THE DEVELOPMENT OF SOUTH AFRICAN VEHICLE EMISSION FACTORS

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Abstract

There are numerous compounds present in vehicular exhaust emissions which are of relevance in terms of potential impacts on human health and the environment. The impact of vehicle emissions on air quality is generally estimated from emission factors for each pollutant, which have been derived from monitoring campaigns in Europe and the USA.

In this study, direct exhaust emission monitoring was performed on 58 diesel and 78 petrol passenger vehicles in both idling and accelerated modes. South African petrol passenger vehicle emission factors were calculated from this data and vehicle fuel consumption specifications, and were found to be 19.7 $g.\ell^{-1}$ (CO, idling conditions); 19.1 $g.\ell^{-1}$ (CO, 2 000 rpm conditions); 2.08 $g.\ell^{-1}$ (HCs, idling conditions); and 1.98 $g.\ell^{-1}$ (HCs, 2 000 rpm conditions).

Keywords: passenger vehicles, petrol, diesel, emissions, emission factors, exhaust emission monitoring.

1. Introduction

1.1. Vehicular emissions & the need for the development of South African emission factors

It is estimated that vehicular exhaust emissions contain over 20 000 chemical compounds (Boström *et al*. 2002), including

- organic compounds, such as volatile organic compounds (VOCs); paraffins; and aromatic compounds for example, polycyclic aromatic hydrocarbons (PAHs)
- inorganic compounds, primarily CO, CO_2, NO and NO_2
- and particulate matter.

The emission rate of these air pollutants is dependant on many factors including fuel type and composition; vehicle type and age; driver behaviour; vehicle maintenance; and travel speed.

When these factors are considered, it is clear that emission factors (EFs) which have been derived under European or American conditions may well be unsuitable for use in calculating emissions from South African vehicles.

The aim of this study was therefore to determine South African passenger vehicle emission factors and to compare them to existing published and modelled values derived elsewhere.

1.2. Methods of monitoring vehicular emissions

The choice of compounds to be monitored in vehicular exhaust emissions is based on considerations including expected concentrations (emission rates), potential environmental and human health effects, and ease of monitoring (equipment availability and cost).

The three main means of monitoring vehicular emissions are via tunnel testing, remote sensing (typically using non-dispersive infrared and ultraviolet spectrometers) and via direct exhaust measurements. Some of the main features of each of these are summarised in Table 1 (adapted from Kuhns *et al.* 2004).

The EFs determined in this study were for use in a larger research project (called AQUILA) which dealt with the development of a scientific approach to assess the impacts of traffic interventions on air quality and specifically focused on the N1 highway in Gauteng.

Due to the fact that there are no tunnels on this roadway, tunnel testing was excluded as a possible means of monitoring and the capital equipment required for remote sensing was deemed to be too expensive. Direct exhaust measurements were therefore decided on, as described in the following section.

Parameter	**Direct exhaust measure-ments**	**Tunnel testing**	**Remote sensing**
Capital cost	Low	Medium	High
Cost per vehicle tested	High	Low	Low
Measurement type	Individual vehicle	Average vehicle	Individual vehicle
Test duration	Medium	Medium	Fast
Precision	Excellent	Fair	Fair
Accuracy of EFs thus derived	Poor (smaller sample size)	Good	Excellent
Availability of vehicles to be tested	Poor	Excellent	Excellent
Driving modes tested	All	Average only	Varies

Table 1. Comparison of different vehicle emissions measurement techniques.

2. Monitoring methodology

2.1. Diesel vehicles

Diesel vehicle emissions in idling and accelerated mode (2 000 rpm) were tested by means of an IMR 1400 Diga portable gas analyser (Sperosens), which monitored CO (%), O_2 (%), NO (ppm) and NO_x (ppm) based on electrochemical cell principles.

Additional information was collected for each vehicle monitored by means of a questionnaire which covered parameters such as:

- Cold/warm engine conditions
- Fuel type
- Vehicle make and model
- Vehicle age
- Engine size and type
- Service frequency, and
- Odometer reading.

2.2. Petrol vehicles

Petrol vehicle emissions were similarly monitored using a TEXA Gas box (Test Equipment Training and Consulting) for CO (%), O_2 (%), CO_2 (%) and hydrocarbons (HCs, ppm).

2.3. Sampling strategy

The choice of sampling locations was based on ease of access, which also minimised inconvenience to the drivers of the vehicles tested, and therefore improved the likelihood of drivers agreeing to the monitoring of their vehicles.

Light passenger vehicles were therefore sampled at the CSIR campus in Pretoria and at a petrol station on Meiring Naude road in Pretoria.

No personal details of the driver or identifying details of the vehicles were recorded.

3. Results and discussion

3.1. Emissions

The average emission concentrations which were determined are summarised in Table 2, although it must be noted that there was a large range in the measured values.

Parameter	**Diesel**		**Petrol**	
	Idling	**2 000 rpm**	**Idling**	**2 000 rpm**
No. of vehicles monitored	58	53	78	74
Mean vehicle age	2003	2004	2001	2001
Range of vehicle age	1976-2008		1982-2008	
Range of odometer reading (km)	6 270-409 684		4 964-402 860	
Mean CO (%)	0.027	0.031	1.44	1.68
Mean CO_2 (%)	NA	NA	11.5	11.5
Mean HC (ppm)	NA	NA	476	460
Mean NO (ppm)	150	118	NA	NA
Mean NO_x (ppm)	157	124	NA	NA

Table 2. Summarised monitoring data obtained for diesel and petrol light passenger vehicles. NA = not applicable.

It is evident that the average CO emissions were considerably higher for petrol vehicles than for diesel vehicles and that these emissions increased with acceleration, whilst the average CO_2 emissions remained constant (petrol vehicles). The mean petrol HC emission level may have decreased slightly upon acceleration, although a very high idling emission of one vehicle (9 241 ppm) would have significantly impacted on the mean value.

The NO and NO_x emissions from diesel passenger vehicles decreased under accelerated conditions, and it was evident that the majority of NO_x emissions was in the form of NO, as the NO_x concentrations were only slightly higher than that of NO.

The range of models which were monitored is shown in Figure 1, and it can be seen that the majority of vehicles were 2001 models or later, and that there was more of a range in the petrol vehicle model than for diesel vehicles. The oldest car tested was a 1976 diesel vehicle, and the odometer reading was generally higher for older vehicles.

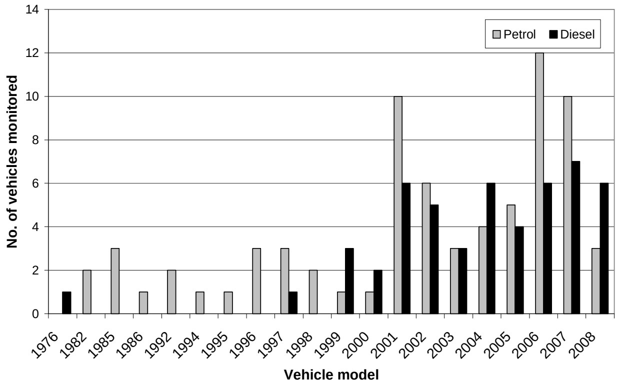

Figure 1. Range of vehicle models monitored.

There was a slight decreasing trend in CO emissions for more recent petrol vehicle models, while diesel passenger vehicles older than 1999 models had considerably higher CO emissions than the more recent models.

The CO_2 emissions from petrol vehicles were fairly constant for the different models monitored, but were lower for the few older idling vehicles, which had correspondingly higher CO and HC emissions, indicating the poor combustion efficiencies of these vehicles. The HC emissions from petrol passenger vehicles were fairly constant, with the exception of vehicles older than 1995 models.

No clear trend was evident for NO and NO_x emissions from diesel passenger vehicles, although emissions from more recent vehicle models appeared to be somewhat lower than for older vehicles.

The data was analysed based on the percentage of the total measurements which contributed to different emission level categories for each pollutant. The majority of petrol vehicles were in the lowest CO emission category (1-2 % CO), although one vehicle had emissions exceeding 11 % CO (Figure 2). There was more of a range of CO emission levels for diesel passenger vehicles (Figure 3), with a few vehicles emitting more than 0.1 % CO.

The distribution of CO_2 emissions from petrol passenger vehicles were almost Gaussian around 14 % CO_2, with a small number of vehicles emitting at the lower levels. The HC emissions of these vehicles were predominantly in the 200 to 800 ppm categories, but there was a wide distribution overall, with some vehicles emitting at >2 400 ppm.

The NO emission profile of diesel passenger vehicles followed a Gaussian distribution around 100-200 ppm, and was very similar to the NO_x profile as most of the NO_x was NO, as was previously mentioned.

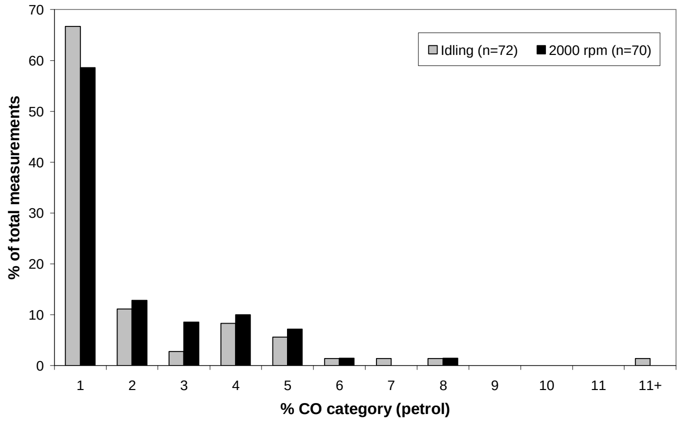

Figure 2. Percentage of petrol vehicle measurements in each emission category for CO.

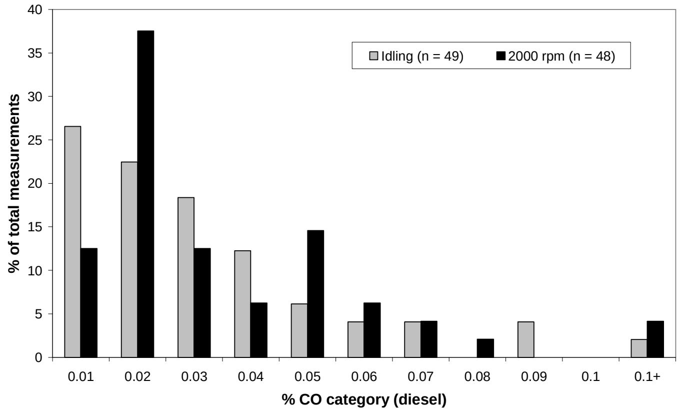

Figure 3. Percentage of diesel vehicle measurements in each emission category for CO.

In all cases a small percentage of the total number of measurements contributed to the highest emission category, which would have impacted on the average emission levels reported.

Upon comparison with other reported emission levels, it was found that the results of this study were generally higher than that reported for Denver, USA (Burgard *et al*. 2003), but our average petrol emission values were comparable to those determined in Mexico City (Shifter 2003) (refer to Table 3).

Parameter	**Denver, USA (Burgard *et al*. 2003)**	**Mexico City (Schifter *et al*. 2003)**	**This study (Average petrol)**	**This study (Average diesel)**
Monitoring method	Remote sensing	Remote sensing	Direct exhaust	Direct exhaust
% CO	0.35	1.31	1.56	0.029
ppm HC	88	440	468	NA
ppm NO	456	914	NA	134

Table 3. Comparison of emission concentrations.

3.2. Emission factors

EFs may be calculated from the concentrations of emitted vehicle pollutants obtained from remote sensing (Chan and Ning 2005) or on-board exhaust measurements (Holmén and Niemeier 1998), by means of equations which are based on molar conversions of the volume percentage emission concentrations. For example, the EF for CO may be calculated from:

$$E_{CO}(g.\ell^{-1}) = \frac{\dfrac{28 \times \%CO}{\%CO_2}}{\dfrac{\%CO}{\%CO_2} + 1 + [3 \times \dfrac{\%HC}{\%CO_2} / 0.493]} \times \frac{D}{M}$$

- Equation 1

where *D* is the density of the fuel and M is the molar mass thereof.

As the diesel monitor did not determine CO_2 and HC concentrations, it was not possible to calculate EFs for the diesel vehicles.

EFs for CO and HCs were determined for petrol vehicles, using an average gasoline density of 740 $g.\ell^{-1}$ (Guo *et al*. 2007) and a molar mass of 114.23 $g.mol^{-1}$, based on the molar mass of octane.

These EFs were then converted to distance based EFs with the use of average fuel consumption data derived from the vehicle manufacturer's specifications (NAAMSA 2009).

The EFs were then compared to literature values as well as to those derived from the COPERT IV emission modelling programme, which is often used to generate vehicular EFs for transport studies (refer to Table 4).

Parameter	Taiwan (Hung-Lung *et al*. 2007)	COPERT IV (Gasoline Euro 2 & 3 passenger at 10 $km.hr^{-1}$)	This study (Petrol idling)	This study (Petrol 2 000 rpm)
Monitoring method	Tunnel	Modelled	Direct exhaust	Direct exhaust
CO $g.km^{-1}$	1.89	E2: 1.853 E3: 0.564	1.77	1.71
HC $g.km^{-1}$	0.46	E2: 0.254 (VOC) E3: 0.034 (VOC)	0.19	0.18
NO_x $g.km^{-1}$	0.73	E2: 0.257 E3: 0.089	NA	NA

Table 4. Comparison of emission factors, where E2 refers to Euro 2 and E3 to Euro 3 vehicles, respectively. The COPERT VOC EFs were used as a proxy for HC EFs.

It is evident that the CO EFs determined in this study are similar to those obtained by Hung-Lung *et al*. (2007), whilst our HC EFs were lower.

The EFs from COPERT IV at a low speed of 10 $km.hr^{-1}$ were used for comparison, as the measured emissions were obtained at low acceleration rates. HCs are only one class of compounds which would contribute to VOC emissions, therefore it is expected that the VOC EF would be larger than that of HCs.

The Euro 3 COPERT EFs were approximately three times lower than those derived from measured data, whilst the Euro 2 EFs were slightly higher than the measured data but were of a similar order of magnitude. This is most likely due to the fact that the South African vehicle fleet currently consists of a mix of Euro 2 and Euro 3 passenger vehicles, which may impact on conclusions drawn from studies which are based on modelled values.

4. Conclusion

We have developed South African emission factors for petrol passenger vehicles, which are applicable to dense traffic conditions (idling and low acceleration situations).

The COPERT IV Euro 3 emission factors for passenger vehicles appear to be approximately three times too low for South African conditions, whilst the Euro 2 EFs were comparable to measured data, although they may overpredict emissions.

Good correlations were obtained between our results and those of other comparable international studies, both in terms of emission concentrations and the emission factors derived therefrom.

It is acknowledged that the sample size was very limited, and a wider coverage of vehicles in the South African vehicle fleet is needed to improve the accuracy of the results.

Additional analyte monitoring is also required, particularly for diesel vehicles, in order to allow for a full suite of South African vehicular EFs to be calculated.

On-board emissions testing would also allow for EF determinations under driving conditions.

The results obtained indicate the need for the development of South African vehicular emission factors to allow for more accurate predictions of the impact of traffic and traffic interventions on air quality and human health.

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