# PARTICLE AND CARBON DIOXIDE EMISSIONS FROM PASSENGER VEHICLES OPERATING ON UNLEADED PETROL AND LPG FUEL

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## Abstract

A comprehensive study of the particle and carbon dioxide emissions from a fleet of six dedicated liquefied petroleum gas (LPG) powered and five unleaded petrol (ULP) powered new Ford Falcon Forte passenger vehicles was carried out on a chassis dynamometer at four different vehicle speeds – 0 (idle), 40, 60, 80 and 100 km $h^{-1}$. Emission factors and their relative values between the two fuel types together with a statistical significance for any difference were estimated for each parameter. In general, LPG was found to be a 'cleaner' fuel, although in most cases the differences were not statistically significant owing to the large variations between emissions from different vehicles. The particle number emission factors ranged from $10^{11}$ to $10^{13}$ $km^{-1}$ and was over 70% less with LPG compared to ULP. Corresponding differences in particle mass emission factor between the two fuels were small and ranged from the order of 10 μg $km^{-1}$ at 40 km $h^{-1}$ to about 1000 μg $km^{-1}$ at 100 km $h^{-1}$ The count median particle diameter (CMD) ranged from 20-35 nm and was larger with LPG than with ULP in all modes except the idle mode. Carbon dioxide emission factors ranged from about 300 to 400 g $km^{-1}$ at 40 km $h^{-1}$ , falling with increasing speed to about 200 g $km^{-1}$ at 100 km $h^{-1}$. At all speeds, the values were 10% to 18% greater with ULP than with LPG.

***Keywords***: liquefied petroleum gas, emission factor, particle emission, gaseous emission, environmental pollution

## 1. Introduction

Motor vehicles comprise a significant source of atmospheric pollutants. Exhaust emissions from spark ignition vehicles consist of a hot and complex mix of both gaseous and particle phases. The gaseous emissions include carbon dioxide ($CO_2$) which plays a major role in global warming. The particles emitted range in size from 10 to 80 nm. They are mostly carbonaceous spherical submicron agglomerates formed as a result of incomplete combustion in the engine and are very often coated with various organic compounds (Hildemann et al., 1991; Ristovski et al., 1998; Kleeman et al, 2000). The particle phase consists of soot, ash, trace elements such as lead, iron, chlorine and bromine and organic compounds – mainly polycyclic aromatic hydrocarbons (PAHs) (Zinbo et al., 1995).

Several adverse health and environmental effects have been attributed to emissions from urban vehicular traffic. Epidemiological studies have linked particulate matter in urban environments with mortality, hospital admission increases and various cardiovascular and respiratory diseases (Seaton et al., 1995; Vedal, 1997; Pope, 2000). The size distribution of these particles plays an important role as, during inhalation, the smaller particles penetrate deeper into the human respiratory system and are more likely to be retained there, enhancing harmful toxicological effects (Ferin et al., 1992; Donaldson et al., 1998). A knowledge of the particle size distributions in vehicle emissions, particularly in relation to different types of fuel used, is therefore of great importance in the understanding of these adverse effects.

Recently, there has been a move towards the use of Liquefied Petroleum Gas (LPG) as it is believed to be a cleaner fuel than Unleaded Petrol (ULP) (Gamas et al., 1999). It is widely used as an alternative vehicle fuel in the US, Canada, the Netherlands, Japan and several other countries. In Japan, 94% of the taxi fleet – about 260,000, operate on LPG fuel. Almost half a million – nearly 5% of vehicles in Australia use LPG, and the automotive LPG market is growing at more than 10% per annum. LPG is a mixture of petroleum and natural gases that exist in the liquid state at normal temperature and pressure. It has a lower density than petrol and its composition is much simpler. Its main constituent is propane (about 80% by volume) with some butane (11%) and isobutane (5%) (Chang et al, 2001). It provides about 8% more energy per unit weight than ULP. Although vehicle operation with LPG is expected to be more efficient than with ULP in terms of fuel consumption and mileage, in practice this is not seen unless the engine design is optimised for LPG fuel (Gamas et al, 1999; Caton et al, 1997). In such cases, LPG-fuelled engines possess performance and efficiency parameters as good as, or better than petrol-fuelled engines while also showing lower exhaust emissions. LPG typically produces 15% less carbon dioxide than ULP, provided LPG equipment and engines are installed and maintained correctly.

Ford Australia has recently developed a dedicated LPG 4 litre, six-cylinder engine where the entire standard fuel system has been removed and replaced by a system optimised for LPG operation. This is one of the key advantages of a single-fuel LPG vehicle - that it can be tuned specifically for LPG, resulting in energy efficiencies and optimum environmental performance. According to the sales information of Ford, Australia, the newly designed LPG engine is reputed to offer significant greenhouse benefits with a potential of reducing global warming by up to 20% per vehicle compared with petrol-powered vehicles. The aim of the present study was to measure the particle and carbon dioxide emissions from a fleet of eleven in-service new Ford Falcon Forte passenger vehicles – six operating on LPG and five on regular ULP and to draw conclusions regarding any differences in the emissions using the two types of fuel.

## 2. Methods

### 2.1 Experimental Methods

Four sets of measurements were made on the same group of vehicles in February, June, August and November 2001. The vehicle emissions were monitored on a chassis dynamometer at five steady-state operating modes defined by road speeds 40 km $h^{-1}$ (mode1), 60 km $h^{-1}$ (mode2), 80 km $h^{-1}$ (mode3), 100 km $h^{-1}$ (mode4) and idle speed (mode5). The tail pipe of the vehicle exhaust was attached to a 3-inch tube (diameter 76.2 mm) forming the primary segment of the sampling line. The volumetric flow rate of the exhaust gas was calculated by measuring the pressure difference across a restriction orifice in the primary segment tube. The pressure meter was used with a sample interval of 15 s. Readings were stored at regular intervals and automatically averaged by the instrument. A thermocouple was used to measure the temperature of the primary exhaust air. A small portion of the sample flow was introduced into a dilution tunnel where it mixed with a steady flow of clean ambient air drawn through a high-flow HEPA filter by means of an air pump. Care was taken to ensure that the flow rate through the pump was sufficiently high to maintain turbulent mixing conditions within the dilution tunnel. This was achieved at a minimum airflow speed of 0.44 m $s^{-1}$ as measured with a digital air velocity meter. Typical dilution ratios (clean air–exhaust mix to engine exhaust) varied between 10 and 15 in the four operating modes 1-4. In the idle mode (mode 5), the ratio was higher (between 20 and 30) owing to the lower exhaust flow rate. The temperature in the dilution tunnel was measured with an electronic thermometer. At a steady environmental temperature of 25°C, the mean temperature in the dilution tunnel varied from about 30°C in mode 5 (idle) to about 42°C in mode 4 (100 km $h^{-1}$).

$CO_2$ was sampled directly from the primary exhaust and the dilution tunnel using a portable CODA engine emission gas analyzer. The dilution ratio was calculated as the ratio of the concentration of $CO_2$ in the primary exhaust to that in the dilution tunnel. Particles were sampled from the dilution tunnel. A TSI Model 3934 Scanning Mobility Particle Sizer (SMPS) was used to measure the size distribution of the sampled aerosol within a window of 0.008 to 0.4 μm.

Two to three vehicles were tested on each day. Before being tested, the vehicles were fuelled and conditioned by running on-road for several kilometers. In each dynamometer test, the engine was first allowed to run at the required speed for a few minutes until the exhaust temperature and gas concentrations had attained steady state values. Measurements were then made over periods of 10 min in each consecutive operational mode. Longer sampling periods were avoided in order to prevent engine overheating, especially in mode 4. At least three SMPS scans were obtained for each vehicle in each mode.

### 2.2 Statistical Methods

Care was taken to compare the mean values of the emissions from the vehicles operating on the two types of fuels – ULP and LPG – and to ascertain whether any differences were statistically significant. This statistical comparison was performed through a two-sample students heteroscedastic two-tailed t-test to determine significant differences between the group means. The test statistic, distributed as t on number of degrees of freedom df, was determined from

$$t = \frac{\bar{x} - \bar{y}}{\sqrt{\frac{s_1^2}{m} + \frac{s_2^2}{n}}}$$

and

$$df = \frac{\left(\frac{s_1^2}{m} + \frac{s_2^2}{n}\right)^2}{\frac{\left(s_1^2/m\right)^2}{(m-1)} + \frac{\left(s_2^2/n\right)^2}{(n-1)}}$$

where $\bar{x}$ and $\bar{y}$ are the sample means, $s_1$ and $s_2$ are the sample standard deviations and m and n are the number of observations in each of the two groups.

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.

## 3. Results and Discussion

Throughout this paper, the results are expressed as emission factors - defined as the total number or mass of a concerned pollutant emitted per unit distance traveled by the vehicle. The corresponding units are number $km^{-1}$ and $\mu g\ km^{-1}$ for particles and $g\ km^{-1}$ for carbon dioxide. The range of particle size measured by the SMPS was 0.008 – 0.4 µm. Observations of the SMPS data in these experiments indicated hardly any particles larger than about 0.2 µm, suggesting that the amount of PM mass contributed from sizes larger than the detectable limit of 0.4 µm was negligible. Observations of TSP results obtained on filters and the corresponding mass-size distributions calculated from the SMPS data in a similar set of experiments carried out on a fleet of diesel buses (Ristovski et al, 2004; to be submitted for publication) showed that the total mass of particles larger than 0.4 µm was less than 2% of the total particle mass.

Results are presented for modes 1 to 4. The emission factor has no relevance in mode 5 where the vehicle is in idle and the speed is zero. Emissions are averaged separately for the vehicles using each of the two types of fuel over the four test rounds and the results are presented as means for each of the four test modes. The error bars shown in the figures represent standard errors of the mean.

### 3.1 Particles

The particle properties monitored by the SMPS were size and number concentration. Figure 1 shows a typical SMPS particle number-size distribution scan. This example is for an LPG-powered vehicle in mode 4. The corresponding count median diameter (CMD) was 19.2 nm and the total particle number concentration 1.71 x $10^7$ $cm^{-3}$. Total particle mass was calculated from the number-size distributions, assuming particle sphericity and unit bulk density. Figure 2 shows the emitted particle CMD for the two fuel types in each of the five modes. The CMD ranged from 20-35 nm and was larger with LPG than with ULP in all modes except the idle mode. The statistical analysis showed that the CMD's were significantly different in modes 2 and 3. With both types of fuel, the CMD decreased with increasing vehicle speed.

The emission factors ($km^{-1}$) were calculated from the number and mass concentrations by using the corresponding volumetric flow rate of the exhaust gas and the dynamometer speed of the vehicle in each mode. Particle concentrations were corrected for temperature. Figures 3 and 4 show the calculated particle number and mass emission factors respectively. Particle number emission factors ranged from the order of $10^{11}$ $km^{-1}$ at 40 km $h^{-1}$ to $10^{13}$ $km^{-1}$ at 100 km $h^{-1}$, and were from 69% to 98% less with LPG compared to ULP. The calculated particle mass emission factors ranged from about 10 μg $km^{-1}$ at 40 km $h^{-1}$ to 1 mg $km^{-1}$ at 100 km $h^{-1}$. The mean mass emission factors with ULP were greater than with LPG at all speeds except at 60 km $h^{-1}$. However, there was considerable scatter in the particle emission factors between vehicles in any given mode and test round. Particle number emission factors in a given mode varied over three to five orders of magnitude. In addition to the wide variations observed between vehicles, even with the same vehicle the measured emissions varied considerably in time. Careful observations showed that these variations were not due to instrument error. It has been reported before that spark ignition exhaust particle emissions are highly unstable with occasional 'spikes' as high as two orders of magnitude over the baseline concentration (Hall and Dickens, 2000; Graskow et al, 1998). These spikes are thought to be composed of nearly all volatile particles smaller than 30 nm in diameter released from the walls of the exhaust system due to heating. The large variation in particle number concentration in the present experiments were observed over longer time scales, at times lasting up to 10 or 15 mins. We use the observations of short-term spikes in the literature merely to substantiate our observation of these variations and suggest that they occur due to the same cause. These unpredictable variations made a statistical comparison between the particle emissions with the two fuel types difficult.

### 3.2 Carbon Dioxide

Figure 5 shows the carbon dioxide mass emission factors. The values with ULP fuel were higher than with LPG in all four modes. The LPG powered vehicles produced 10% to 18% less carbon dioxide than the ULP powered vehicles, in good agreement with the specification of 15% by the manufacturers. The reduction in carbon dioxide emissions from ULP to LPG powered vehicles was statistically significant at the highest speed (mode 4). The emission factor decreased with increasing vehicle speed from between 300 to 400 g $km^{-1}$ at 40 km $h^{-1}$ to about 200 g $km^{-1}$ at 100 km $h^{-1}$ with both types of fuel.

## 4. Conclusions

Comparing the emissions from the vehicles operating on the two types of fuel, LPG was found to be the 'cleaner' fuel with respect to both particle and carbon dioxide emissions. However, in most cases the differences were not statistically significant owing to the large variations between emissions from different vehicles. Statistically significant differences were observed only for some parameters and only in certain operational modes.

In all operational modes, the particle number emission factor was over 70% less with LPG compared to ULP. The corresponding differences in particle mass were small. The count median particle diameter (CMD) ranged from 20-35 nm and was larger with LPG than with ULP in all modes except the idle mode, with the statistical analysis showing significant differences at 60 and 80 km $h^{-1}$. $CO_2$ emission factors with ULP were 10% to 18% greater than with LPG, with a statistically significant difference being observed at 100 km $h^{-1}$.

These results strongly suggest that, in order to arrive at more statistically significant comparisons of the emissions using the two types of fuel, a much larger number of vehicles need to be tested.

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## Figure Captions

1. A typical SMPS particle number-size distribution. This example is for an LPG-powered vehicle in mode 4 (100 km $h^{-1}$).
2. The particle count median diameter (CMD) in the five modes.
3. The particle number emission factors.
4. The particle mass emission factors.
5. Emission factors of carbon dioxide.

Figure 1

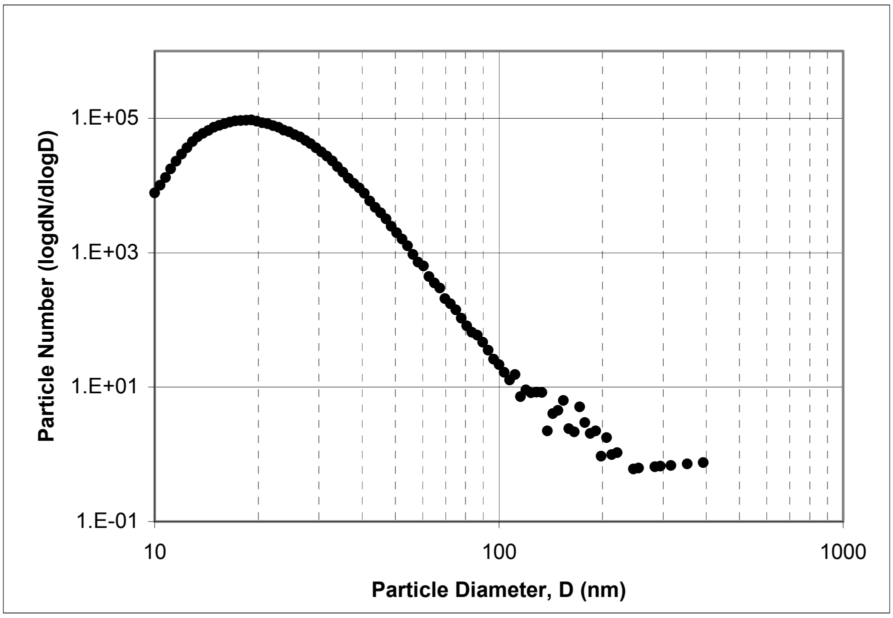
1.E+05
1.E+03
1.E+01
1.E-01
Particle Number (logdN/dlogD)
10
100
1000
Particle Diameter, D (nm)

Figure 2

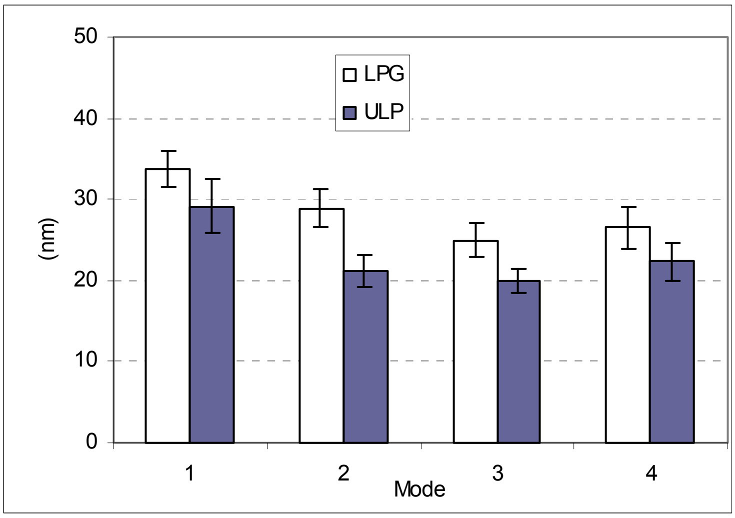

Figure 3

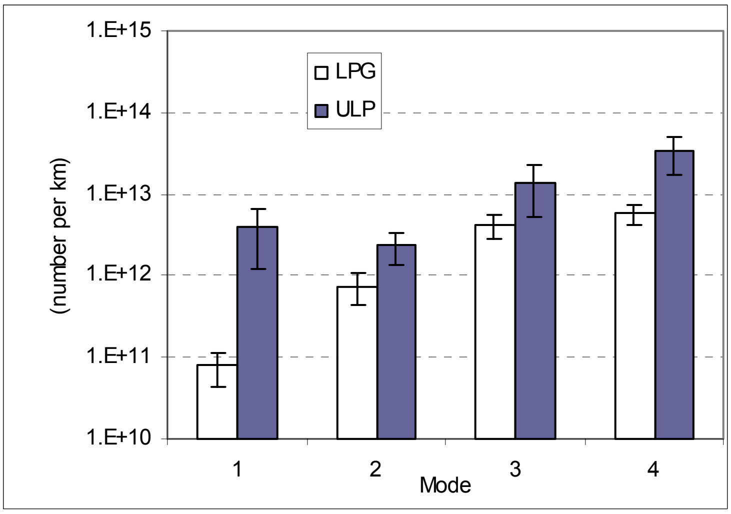

Figure 4

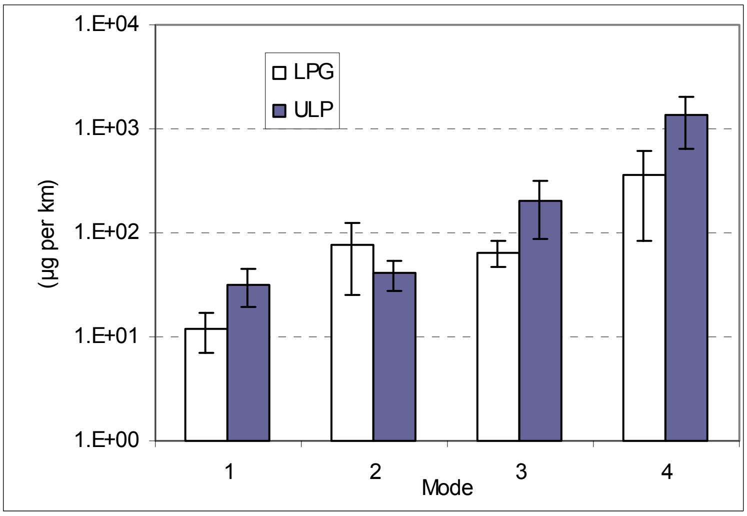

Figure 5