# THE COMPARISION OF MODELLED AND ON-ROAD LIGHT DUTY VEHICLE EMISSION FACTORS

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REPORT

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## 1.0    BACKGROUND

The project to compare light duty vehicle emission factors from the Vehicle Emission Prediction Model (VEPM) and on-road emission monitoring (Remote Sensing Data (RSD)) was a collaborative project co-funded by Auckland Council (AC) and the New Zealand Transport Agency (Transport Agency).  The project consisted of two discrete tasks.

Task 1 required the generation light duty vehicle emission factors from RSD and the comparison of these against VEPM emission factors.  Task 1 was funded by Auckland Council and undertaken by Golder Associates New Zealand Ltd (Golder) and the National Institute of Water and Atmospheric Research (NWIA).  Task 1 was complete in June 2013.

Task 2 required the reporting of the outputs from Task 1.  Task 2 was funded by the Transport Agency and undertaken by Golder.  This report[1] is the contracted deliverable from Task 2 and presents the comparison of light duty vehicle emission factors produced by VEPM and from the RSD.

## 1.1    Introduction

The VEPM has been developed by AC and the Transport Agency Transport Agency to quantify vehicle emissions, and predict how these are likely to change over time.  VEPM is based on results from international and New Zealand emission tests, in which selected vehicles are run through a simulated drive cycle on a chassis dynamometer.  The exhaust emissions are collected and analysed to provide representative emissions for that vehicle type and drive cycle.  These tests are relatively time-consuming and expensive.  This means that VEPM is necessarily based on a limited number of test results, which have been extrapolated to represent the whole fleet.

To ensure that VEPM is providing useful and realistic information, it is beneficial to check whether the emission estimates accurately represent the pollutants being discharged by vehicles in the "real-world" fleet.  One way of undertaking this check is to measure vehicle emissions in roadside situations using remote sensing technology.  Remote sensing measurement of light duty vehicle emissions has been undertaken in four separate campaigns in Auckland in the years 2003, 2005, 2009 and 2011.  These four emission monitoring campaigns and the development of the resulting vehicle emission data base is detailed in Kuschel, Bluett and Unwin (2013).  These four Remote Sensing Data (RSD) sets provide a resource that can be examined to assess long term trends in on-road vehicle emissions, changes in on-road vehicle fleet profile and to assess the performance of vehicle emission models.

## 1.2    Project Objective and Tasks

The objective of this project is to compare the RSD and VEPM emission factors for light duty vehicles. This comparison will indicate if VEPM is providing useful and realistic estimates of light duty vehicle emissions and if so, increase stakeholder confidence in the emission data produced by VEPM.  To achieve this objective, the project was structured into three sequential tasks:

■    Calculate on-road emission factors for light duty vehicles from the RSD

■    Assess the day-to-day and from site-to-site variation in RSD emission factors

■    Compare the RSD and VEPM emission factors for light duty vehicles

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[1] This report is subject to the Limitations attached as Appendix A.

## 1.3    Structure of the Report

To deliver on the project objectives, the report is structured as follows:

- VEPM emission factors (Section 2)

- On-road RSD measurement programmes (Section 3)

- Method used to generate on-road emission factors from the RSD (Section 4)

- Limitations of on-road emission factors (Section 5)

- Site-to-site variability of RSD emission factors (Section 6)

- Day-to-day variability of RSD emission factors (Section 7)

- Comparison of VEPM and on-road fleet profile (Section 8)

- Comparison of VEPM and RSD emission factors for the following vehicle classes (Section 9)

    - Petrol cars

    - Petrol light commercial vehicles (LCV)

    - Diesel cars

    - Diesel LCV

- Summary of findings (Section 10)

- Conclusions (Section 11)

- Recommendations for further work (Section 12)

## 2.0    VEPM EMISSION FACTORS

VEPM is described in detail in the 'Vehicle Emissions Prediction Model (VEPM) Version 5.0 Development and User Information' report (Jones et al. 2011) and in the 'Vehicle Emissions Prediction Model (VEPM 5.1) users guide" (http://air.nzta.govt.nz/predictions/nz-vepm).  Emission factors from an earlier version of VEPM (version 4.1) have been used by AC for the most recent (2006) Auckland air emissions inventory (Xie, Sridhar and Metcalfe 2011).  The data and methods used to estimate motor vehicle emissions in the Auckland 2006 air emissions inventory are described in detail in the Auckland Motor Vehicle Emissions Inventory for 2006 (AC 2013) and are summarised below.

Motor vehicle emissions for the Auckland Motor Vehicle Emissions Inventory were calculated using emission factors from the vehicle emission prediction model (VEPM) version 4.1 and outputs from the Auckland Regional Transport Model Version 3 (ART3).  Emission factors are generated by the vehicle emission prediction model for the year 2006 and defined for:

- All speeds between 10 and 99 kilometres per hour

- All vehicle types

- All pollutants in the inventory

For the purposes of comparing the VEPM vehicle emission factors used for the AC 2006 air emissions inventory with the on-road RSD emission factors, the following selection criteria were used:

- RSD from the 2005 monitoring campaign (the year with monitoring data closest to the inventory year)

- Light duty vehicle types and speeds (based on the speed measured in the 2005 road-side monitoring campaign):

  - Petrol cars (58 km/hr)

  - Petrol LCV (45 km/hr)

  - Diesel cars (47 km/hr)

  - Diesel LCV (54 km/hr)

- Pollutants monitored by the RSD

  - Carbon monoxide (CO)

  - Hydrocarbons (HC) - Volatile organic compounds (VOC) in VEPM

  - Nitrogen monoxide (NO) – NOx in VEPM

  - UVsmoke as an indicator of particulate matter – Exhaust $PM_{2.5}$ in VEPM

# 3.0   ON-ROAD VEHICLE EMISSION MEASUREMENTS

The RSD system was originally developed by Donald Stedman and his team at the Fuel Efficiency Automobile Test Data Centre (FEAT), University of Denver, Colorado, USA and is described in detail in Williams, Bishop and Stedman (2003).

The RSD system consists of an infrared (IR) detector for measuring carbon monoxide (CO), carbon dioxide ($CO_2$) and hydrocarbons (HC), together with an ultraviolet (UV) spectrometer for measuring nitric oxide (NO). The RSD also measures UV absorbance at (~100 nm) which provides a good indicator of particulate emissions particularly from diesel vehicles. The RSD particulate measurement is known as uvSmoke. The source / detector module (SDM) was positioned on one side of the road, with a corner cube reflector on the opposite side. Beams of IR and UV light were passed across the roadway into the corner cube reflector and returned to the detection unit. The light beams were then focused onto a beam splitter, which separated the IR and UV components which were then sent to the respective detectors.

The path length and density of the observed plume vary considerably between vehicles and depend on (among other things) the height of the vehicle's exhaust pipe, wind, and turbulence behind the vehicle. For these reasons, the remote sensor can only directly measure ratios of CO, HC or NO to $CO_2$. These ratios are constant for a given exhaust plume, and on their own are useful parameters for describing the combustion products discharged from the vehicle.

The RSD used in the Auckland in the 2005 monitoring campaign (the RSD 4000EN) reported the %CO, ppm HC and ppm NO in the exhaust gas, corrected for water vapour and excess oxygen not used in combustion. Particulate emissions were measured by a UV detector to provide a parameter denoted uvSmoke. A detailed technical description of the way the RSD 4000EN measures particulate pollutants can be found in Stedman and Bishop (2002).

The RSD 4000EN also included speed and acceleration bars, which provided information about the driving conditions of the vehicles at the time of the measurements. The bars were set up as close as practical (~2 m) to the SDM to minimise any changes in speed and acceleration prior to a vehicle's emissions being measured. These data were also used to derive a vehicle performance measure, vehicle specific power (VSP). VSP is a measure of the load on a vehicle as it drives along and is defined as the power per unit mass to overcome road grade, rolling resistance, aerodynamic resistance, and internal friction.

Campaigns to measure vehicle emission using remote sensing were undertaken in Auckland in 2003, 2005, 2009 and 2011.  Each campaign involved multiple agencies, including the Auckland Regional Council (ARC) from 2003 to 2009, the newly-formed Auckland Council (AC) in 2011, and the Transport Agency, Ministry for Transport (MoT), and National Institute of Water and Atmospheric Research (NIWA).

The database contains a complete record of all on-road vehicle emission measurements made in Auckland between 2003 and 2011 (approximately valid 146,000 records).  The 2005 on-road emissions monitoring programme captured data from approximately 25,000 light duty vehicle.  The details of all the RSD monitoring programmes and the development of the vehicle emissions data base are detailed in Bluett et al. (2013).

The ownership of the data within the on-road vehicle emission database rests with the organisations which funded each of the specific monitoring campaigns.  Auckland Council funded and own the data collected for the 2005 on-road vehicle emission monitoring programme and that data is used for this project with permission by Auckland Council.

# 4.0    METHOD USED TO GENERATE EMISSION FACTORS FROM RSD

The on-road pollutant measurements are reported in concentrations of CO (%), HC (ppm) and NO (ppm) in the exhaust plume.  The particulate emissions are monitored using a metric named UV smoke index which is recorded in units of grams of diesel particulate matter per 100 g of fuel burned.  The emission factors used in the Auckland Air Emissions Inventory 2006 are expressed in grams of pollutant emitted per km travelled (g/km).  Therefore, before a comparison between the RSD and VEPM emission factors can be made, the RSD values for CO, HC and NO must be converted into g/km emission factors.  This conversion of CO, HC and NOx RSD to g/kg emission factors requires four steps:

■    Step one requires the conversion of the CO, HC and NO concentrations into emission factors measured as grams of pollutant per kg of fuel burned (g/kg).  The conversion uses the stoichiometry of fuel combustion, described in detail by Pokharel et al. (2002), and has been used more recently by Guo et al. (2007), Smit and Bluett (2011) and Rhys-Tyler and Bell (2012).  The equations used to make this conversion are provided in Appendix B.

■    Step two converts the g/kg emission factors (from step 1) into g/L emission factors assuming the density of petrol to be 750 g/L and the density of diesel to be 830 g/L.

■    Step three converts the g/L emission factor (from step 2) into g/km emission factors by employing a fuel consumption rate (in L/100km).  The fuel consumption rates used to make the g/L to g/km conversions was taken from the VEPM model run for the Auckland 2006 inventory and are detailed in Table 1.

■    Step four only relates to the pollutant NO.  The RSD measures NO but the Auckland inventory provides estimates of NOx (NO + $NO_2$) emissions.  To compare the NO RSD emission factors with the inventory NOx emission factors, the RSD NO must be converted to NOx by making an assumption about $NO/NO_2$ ratios in the exhaust plume.  Typical $NO/NO_2$ ratios are different for petrol vehicles versus diesel vehicles.  There is significant debate about $NO/NO_2$ ratios in vehicle exhaust.  However, the assumptions made for this comparison (10 % for petrol and 20 % for diesel) are considered to provide a sensible first order estimate that enables the comparison between RSD and VEPM NOx emission factors to be made.

■    The work required to generate the RSD emission factors was undertaken by NIWA and Golder for AC as part of Task 1 of this project.

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**Table 1: Fuel consumption by vehicle type.**

| Fuel | Vehicle type | Fuel consumption (L/100km) (AC, 2013) |
|---|---|---|
| Petrol | Car | 9.47 |
| Petrol | LCV | 10.22 |
| Diesel | Car | 8.60 |
| Diesel | LCV | 8.97 |
| Fleet average | | 9.41 |

# 5.0   LIMITATIONS OF THE METHOD USED TO GENERATE ON-ROAD EMISSION FACTORS

While the on-road emission factors provide a useful comparison for VEPM emission factors there are some limitations to the method used to generate the RSD emission factors.  The limitations of the RSD emission factors must be acknowledged and include:

- Remote sensing techniques measure instantaneous emission rates associated with driving conditions at a particular point on the road. VEPM emission factors represent a particular driving cycle (g/km) measured in a laboratory over 10 to 30 minutes of driving (a 'journey').  Therefore, RSD may not be representative of the average emissions over a full drive cycle.

- The monitoring sites used are single lane on- or off-ramps, arterial roads, or one way streets.  For this reason, the emissions monitored will reflect driving conditions that predominate on these types of roadways and will not necessarily be representative of emissions generated on other roadway types, e.g., at busy intersections.

- The measurement of emissions is made using open path technology and is unlikely to be as accurate as that collected by a dynamometer set up.  The RSD is capable of CO, HC and NO measurements within ±5%, ±15% and ±5% respectively of measurements reported by an on board gas analyser (Lawson et al. 1990).  The manufacturers of the RSD 4000EN quote the precision of the CO, HC and NO measurements as ±0.007%, ±6.6ppm and ±10ppm respectively, or as ±10% of the value, whichever is the greatest (see www.rsdaccuscan.com).

- RSD measures NO and not NOx (i.e., NO + $NO_2$).  Direct use of NO data from RSD would result in a bias (underestimation) of RSD NOx emission rates.  A correction is therefore needed and RSD NOx is estimated by multiplication of NO with a scaling factor.

- A factor of 2 is applied to the HC measurements because the non-dispersive infrared HC measurement calibrated with propane only determines around 50 % of the HC mass compared to flame ionisation detection (FID) techniques (Singer et. Al. 1998).

- The measurement of particulate emissions using open path technology is problematic.  Therefore the RSD uvSmoke data cannot be assumed to be equivalent to the results that would be obtained from gravimetric analysis carried out on a dynamometer.  The RSD 4000EN manufacturers quote the precision of the uvSmoke measurements as ±0.05 or ±10 % of the uvSmoke reading, whichever is the greatest.

- The RSD measures particulates (uvSmoke) for peak mass density of diesel exhaust particulates (~100 nm).  Because the RSD's UV wavelength is selected for peak mass density of diesel exhaust particulates, it should be a good approximation for the comparison against the VEPM diesel $PM_{2.5}$

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exhaust emission factor.  However, the uvSmoke data from petrol vehicles contains more uncertainty than uvSmoke data from diesel vehicles.  In summary, the interpretation of uvSmoke data from petrol vehicles in particular and the comparison VEPM and RSD $PM_{2.5}$ exhaust emission factors in general must be treated with due caution.

■   The conversion of RSD g/kg to g/km emission factors relies on a fuel consumption rate which is obtained from VEPM. For the comparison this creates a dependence on the VEPM fuel consumption rate.  A more direct comparison between the VEPM and RSD could be undertaken by using g/kg emission factors for both VEPM and RSD.  VEPM g/kg emission factors can be calculated by converting the VEPM g/km emission factor to a VEPM g/kg by using the VEPM fuel consumption rate. However, given that the fuel consumption rate is a constant whether it is applied to the VEPM or RSD g/kg emission factors, the conclusions reached using a g/kg comparison would be identical to those using a g/km comparison.

In summary, the data provided by an RSD programme will not be identical to those obtained from dynamometer drive cycle testing upon which the VEPM emission factors are based and there are a number of limitations to the method used to generate RSD emission factors.  Despite these differences and limitations the RSD information does provide a complementary data stream that can be used to check the VEPM emission factors which are based on a smaller number of dynamometer drive cycle tests.  A number of recommendations are made at the end of this report to address some of the limitations of the RSD highlighted in this section.

# 6.0   PRESENTATION OF RESULTS

Box and whisker plots are used to characterise vehicle emissions throughout this report.  These plots provide a compact summary of the mean, median, and range for each pollutant, in a format that emphasises variation among and within vehicle type.  The conventions used to construct each plot (see Figure 1) are as follows:

■   Each box and whisker icon comprises a connected set of graphical elements which summarise the underlying data as measured along the vertical axis.

■   The upper and lower limits of the central box show the upper and lower quartiles.  Thus, the box contains the central 50 per cent of the raw data.

■   The whiskers represent the 5th and 95th percentile values.  More extreme data values, possibly extending well beyond the maximum axis value, are not displayed.

■   Red circles shows the mean, whilst the median is represented by a "belt" across the box.

■   The point at which the belt crosses the box, a "waist" is shown.  The extent of the waist of the boxes (whether it is short or long) indicates the confidence intervals around the median.  If the "waists" of two adjacent boxes do not overlap then the means are statistically different and vice versa.

■   Box width is proportional to sample size.  For example, in Figure 1 the sample size for Lagoon Drive (7,779 vehicles) is roughly three times of that at Universal Drive (2,542 vehicles).

■   For the plots which show VEPM emission factors these are marked with a black astrix.
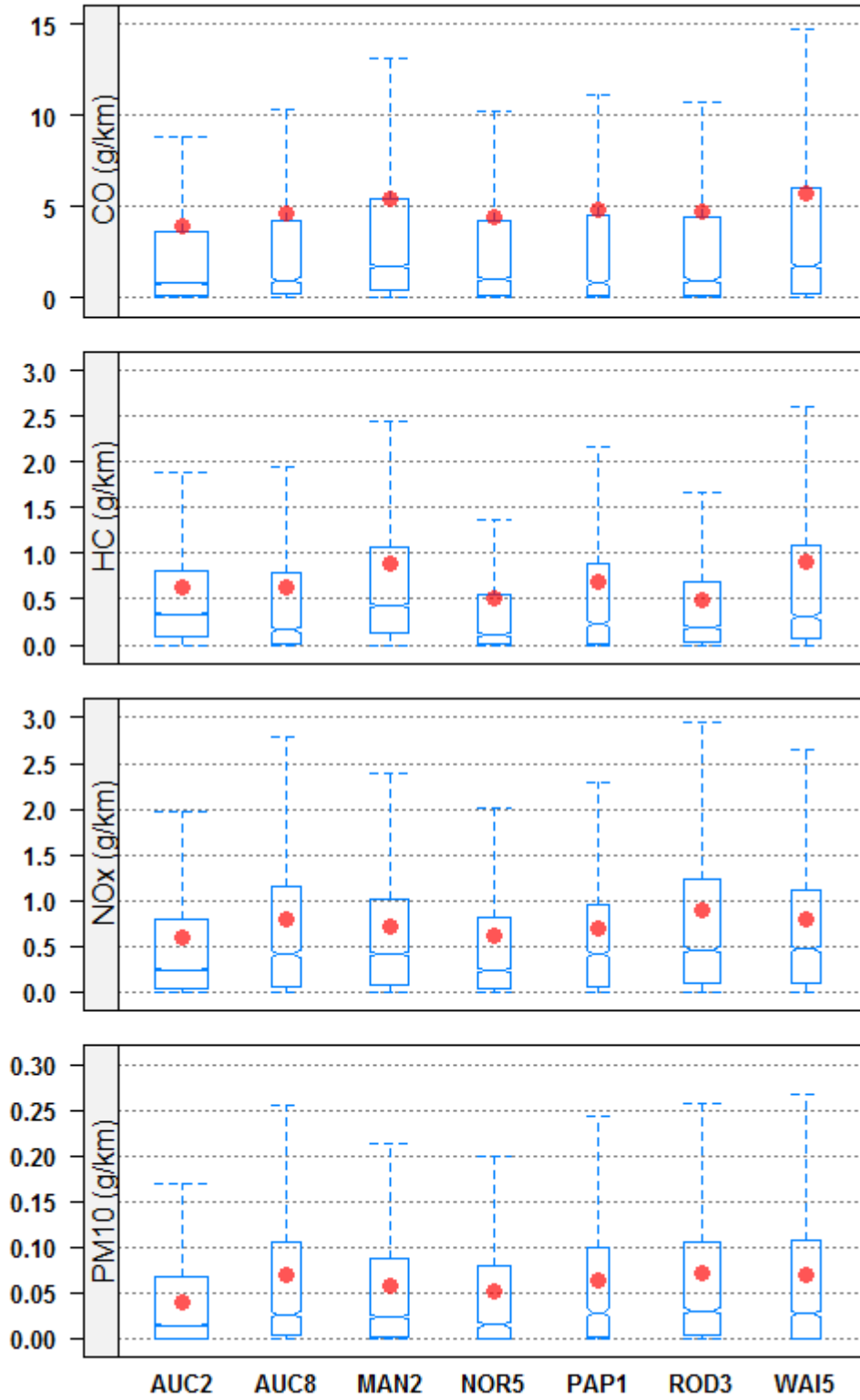
*Figure 1: Comparison of RSD derived emission factors by monitoring site.*

# 7.0    SITE-TO-SITE VARIABILITY OF RSD EMISSION FACTORS

The RSD measurements are specific to the site at which they are monitored and are defined by the vehicle fleet that passes through that specific geographical point.  The VEPM emission factors are not site specific and are designed to represent the regional fleet profile.  Therefore, it is important to understand the site-to-site variability of the RSD emission factors.  The RSD g/km emission factors for CO, HC, NOx and $PM_{10}$ by monitoring site are shown in Table 2 and Figure 1.

**Table 2: Site-to-site variability of RSD emission factors.**

| Site name (site code) | Lagoon Dr (AUC2) | West End Rd (AUC8) | Lambie Dr (south-bound) (MAN2) | Upper Harbour Highway (west-bound) (NOR5) | Elliot St (west-bound) (PAP1) | Whangaparaoa Rd (ROD3) | Universal Dr (WAI5) |
|---|---|---|---|---|---|---|---|
| **Number of vehicles** | 7,779 | 2,554 | 4,292 | 2,990 | 1,365 | 3,848 | 2,542 |
| **CO g/km mean (median)** | 3.964 (0.823) | 4.593 (0.983) | 5.394 (1.715) | 4.420 (1.040) | 4.833 (0.853) | 4.748 (0.983) | 5.682 (1.770) |
| **HC g/km mean (median)** | 0.629 (0.337) | 0.635 (0.165) | 0.892 (0.426) | 0.500 (0.114) | 0.690 (0.227) | 0.482 (0.186) | 0.911 (0.312) |
| **NOx g/km mean (median)** | 0.594 (0.242) | 0.799 (0.415) | 0.704 (0.406) | 0.620 (0.236) | 0.696 (0.407) | 0.887 (0.458) | 0.791 (0.469) |
| **$PM_{10}$ g/km mean (median)** | 0.039 (0.014) | 0.069 (0.026) | 0.057 (0.024) | 0.051 (0.015) | 0.064 (0.029) | 0.071 (0.030) | 0.070 (0.027) |

A comparison of the emission factors recorded at different sites was undertaken using the Kruskal-Wallis (K-W) test for statistical significance.  The K-W test is an appropriate and useful tool to analyse highly skewed data sets, such as on-road vehicle emissions.  The data displayed in Table 2 and Figure 1 and the results from the K-W test show that there is considerable variation of emission factors from site-to-site with a large number of the differences between sites being statistically significant.  The HC emission factors exhibit the highest site-to-site variability. For all pollutants Lagoon Drive consistently had the lowest emission factor while Universal Drive is always toward the high end of the measurements for all contaminants.

The site-to-site variability of the emissions is most likely caused by the difference in vehicle fleet composition, the age of the vehicles that are passing through the site and the slope of the road upon which the monitoring is being undertaken.  To a large degree, the RSD quality assurance process controls for the variation in emissions caused by the site-to-site differences in road slope.  Therefore, the most likely cause of the observed site-to-site variation is vehicle age and fleet profile.  The analysis of the site-to-site variation in vehicle age and fleet profile can be achieved using the RSD database but is outside the scope of the current project.

The observed site-to-site variation in emission factors suggests that the best approach to employing the RSD for the VEPM comparison is to aggregate the RSD data from each site up into a city-wide dataset that will average out any site specific differences observed in the data. This approach will provide a better comparison against the VEPM emission factor which reflects the fleet characteristics of a much wider geographical region, than selecting RSD from a specific site.

## 8.0 DAY-TO-DAY VARIABILITY OF RSD EMISSION FACTORS

The RSD measurements are specific to the day on which they were taken. Therefore it is important to understand the magnitude of any day-to-day variability of the RSD emission factors measured at a specific site. The RSD g/km emission factors for CO, HC, NOx and $PM_{10}$ for two different days monitoring at the Lagoon Drive (AUC2), Upper Harbour Highway (NOR5) and Whangaparaoa Road (ROD3) sites are shown in Table 3 and Figure 2.

**Table 3: Day-to-day variability of RSD emission factors.**

| | Lagoon Drive (AUC2) | | Upper Harbour Highway (west-bound) (NOR5) | | Whangaparaoa Rd (ROD3) | |
|---|---|---|---|---|---|---|
| | Day 1 | Day 2 | Day 1 | Day 2 | Day 1 | Day 2 |
| **Number of vehicles** | 1,988 | 2,054 | 3,110 | 2,549 | 4,537 | 4,672 |
| **CO g/km mean (median)** | 2.632 (0.455) | 2.702 (0.439) | 3.965 (0.540) | 3.532 (0.471) | 2.956 (0.525) | 3.057 (0.535) |
| **HC g/km mean (median)** | 0.329 (0.107) | 0.321 (0.094) | 0.271 (0.134) | 0.274 (0.131) | 0.361 (0.213) | 0.303 (0.147) |
| **NOx g/km mean (median)** | 0.351 (0.053) | 0.319 (0.043) | 0.514 (0.107) | 0.539 (0.114) | 0.611 (0.227) | 0.561 (0.168) |
| **$PM_{10}$ g/km mean (median)** | 0.022 (0.002) | 0.031 (0.013) | 0.047 (0.020) | 0.042 (0.014) | 0.038 (0.010) | 0.051 (0.020) |
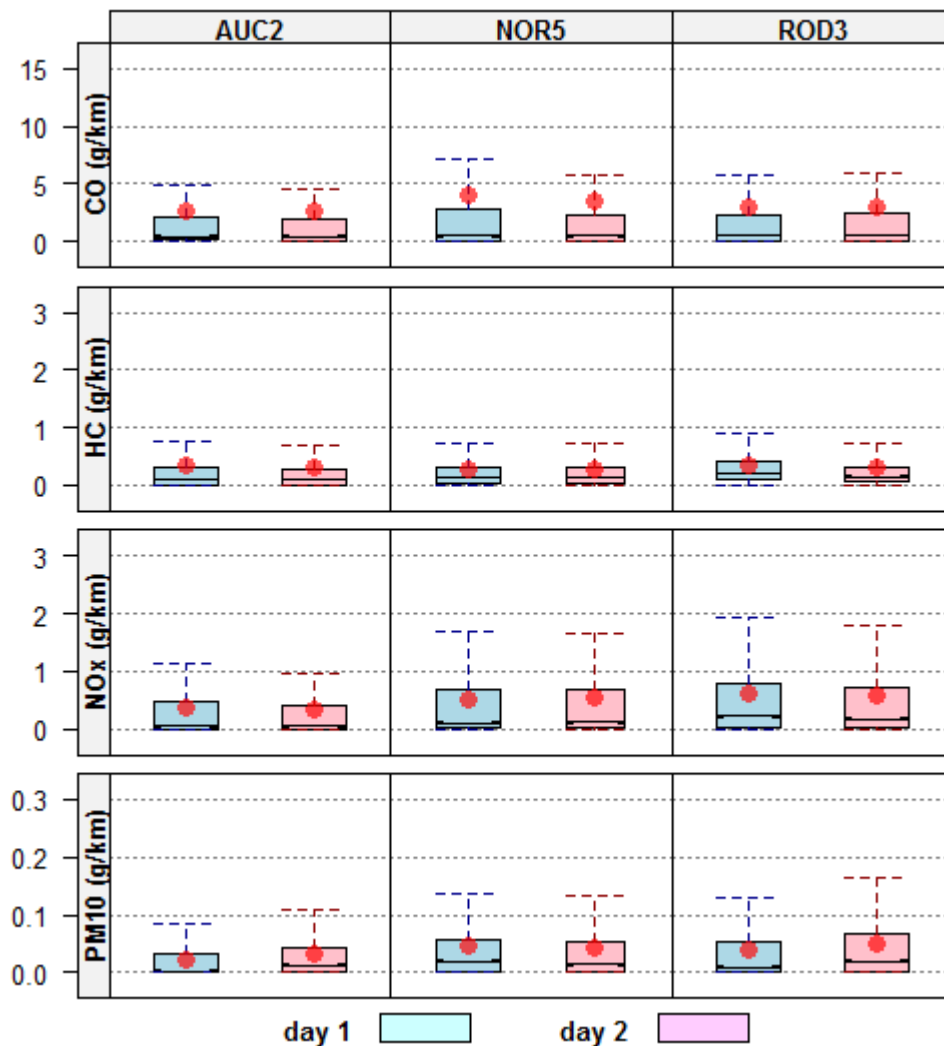
*Figure 2: Comparison of RSD derived emission factors by day of monitoring for three different site locations.*

A comparison of the emission factors recorded on different days at the same site was undertaken using the Kruskal-Wallis (K-W) test for statistical significance. The data displayed in Table 3 and Figure 2 and the results from the K-W test show that there is:

■ No significant day-to-day variation in the CO emission factors at any of the three sites.

■ Significant day-to-day variation in the HC emission factors only at the Whangaparaoa Road site.

■ Significant day-to-day variation in the NOx emission factors at the Lagoon Drive and Whangaparaoa Road sites.

■ Significant day-to-day variation in the $PM_{10}$ emission factors at all three sites.

The reasons for the observed day-to-day variability in emission factors are not immediately clear. The sites were all monitored on weekdays and over the same period on each day of monitoring, therefore minimising the potential for day-to-day variation in vehicle age and fleet profile. Another observation that does not immediately have a clear explanation is that some pollutants vary day-to-day at all sites (e.g. $PM_{10}$), while there is no day-to-day variation observed in CO emissions. While potentially interesting, a more detailed investigation into the causes of the observed day-to-day variation in emissions factors falls outside the scope of the current project.

The observed day-to-day variation in emission factors suggests that the best approach to employing the RSD for the VEPM comparison is to aggregate the RSD data from all days up into a time averaged dataset that is likely to smooth out any time specific differences observed in the data. This approach will provide a better comparison against the VEPM emission factor which reflects the characteristics of a much less temporal specific vehicle fleet than selecting RSD from a specific day.

## 9.0    COMPARISON OF VEPM AND ON-ROAD LIGHT DUTY FLEET PROFILES

The proportion of the vehicle type (car or LCV) and fuel types (petrol or diesel) which make up a fleet profile is an important factor in determining fleet average emission factors. Therefore, it is important to understand and compare the AC 2006 inventory and the 2005 on-road light duty fleet profiles (Table 4).

**Table 4: Vehicle fleet profile from the AC 2006 inventory and 2005 on-road measurement programme.**

| Vehicle type | Fuel | Per cent of AC 2006 inventory fleet | Per cent of 2005 on-road fleet |
|---|---|---|---|
| **Car** | Petrol | 76.3% | 80.2% |
| **Light commercial** | Petrol | 4.5% | 5.1% |
| **Hybrid & Electric** | Petrol | 0.1% | 0.0% |
| **Car** | Diesel | 8.7% | 7.0% |
| **Light commercial** | Diesel | 10.5% | 7.7% |
| **Total petrol** | | 80.8% | 85.3% |
| **Total diesel** | | 19.2% | 14.7% |

Table 4 shows AC 2006 inventory and the 2005 on-road light duty fleet profiles are similar with the variation between any specific vehicle or fuel type being less than 5 %. The largest differences between the AC 2006 inventory and the 2005 on-road light duty fleet profiles are:

■    The proportion of petrol vehicles within the AC 2006 inventory is lower than the on-road fleet (81 % vs 85 %)

■    The proportion of diesel vehicles within the AC 2006 inventory is higher than the on-road fleet (14 % vs 19 %)

■    The proportion of petrol cars within the AC 2006 inventory is lower than the on-road fleet (76 % vs 80 %)

## 10.0   COMPARISON OF VEPM AND RSD FACTORS

## 10.1   Overview

This section of the report presents the results from the comparison of VEPM and RSD emission factors (aggregated by location and time of day) by pollutant type. Comparisons are made between VEPM and RSD emission factors for fleet average and for the four specific vehicle types under consideration.

## 10.2   Carbon Monoxide

Table 5  and Figure 3 compare the fleet average VEPM and RSD CO emission factors.  Table 5 and Figure 3 shows, that on a fleet average basis, the VEPM CO emission factor is 66 % higher than the mean RSD value.

**Table 5: Fleet average RSD and VEPM CO emission factors.**

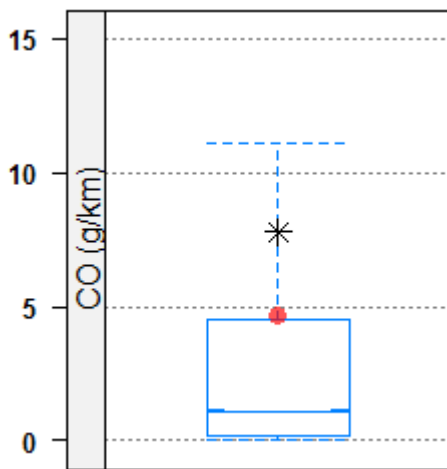| | |
|---|---|
| **Number of vehicles** | 25,370 |
| **RSD – mean (g/km)** | 4.66 |
| **VEPM (g/km)** | 7.78 |



*Figure 3: Comparison of fleet average RSD and VEPM CO emission factor.*

Table 6 and Figure 4 compare the VEPM and RSD CO emission factors by vehicle type.  Table 6 and Figure 4 show that the VEPM CO emission factors are consistently higher than the respective RSD emission factors for all vehicle types.  The difference between VEPM and RSD CO emission factors ranges from 46 % for diesel cars to 36 % for diesel LCVs.  The difference for petrol cars which dominate vehicle fleet numbers was 68 %.

**Table 6: RSD and VEPM CO emission factors by vehicle type.**

| | Petrol car | Petrol LCV | Diesel car | Diesel LCV |
|---|---|---|---|---|
| **Number of vehicles** | 20,350 | 1,288 | 1,776 | 1,956 |
| **RSD mean (g/km)** | 5.19 | 8.75 | 0.37 | 0.33 |
| **VEPM (g/km)** | 8.71 | 13.86 | 0.54 | 0.78 |
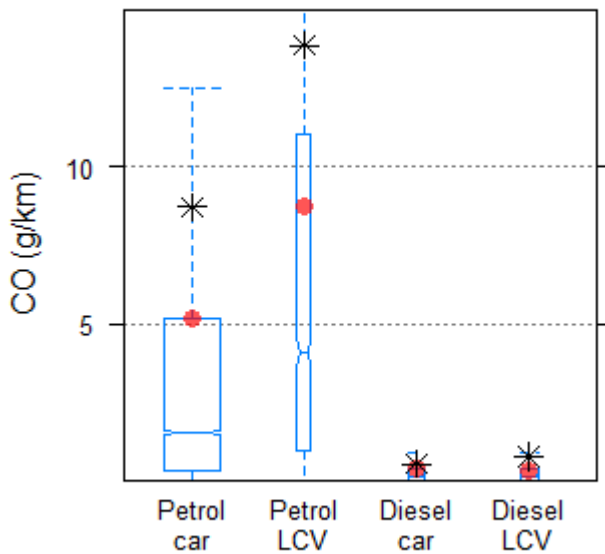
*Figure 4: Comparison of RSD and VEPM CO emission factor by vehicle type.*

## 10.3    Hydrocarbons

Figure 5 and Table 7 compare the fleet average VEPM and RSD HC emission factors and show that on a fleet average basis the VEPM HC emission factors is 31 % lower than the mean RSD value.
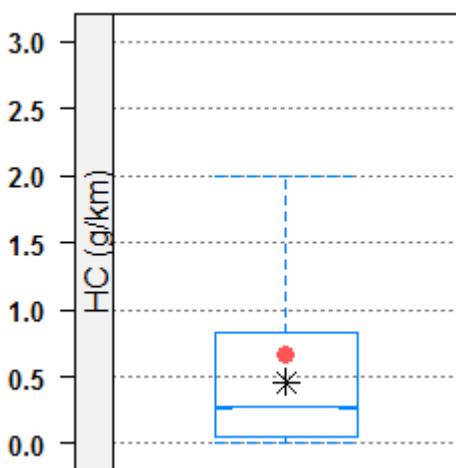


*Figure 5: Comparison of fleet average RSD and VEPM HC emission factor.*

**Table 7: Fleet average RSD and VEPM HC emission factors.**

| Number of vehicles | 25,370 |
|---|---|
| **RSD mean (g/km)** | 0.67 |
| **VEPM (g/km)** | 0.46 |

Table 8 and Figure 6 compare the VEPM and RSD HC emission factors by vehicle type. Table 8 and Figure 6 show that the VEPM HC emission factors are lower than the respective RSD emission factor for petrol cars, diesel cars and diesel LCV. The difference between VEPM and RSD CO emission factors ranges from 78 % for diesel LCVs to 31 % for petrol cars which dominate vehicle fleet numbers. In contrast, the VEPM HC emission factor for petrol LCVs was slightly higher than the RSD emission factor (approximately 11 %).

**Table 8: RSD and VEPM HC emission factors by vehicle type.**

|  | Petrol car | Petrol LCV | Diesel car | Diesel LCV |
|---|---|---|---|---|
| Number of vehicles | 20,350 | 1,288 | 1,776 | 1,956 |
| RSD mean (g/km) | 0.69 | 1.23 | 0.35 | 0.37 |
| VEPM (g/km) | 0.48 | 1.37 | 0.10 | 0.08 |
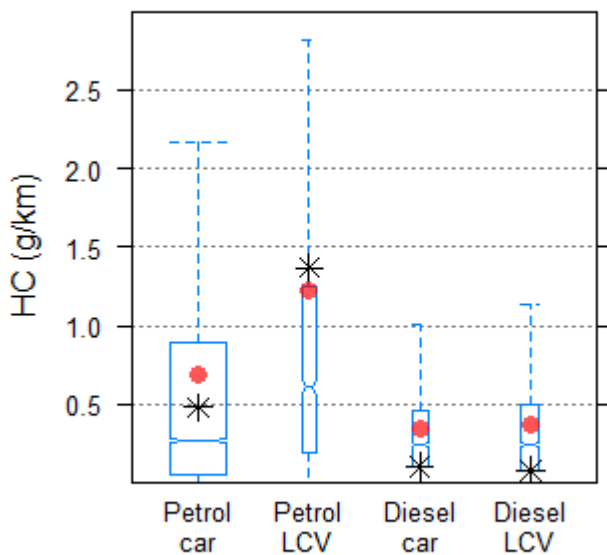


*Figure 6: Comparison of RSD and VEPM HC emission factor by vehicle type.*

## 10.4 Oxides of Nitrogen

Table 9 and Figure 5 compare the fleet average VEPM and RSD NOx emission factors. Table 9 and Figure 5 show that on a fleet average basis, the VEPM NOx emission factors compare well with the RSD NOx emission factor, being only 8 % higher than the mean RSD value.

**Table 9: Fleet average RSD and VEPM NOx emission factors.**

| Number of vehicles | 25,370 |
|---|---|
| RSD mean (g/km) | 0.71 |
| VEPM (g/km) | 0.77 |
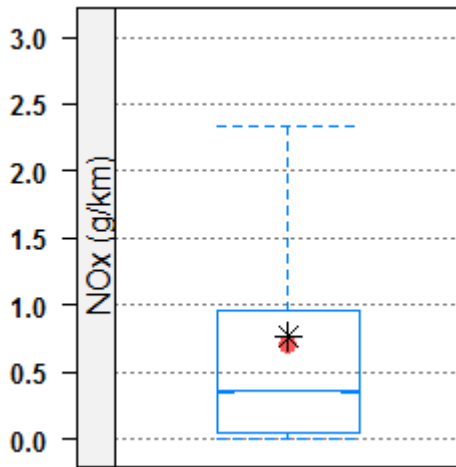
*Figure 7: Comparison of fleet average RSD and VEPM NOx emission factors.*

Table 10 and Figure 8 compare the VEPM and RSD NOx emission factors by vehicle type and show that the VEPM NOx emission factors for petrol cars compares very well with the equivalent RSD emission factor (1 % difference). However, the VEPM NOx emission factor for petrol LCVs is lower than the RSD emission factor (30 % difference). The VEPM NOx emission factor for diesel cars and diesel LCV is significantly higher than the equivalent RSD emission factors, with the difference ranging from 101 % for diesel LCVs to 63 % for diesel cars.

**Table 10: RSD and VEPM NOx emission factors by vehicle type.**

|  | Petrol car | Petrol LCV | Diesel car | Diesel LCV |
|---|---|---|---|---|
| **Number of vehicles** | 20,350 | 1,288 | 1,776 | 1,956 |
| **RSD mean (g/km)** | 0.68 | 1.37 | 0.52 | 0.67 |
| **VEPM (g/km)** | 0.69 | 0.96 | 0.85 | 1.35 |
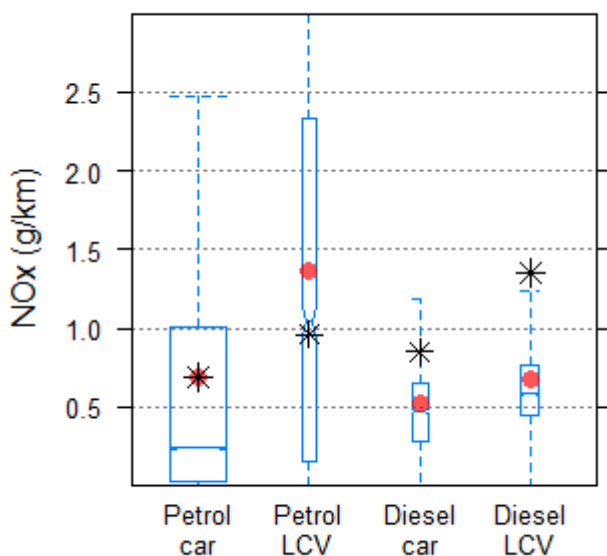


*Figure 8: Comparison of RSD and VEPM NOx emission factors by vehicle type.*

## 10.5    Particulate Matter (PM)

Table 11 and Figure 9 compare the fleet average VEPM and RSD PM exhaust emission factors.  VEPM PM tailpipe emissions are reported as $PM_{2.5}$. RSD emission factors are reported as peak mass density of diesel exhaust particulates, which will approximate well to $PM_{2.5}$. For simplicity the comparison made here between VEPM and RSD emission factors is referred to as PM.  Table 11 and Figure 9 show that on a fleet average basis, the VEPM PM exhaust emission factor is approximately 33 % lower than the mean RSD PM emission factor.

**Table 11: Fleet average RSD and VEPM PM exhaust emission factors.**

| Number of vehicles | 25,370 |
|---|---|
| RSD mean (g/km) | 0.06 |
| VEPM (g/km) | 0.04 |
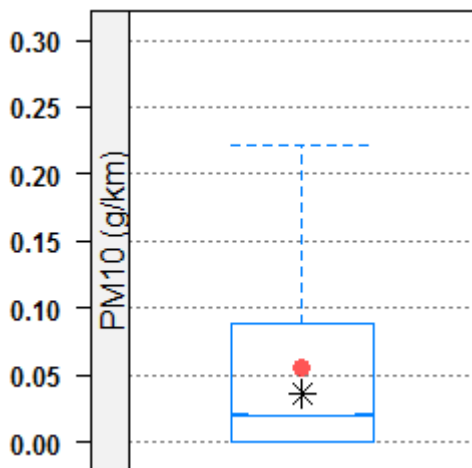


*Figure 9: Comparison of fleet average RSD and VEPM PM exhaust emission factor.*

Table 12 and Figure 10 compare the VEPM and RSD PM exhaust emission factors by vehicle type, which show the VEPM PM exhaust emission factors for petrol cars and petrol LCVs are much lower (88 % and 95 % respectively) than the equivalent RSD emission factor.  In contrast, the VEPM PM exhaust emission factors for diesel cars and diesel LCVs are significantly higher (90 % and 50 % respectively) than the equivalent RSD emission factors.

**Table 12: RSD and VEPM PM exhaust emission factors by vehicle type.**

|  | Petrol car | Petrol LCV | Diesel car | Diesel LCV |
|---|---|---|---|---|
| **Number of vehicles** | 20,350 | 1,288 | 1,776 | 1,956 |
| **RSD mean (g/km)** | 0.041 | 0.084 | 0.138 | 0.115 |
| **VEPM (g/km)** | 0.005 | 0.004 | 0.264 | 0.174 |

*Figure 10: Comparison of RSD and VEPM PM exhaust emission factor by vehicle type.*

# 11.0   SUMMARY OF FINDINGS

A summary of the key outcomes and findings from this project are as follows:

■ Significant site-to-site differences in RSD emission factors were observed between some, but not all, monitoring sites.
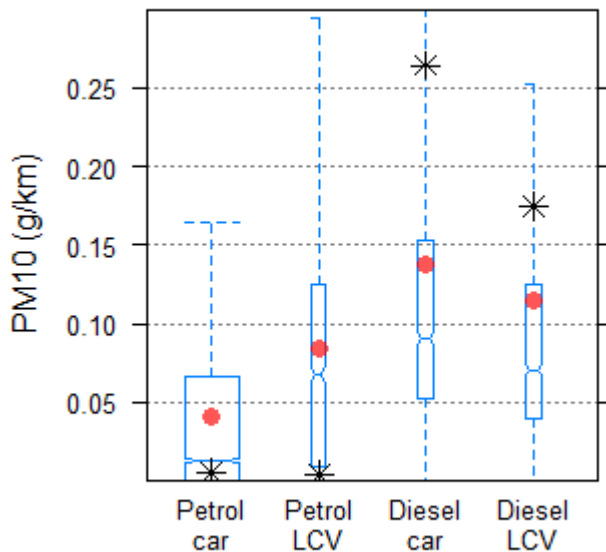
■ No day-to-day variability was observed in the CO RSD emission factors at the three sites considered. However, significant day-to-day variability was observed for the HC RSD emission factor (1 site) and NOx RSD emission factor for two of the three monitoring sites.  Significant day-to-day variability was observed for PM RSD emission factors at all three sites considered.

■ The light-duty vehicle fleet profiles used for the Auckland 2006 inventory and the on-road RSD monitored fleet were similar.  However, the on-road monitored fleet had approximately 5 % more petrol and 5 % less diesel vehicles than the fleet profile used for the Auckland 2006 inventory.

■ Differences between the fleet average VEPM and RSD emission factors were observed.  The magnitude of the differences varied with pollutant, +66 % for CO, -31 % for HC, +8 % for NOx and -33 % for PM.

■ Differences were observed between VEPM and RSD emission factors for the four vehicle types considered.  A summary of the VEPM to RSD emission factors ratios for each of the four vehicle types is provided in Table 13.  VEPM to RSD emission factor ratios indicating good agreement (0.67 to 1.5, i.e., less than 50 % difference) are shaded green. VEPM to RSD emission factor ratios indicating moderately good agreement (0.5 to 0.67 and 1.5 to 2.0 i.e., between than 50 % and 100 % difference) are shaded orange. VEPM to RSD emission factor ratios indicating poor agreement (<0.5 and < 2.0 i.e., greater than 100 % difference) are shaded red.

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**Table 13: Ratio of VEPM to RSD light duty emission factors.**

|  | Petrol Cars | Petrol LCV | Diesel Cars | Diesel LCV |
|---|---|---|---|---|
| CO | 1.7 | 1.6 | 1.5 | 2.4 |
| HC | 0.7 | 1.1 | 0.3 | 0.2 |
| NOx | 1.0 | 1.4 | 0.6 | 0.5 |
| PM | 8.2 | 21.0 | 0.5 | 0.7 |

Table 13 shows that:

- VEPM CO emission factors are higher (ratios greater than 1.0) than the respective RSD CO emission factors for all four vehicle types.

- VEPM HC emission factors are lower (ratios less than 1.0) than the respective RSD HC emission factor for petrol cars, diesel cars and diesel LCV. The VEPM and RSD HC emission factor for petrol LCVs compared well.

- VEPM and RSD NOx emission factors for all four vehicle types compared well.

- VEPM PM emission factors are significantly higher than the respective RSD PM emission factor for petrol cars and petrol LCVs. VEPM and RSD PM emission factors for diesel cars and diesel LCV compared relatively well.

# 12.0  CONCLUSIONS

The objective of this project was to compare the RSD and VEPM emission factors for light duty vehicles. The results from this project suggest that VEPM is providing useful and realistic estimates of light duty vehicles:

- Well for six emission factors (NOx all four vehicle types, HC petrol LCV and PM diesel cars).

- Moderately well for seven emission factors( CO for petrol cars, petrol LCVs and diesel cars, HC for petrol cars, diesel cars and diesel LCVs and PM for diesel LCVs)

- Poorly for three emission factors (CO for Diesel LCVs, PM for petrol cars and petrol LCVs)

These findings must be considered in light of the limitations and uncertainties of the method used to generate g/km emission factors from RSD. In particular:

- VEPM emission factors are derived from complete drive cycles, while RSD emission factors represent instantaneous emissions only a limited range of driving conditions.

- The simplified assumptions made around the ratios of NO to $NO_2$ needed to convert RSD NO emission factors to NOx emission factors.

- The method used by the RSD to measure PM emissions should be considered only as a first order estimate as open path measurement of particulate matter has a number of limitations.

In conclusion, despite the limitations of the method and data used, the findings of this study should provide increased stakeholder confidence in the emission factors produced by VEPM for most combinations of vehicle type and pollutant. However, stakeholder confidence in VEPM, but may be reduced in the three categories of vehicle and fuel type that do not compare well.

## 13.0   RECOMMENDATIONS FOR FURTHER WORK

Considering the findings and conclusions of this work in the context of the project's objective of comparing the RSD and VEPM emission factors for light duty vehicles and increasing stakeholder confidence in the emission data produced by VEPM, a number of recommendations for future work are made:

- Put the findings of this study in context with VKT travelled by each vehicle class, i.e., a large difference in VEPM and RSD emission factors may not be so critical if that class of vehicles do not have a high VKT.

- Undertake a more detailed comparison of VEPM and RSD emission factors which considers the variation of emission factors with speed.  Given the high number of RSD required to make this comparison informative, it may prove only to be practical for petrol cars.

- Review and consider the implications of the findings on the HC emission factors from diesel vehicles and on PM emission factors from petrol vehicles which show large particularly large differences between VEPM and RSD estimates.

- Evaluate the validity of the comparison between VEPM and RSD PM exhaust emission factors given the limitations of open-path monitoring of particulate matter.

- Gain a more quantitative understanding of uncertainties associated with generating the RSD Emission factors.

- Explore why RSD NOx and PM emission factors for petrol vehicles are consistently higher than the VEPM equivalent emission factors, while the RSD NOx and PM emission factors for diesel vehicles are consistently lower than the VEPM equivalent emission factors.

- Assess if the comparison of VEPM and RSD emission factors can usefully be extended to heavy duty diesel vehicles.

- Gauge if the comparison of VEPM and RSD emission factors can usefully be extended to additional years and whether future RSD monitoring programmes (post 2011) would add value to this.

- Investigate the causes of and potential implications of day-to-day variation in RSD emissions factors.

- Examine the causes of and potential implications of site-to-site variation in RSD emissions factors.

- Plan any future RSD monitoring programmes with the aim of, as far as practical, filling in the knowledge gaps identified in this study.

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# APPENDIX A
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# APPENDIX B
## RSD measurements to Emission factors

## RSD MEASUREMENTS TO EMISSION FACTORS

The RSD instrument measured three exhaust gas ratios; CO/CO2, HC/CO2, and NO/CO2.  These measured ratios are utilised to produce estimates of grams of pollutant per kg of fuel burned, following the form used by Pokharel et al. (2002).

$$\frac{\text{g CO}}{\text{kg fuel}} = \frac{28 \times Q \times 860}{(1 + Q + (2 \times 3Q')) \times 12}$$

$$\frac{\text{g HC}}{\text{kg fuel}} = \frac{2 \times 44 \times Q' \times 860}{(1 + Q + (2 \times 3Q')) \times 12}$$

$$\frac{\text{g NO}}{\text{kg fuel}} = \frac{30 \times Q'' \times 860}{(1 + Q + (2 \times 3Q')) \times 12}$$

Where $Q = (CO\%)/(CO_2\%)$, $Q' = (HC\%)/(CO_2\%)$, $Q'' = (NO\%)/(CO_2\%)$.

This assumes a fuel carbon fraction of 86 %, 12 g/mol for carbon, 28 g/mol for carbon monoxide, 44 g/mol for HC, 30 g/mol for nitric oxide, and 3 carbon atoms per molecule of fuel (propane).  A factor of 2 is applied to $Q'$ because the non-dispersive infrared HC measurement calibrated with propane determines only around 50 % of the HC mass compared to the flame ionization detector (FID) techniques used in the NEDC type approval test 14.  The RSD instrumentation also reports a "UV Smoke index", recorded in units of grams of diesel particulate matter per 100 g of fuel, based on opacity measurements made at ultraviolet wavelengths in the 230 nm UV spectral range.  A worked example of converting RSD data to g/km emission factors for petrol cars is shown in Table 14.

**Table 14: Worked example RSD data to g/km emission factors – petrol cars.**

| pollutant | %Pollutant /% $CO_2$ [*] | Pollutant (g) | fuel (kg) | g pollutant /kg of fuel | g pollutant/ litre of fuel | fuel consumption (L/km)** | g pollutant /km |
|---|---|---|---|---|---|---|---|
| CO | Q=0.0152 | 365.0 | | 29.8 | 22.4 | | 2.18 |
| HC | Q'=0.0007 | 52.9 | 12.2 | 4.3 | 3.2 | 0.097 | 0.32 |
| NOx | Q''=0.0012 | 31.2 | | 2.6 | 1.9 | | 0.21*** |
| PM | NA | 0.09 | 0.1 | 0.9 | 0.7 | | 0.07 |

* from the RSD data base

** from AC 2006 VEPM model run

*** includes NO to NOx adjustment of 1.11

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