Jayaratne, Rohan and Ristovski, Zoran and Meyer, Nickolas K. and Morawska, Lidia (2009) ***Particle and gaseous emissions from compressed natural gas and ultralow sulphur diesel-fuelled buses at four steady engine loads.*** Science of the Total Environment, 407(8). pp. 2845-2852.

Particle and Gaseous Emissions from Compressed Natural Gas and Ultralow Sulphur Diesel-Fuelled Buses at Four Steady Engine Loads

E.R. Jayaratne, Z.D. Ristovski*, N. Meyer and L. Morawska

International Laboratory for Air Quality and Health

Institute for Health and Biomedical Innovation

Queensland University of Technology

GPO Box 2434, Brisbane, QLD 4001, Australia

November 2008

* Corresponding author contact details:

Tel: (617) 3864 1129; Fax: (617) 3864 9079

Email: z.ristovski@qut.edu.au

Abstract

Exhaust emissions from thirteen compressed natural gas (CNG) and nine ultralow sulphur diesel in-service transport buses were monitored on a chassis dynamometer. Measurements were carried out at idle and at three steady engine loads of 25%, 50% and 100% of maximum power at a fixed speed of 60 kmph. Emission factors were estimated for particle mass and number, carbon dioxide and oxides of nitrogen for two types of CNG buses (Scania and MAN, compatible with Euro 2 and 3 emission standards, respectively) and two types of diesel buses (Volvo Pre-Euro/Euro1 and Mercedez OC500 Euro3). All emission factors increased with load. The median particle mass emission factor for the CNG buses was less than 1% of that from the diesel buses at all loads. However, the particle number emission factors did not show a statistically significant difference between buses operating on the two types of fuel. In this paper, for the very first time, particle number emission factors are presented at four steady state engine loads for CNG buses. Median values ranged from the order of 10^{12} particles min^{-1} at idle to 10^{15} particles km^{-1} at full power. Most of the particles observed in the CNG emissions were in the nanoparticle size range and likely to be composed of volatile organic compounds The CO_2 emission factors were about 20% to 30% greater for the diesel buses over the CNG buses, while the oxides of nitrogen emission factors did not show any difference due to the large variation between buses.

Keywords: *vehicle emissions, particle number, diesel, CNG, PM emissions*

1. Introduction

Compressed natural gas (CNG) engines are thought to be less harmful to the environment than conventional diesel engines, especially in terms of emissions such as particulate matter (PM), carbon dioxide (CO_2) and oxides of nitrogen (NO_x). Diesel emissions contain a range of toxic substances such as polycyclic aromatic hydrocarbons and formaldehydes that are well known carcinogens. In contrast, the main emission product of CNG is methane. Although, it is an effective greenhouse gas, methane is non-toxic. For these reasons, CNG is considered to be the safer fuel. In recent years, there has been a major drive to replace diesel powered vehicles with CNG, especially in large transport fleets such as taxis and buses. For example, over the past six years, 40% of the Brisbane City Council transport bus fleet has been gradually converted from diesel to CNG. In New Delhi, India, one of the most polluted cities in the world, converting the entire transport fleet to CNG in 2000 has resulted in a significant improvement in air quality in terms of suspended particulate matter, CO, SO_2 and NO_x (Goyal, 2003). In spite of these obvious advantages, some concerns have been expressed on the concentrations of ultrafine particles (particles smaller than 100 nm in diameter) emitted by buses operating on diesel and CNG. It has been shown that these small particles are able to penetrate deeper into the human lung and may prove to be more toxic than larger particles (Donaldson et al, 1998). Therefore, there is a great need to study and compare emissions, particularly particle number-size distributions, from vehicles operating on diesel and CNG fuel with a view of ascertaining their relative merits and demerits from health and environmental perspectives.

2. Previous Studies

There have been several studies conducted with the aim of comparing particle emissions from diesel and CNG buses. While, most of these studies have shown a consistency with respect to particle mass emission factors, there is considerable disagreement between results of particle number emission measurements.

Particle Mass: Table 1 presents a summary of the results of particle mass emission factors (MEF) in some previous studies. In general, most of these studies have shown that the particle mass emissions from CNG buses were less than 5% that from diesel buses when no after-treatment devices were employed. With after treatment devices, particularly particle traps and filters, mass emissions were reduced sufficiently to be comparable with CNG emissions.

Particle Number: Although, in the absence of any after-treatment devices, there is a clear difference between particle mass emissions from CNG buses and diesel buses, there is significant inconsistency in the relative particle number emission factors from the two types of buses. In the first instance, this is particularly due to the small number of measurements that have been carried out, and the difficulties in quantifying the effects of engine operating and testing conditions, and fuel and lubricating oil composition, on secondary particle production. Most studies of particle number emissions from CNG vehicles under steady state conditions express particle number emissions as number concentrations, and emission factors have not been calculated and presented (Holmen and Ayala, 2002; Holmen and Qu, 2004; Lanni et al, 2003). Nylund et al. (2004) determined particle number emission factors from diesel and CNG buses in two transient cycles. No study has reported particle number emission factors from CNG buses under steady state operating conditions. In general, particle number emissions from CNG buses appear to be smaller than from diesel buses, but there are some exceptions, particularly related to high engine load conditions (Holmen and Qu, 2004; Jayaratne et al., 2007).

The present study was aimed at resolving some of these uncertainties and to provide particle number emission factors for diesel and CNG buses under different steady engine load conditions for use in dispersion modelling for a specific fleet operating on a dedicated busway. The information for particle number emissions from CNG buses under steady engine loads is not available at present. In-use vehicle emissions in Australia are clustered under the umbrella of NEPM (National Environmental Protection Measures). Within Diesel NEPM, only PM_{10} and NO_x are monitored. Thus, it was decided to monitor the emissions of these two parameters and, in addition, CO_2, as it is the most important greenhouse gas emitted by motor vehicles.

3. Methods

3.1 Specification of buses

The test vehicles were chosen so that they represented a snapshot of the entire fleet (Table 2). Note that the older diesel B10 buses are currently being replaced by the more modern Mercedez OC500 buses, which necessitated the testing of a larger sample of the latter. We tested 22 different buses, including 13 CNG buses and 9 diesel buses under identical conditions. The tests were carried out in two rounds (R1:April and R2:November 2006) and the number and types of buses tested in the two rounds are given in the table, together with the engine types and the effective emission standards. Five of the CNG Scania's and one of the Diesel OC500's were tested in both rounds. All of the diesel buses were operated on ultralow sulphur (50 ppm) fuel. The four older Volvo B10 buses consisted of three Volvo B10M Euro I or older (engine type THD101GC) and one Volvo B10L Euro II (engine type D10HA). All buses belonged to the same transport fleet and were subject to the same running and service pattern. They were all six-cylinder engines and each had a carrying capacity of 60-75 passengers.

3.2 Operating Conditions

Engine dynamometer studies generally express emission factors for heavy-duty vehicles in g kWh^{-1}. However, the present study was conducted on a chassis dynamometer, primarily to provide emission factor data for use in dispersion modelling near a dedicated busway. Thus, it was necessary to maintain the vehicle speed at the urban speed limit of 60 km h^{-1} and to vary the operational load to account for level road acceleration and road gradients. Emission measurements were carried out at four steady state engine loads set at 0% (idle), 25%, 50% and 100% of the maximum engine power at 60 km h^{-1}. In this paper, these four operational modes shall be denoted as L0, L25, L50 and L100 respectively. The engine was first warmed up by running at a high load for about 10 min, during which time the maximum engine power at a steady speed of 60 km h^{-1} was determined. Next, the engine was first allowed to idle for about 10 min while emissions were monitored. Then the load was sequentially set to 25%, 50% and 100% of the maximum power for approximately 10 mins each, while monitoring was continued. The operating conditions of the bus, such as load and speed, were monitored and recorded in real time.

3.3 Measurement System

As shown in the schematic diagram in Fig 1, the system employed a continuous volume sampling method, where the entire exhaust from the bus was channelled into a flexible tube of diameter 300 mm. The exhaust gas and ambient air was sucked through the tube into the primary sampling line, which was a stainless steel tube of diameter 300 mm, by means of an air pump attached to the other end, ensuring a steady flow rate of 500 L s^{-1}. The mixing of ambient air into the exhaust resulted in a dilution factor of about 2 within the primary sampling line. Parameters, such as air flow rate, temperature, pressure and humidity were measured and recorded in real time.

The CO_2 and NO_x concentrations were determined by dedicated gas analysers, sampling directly from the primary sampling line. The sample for the PM_{10} was further diluted by a factor of 5 with filtered, compressed air and measured with a TSI 8520 DustTrak aerosol monitor. Particle mass concentration in the size range 0.1 to 10 µm was measured to an accuracy of 1 µg m^{-3}. The sample for the particle number and size measurements was extracted from the primary sampling line and passed through an ejector type diluter (Dekati Ltd) where it was diluted by filtered, compressed air by a factor of approximately 10 before being drawn into the following instruments:

- A TSI 3022 condensation particle counter (CPC) that measured the total particle number concentration in the size range 5 nm to about 4 µm.
- A TSI Scanning Mobility Particle Sizer (SMPS) consisting of a TSI 3085 Electrostatic Classifier and a TSI 3025 CPC. The SMPS sample and sheath air flow rates were set to measure particle size distribution in the range 5-160 nm.
- A Sable CA-10A fast-response CO_2 monitor of resolution 1 ppm.

The air flow speed in the primary sampling line was about 7 m s^{-1}. The sampling point was less than 4 m along the tube from the exhaust. Thus, the residence time of the particles in the tube prior to sampling was a fraction of a second, which was too short for any significant degree of coagulation of particles to take place.

All instruments were tested and calibrated in the laboratory prior to the commencement of the measurements. All data were logged at 1s intervals in real time.

The second stage dilution ratio was calculated as the ratio of CO_2 concentrations measured by the Sable monitor to that determined in the primary sampling line. The particle concentrations in the primary sampling line were estimated by multiplying the concentrations measured by the CPC and SMPS by the corresponding second stage dilution factors. In a CVS system, the entire exhaust is directed into the primary sampling line and diluted with ambient air. Knowing the flow rate of the air in the primary sampling line and the ambient concentrations of CO_2 and particle number, it was possible to determine the particle concentrations in the exhaust and, thereby, the respective emission rates/factors.

3.4 Emission Units

Vehicle emission results, especially for the purposes of modeling, are generally specified as emission factors, in units of number of particles or mass of a pollutant per km traveled. This definition is not applicable to the idle mode, where the bus remains stationary. Thus, in the idle mode, results are given as emission rates, in units of particle number or mass of a pollutant per minute. However, it may be noted that, in the three driving modes, since the bus speed was fixed at 60 kmph, the emission factor (in km^{-1}) and the emission rate (in min^{-1}) were numerically identical. This is merely a coincidence in this study only. However, it affords a direct method for the extraction of emission rates for the three driving modes, if required in modelling applications.

3.5 Analytical and Statistical Methods

Emission factors and rates were calculated and are presented as median values for each of the bus/fuel combinations shown in Table 2. Mean or average values were avoided as, very often, there were outliers in the emission results, where one or two buses showed significantly high emissions over the other buses in a group. Percentile levels of 25% and 75% were computed to show the variation about the median value, and these are shown as error bars on the histograms.

Emission factors and rates for the various bus/fuel groups were compared using t-test analysis. For this analysis, the mean and standard deviation were calculated for each parameter at each mode. The corresponding mean values for the buses in each group were computed and compared. The statistical comparison was performed through a two-sample students paired two-tailed t-test to determine significant differences between the group means. From the test statistic, a confidence level was calculated for the two distributions to be significantly different. A confidence level greater than or equal to 95% was taken to indicate that the means of the two distributions were significantly different to each other.

Using the number distribution of buses in the fleet., as shown in column 2 of Table 1, weighted emission factors and rates were calculated for buses operating on each of the two fuel types.. This enabled the comparison of emission factors and rates of diesel and CNG buses pertaining to the fleet under consideration. Error bars for the fleet-weighted emission factors were derived by appropriately weighting the error bars associated with the different types of buses according to the numbers in the test sample.

4. Results

Since the aim of this study was to provide average diesel and CNG emission factor data for use in dispersion modelling for a specific fleet operating on a dedicated busway, we have placed more emphasis on the fleet-weighted results rather than the individual results of the test-vehicles. The tables presented in this section give the median emission rate/factors of each of the parameters for the four bus/fuel combinations in the four engine loads. The last two columns in each table show the weighted values for a bus in the diesel fleet and the CNG fleet, respectively. The accompanying figures show a comparison of these two values at each of the four modes. The error bars represent the corresponding 25% and 75% percentile values in each distribution.

4.1 Total Particle Number

The median particle number emission rate/factors for the four bus/fuel combinations in the four engine loads are given in Table 3. The median particle number emission rate/factors increased with engine load within each of the four bus/fuel groups. At a given mode, the emission rate/factors varied widely between buses. Figure 2 shows the fleet-weighted particle number emission rate/factors for the buses operating on diesel and CNG at the four modes. The particle number emission rate/factor in each of the four modes was greater for the diesel buses over the CNG buses, but the difference was statistically significant only at L50.

4.2 Particle Number Size Distributions

Figure 3 shows a typical set of SMPS scans for a diesel bus at the four operational modes. This particular example is for a Euro I compatible B10M bus (odometer 772,000 km). In general, all diesel buses showed log-normal distributions with a modal size of about 80-90 nm in all four operational modes.

At a given operational mode, the SMPS number-size scans for a given diesel-powered bus showed a consistent trend in both particle number and particle size.

For example, Figure 4 shows the three particle number-size distributions measured with the SMPS at the 100% load for the same bus above. The modal size and the total number of particles (shown) were very consistent between scans. However, there was considerable variation between different buses under the same conditions.

The SMPS number-size scans for a given CNG-powered bus at a given mode showed a consistent trend in particle size but not in particle number. For example, Figure 5 shows the three particle number-size distributions measured with the SMPS at the 100% load for one of the Scania CNG buses. It can be observed that the modal size was consistent between the scans, being around 10-12 nm. This was significantly less than the values for the diesel buses. However, the total numbers of particles (shown) were not consistent between scans. Moreover, there was considerable variation of particle number between different buses under the same conditions. This variation was much greater than that between the diesel buses.

4.3 Particle Mass (PM_{10})

The median PM_{10} emission rate/factors for the four bus/fuel combinations at the four engine loads are given in Table 4. Figure 6 shows the weighted PM_{10} emission rate/factors for the buses operating on diesel and CNG at the four engine loads.

The PM_{10} emission rate/factors increased with engine load for the diesel buses. With most of the CNG buses, in the idle and 25% power loads, the PM_{10}

concentrations were below the lower detectable limit of the instrument which corresponded to an emission rate/factor of about 0.1 mg min^{-1}. At a given load, the emission rate/factor of the CNG buses varied widely between buses. As observed by the error bars in Fig 6, the diesel buses did not exhibit such a large variation.

The weighted PM_{10} emission rate/factors for the CNG buses were at least two orders of magnitude lower than that for the diesel buses. This difference was statistically significant at the 95% confidence level at each of the four operating modes.

4.4 Carbon Dioxide (CO_2)

The median CO_2 emission rate/factors for the four bus/fuel combinations in the four modes are given in Tables 5. Figure 7 shows the weighted CO_2 emission rate/factors for the buses operating on diesel and CNG at the four engine loads.

The CO_2 emission rate/factors increased steadily with engine load with every one of the buses, both diesel and CNG. The median CO_2 emission rate/factors increased with engine load for all bus/fuel combinations. At a given load, the emission rate/factors were relatively stable between buses using the same fuel. In the three driving modes, the weighted CO_2 emission rate/factors at a given load for the diesel buses were significantly greater than that for the CNG buses, the difference being from 20% to 30%. The relatively large width of the error bars for the CNG buses was a consequence of the wide range of maximum engine powers that varied considerably between buses depending on their service histories, especially within the Scania buses tested.

4.5 Oxides of Nitrogen (NOx)

The median NO_x emission rate/factor for diesel and CNG buses in the four modes are given in Table 6. Figure 8 shows the weighted NO_x emission rate/factors for the buses operating on diesel and CNG at the four engine loads.

The median NO_x emission rate/factors increased sharply with engine load for both diesel and CNG buses. At a given load, the emission rate/factors varied widely between buses, especially with the CNG buses. There were no statistically significant differences between the NO_x emission rate/factors between buses operating on the two types of fuel at any of the operating modes.

5. Discussion

In this study, we tested 22 different buses, including 13 CNG buses and 9 diesel buses under identical steady state engine load conditions. Most other studies have been carried out on transient cycles and mainly for particulate mass and not number emissions. Except for Wang et al (1997), all other studies of particle mass emissions from buses have not studied more than seven buses each (Table 1). There are very few studies of particle number emissions from buses and that too have been on transient cycles. In this respect, we believe that the present study comprises a unique study on a relatively large number of buses that may be considered representative of the fleet under consideration.

The observed difference in PM_{10} emission rate/factors between the diesel and CNG buses is in agreement with previous studies summarised in Table 1. The diesel buses, with no after-treatment showed PM_{10} emissions that were at least two orders of magnitude greater than from the CNG buses fitted with oxidation catalysts. We compare this with Nylund et al (2004) who found that the PM_{10} emissions from a diesel bus with no after-treatment was about 17 times larger than that from a CNG bus with an oxidation catalyst.

In a previous study, we determined the particle number emission factors from 12 pre-Euro and Euro 1 diesel buses from the same fleet using ultralow sulphur fuel (Ristovski et al, 2006). The tests were carried out on a dynamometer at the same four steady state engine loads used in the present study, but at a higher speed of 90 km h^{-1}. In Table 7, we compare these values with the values obtained in the present study for the B10 diesel buses. The values differ by a factor of about 2-4 at each of the four engine loads. However, considering the large variation of experimental conditions and the widely varying particle number emission rates between similar buses, the result was encouraging. Moreover, a statistical analysis showed that the mean values of the particle number emission rates/factors for the groups of buses in the two studies were not significantly different at any of the operating modes.

In the present study, the particle number emission rate/factors in each of the four modes were greater for the diesel buses over the CNG buses, but the difference was not statistically significant in three of the four modes. It is difficult to compare our particle number emission results for the CNG buses with previous studies reported in the literature because, not only are there very few particle number emission measurements from CNG buses, these studies have been carried out under different engine operating conditions, using various types of aftertreatment devices. Moreover, particle emissions are often reported in different units, such as number per unit volume of air. For example, Holmen and Ayala (2002) tested two transit buses in three configurations as follows: a diesel bus with an OEM catalyzed muffler, the same diesel bus with a particulate filter (CRT) and a CNG bus with no catalyst. Sampling was carried out with both a mini diluter and a constant volume sampling (CVS) method to dilute the exhaust. Tests were conducted on a chassis dynamometer at idle and at a steady speed of 55 mph. Particle number distributions were determined with an SMPS in the size range 6-237 nm. Particle emissions were reported as number cm^{-3} and do not give an indication of the emission factors. During the idle tests, the diesel OEM bus showed a distinct bimodal distribution and particle number concentrations were generally 1-2 orders of magnitude higher than from the CRT and CNG buses. At the steady cruise of 55 mph, the OEM bus generally showed particle number concentrations over an order of magnitude greater than from the other two configurations, with accumulation mode number concentrations being consistently 20-100 times greater. However, under some sampling conditions, both the CNG bus and CRT diesel bus showed large nuclei modes (<10 nm) and particle number concentrations equal to or greater than from the OEM bus. It was hypothesized that the absence of nuclei modes in the diesel OEM bus emissions were due to the use of ultralow sulphur diesel fuel. It was suggested that, as this fuel became more widely used, nanoparticle emissions from diesel vehicles would generally decrease. They also concluded that the use of alternative fuels and vehicles, such as CRT diesel and CNG, may sometimes result in elevated nanoparticle emissions comparable to diesel vehicles.

Holmen and Qu (2004) reported on further studies, using the same three buses used in the above study. In addition to the two steady state cycles used earlier, they studied particle number emissions during three transient cycles (CBD, NYB and UDDS) using an electrical low pressure impactor (ELPI) with high temporal resolution in twelve impactor stages between 29 nm and 10 µm. The diesel bus with the OEM catalyzed muffler showed a significantly higher ultrafine particle number emission concentration than the other two buses - diesel CRT and CNG, in all ELPI size ranges in all the transient cycles as well as in the steady state cycles. The measured particle number concentrations were not presented as emission factors.

Lanni et al (2003) tested a range of emissions from two diesel (30 ppm sulphur) and three CNG buses on one steady state cycle at 30 mph and two transient driving cycles, CBD and NYB. Both diesel buses were equipped with CRT particle traps while the three CNG buses had no after treatment devices attached. In the steady state cycle, there was no difference between the particle number emissions from the two types of buses as measured by an SMPS. Observed size modes of the number distributions ranged from 10 to 30 nm, with an apparent shifting towards smaller diameters for the CNG buses. The measured particle number concentrations were not presented as emission factors.

Nylund et al (2004) tested three diesel and four CNG buses, all certified as Euro 3 or better, on two different European transient driving cycles. Emissions from a diesel bus with no after treatment device were used as a baseline. All other buses were fitted with after treatment devices. Particle number concentration was measured with an ELPI and a condensation particle counter (CPC). The measured values for three of the CNG buses and the diesel buses fitted with a particle filter (4 x 10^{12} km^{-1}) were found to be two orders of magnitude lower than for the baseline bus (5 x 10^{14} km^{-1}). The fourth CNG bus had particle numbers roughly one order of magnitude greater than the other CNG buses but an order of magnitude less than the baseline bus.

In all of these studies, except Nylund et al (2004), particle emissions are reported as number cm^{-3} and do not give an indication of the emission factors. Moreover, they are derived from transient cycles with only one study presenting results under a steady load condition. Thus, there are no particle number emission factors for CNG vehicles available in the literature for steady state driving conditions. This makes it difficult to apply these results into emissions modelling studies. Our results, for the first time, present particle number emission factors for CNG buses in four steady state engine loads. We also show that, although the CNG buses emitted as many particles as the diesel buses, these particles were of a much smaller size (Figs 4 and 5). Holmen and Ayala (2002) also reported that the CNG bus consistently emitted higher nanoparticle concentrations than the diesel bus. In Figs 4 and 5, note also how the particle number-size distributions at a given load are very consistent for the diesel buses, while they vary considerably between scans for the CNG buses. The total numbers of particles detected in the three scans shown in Fig 4 for a diesel bus do not vary by more than about 12%, whereas in Fig 5 the corresponding values for a CNG bus vary by over a factor of two. This large difference in total particle numbers between scans under identical engine operating conditions is not unusual (Holmen and Qu, 2004) and may be attributed to the formation of secondary aerosols in the exhaust as it cools and dilutes with ambient air. It is clear that, unlike in diesel emissions, most of the particles observed in the CNG emissions were in the nanoparticle size range and likely to be composed of volatile organic compounds. The formation of these nanoparticles is highly affected by the cooling and dilution processes (Khalek et al, 1999) and, therefore, it is not unusual that the particle number emission factors of CNG buses is highly variable. Particle number emissions from other spark ignition vehicles, such as those using petrol, can also vary considerably in time between vehicles operating under seemingly identical conditions (Maricq et al, 1999). It is likely that this effect may be able to explain the large differences in particle number emissions observed between the CNG buses.

The CO_2 emission factors of a motor vehicle are directly proportional to the fuel consumption rate and will therefore depend on engine load. Average emission factors obtained under various driving cycles have proved to be heavily influenced by type of cycle and driving technique. Measured values ranged from about 1000 to 4000 g km^{-1} for both diesel and CNG buses with the average CO_2 emission factor from a CNG bus being 15-20% less than from a diesel bus (Clark et al, 1999; Lanni et al, 2003; Ullman et al, 2003; Nylund et al, 2004). These studies were mostly carried out under transient cycles and cannot be directly compared with the present study that was conducted at specific steady engine loads.

However, there is broad agreement with the present results where the median CO_2 emission rate/factors varied from about 480-620 g km^{-1} at the 25% power load to 1090-1325 g km^{-1} at the 100% power load for both diesel and CNG buses with the values for the diesel buses being about 20% to 30% greater than that for the CNG buses at each of the four modes.

At a given load, the NO_x emission rate/factors varied widely between buses, especially with the CNG buses, with no statistically significant differences between the two types of buses at any of the operating modes. This is not unexpected as NO_x emission factors from buses vary widely with engine operating conditions. Values measured on dynamometers under various driving cycles have ranged from 8 to 20 g km^{-1} for diesel buses and from 6 to 18 g km^{-1} for CNG buses (Wang et al, 1997; Clark et al, 1999; Lanni et al, 2003; Ullman et al, 2003; Nylund et al, 2004; Herndon et al, 2005). In good agreement in the present study, the NO_x emission factors in the three driving modes investigated ranged from about 6 to 18 g km^{-1} for diesel buses and from 5 to 32 g km^{-1} for CNG buses.

Acknowledgements: This study was funded by Queensland Transport, Queensland Government. We would like to thank Ray Donato and Bill Duncan for their advice and assistance in arranging the logistics. We are grateful to Rod Chippendale and Malcolm Knowles, Brisbane City Council, for their invaluable and friendly assistance throughout the testing period in operating the dynamometer and providing the gaseous emissions and diagnostic test data. Olivier Weitten and Branka Miljevic assisted with the data acquisition.

References

Clark, N.N., Gautam, M., Rapp, B.L., Lyons, D.W., Graboski, M.S., McCormick, R.L., Alleman, T.L. and Morton, P. 1999. Diesel and CNG transit bus emissions characterization by two chassis dynamometer laboratories: Results and issues. SAE Technical Paper Series, 1999-01-1469. Society of Automotive Engineers.

Donaldson, K., Li, X.Y. and MacNee, W. 1998. Ultrafine (nanometre) particle mediated lung injury. J. Aerosol. Sci. 29, 553-560.

Goyal, S.P. 2003. Present scenario of air quality in Delhi: a case study of CNG implementation. Atmos. Environ. 37, 5423-5431.

Herndon, S.C., Shorter, J.H., Zahniser, M.S., Wormhoudt, J., Nelson, D.D., Demerjian, K.L. and Kolb, C.E. 2005. Real-time measurements of SO_2, H_2CO, and CH_4 emissions from in-use curbside passenger buses in New York City using a chase vehicle. Environ. Sci. Technol. 39, 7984-7990.

Holmen, B.A. and Ayala, A. 2002. Ultrafine PM emissions from natural gas, oxidation-catalyst diesel and particle-trap diesel heavy-duty transit buses. Environ. Sci. Technol. 36, 5041-5050.

Holmen. B.A. and Qu, Y. 2004. Uncertainty in particle number modal analysis during transient operation of compressed natural gas, diesel, and trap-equipped diesel transit buses. Environ. Sci. Technol. 38, 2413-2423.

Jayaratne, E.R., He, C., Ristovski, Z.D., Morawska, L. and Johnson, G.R. 2007. A comparative investigation of ultrafine particle number and mass emissions from a fleet of on-road diesel and CNG buses. Submitted to Environ. Sci. Technol.

Kado, N.Y., Okamato, R.A., Kuzmicky, P.A., Kobayashi, R., Ayala, A., Gebel, M.E., Rieger, P.L., Maddox, C. and Zafonte, L. 2005. Emissions of toxic pollutants from compressed natural gas and low sulphur diesel-fuelled heavy-duty transit buses tested over multiple driving cycles. Environ. Sci. Technol. 39, 7638-7649.

Khalek, I.A., Kittelson, D. and Brear, F. 1999. The influence of dilution conditions on diesel exhaust particle size distribution measurements. SAE Technical Paper Series, 1999-01-1142. Society of Automotive Engineers.

Lanni, T., Frank, B.P., Tang, S., Rosenblatt, D. and Lowell, D. 2003. Performance and emissions evaluation of compressed natural gas and clean diesel buses at New York City’s metropolitan transit authority. SAE Technical Paper Series, 2003-01-0300. Society of Automotive Engineers.

Maricq, M.M., Podsiaklik, D.H. and Chase, R.E. 1999. Gasoline vehicle particle size distributions: comparison of steady state, FTP and US06 measurements. Environ. Sci. Technol. 33, 2007-2015.

Nylund, N., Erkkila, K., Lappi, M. and Ikonen, M. 2004. Transit Bus Emission Study: Comparison of emissions from diesel and natural gas buses. Research Report PRO3/P5150/04. Technical Research Centre, VTT Processes, Finland.

Ristovski, Z.D., Jayaratne, E.R., Lim, M., Ayoko, G.A. and Morawska, L. 2006. Influence of diesel fuel sulphur on nanoparticle emissions from city buses. Environ. Sci. Technol. 40, 1314-1320.

Ullman, T.L., Smith, L.R., Anthony, J.W., Slodowske, W.J., Trestrail, B., Cook, A.L., Bunn, W.B., Lapin, C.A., Wright, K.J. and Clark, C.R. 2003. Comparison of exhaust emissions, including toxic air contaminants, from school buses in compressed natural gas, low emitting diesel, and conventional diesel engine configurations. SAE Technical Paper Series, 2003-01-1381. Society of Automotive Engineers.

Wang, W.G., Clark, N.N., Lyons, D.W., Yang, R.M., Gautam, M., Bata, R.M. and Loth, J.L. Emissions comparisons from alternative fuel buses with a chassis dynamometer testing facility. Environ. Sci. Technol. 31, 3132-3137.

Table Captions

Table 1: Particle mass emission factors (MEF) from comparative studies of diesel and CNG buses. (OC: oxidation catalyst; PT: particle trap).

Table 2: Specifications of buses tested in the study. R1 and R2 are the numbers of buses tested in Rounds 1 and 2 respectively.

Table 3: Particle number emission rate/factors of the buses.

Table 4: PM_{10} Emission rate/factors of the buses.

Table 5: CO_2 emission rate/factors for the buses.

Table 6: NO_x emission rate/factors of the buses.

Table 7: Comparison of particle number emissions in the present study with the earlier study by Ristovski et al (2006).

Figure Captions

Figure 1. Schematic diagram of the measurement system

Figure 2. Comparison of fleet-weighted particle number emission rates/factors between the two types of buses. The idle mode values are emission rates in units of particles min^{-1}. The other three modes are emission factors in units of particles km^{-1}.

Figure 3. Particle number-size distributions at the four engine operating modes for a Euro I diesel-powered bus.

Figure 4. Three SMPS particle number-size distributions for the diesel bus in Figure 3, all at the 100% load.

Figure 5. Three SMPS particle number-size distributions for a Scania CNG bus obtained at the 100% load.

Figure 6. Comparison of fleet-weighted PM_{10} emission rate/factors between the two types of buses. The idle mode values are emission rates in units of mg min^{-1}. The other three modes are emission factors in units of mg km^{-1}.

Figure 7. Comparison of fleet-weighted CO_2 emission rate/factors between the two types of buses. The idle mode values are emission rates in units of mg min^{-1}. The other three modes are emission factors in units of mg km^{-1}.

Figure 8. Comparison of fleet-weighted NO_x emissions between the two types of buses. The idle mode values are emission rates in units of mg min^{-1}. The other three modes are emission factors in units of mg km^{-1}.