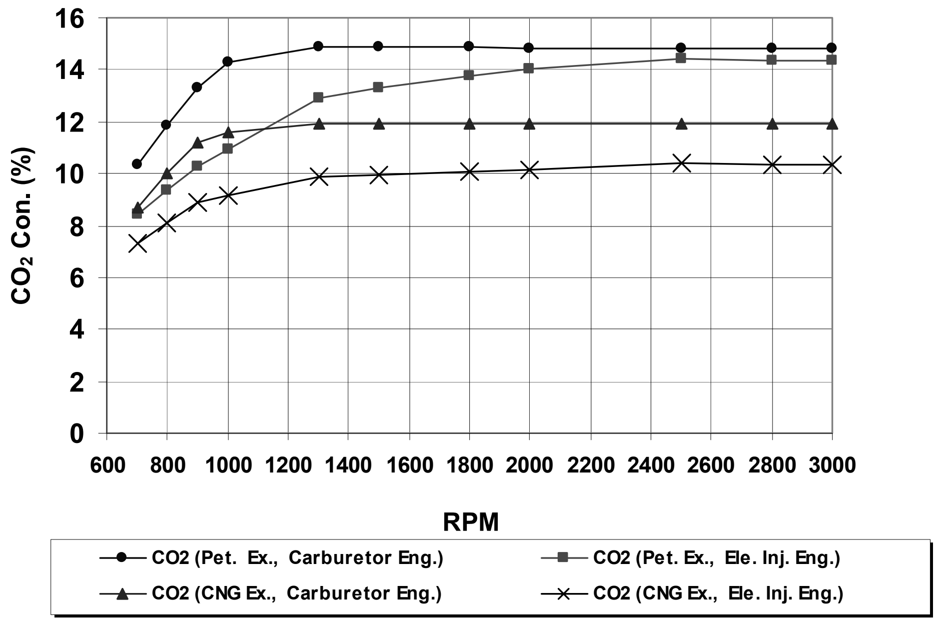
Regarding the low concentrations of CO and HC in the CNG exhaust, this is because natural gas provides excellent cold start emissions behaviour at normal and low temperatures [9]. Furthermore, it will allow spark ignition engines to operate on the lean side more efficiently than petrol [20,21]. Moreover, its gaseous state leads to better mixing between the fuel and air, which causes better distribution and more complete combustion than liquid fuels leading to low concentrations of CO and HC in exhaust emissions.

3.3 Carbon dioxide (CO_2)

The variation of CO_2 concentrations in petrol and CNG exhaust for the two investigated engine types is shown in Figure 5. This shows that the CO_2 concentrations detected in the four exhausts were in direct proportion to the engine speed. Regarding the carburettor engines, CO_2 concentrations increased from 10.4% and 8.7% at 700 rpm to 14.9% and 12.0% at 1300 rpm and no significant variation was observed after that. The average was 14.0% and 11.4% in petrol and CNG exhaust, respectively. For electronic fuel-injection engines, the corresponding CO_2 concentrations in petrol and CNG exhaust increased from 8.4% and 7.3% to 14.4% and 10.4%, respectively and the associated average was 12.4% and 9.5%, respectively. Figure 5 also shows that the maximum concentration of CO_2 in petrol and CNG exhausts for carburettor and electronic injection engines was found at 1300 and 2500 rpm, respectively.

It was found that average CO_2 concentrations in petrol exhaust for both engine types were higher (1.3 times) than those in the CNG exhaust. Figures 2A and 2B show the reduction percentages in CO_2 concentrations for the two engine types using CNG compared to their concentrations in petrol exhaust. For the carburettor engines the reduction percentages in CO_2 concentrations (R_1) increased from 16% to 20% at 1300 rpm and then remained constant after that. The average reduction was in the order of 19% (Figure 2A). For the electronic injection engines, Figure 2B shows that the corresponding reduction percentages (R_4) had a constant value of 13% at 700, 800 and 900 rpm. It increased after that to 28% at 2500 rpm with an average of 21%.

Figure 5 CO_2 concentrations (%) detected in petrol and CNG exhaust for the electronic fuel-injection and carburettor engines at different rpm



Figures 3A and 3B show the reduction percentages for CO_2 using electronic fuel-injection engines for petrol and CNG compared to their concentrations detected in the carburettor engines' exhaust. The reduction percentages for CO_2 concentrations in petrol exhaust ($R^{\backslash}_{1}$) were relatively higher, between 19% and 23% at lower rpm values (700-1000 rpm). The value decreased to only 3% at 2500 rpm and remained constant after that. The average reduction was of the order of 12%. Figure 3B reveals that the corresponding reduction percentages in CO_2 concentrations in CNG exhaust ($R^{\backslash}_{4}$) showed a similar trend to that of the petrol version. It increased from 16% at 700 rpm to 21% at 1000 rpm and decreased to 13% at 2500 rpm, whilst the average reduction percentage was relatively higher at 17%.

The obtained concentrations of CO_2 in petrol exhaust emissions for both electronic fuel-injection and carburettor engines are similar to those reported in [11,22,] at the lower engine speeds but are slightly higher than those found by the same investigators at higher speeds.

The low concentrations of CO_2 in CNG exhaust, compared to their concentrations determined in the petrol exhaust, can be attributed to the advantages of the natural gas, which has more stable lean combustion [6]. Besides, it contains less carbon and more hydrogen than petrol and so gives a lower amount of CO_2 [19].

The increase of CO_2 and decrease of CO emissions in the vehicle exhaust at higher engine speeds could be explained thus. Given sufficient time to soak at the prevailing temperature and pressure, an equilibrium situation will be reached and under this condition equation (3) will hold [17].

$$CO + \tfrac{1}{2}O_2 \text{----------}\rightarrow CO_2 \qquad (3)$$

Although the environmental performance of LPG is competitive with CNG and superior to that of methanol and gasoline [23], the present paper illustrates that CNG as an automotive fuel has similar advantages, if not better. Where the reduction percentages in CO and HC concentrations for LPG engines were about 40%, these were recorded only at the higher speeds [24], whilst the corresponding reduction for methanol (M85) engines was 15% for CO_2 concentrations, whilst CO levels were similar to those from petrol [25].

Finally, the relative lower concentrations of CO, HC and CO_2 detected in the exhaust released from electronic fuel-injection engines, compared to their concentrations determined in well-carburetted engines' exhaust, can be linked to the advantages of the electronic fuel- injection system. Generally, fuel injection systems lead to improved fuel distribution and lean mixture drivability, thereby decreasing HC and CO emission through leaner operation. Besides, fuel injection is best for improving full load power where maximum volumetric efficiency is required [17]. In addition, in the carburettor systems the fuel is transported from the fuel tank to the carburettor by a fuel pump powered by the camshaft of the distributor shaft. In the fuel-injection system a hydrodynamic electric fuel pump, which generally is installed in the fuel tank, is used. The injection system also has the ability to prevent the formation of air bubbles because the injector is flushed continuously by the fuel that surrounds it. Furthermore, the electronic fuel-injection system easily treats and solves the problems which would exist at cold starts because it can provide additional fuel and also during the immediate post-start by extending the injection time and warm-up phases [26].

4 Conclusions

Our study demonstrates that, compared to petrol, CNG has the potential to reduce CO, HC and CO_2 emissions in vehicle exhausts of electronic fuel-injection and well-carburetted engines by averages of 69.5%, 35% and 20%, respectively. Compared to vehicles with well-carburetted engines, vehicles with electronic fuel-injection engines reduced the same pollutant emissions in both petrol and CNG exhaust by averages of 74%, 48.5% and 14.5%, respectively. The study also confirmed that there are substantial differences in pollutant emissions associated with actual speed and operating conditions. Finally, the present study shows that air pollution emissions related to auto exhausts can be reduced by converting conventional petrol engines to CNG and by using vehicles with electronic fuel-injection systems in all activities.

It is also of great importance to acknowledge the potential for expanding the use of CNG as a substitute for conventional fuels in many other activities: power plants, industrial activity (cement production, fertilizer, steel manufacturing and metallurgical industries) and in various commercial sectors such as restaurants and bakeries. This would assist in reducing the air pollution levels in cities such as Cairo, which is characterised by high population and road vehicle densities.

Acknowledgement

The authors would like to thank the GUPCO management committee head and all the engineers for their assistance and cooperation in providing us with the investigated vehicles and modern exhaust analyser equipment.

References

1 El-Abssawy, A.A. (1995) 'Trends of air pollution emissions in Egypt with special reference to Greater Cairo', *PhD Thesis*, Fac. of Sci., Ain Shams University, Cairo, Egypt.

2 Shakour, A.A., El-Taieb, N.M., Mohamed, S.K. and Zakey, A.S. (1998) 'Investigation of air quality in the industrial area North Cairo', *Central European J. of Occupational and Environmental Medicine*, Vol. 4, No. 2, pp.192-203.

3 Cypra, A., Beer, A. and Bauer, H. (1996) *Automotive Handbook*, 4th edition, Robert Bosch GmbH, pp.459, 462 and 463.

4 Ingersoll, J.G. (1994) *Natural Gas Vehicles*, Fairmont Press, GA.

5 Elkady, M.A and Abdelaal, M.M. (1997) 'An overview of the use of alternative fuels and air pollution crisis', *1st Int. Conf., Trade Fair on Environmental Management and Technologies*, Cairo, Egypt, 16-18 February.

6 Springer, K.J., Smith, L.R. and Ickinson, A.G. (1993) *Energy-Source Technology Conference and Exhibition*, Houston, Texas, ASME, 31 January-4 February.

7 Gambino, M., Iannaccone, S. and Unich, A. (1991) 'Light duty and heavy duty spark ignition engines fueled with methane', *Intern. Conf. on the Analysis of Thermal and Energy Systems,* Atene, 3-6 June, pp.631-641.

8 Gambino, M., Iannaccone, S. and Unich, A. (1992) ' Heavy-duty cng fueled engines, their possibility to meet present European legislation limits', *II Workshop Istituto Motori*, Capri, 14/19 September, pp.401-405, 92P722.

9 Weaver, C.S. (1989) 'Natural gas vehicles – a review of the state of the art', *SAE, Paper 892133*.

10 Ahimaz, F., King, T., Santini, D., Saricks, C. and Sekar, R. (1994) 'Compressed natural gas technology' – a pilot project for CTA garage in Cairo, *Presentation at the CNG Workshop*, Cairo, Egypt, 21-22 November.

11 Shakour, A.A. (1976) 'Studies on motor vehicles exhaust gases', *MSc Thesis*, Fac. of Sci., Cairo University, Egypt.

12 Samaras, Z. and Zachariadis, T. (1995) 'The inspection of in-use cars in order to attain minimum emissions of pollutants and optimum energy efficiency', *LAT Report 9502*, Project Funded by the European Commission, Aristotle University, Thessaloniki, Fac. of Eng.

13 O'Flaherty, C.A. (1972) 'Auto-exhaust emissions of hydrocarbons and nitrogen oxides into Cairo atmosphere', in M.M. Nasralla and A.A. Shakour (Eds.) (1984) *Int. J. of Environ. Studies*, Vol. 3, pp.265-285, 2nd Egyptian Congress of Chemical Engineers, 18-20 March 1984, pp.1209-1221.

14 Seinfeld, J.H. (1986) *Atmospheric Chemistry and Physics of Air Pollution*, John Wiley and Sons, New York.

15 Colls, J. (1997) *Air Pollution: An Introduction*, E and FN Spon, London, p.45.

16 Farrow, I.K. *et al.* (1993) *LR 978: Vehicle Exhaust Emissions in Very Congested Traffic at Low Temperature*, Stevenage, Warren Spring Laboratory.

17 Patterson, D.J. and Henein, N.A. (1973) *Emissions from Combustion Engines and Their Control*, Ann Arbor Science Publishers, Michigan.

18 Wark, K. and Warner, C.F. (1981) *Air Pollution: Its Origin and Control*, 2nd edition, Harper and Row, New York.

19 Stern, A.C. (1977) *Air Pollution*, Academic Press, New York.

20 Fleming, R.D. and O' Neal, G.B. (1986) 'Potential for improving the efficiency of spark ignition engine for natural gas fuel', *SAE, Paper 852073*.

21 Gupta, M. and Bell, S.R. (1994) 'Investigation of lean combustion in a natural gas fueled spark ignition engine', *ASME*, Vol. 21, pp.37-46.

22 Lareson, G.P., Chipman, J.C. and Kauper, E.K. (1964) 'Vehicle emissions', *Part 1. Selected SAE Papers (1955-1964)*, Soc; of Automotive Engineers, Inc. NY.

23 Webb, R.F. (1991) *An Assessment of Propane as an Alternative Transportation Fuel in the United States*, issued by the National Propane Gas Association.

24 Soliman, H.A., Beshai, S.W., El-Beheri, Z. and Hussien, K. (1994) 'The use of LP-gas as a spark ignition engine fuel', *Proc. of the 4th Int. Conf. on Energy, Development and Environment*, Cairo, Egypt.

25 Abdel-Gayed, R.G. and Girgis, N.S. (1994) 'Performance and emissions of a spark ignition engine fueled with methanol (M85)', *Proc. of the 4th Int. Conf. on Energy, Development and Environment*, Cairo, Egypt.

26 Bata, R., Clark, N., Grautam, M., Lyons, D. and Wang, W. (1997) 'Natural gas as an environmentally clean vehicular fuel for cities', *1st Int. Conf., Trade Fair on Environmental Management and Technologies*, Cairo, Egypt, 16-18 February.