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Carbon Dioxide Emissions from Diesel and Compressed Natural Gas Buses during Acceleration

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Abstract

Motor vehicle emission factors are generally derived from driving tests mimicking steady state conditions or transient drive cycles. However, neither of these test conditions completely represents real world driving conditions. In particular, they fail to determine emissions generated during the accelerating phase – a condition in which urban buses spend much of their time. In this study we analyse and compare the results of time-dependant emission measurements conducted on diesel and compressed natural gas (CNG) buses during an urban driving cycle on a chassis dynamometer and we derive power-law expressions relating carbon dioxide (CO_2) emission factors to the instantaneous speed while accelerating from rest. Emissions during acceleration are compared with that during steady speed operation. These results have important implications for emission modelling particularly under congested traffic conditions.

Keywords: motor vehicle emissions, carbon dioxide, greenhouse gas emissions, traffic congestion, bus emissions.

1. Introduction

The impact of greenhouse gas (GHG) emissions from the transportation sector on the atmosphere is of increasing concern. At present, this sector accounts for about 14% of the total anthropogenic GHG emissions and constitutes one of the strongest growing sources (IPCC, 2007). This clearly has significant implications for global climate change and has led to calls for urgent and effective measures and strategies to reduce GHGs from road transport (OECD, 2002). Since many of these depend on effective modelling studies to assess and project GHG emissions from the use of transportation, there is a pivotal need for reliable emission factors pertaining to the various types of vehicles and driving conditions.

Motor vehicle CO_2 emission factors may be calculated from fuel consumption statistics assuming stoichiometric conditions or determined directly through emission measurements. Calculated emissions assume complete decomposition of hydrocarbon fuels to H_2O and CO_2, while measured emissions incorporate combustion inefficiencies and, as such, deviate somewhat from the stoichiometric reaction form, where the complete combustion of 1 L of petrol and diesel fuel yields about 2.5 and 2.7 kg of CO_2, respectively (AGO, 2003). The direct measurements are generally carried out on dynamometers at steady engine loads and speeds or over specified drive cycles that consist of a range of driving conditions. Several studies have reported CO_2 emission factors for diesel and CNG buses based on complete dynamometer drive cycles (Clark et al, 1999; Lanni et al, 2003). However, the values thus derived are averages over a range of driving conditions and do not provide speed-dependent emission factors. Although there are some reports of speed-dependent emission factors during acceleration for light-duty vehicles (Ahn et al, 2002; El-Shawarby et al, 2005), there are no emission factors available in the literature for accelerating buses. This is of particular concern as a significant fraction of emissions from motor vehicles are thought to occur during acceleration – a condition in which an increasingly large number of buses operate due to worsening urban traffic congestion. Furthermore, bus emission factors during acceleration are crucial in urban traffic simulation and environmental impact models.

In the present study, we analysed CO_2 emission data obtained during acceleration segments of a transient cycle from diesel and CNG powered transport buses to determine emission factors during acceleration. We used these results to estimate the total CO_2 emission from a bus as it accelerated from rest to a given speed, and compared this value with the total emission when the bus cruised through the same distance without stopping. These findings enable us to investigate the effects of traffic congestion on CO_2 and, hence, greenhouse gas emissions.

2. Methods

2.1 Transient Test Cycle

The buses were tested on a chassis dynamometer using the DT-80 transient urban driving cycle. This cycle consists of a 1 min idle segment, three hard accelerations from rest to 80 km h^{-1} and a 1 min cruise segment at 80 km h^{-1} as shown in the speed-time diagram in Fig 1(a). In each of the first and second acceleration segments, the speed of the bus was increased from zero to 80 km h^{-1}, when the foot was taken off the accelerator, allowing it to drop to zero again. In the third acceleration segment, once the speed reached 80 km h^{-1}, it was maintained at this speed for 1 min before being decreased to zero. The duration of each cycle was 5-6 mins and the distance covered was 3.5-4.0 km. Each bus was tested at least three times, providing at least 9 acceleration segments per bus.

2.2 Vehicles Tested

The vehicles tested included 9 diesel and 13 CNG buses from the same urban fleet. The diesel buses consisted of 5 Euro3 Mercedes OC-500, each less than 2 years old with an odometer reading of 165-217 x 10^3 km, and 4 older Volvo Euro1 B10M and Euro2 B10L buses ranging from 8-16 years in service with odometer readings between 596-1045 x 10^3 km. They were all operated on 50 ppm ultralow sulphur diesel and contained no after-treatment devices. The CNG buses consisted of 5 Euro3 MAN, all less than 1 year old with odometer readings of 2-20 x 10^3 km, and 8 Euro2 and Euro3 Scania buses, 3-5 years old with the odometer between 134-226 x 10^3 km. All CNG buses were fitted with oxidation catalysts. All buses belonged to the same city fleet and were subject to similar operation and service patterns.

2.3 Sampling Methods

During testing, each bus was mounted on the chassis dynamometer and the emissions were monitored using a constant volume sampling system with the entire exhaust drawn into a sampling line of diameter 300 mm and diluted with ambient air to give a total air flow rate of 500 L s^{-1}. The CO_2 concentration in the tunnel was measured with a non-dispersive infra-red CO_2 monitor from California Analytical Instruments Inc. The response time and the accuracy of the instrument were 1 s and ± 10 ppm, respectively. CO_2 emission rates from the bus were calculated in real time at 1 s intervals during the course of each test cycle. Operational characteristics such as instantaneous speed, distance covered, engine power and load were also recorded.

3. Results

3.1 Emission Rates during Acceleration

Fig 1 shows (a) the instantaneous speed and (b) the corresponding CO_2 emission rate from a CNG bus in a typical DT-80 cycle. The measurements show that, when the bus accelerated, the emission rate increased sharply. The shape of the emission rate curve was typical for all buses and the undulations reflected the gear changes during acceleration. With each gear change, the emission rate dropped and then recovered with further increase in speed. After the first two accelerating segments the speed was reduced to zero when it reached 80 km h^{-1}. In the third accelerating segment the speed was again increased to 80 km h^{-1} and then maintained at this speed for a further 1 min. Note that, as soon as the acceleration was complete, the emission rate dropped from about 22 g s^{-1} to about 15 g s^{-1}.

Next, we look at the acceleration segments in more detail. In Fig 2, we have plotted the emission rates as a function of instantaneous speed for all three acceleration segments in a drive cycle for (a) a diesel bus (Volvo B10L) and (b) a CNG bus (Scania). The shapes of the three curves for a given bus were generally consistent and reproducible over every acceleration segment. The shapes of the curves for diesel buses and CNG buses were similar except for some general differences. For example, the peak emission rates of the diesel buses were generally about 15-20% greater than for the CNG buses. The CNG buses showed the effect of gear changes much more clearly than the diesel buses.

Over a given gear position, the emission rate was approximately linear with speed. For example, the bus started in first gear and the change to second gear occurred below 5 km h^{-1}. The change to third gear took place at 40-45 km h^{-1} (see Fig 2), so that between 5 and 40 km h^{-1} the bus operated in second gear. Fig 3 shows the mean emission rates of all the diesel and CNG buses tested, as a function of instantaneous speed from 5 to 30 km h^{-1}. In this speed range, the emission rates for all buses of a given fuel type increased consistently as a quadratic function of speed. The quadratic functions are near-linear and, for simplicity, may be reasonably approximated to linear functions. The best fit linear relationships for the emission rate (ER in g s^{-1}) in terms of the instantaneous speed (V in km h^{-1}) are as follows:

For diesel buses: $ER = 0.47\ V + 2.73$

For CNG buses: $ER = 0.33\ V + 1.87$ $(5 \leq V \leq 30)$

These simplified expressions can be applied in modelling studies where the bus speeds are between 5 and 30 km h^{-1}. At higher speeds, as indicated in Fig 1, the emission rates fluctuated widely with gear changes and it was not possible to derive simple relationships between the emission rates and the speed. The emission rates from the diesel buses were about 20% greater than from the CNG buses at all speeds in this range.

3.2 Emission Factors during Acceleration

Emission factors were calculated from the emission rates and the instantaneous speeds. Fig 4 shows the mean emission factors for all buses as a function of speed in the range 5 to 80 km h^{-1}. Emission factors for both types of buses decreased with speed and exhibited the typical power law form. At a speed of 5 km h^{-1}, the diesel and CNG bus emission factors were 5500 and 3500 g km^{-1}, respectively, - a difference of 57%. This difference decreased with increasing speed. At the maximum speed of 80 km h^{-1}, the diesel emission factor was about 15% higher than the corresponding CNG value.

The dependence of emission factor on speed best fits the following power law expressions:

Diesel buses: $EF = 13217\ V^{-0.554}$

CNG buses: $EF = 6581\ V^{-0.41}$

where V is in km h^{-1} ($5 \leq V \leq 80$) and EF is in g km^{-1}.

3.3 Comparison with previous work

Next, we compare our results with speed-related emission factors for buses reported in some previous studies (Fig 5). Fig 5(a) shows the present mean values obtained for diesel buses during the three acceleration segments of the DT-80 cycle together with the results of these other studies. Ronkko et al (2006) determined the fuel consumption rate of a model year 2002 Euro 3 diesel bus on a test road, under different driving conditions at various speeds ranging from 20 to 80 km h^{-1}. Assuming, stoichiometric conditions, we converted the fuel consumption rates (L h^{-1}) to CO_2 emission factors (g km^{-1}) and divided the results into two classes according to apparent engine power/torque. In the figure, the emission factors during high power/torque driving conditions are shown alongside the values under low power/torque conditions. The CO_2 emission factors determined for diesel buses at three steady engine loads corresponding to 25%, 50% and 100% full-power at 60 km h^{-1} by Jayaratne et al. (2009) are shown together with the corresponding values at 80 km h^{-1} by Ristovski et al, (2006). In each of these sets of three, the emission factors increase with power; that is the lowest emission factor corresponds to 25% power and the highest corresponds to 100% power.

Also shown in this figure are the emission factors calculated from an empirical formula for the fuel consumption rate for transport buses recommended by Austroads (2004). The equation has the form

$$F = A + \frac{B}{V} + CV + DV^2$$

where V is the average speed in km h^{-1} and F the fuel consumption rate in L/100 km. The coefficients A, B, C and D are assigned two different sets of values at speeds below and above 60 km h^{-1}, accounting for the break in the curve at this speed.

It is not surprising that the emission factors determined in the DT-80 cycle for accelerating buses are higher than both Ronkko et al and Austroads. The Ronkko et al measurements were carried out on an open road under a range of mixed driving conditions including steady speed and acceleration. The Austroads values are based on a range of urban driving conditions that generally include steady speed, stop and start conditions. The steady speed dynamometer measurements at 60 km h^{-1} all show emission factors that are lower than the present accelerating value at this speed. At 80 km h^{-1}, the emission factors at 25% and 50% engine power are lower than the present value during acceleration. However the emission factor at 80 km h^{-1} at full engine power is greater than in the DT-80 acceleration segment. It is possible that the engine power/torque of a bus at this high speed and load exceeds that during acceleration.

Fig 5(b) shows the CO_2 emission factors derived for CNG buses during the three acceleration segments of the DT-80 cycle, together with the corresponding values determined for CNG buses at the three steady engine loads corresponding to 25%, 50% and 100% full-power at 60 km h^{-1} by Jayaratne et al, (2009). The steady state emission factors increase with engine power but are all less than the value for the accelerating buses found in the present study at 60 km h^{-1}.

3.4 Emissions from a bus accelerating from rest

Thus far, we have shown that, at a given speed, the CO_2 emission from an accelerating bus is greater than that when travelling at steady speed. This has implications for the greenhouse gas budget, especially in urban settings, where buses spend much of the time slowing down, stopping and accelerating from rest. Thus, it is very important to be able to estimate the emissions during acceleration.

In order to study this in detail, we determined mean CO_2 emission factors for the four diesel Volvo B10 buses as a function of speed and used the results to derive an expression for the instantaneous emission factor as a function of speed for an accelerating bus. The best fit equation for the data was

$$EF = 14116\, V^{-0.568}$$

where EF is the emission factor in g km^{-1} and V is the instantaneous speed in km h^{-1}.

Having derived an equation that gives the CO_2 emission rate at each instantaneous speed during the acceleration from rest to 80 km h^{-1}, we used it to estimate the total emissions during this phase and compared it with the emissions that would be emitted had the bus travelled the same distance at a steady speed of 80 km h^{-1} without stopping. As an example, we used the first acceleration segment from a DT-80 cycle of diesel bus B10L. Fig 6 shows the CO_2 emission rate measured from this bus during the accelerating segment together with the corresponding values calculated using the above equation. The total time taken to accelerate to 80 km h^{-1} from rest was 57s and the distance covered was 850 m. The acceleration peaked at about 1.0 m s^{-2} in the first 10 m after starting from rest and remained steady at about 0.2 m s^{-2} after the first 300m. The total CO_2 emission during the entire accelerating segment was 1204.8 g.

From the data such as shown in Fig 1(b), we estimated that the CO_2 emission rate when the bus travelled at steady speed of 80 km h^{-1} was 19.3 g s^{-1}. This gives a total emission of 738.5 g over the distance of 850.3 m had the bus cruised past without stopping. Thus, we see that the CO_2 emission from the bus is 63% greater when accelerating from rest to 80 km h^{-1} over cruising past at this maximum speed. We repeated the calculation for all three accelerating segments, all cycles and all B10 diesel buses and found that the increased emissions was 58% ± 8%.

It is also instructive to investigate the spatial distribution of the emissions during the accelerating segment. In the model, we used the speed-time data, similar to that shown in Fig 1(a) to calculate the distances travelled by the bus in each second and, hence, the mean CO_2 emissions per metre as a function of distance from start. The bus begins to accelerate at distance = 0 and reaches the top speed of 80 km h^{-1} at distance = 850 m. The graph in Fig 7 shows the emissions at each distance from rest as a multiple of the cruise emissions, that is the emissions had the bus travelled at a steady speed of 80 km h^{-1} without stopping. It is clear that the highest emissions occur soon after beginning to accelerate from rest. For example, within the first metre after starting, emissions from the accelerating bus were 9.8 times greater than from the cruising bus. Similarly, within the first 10m from start, the emissions were 5.2 times greater and within the first 100m they were 2.8 times greater. This has relevance to situations such as at bus stops, traffic intersections and pedestrian and level crossings, where buses stop and start and are especially applicable to urban locations where traffic congestion is an increasing problem.

4. Conclusions

We used experimental data to derive power-law expressions relating CO_2 emission factors for diesel and CNG buses to the instantaneous speed when accelerating from rest to 80 km h^{-1}. During acceleration, the emission rate from a diesel bus was about 15-20% greater than from a CNG bus at all speeds. We used the expressions to calculate CO_2 emissions from a diesel bus while accelerating and compared it with the emissions had it travelled through the same distance at a steady speed and showed that the CO_2 emissions increased by 58 ± 8%. Most of the increase occurred in the first few metres after starting from rest. These results are important for transport modellers because, until now, CO_2 emission factors for buses have been available only under steady speed conditions or for standard drive cycles, neither of which are suitable to calculate emissions during acceleration – a condition in which urban buses spend much of their time.

Acknowledgements

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Figure Captions

Fig 1: (a) Instantaneous speed and (b) CO_2 emission rates in a typical DT-80 transient drive cycle for a CNG bus.

Fig 2: Emission rates as a function of instantaneous speed for all three acceleration segments in a drive cycle for (a) a diesel bus and (b) a CNG bus.

Fig 3: Mean emission rates of accelerating buses as a function of instantaneous speed in the range 5 to 30 km h^{-1}.

Fig 4: Mean emission factors of accelerating buses as a function of instantaneous speed.

Fig 5: Comparison of emission factors in present study with previous results on (a) diesel and (b) CNG buses.

Fig 6: Measured emission rate of a B10L bus during acceleration from rest to 80 km h^{-1} together with the calculated value using the equation derived in Fig 6.

Fig 9: Calculated emissions per metre as a function of distance from rest for an accelerating B10L bus, expressed as a multiple of the cruise emissions.

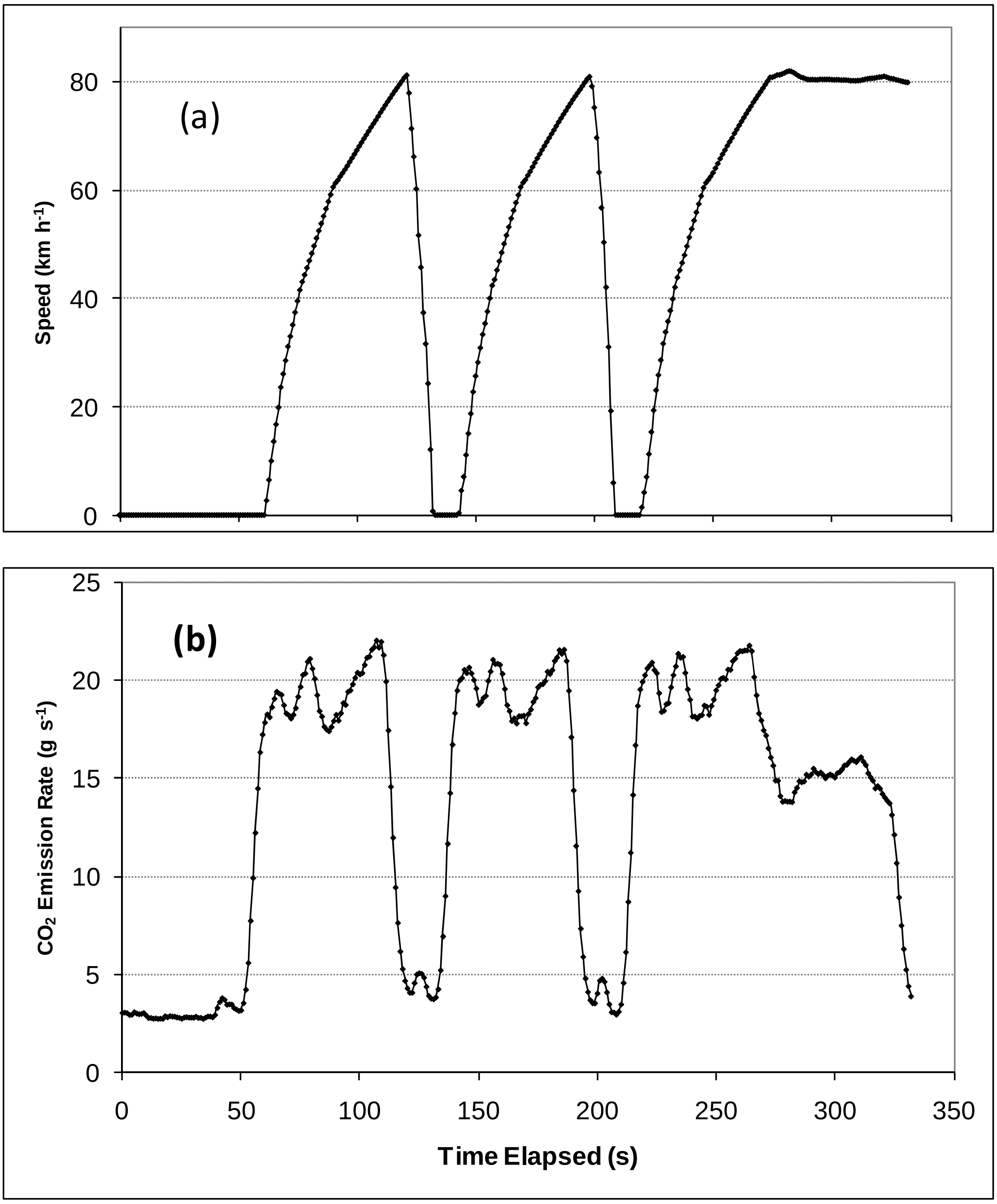

(a)
Speed (km h⁻¹)
0
20
40
60
80
(b)
CO_2 Emission Rate (g s⁻¹)
0
5
10
15
20
25
0
50
100
150
200
250
300
350
Time Elapsed (s)

Fig 1

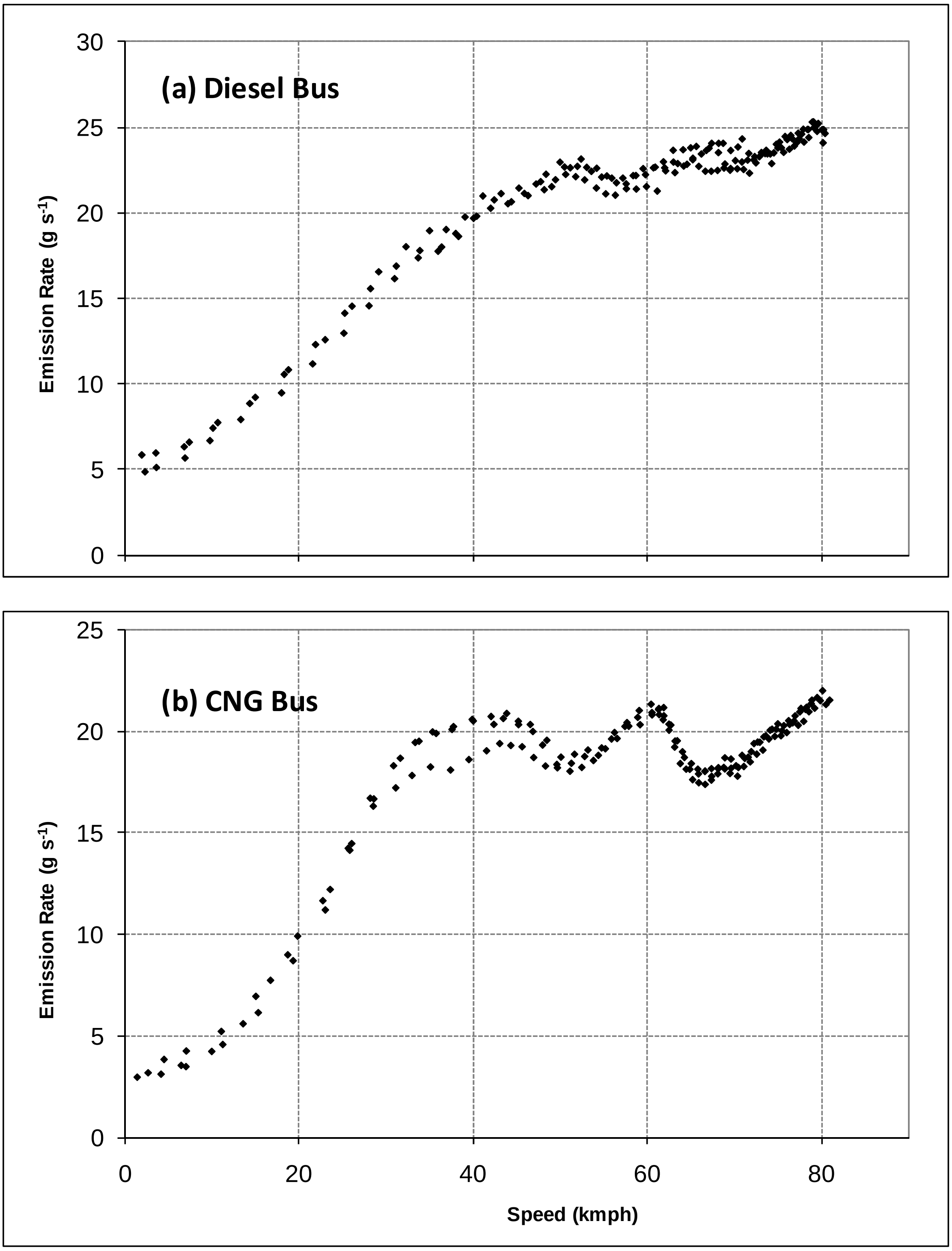
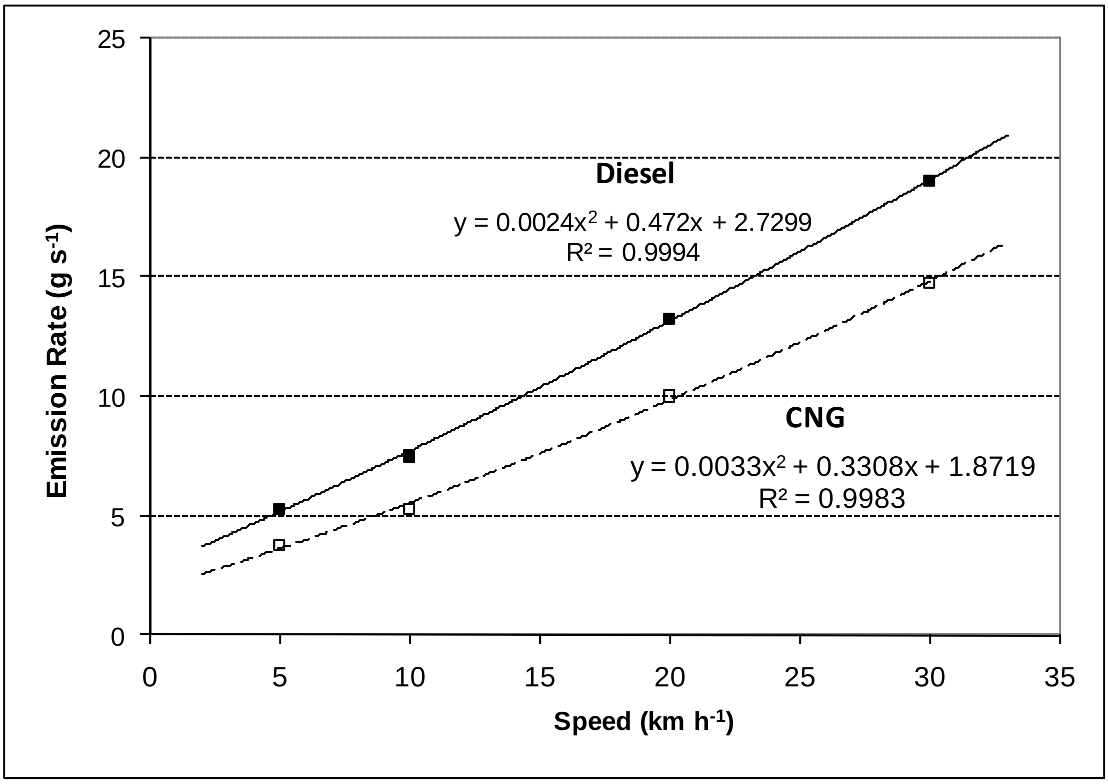

(a) Diesel Bus
Emission Rate (g s-1)
30
25
20
15
10
5
0
(b) CNG Bus
Emission Rate (g s-1)
25
20
15
10
5
0
0
20
40
60
80
Speed (kmph)

Fig 2



25
20
15
10
5
0
Emission Rate (g s-1)
0
5
10
15
20
25
30
35
Speed (km h-1)
Diesel
y = 0.0024x2 + 0.472x + 2.7299
R² = 0.9994
CNG
y = 0.0033x2 + 0.3308x + 1.8719
R² = 0.9983

Fig 3

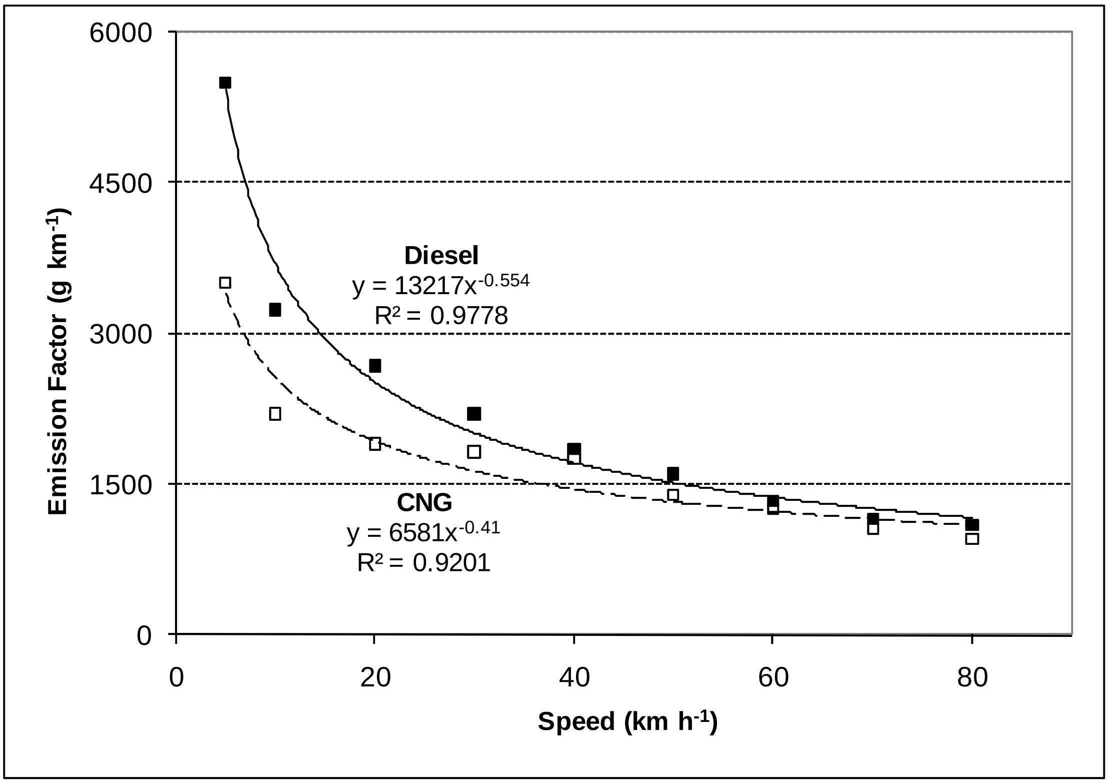
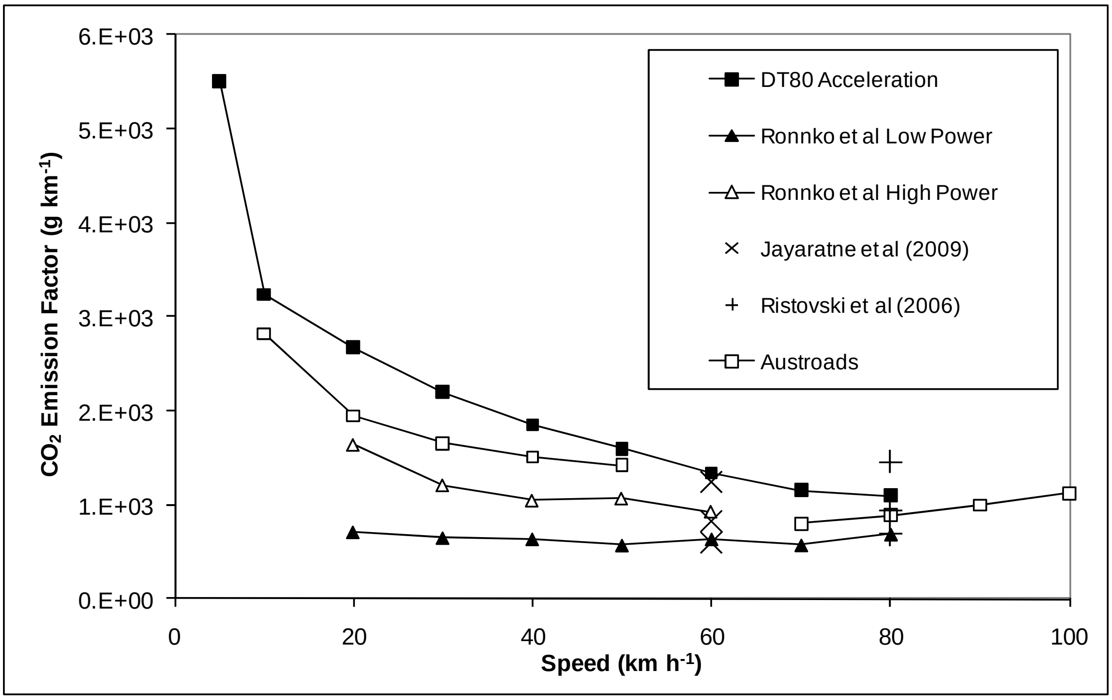
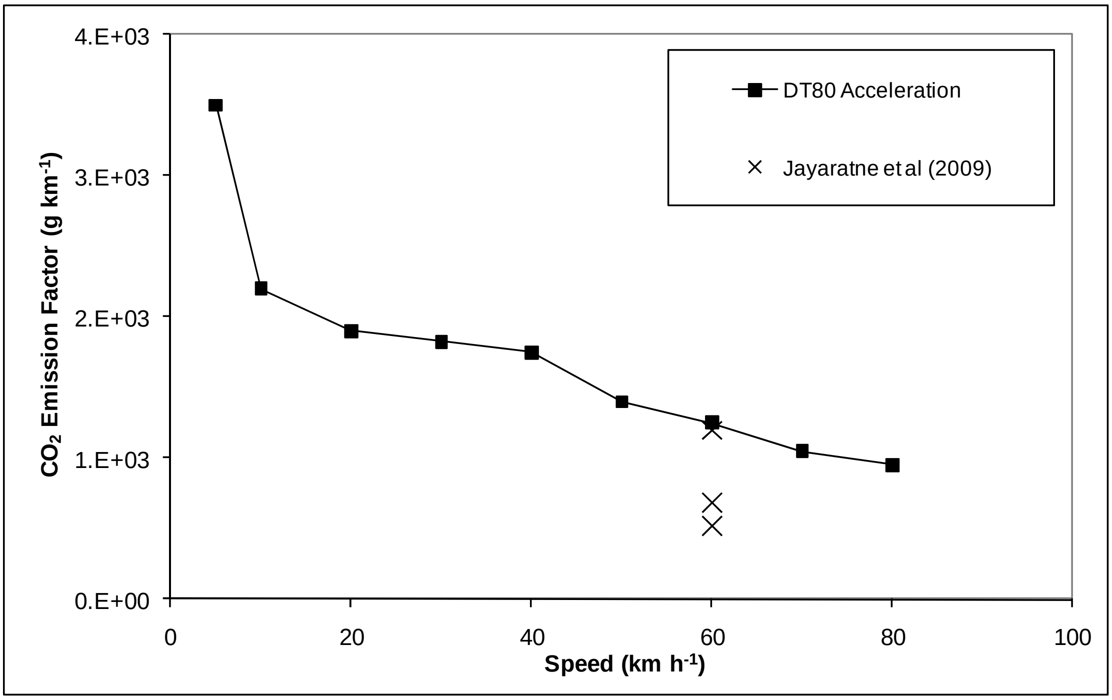

6000
4500
3000
1500
0
Emission Factor (g km-1)
Diesel
y = 13217x-0.554
R² = 0.9778
CNG
y = 6581x-0.41
R² = 0.9201
0
20
40
60
80
Speed (km h-1)

Fig 4



6.E+03
5.E+03
4.E+03
3.E+03
2.E+03
1.E+03
0.E+00
CO_2 Emission Factor (g km^{-1})
0
20
40
60
80
100
Speed (km h^{-1})
DT80 Acceleration
Ronnko et al Low Power
Ronnko et al High Power
Jayaratne et al (2009)
Ristovski et al (2006)
Austroads



4.E+03
3.E+03
2.E+03
1.E+03
0.E+00
CO_2 Emission Factor (g km^{-1})
0
20
40
60
80
100
Speed (km h^{-1})
DT80 Acceleration
Jayaratne et al (2009)

Fig 5

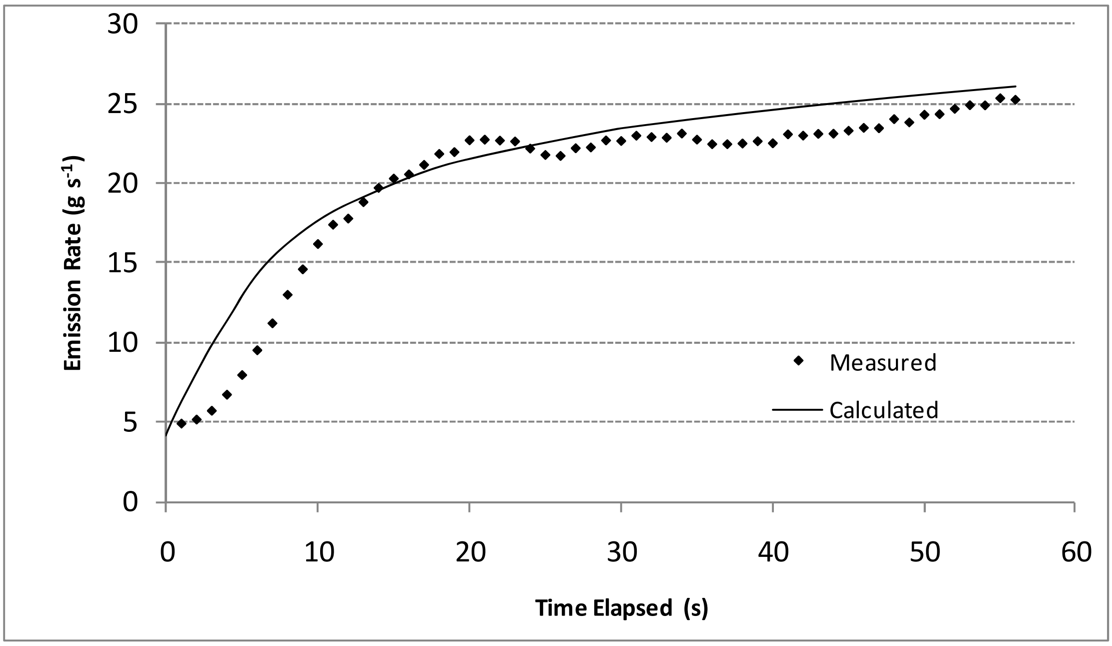

30
25
20
15
10
5
0
Emission Rate (g s-1)
Measured
Calculated
0
10
20
30
40
50
60
Time Elapsed (s)

Fig 6

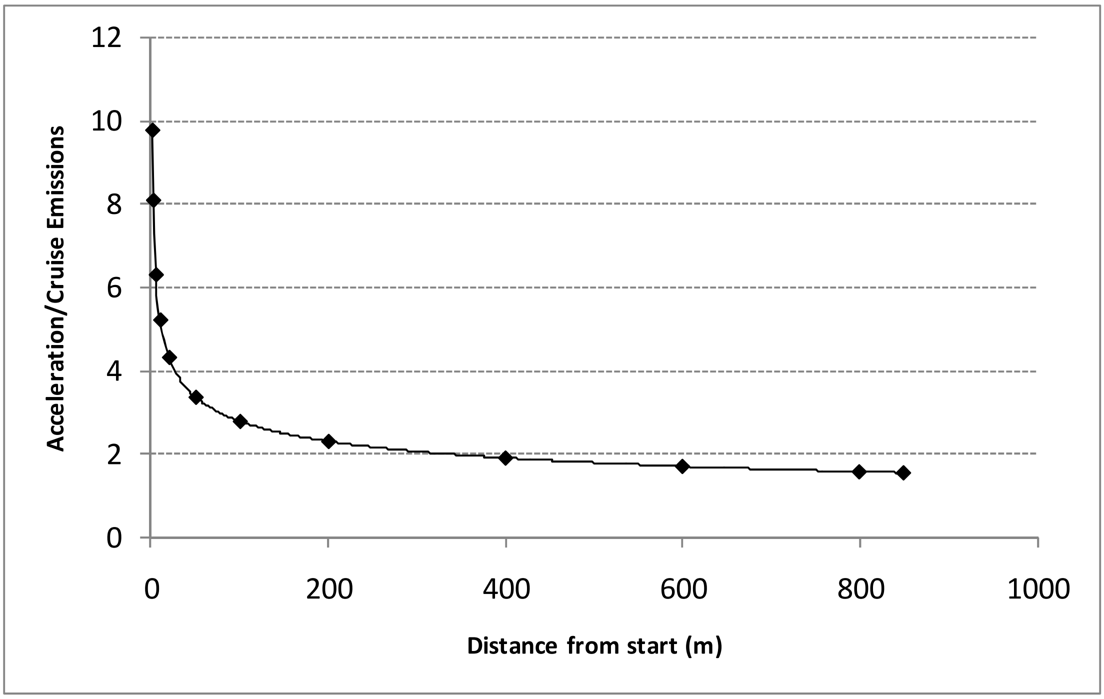

12
10
8
6
4
2
0
Acceleration/Cruise Emissions
0
200
400
600
800
1000
Distance from start (m)

Fig 7