Auckland
Regional Council
TE RAUHĪTANGA TAIAO

Auckland Vehicle Emission Measurements

Light and Heavy Duty Diesel Vehicles

October TR 2010/063

Auckland Regional Council
Technical Report No.063 October 2010
ISSN 1179-0504 (Print)
ISSN 1179-0512 (Online)
ISBN 978-1-927135-19-8

Reviewed by:

Name: Janet Petersen

Position: Manager Air Quality Policy

Organisation: Auckland Regional Council

Date: 27 October 2010

Approved for ARC Publication by:

Name: Alastair Small

Position: Group Manager Environmental Policy and Planning

Organisation: Auckland Regional Council

Date: 27 October 2010

Recommended Citation:

Bluett, J.; Kuschel, G.; Unwin, M. (2010). Remote Sensing of Vehicle Emissions: Light and Heavy Duty Diesel Vehicles. Prepared by NIWA and Emission Impossible Ltd for Auckland Regional Council. Auckland Regional Council Document Technical Report 2010/063

Auckland Vehicle Emission Measurements: Light and Heavy Duty Diesel Vehicles

Jeff Bluett

Gerda Kuschel (Emission Impossible Ltd)

and

Martin Unwin

Prepared for

Auckland Regional Council

By

National Institute of Water and Atmospheric Research Ltd

NIWA Client Report: CHC2010-131
October 2010

NIWA Project: ARC05107

National Institute of Water & Atmospheric Research Ltd
10 Kyle Street, Riccarton, Christchurch
PO Box 8602 Christchurch New Zealand
Phone +64-3-348-8987, Fax +64-3-348-5548
www.niwa.co.nz

Acknowledgements

This work was funded by the Auckland Regional Council (ARC).

A number of people contributed to the success of this programme including:

Lou Reddish, NIWA

Katie Dey, NIWA

And many others from a number of organizations, whose valuable input, assistance and permission was required, including:

Auckland City Council

Birkenhead Transport Ltd

Franklin District Council

Howick and Eastern Buses Ltd

Land Transport New Zealand (now the NZ Transport Agency)

Manukau City Council

Ministry of Transport

North Shore City Council

Papakura District Council

Ports of Auckland Ltd

Rodney District Council

Stagecoach Bus Ltd

Waitakere City Council

… and the motorists of Auckland.

Contents

List of Figures

List of Tables

Reviewed by:

Jeff Smith cc Jeff Bluett

Approved for release by:

Charles Pearson

Executive Summary

Remote sensing has been employed in several measurement campaigns by the Auckland Regional Council since 2003 to establish "real world" emissions from the Auckland vehicle fleet. This report focusses on the emissions from diesel vehicles, given their disproportionate contribution to air pollution health effects in the region, and covers a remote sensing programme of measurements undertaken in late 2004 and mid 2005. Motor vehicles are the largest single cause of Auckland's air pollution, contributing between 50 and 80 per cent of the emissions depending on the pollutant. Understanding how these emissions are changing over time is critical as it highlights whether additional strategies and policies might be required to meet reduction targets. Emissions models, laboratory testing and fleet profiles are used to estimate vehicle emissions and ambient monitoring is used to measure the levels of air pollutants in Auckland's air. However, there is the need to check whether emission estimates are realistic by measuring emissions in the 'real world' vehicle fleet. Laboratory testing can only measure a small number of vehicles and does not provide data about the 'gross emitters' or how the vehicle fleet emissions change over time. Remote sensing of vehicle emissions is a cost effective method for achieving all of these objectives.

The main objectives of the diesel remote sensing programme were to:

- characterise the features of Auckland's diesel vehicle fleet;
- identify the factors that most strongly influence diesel vehicle emissions;
- compare emissions from New Zealand new and Japanese used imported Light Duty Diesel (LDD) vehicles and Heavy Duty Diesel (HDD) trucks;
- determine the effect of emission standard on "real world" bus emissions;
- assess the effect of "gross emitting" diesel vehicles; and
- create a database of "real world" emissions from heavy and light duty diesel vehicles to enable measurements to be compared with results from other remote sensing and emissions testing programmes.

The remote sensing measurements were from two campaigns – the first undertaken in November/ December 2004 and the second in May/June 2005. Vehicles were sampled at the Ports of Auckland (trucks), five Auckland bus depots (buses), and 20 roadside sites (heavy and light duty vehicles), yielding valid results for approximately 1,440 HDD and 7,200 LDD vehicles in total.

Emissions were recorded for four pollutants – carbon monoxide (CO), hydrocarbons (HC), nitric oxide (NO) and uvSmoke (as a proxy for particulates) – together with information on each vehicle's characteristics. The combined datasets were then analysed for a range of vehicle parameters, such as vehicle type, year of manufacture, mileage, vehicle weight and country of first registration to establish which of these had the greatest influence on emissions. The analyses were undertaken for the LDD and HDD fleet overall, with the HDD fleet broken down further into trucks and buses (where sufficient data existed for the statistical analyses). Separate assessments of

the influence of emission standards on bus emissions and the effect of diesel gross emitters were also performed.

The most significant findings were:

- Approximately 40 per cent of the LDDs were New Zealand new vehicles (NZN), the remaining 60 per cent were imported used from Japan (JPN). For HDDs, approximately 56 per cent were NZN, the remaining 44 per cent were JPN. However these proportions varied significantly depending on whether the HDDs were trucks or buses, with 39 per cent of the trucks and 89 per cent of the buses being NZN vehicles. For all types of diesel vehicles, the JPN vehicles were between four and seven years older than the NZN vehicles on average;
- LDD vehicles were found to emit significantly less of all four pollutants on average than the HDD vehicles;
- For LDDs and HDDs, older vehicles and those with higher odometer readings tended to emit more CO, HC and uvSmoke but NO emissions were largely unchanged. Average emissions of NO from NZN LDDs and NZN trucks were significantly higher than from their JPN counterparts. However, CO and uvSmoke emissions from JPN trucks were higher than from NZN vehicles;
- HDD emissions of HC and uvSmoke increased with gross vehicle mass (GVM) but this trend was not seen for CO or NO emissions;
- Buses, on average, emitted significantly more NO than trucks but this trend was reversed for uvSmoke. Measured emissions generally reduced with improving bus emission standard but not to the full extent of the relative change in the emissions limits; and
- The highest emitting 10 per cent (gross emitting) diesel vehicles in all categories – LDD, HDD, truck and bus - were found to disproportionately influence the fleet performance. For LDDs, gross emitters contributed 63 per cent, 39 per cent, 25 per cent and 42 per cent of the total CO, HC, NO and uvSmoke emissions respectively. HDD gross emitters were slightly less influential at 43 per cent, 35 per cent, 22 per cent and 33 per cent of the total CO, HC, NO and uvSmoke emissions respectively.

The data collected and key findings from this project have valuable scientific and policy implications for the Auckland Regional Council. These include (but are not limited to):

- Evaluation of the potential benefits of implementing different diesel emission control strategies;
- Assisting with the development of targeted diesel vehicle emission reduction strategies;
- Providing benchmark data to assess changes in fleet characteristics of and emissions from diesel vehicles over time

- Assessing the likelihood that ARC's vehicle emission reduction targets will be met; and
- Refining and/or validating vehicle emission models (e.g. VEPM and BEPM) and improving confidence in the ARC's air emissions inventory.

The results of this diesel emissions programme brings the total number of remote sensing campaigns completed to date in Auckland to three and has already proved invaluable for the identification and assessment of the key trends that influence the emissions performance of the fleet and its principal characteristics.

The main recommendations for future work are to continue with regular roadside remote sensing once every two years (to monitor trends in the light duty fleet in particular) and to consider further bus-depot monitoring because of the additional benefits it offers for heavy duty vehicle characterisation.

1 Introduction

1.1 Background

Motor vehicles are the single largest contributor to air pollution in the Auckland region. It is estimated that between 50 to 80 per cent of the all air contaminants come from motor vehicles (ARC, 2006). Vehicle emissions have serious adverse effects on public health and the environment, especially in surrounding transport corridors, and are precursors to photochemical smog. Degraded air quality results in increased cardiovascular and respiratory illnesses such as asthma, increased hospitalisation and increased mortality.

Diesel vehicles in Auckland are estimated to be responsible for 91 per cent of all vehicle-related air pollution health costs, despite making up only 20 per cent of the fleet based on mileage (ARC, 2006). Just over half of this contribution comes from heavy duty trucks and buses.

Market pricing of petrol and diesel fuel has encouraged a rapid growth in the number of light duty diesel vehicles on Auckland roads since 2000, with around 17 per cent of passenger cars in 2005 being fuelled by diesel (ARC, 2010). In addition, travel by heavy duty diesel vehicles has been increasing at a faster rate than that of light duty vehicles (MoT, 2010).

As a consequence, initiatives designed to target diesel vehicles in particular are likely to yield the best improvement for Auckland's air quality and minimise the associated health burden.

1.2 Aims and objectives of study

Remote sensing has been undertaken in four phases by the Auckland Regional Council since 2003 to establish "real world" emissions from the Auckland vehicle fleet, as follows:

- Phase 1 - Light duty vehicle measurement and education campaign in 2003 (ARC, 2003);
- Phase 2 – Heavy duty bus and truck measurement and four day roadside light duty vehicle measurement campaign in 2004;
- Phase 3 - Light duty vehicle measurement and education campaign in 2005 (ARC, 2010)[1]; and
- Phase 4 - Light duty vehicle measurement campaign in 2009 (pending).

[1] Which provided drivers with immediate feedback of their emissions through the use of a "smart sign".

This report covers the second campaign which was undertaken in two phases – the first in November/December 2004 and the second in May/June 2005. The major difference between this campaign and the others was the focus on capturing emissions from heavy duty diesel vehicles (buses and trucks) which required special siting of the remote sensing equipment and considerable liaison with stakeholders at various Auckland bus depots and at the Ports of Auckland facility.

The main objectives of the diesel investigations were to:

- Characterise the features of Auckland's diesel vehicle fleet;
- Investigate the factors that most strongly influence diesel vehicle emissions;
- Compare emissions from New Zealand new and Japanese used imported LDD vehicles and HDD trucks;
- Evaluate the effect of emission standards on measured bus emissions;
- Assess the effect of "gross emitting" diesel vehicles; and
- Create a database of "real world" emissions from heavy and light duty diesel vehicles which can be compared with results from other remote sensing and emissions testing programmes.

The aim was to obtain emissions information for a representative profile of light duty and heavy duty diesel vehicles in the Auckland region. The measured pollutants included; carbon monoxide (CO); hydrocarbons (HC); carbon dioxide (CO_2); nitric oxide (NO); and UVsmoke (as a qualitative indicator of particulates.

This report is part of a suite of technical reports that have been (or are currently being) prepared by the ARC on vehicle emissions. For additional information, please refer to:

- On-Road Remote Sensing of Vehicle Emissions in the Auckland Region, Technical Publication 198, August 2003;
- Vehicle Emissions Prediction Model version 3.0, February 2009; and
- Remote Sensing of Vehicle Emissions 2005: The Big Clean Up "Tune Your Car" Campaign, Technical Report Report No. 2010/028, July 2010.

1.3 Structure of report

This report is structured as follows:

- Chapter 2 outlines the equipment, sites and analysis techniques used in this diesel fleet investigation.
- Chapter 3 summarises the main features of the light duty and heavy duty diesel fleets in terms of vehicle characteristics and overall emissions results
- Chapter 4 explores the factors that have the most influence on light duty and heavy duty diesel vehicle emissions

- Chapter 5 investigates the effect of emission control standards on bus emissions
- Chapter 6 establishes the emission profile of the diesel fleet and investigates the effect of “gross emitting” diesel vehicles
- Chapter 7 presents the a summary of the key findings
- Chapter 8 presents the conclusions and recommendations generated by this study

2 Method

2.1 Remote sensing equipment

The remote sensing device (RSD) used in this study was a RSD 4000EN model. The RSD system was developed by Donald Stedman and his team at the Fuel Efficiency Automobile Test Data Centre (FEAT), University of Denver, Colorado, USA.

Technical details on the RSD are provided in Stedman *et al.* (1997) (see www.feat.biochem.du.edu/whatsafeat.html). A schematic diagram of the remote sensor monitoring equipment is shown in

Figure 2.1.

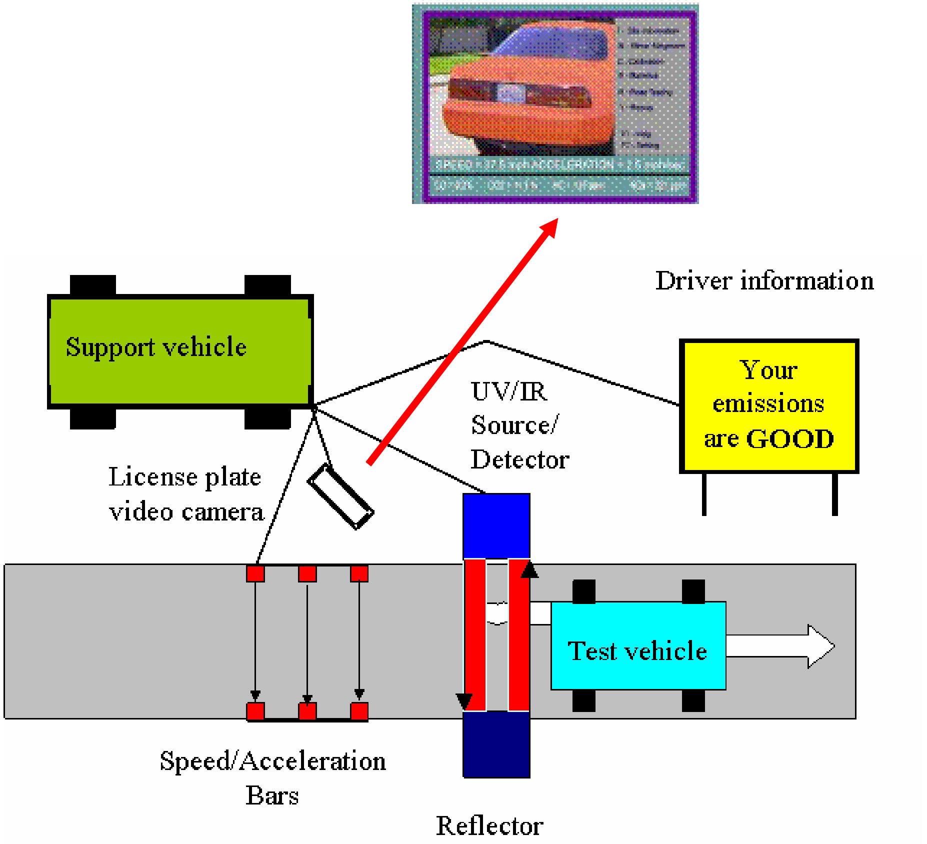


Figure 2.1 Schematic diagram showing the remote sensing system in operation

2.1.1 Measurement of gaseous pollutants

The instrument consists of an infrared (IR) component for detecting carbon monoxied (CO), carbon dioxide (CO_2) and hydrocarbons (HC), together with an ultraviolet (UV) spectrometer for measuring nitric oxide (NO). The source/detector module (

Figure 2.2) is positioned on one side of the road, with a corner cube reflector on the opposite side. Beams of IR and UV light are passed across the roadway into the corner cube reflector and returned to the detection unit. The light beams are then focused onto a beam splitter, which separates the IR and UV components.

Figure 2.2 Source detector module and calibration unit of the RSD 4000EN

Williams *et al.* (2003) describe the analysis of the IR and UV light as follows. The IR light is passed onto a spinning polygon mirror that spreads the light across the four infrared detectors: CO, CO_2, HC and a reference. The UV light is reflected off the surface of the beam splitter and is focused into the end of a quartz fibre-optic cable, which transmits the light to an UV spectrometer. The UV unit is then capable of quantifying NO by measuring an absorbance band in the UV spectrum and comparing it to a calibration spectrum in the same region.

The exhaust plume path length and the density of the observed plume are highly variable from vehicle to vehicle and are dependent upon, 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. The ratios of CO, HC or NO to CO_2 are constant for a given exhaust plume, and on their own are useful parameters for describing a hydrocarbon combustion system. The remote sensor used in this study reports the %CO, ppm HC and ppm NO in the exhaust gas, corrected for water vapour and excess oxygen not used in combustion.

CO, HC and NO data measured by the RSD have been compared to data collected on a dynamometer and gas analyser set up running the IM240 test cycle. Pokharel *et al.* (2000) found that the fleet averaged on-road remote sensing data correlated very well with the fleet average IM240 data. Studies carried out by the California Air Resources Board and General Motors Research Laboratories have shown that 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).

Cautionary note on measuring NO_X emissions. The oxides of nitrogen (NO_X) emissions from motor vehicles principally consist of nitric oxide (NO) and nitrogen dioxide (NO_2). NO is the dominant species and is generally accepted to be a high proportion of the total NO_x that leaves the vehicle's tailpipe. For petrol vehicles the NO:NO_x ratio is 0.9-0.95, for diesel it is 0.75-0.85 (DEFRA, 2003). Once in the atmosphere, NO can be oxidised to NO_2 (the predominant pathway being a reaction with ozone). For adverse human health effects of NO_x, NO_2 is the species of primary concern. The remote sensing equipment used in this project is capable of only measuring NO. The purpose of this report is to present the results of the emission-testing programme and will only refer to NO. The amount of NO_2 discharged by vehicles, and the rate at which NO is converted to NO_2 are not addressed in this report.

2.1.2 Measurement of particulate pollutants

When light illuminates a small particle such as a pollution particle in an exhaust plume, the light is both scattered in all directions and absorbed by the particle. For a particular incident light beam, the nature of the scattering and absorption interaction is determined by the physical characteristics of the individual particles – their size, shape, and material characteristics - as well as by the size and shape distribution of the suspension of particles. If the characteristics of the incident light are known (specifically its direction of propagation, polarisation, wavelength and intensity), then this knowledge, coupled with the nature of the scattered light and a laboratory calibration, can be used to determine some features of particles in an exhaust plume.

A detailed technical description of the way the RSD 4000EN measures particulate pollutants can be found in Stedman and Bishop (2002). Very briefly, smoke is measured in vehicle exhaust plumes based on the absorption and scattering of light beams at ultraviolet (UV) wavelengths (~232 nm). These are the approximate wavelengths for peak mass density of diesel exhaust particulates. With a scattering configuration and an appropriate wavelength(s), and after making some realistic assumptions about particle properties (e.g. particle composition and size distribution), the smoke measurements are translated into particulate measurement units which approximate to grams of particulate per 100 grams of fuel burned. A fuel-based emission factor, with units of grams of particulate per kilogram of fuel burned, can be calculated by considering the stoichiometry of fuel combustion and assumptions of fuel composition.

Cautionary note on measuring particulate emissions. The standard methods of measuring particulate air pollution involve gravimetric analysis of a filter which has had a known volume of ambient air drawn through it. It is accepted that there are many technical difficulties associated with measuring particulate pollution with open path technology, such as that used for remote sensing of vehicle emissions. The manufacturers of the RSD 4000EN acknowledge these issues and as far as practical have addressed these via rigorous and documented development, calibration and quality assurance processes. However, 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 – although it should be a very good approximation.

The main purpose of this report is to assess the relative difference in emissions from vehicles of different ages and types. The RSD uvSmoke data suit this purpose very well. In this report, the RSD particle measurements are reported as a dimensionless uvSmoke index. The RSD 4000EN manufacturers quote the precision of the uvSmoke measurements as ±0.05 or ±10% of the uvSmoke reading, whichever is the greatest.

2.1.3 Calibration and audit

The purpose of the calibration and audit procedure is to ensure that the quality of the data collected meets specified standards. Quality assurance calibrations and audits are performed in the field as required by the standard operating procedures defined by the equipment's manufacturers.

When the source detector module (SDM) has been switched on and is warmed up, the unit is calibrated. Calibration is carried out using a method named cell calibration. A cell which contains a known concentration of calibration gases is placed in the IR beam path and the SDM is then calibrated to the known values of gas within the cell.

The calibration is audited immediately after the calibration process and every hour thereafter that the equipment is operated. The purpose of the audits is to check that the equipment remains correctly calibrated.

Audits are carried out by the computer verified audit (CVA) system which employs a gas puff method. This method involves a puff of gas containing certified amounts of CO, CO_2, propane and NO being released from the gas dispenser box (

Figure 2.3) into the calibration tube, which is mounted on the detector window of the SDM. The measured gas ratios from the instrument are then compared to those certified by the cylinder manufacturer. If the gas ratios measured during any of the audits do not fall with specified limits or if the alignment of the unit has been changed, the RSD must be recalibrated and the audit process begun again.

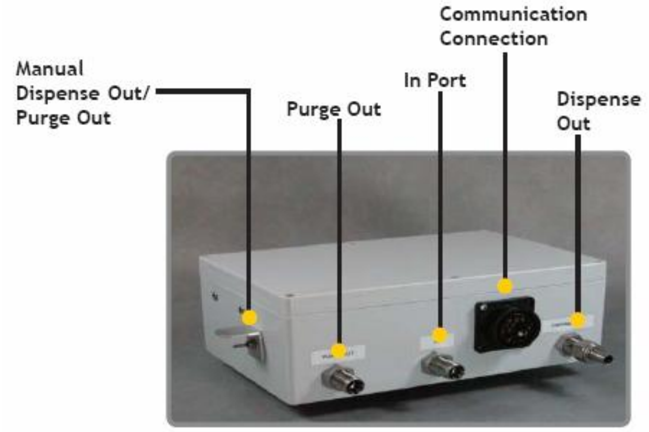


Figure 2.3 Gas dispenser box for the computer verified audit (CVA) process

The audits account for hour-to-hour variation in instrument sensitivity, variations in ambient CO_2 levels and variation of atmospheric pressure and instrument path length. Since propane is used to calibrate the instrument, all hydrocarbon measurements reported by the unit are given as propane equivalents.

2.1.4 Vehicle, speed and acceleration data

The RSD 4000EN system includes a module to record the speed and acceleration of each vehicle when its emissions are measured (

Figure 2.4). This provides valuable information about the driving conditions of the vehicles at the time of the measurements. The speed and acceleration measurements can also be used to derive vehicle specific power (VSP). VSP is a performance measure for determining whether a vehicle is operating within an acceptable power range when it is measured by remote sensing. The emissions dataset from a vehicle is only considered valid if its VSP falls between zero and 40 kW/tonne.

Monitoring sites which generate a relatively low proportion of vehicles providing valid data (a poor vehicle capture rate) can be scrutinised by considering the acceleration data. Sites with poor capture rates often show a large proportion of vehicles undergoing hard accelerations or decelerations during testing. Engine load is a function of vehicle speed and acceleration, the slope of the site, vehicle mass, aerodynamic drag, rolling resistance, and transmission losses. Under moderate to heavy load conditions, vehicle engines will enter enrichment modes that can increase emissions many times. These readings may bias the average results and the vehicles may be incorrectly classified as high emitters. Therefore, it is useful to have a performance measure (e.g. VSP) to screen out measurements of vehicles operating in enrichment mode.

A more detailed description of VSP is provided in Appendix 1 together with an assessment/validation of the VSP results gained in this light/heavy duty diesel monitorng programme.

Figure 2.4 Speed and acceleration detector (see arrows) used in the RSD system

2.1.5 Vehicle information

The RSD 4000EN system includes video equipment to record freeze-frame images of the license plate of each vehicle measured. The camera (

Figure 2.5) takes an electronic image of the licence plate (

Figure 2.6) which is integrated into the RSD's monitoring database. At the completion of the day's monitoring the licence plate information is transcribed into a text file.

Figure 2.5 Licence plate camera used in the RSD system

Figure 2.6 Example of a licence plate image recorded by the RSD system

For the HDD/LDD study, the list of licence plates were submitted to Land Transport New Zealand's vehicle registration database (Motochek) and information obtained for each vehicle. Table 2.1 lists the relevant information that was obtained on the monitored vehicles from Motochek for this project.

Table 2.1 Information obtained on monitored vehicles from Motochek

Motochek Database Field	Description of Data
Make	Company which manufactured the vehicle
Model	
Year of Manufacture	
Body Style	Saloon, Hatchback, Station Wagon, Utility, Light Van, Flat Deck Truck, Heavy Bus/Service Coach etc
Main Colour	
Engine Capacity	cc
Engine Power	kW
Vehicle Type	Passenger Car/Van, Goods Van/Truck/Utility, Motorcycle, Bus, Trailer/Caravan, Tractor etc.
Purpose of Vehicle Use	Private Passenger, Taxi, Commercial Passenger Transport, Licensed Goods, Other (Standard) Goods, Ambulance, Fire Brigade, Diplomatic etc.
Fuel Type	Petrol, Diesel, LPG, CNG, other
Country of Origin	Country where vehicle was manufactured
WOF Expires	Warrant of Fitness expiry date
Registration Status	Active, Cancelled or Lapsed
Country of First Registration	Country where vehicle was first registered
Gross Vehicle Mass	kg
TARE Weight	kg
Odometer Reading	km or miles
Plate Type	Standard, Trade, Personalised, Investment, Diplomatic or Crown
Ownership	Private (male or female), Company, Fleet or Lease
Subject to RUC	Subject to road user charges

2.1.6 Deployment of equipment

In this study the remote sensor was operated on public roadways such as single lane motorway on ramps or arterial roads so that emissions from individual vehicles could be measured. Monitoring was also undertaken at the Ports of Auckland truck depot and five bus depots throughout Auckland. These depot sites were chosen to specifically monitor emissions from heavy duty diesel vehicles. At all sites the equipment was operated by NIWA technicians, and was manned at all times that monitoring was undertaken.

The project required a substantial level of operation of complex equipment on the edge of busy roadways and at the depots. A great deal of effort had to be taken to ensure the safety of the operators, minimise effects on normal traffic flow, and prevent any accidents.

Approvals and advice were sought and obtained from all relevant roading and traffic control authorities. In Auckland, these authorities included the relevant city council (when monitoring was being undertaken on local road networks) and Transit New Zealand (when monitoring was undertaken on the national highway network). An independent traffic management organisation was engaged to develop appropriate traffic management plans for each site. Operating at the truck and bus depots did not require a traffic management plan, but the site specific health and safety procedures were considered and complied with. A post-field programme review found that the operational procedures worked well and no incidents or accidents were reported.

2.1.7 Benefits and limitations of RSD monitoring programmes

Typically, vehicle emission data are obtained by putting selected vehicles on a chassis dynamometer, running them through a simulated drive cycle and collecting the exhaust stream for analysis with a range of gas and particulate analysers. From these measurements, extrapolations are made to the whole fleet, or to particular scenarios. However, studies (e.g. Walsh *et al.*, 1996) show that such methods tend to underestimate real world emissions. This may be due to a number of possible factors such as the simulated drive cycles not being representative of actual drive cycles or not accounting for all vehicles. However, the main reason is that the bulk of real-world emissions generally come from a small proportion of vehicles known as the "gross emitters" and it is difficult to capture the effect of these vehicles adequately in a selected dynamometer testing programme.

The RSD provides a solution to this problem by sampling the actual exhaust emissions of a large number of vehicles in an on-road situation. This has numerous benefits compared to a dynamometer testing programme which tests a selected fleet tested in a simulated drive cycle. The RSD monitoring takes less than one second per vehicle and up to 2,000 vehicles can be sampled each hour. This compares to approximately 30 minutes to complete a single IM240 set up and test. The open path monitoring is also unobtrusive because there is no physical connection to the vehicle and no specific behaviour is required of the driver. The RSD monitoring is therefore very cost effective – typically only $2-$3 per vehicle.

There are, of course, limitations to the vehicle emission data collected by the RSD compared to the data collected using a dynamometer and analyser set up. It is useful to view the results of any RSD study in light of these limitations.

- The RSD measures a vehicle's emissions at a single point in time (generally under slight acceleration) as opposed to integrating the emissions for a series of driving events (involving not only accelerations but also decelerations and steady state behaviour) and therefore 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 roadway and will not necessarily be representative of emissions generated on other roadway types, e.g. at busy intersections;
- The measurement of particulate emissions using open path technology is problematic, as discussed in Section 2.1.2, and is unlikely to be as accurate as that collected using a dynamometer set up. Therefore the particulate data presented in this report should only be compared to dynamometer data with caution; and
- With the RSD, it is not possible to get under the bonnet of the vehicles to inspect the on board diagnostic systems and identify any possible causes of high emissions.

Consequently, the data provided by an RSD programme will not be identical to that obtained from dynamometer drive cycle testing. However, the RSD information does provide a complementary data stream that can be used to check and validate the findings of data collected on a smaller number of dynamometer drive cycle tests.

The RSD technology used to monitor vehicle emissions has taken large strides forward since the initial stages of development in the early 1990s when the pollutants that were monitored were restricted to CO and HC, and neither the vehicle's speed nor acceleration were measured. The benefits of monitoring vehicle emissions at road-side sites using RSD technology is widely accepted internationally. Programmes have been undertaken in Europe, UK, US, Australia and New Zealand. The RSD is employed by a number of environmental authorities in the US to enforce and assess the effectiveness of vehicle inspection and maintenance programmes (e.g. Bishop and Stedman, 2005). The California Air Resource Board (CARB) has evaluated remote sensing for improving California's Smog check programme (CARB, 2008). RSD data has been used to assist in evaluation of Denver's vehicle emissions inventory (Pokharel, Stedman and Bishop. 2002).

Cautionary note on measuring emissions from heavy duty diesel vehicles. Some heavy duty diesel (HDDs) vehicles with a gross vehicle mass (GVM) of greater than 3,500kg have vertical exhausts which discharge pollutants at or above cab height. In the configuration used in this study, the RSD is only capable of measuring emissions discharged at or about road level. Given the focus on heavy duty diesel vehicles, considerable efforts were made to capture a representative number of emission tests by specifically testing at the bus depots and the Ports of Auckland site.

2.2 Monitoring sites

Monitoring was undertaken in two stages – the first in November/December 2004 and the second in May/June 2005. Vehicles were sampled at five Auckland bus depots (buses), the Ports of Auckland (trucks), four roadside sites in 2004 (all vehicle types) and 20 roadside sites in 2005 (all vehicle types), yielding valid results for approximately 1,440 heavy duty diesel (HDD) and 7,200 light duty diesel (LDD) vehicles in total.

2.2.1 Buses

Targetted bus emissions monitoring was carried out in November 2004 at five depots across the Auckland region as shown in Table 2.2: This information was combined with bus emissions data captured at the roadside sites in late 2004 and mid 2005 to yield 283 emissions measurements from 247 individual buses.

Table 2.2 Summary of bus emissions monitoring

Bus Monitoring Phase			Number of Bus measurements
Bus emission measurements at the depot sites (5) 22 November to 26 November 2004			158
Day 1	22 November 2004	North Shore Stagecoach bus depot	53
Day 2	23 November 2004	Central Stagecoach bus depot	21
Day 3	24 November 2004	Mt Roskill Stagecoach bus depot	26
Day 4	25 November 2004	Birkenhead Transport bus depot	28
Day 5	26 November 2004	Howick & Eastern bus depot	30
Buses emission measurements at the Phase 2 roadside sites (4) 18 November to 9 December 2004			21
Buses emission measurements at the Phase 3 roadside sites (20) 18 May to 30 June 2005			104
Total buses measured			283

The target number of busses for the sampling programme at the depots was 500 but fewer bus measurements were achieved because:

- Relatively small numbers of buses were available for testing at the Birkenhead Transport and Howick & Eastern bus depots;
- Wet and windy conditions were experienced in Auckland on the day that monitoring was undertaken at the Howick & Eastern bus depot; and
- Logistics at the Mt Roskill Stagecoach bus depot, e.g. one bus was parked in the lane for some time, preventing other buses from passing through the RSD.

Figure 2.8 shows the remote sensing system in operation at a bus depot sampling site. The buses were driven throught the monitoring site by company drivers. The monitoring equipment was set up with a 100 metre long coned lane leading to the equipment. The drivers were instructed to accelerate slowly in the lane and to ensure that they were travelling at approximately 30 km/hr and still accelerating as they passed through the monitoring site. Buses were typically driven through the monitoring site multiple times to ensure that a valid reading was obtained and to provide an indicator of repeatability.

Figure 2.8 Monitoring emissions from buses at a depot in Auckland

2.2.2 Trucks

Targetted truck emissions monitoring was carried out in December 2004 at the Ports of Auckland trucking terminal as shown in Table 2.3: This information was combined with truck emissions data captured at the roadside sites in late 2004 and mid 2005 to yield 1,159 valid emissions measurements from 988 individual trucks.

.

Table 2.3 Summary of truck emissions monitoring

Truck Monitoring Phase			Number of Truck measurements
Trucks emission measurements at the Ports of Auckland site 1 December to 7 December 2004			196
Day 1	1 December 2004	Heavy duty trucks leaving the port	19
Day 2	2 December 2004	Heavy duty trucks leaving the port	39
Day 3	3 December 2004	Heavy duty trucks leaving the port	29
Day 4	6 December 2004	Heavy duty trucks leaving the port	33
Day 5	7 December 2004	Heavy duty trucks leaving the port	76
Truck emission measurements at the Phase 2 roadside sites (4) 18 November to 9 December 2004			200
Truck emission measurements at the Phase 3 roadside sites (20) 18 May to 30 June 2005			764
Total truck emission measurements			1,159

The number of truck results captured over the five day truck programme was less than the target of 500 trucks, due to three main reasons:

- A greater proportion of the trucks had vertical exhaust discharge systems which could not be monitored by the RSD in the configuration used at the ports of Auckland site;
- Wet and windy conditions on a number of the days reduced the total number of hours monitoring that could be completed; and
- The trucks were loaded and heading out from the depot when thery were monitored. Therefore it was not possible to ask the driver to undertaken repeat runs through the monitoring site to maximise the chances of obtaining a valid reading nor to provide an indicator of repeatability.

By combining results from the roadside campaigns, over 1000 results were obtained, well over the 500 target. Figure 2.9 shows the remote sensing system in operation at the Ports of Auckland sampling site. The trucks were driven throught the monitoring site by the contracted drivers. The monitoring equipment was set up with a 100 metre long coned lane leading to the equipment. The drivers were instructed to accelerate slowly in the lane and to ensure that they were travelling at approximately 30 km/hr and still accelerating as they passed through the monitoring site.

Figure 2.9 Monitoring emissions from trucks at Ports of Auckland

2.2.3 Light duty diesel vehicles

Emissions from light duty diesel vehicles were measured initially in November/December 2004 as part of the overall Phase 1 roadside campaign. This dataset was then supplemented with additional measurements taken as part of another RSD campaign in May/June 2005 (Phase 2) to increase the number of data points available for analysis, as shown in Table 2.4. A total of 6,105 valid measurements were obtained from mid 2005 (phase 3) to yield a total of 7,208 valid emissions measurements from 6484 individual light duty diesel (LDDs) vehicles.

Table 2.4 Summary of the light duty diesel emissions monitoring undertaken

Light Duty Diesel monitoring phase			Number of valid measurements
Total valid measurements made at the Phase 1 roadside sites (4) - 18 November to 9 December 2004			1,208
Day 1	18 November 2004	Lincoln Road on ramp	221
Day 2	19 November 2004	Lambie Drive (south)	312
Day 3	8 December 2004	Lagoon Drive	304
Day 4	9 December 2004	Lagoon Drive	372
Total valid measurements made at the Phase 2 roadside sites (20) - 20 May to 28 June 2005			6,000
Day 5	20 May 2005	Grand Drive (south)	318
Day 6	19 May 2005	Whangaparaoa Road	126
Day 7	23 May 2005	Lagoon Drive	293
Day 8	24 May 2005	St Heliers Bay Road	128
Day 9	25 May 2005	West End Road	341
Day 10	26 May 2005	Whangaparaoa Road	468
Day 11	2 June 2005	Elliot Street	217
Day 12	7 June 2005	Universal Drive	330
Day 13	8 June 2005	Lincoln Road on-ramp	299
Day 14	9 June 2005	Hobsonville Road	455
Day 15	10 June 2005	Hayr Road on ramp	302
Day 16	13 June 2005	Te Atatu North on ramp	230
Day 17	14 June 2005	Parrs Cross Road	513
Day 18	15 June 2005	Lambie Drive (north)	231
Day 19	16 June 2005	Grand Drive (north)	299
Day 20	17 June 2005	Lambie Drive (south)	226
Day 21	20 June 2005	Takanini on ramp	348
Day 22	22 June 2005	Constellation Drive off ramp	427
Day 23	28 June 2005	Upper Harbour Highway	263
Day 24	29 June 2005	Highland Park Drive	59
Day 25	30 June 2005	Greville Road	126
Total LDD emission measurements			7,208

The total number of light duty vehicles(10,350) sampled in Stage 1 in 2004 was slightly short of the original target of 12,500. This was due to wet and windy conditions on a number of the days, which reduced the total number of hours monitoring that could be completed.

However, the dataset was able to be supplemented by the additional vehicles measured in Stage 2 in 2005, yielding a combined set of 7,208 light duty diesel measurements for the subsequent analyses.

Figure 2.10 shows the remote sensing system in operation at the Lagoon Drive roadside sampling site.

Figure 2.10 Monitoring emissions from light duty vehicles at Lagoon Drive

2.3 Statistical tools/techniques for data analysis

Emissions data from vehicles do not conform to a normal distribution. They are highly skewed with many low values and relatively few high values. The skewed nature of the vehicle emission data set collected is further explained in Appendix 2.

For the LDD/HDD campaign, the non-normal distribution of the data sets collected was recognised and accounted for by using appropriate statistical methods and mathematical models which are briefly described below. The Kruskal-Wallis test of significant differences was used because it handles the skewed nature of the data and provides statistically defensible conclusions.

2.3.1 Kruskal-Wallis test for significant differences

Skewed datasets like emissions data (see Appendix 2) can be analysed using the Kruskal-Wallis (K-W) test which is a non-parametric one-way analysis of variance[2]. This test does not assume that the data come from a *normal* distribution but it does assume that all data come from the *same* distribution. The routine converts all values to ranks before analysis, thereby creating a uniform distribution. Therefore the K-W test is an appropriate and useful tool to analyse highly skewed data sets, such as real-life vehicle emissions.

The routine tests the hypothesis that all samples have the same median rank, against the alternative that the median ranks are different. The routine returns a *p*-value for the likelihood that the observed differences could occur purely by chance. The significance level used for all K-W tests in this report was 95 per cent (i.e. $p = 0.05$). A set of example results for the K-W test for significant differences is provided in Appendix 3.

2.3.2 Treatment of negative RSD data

As with all scientific instruments, the RSD is not perfectly precise and there is some uncertainty or error associated with the data that it records, e.g. HC concentrations can be ±6.6 ppm of the value recorded. When measuring pollutant concentrations from lower emitting newer vehicles concentrations are frequently close to or at zero. The pollutant ratio method that the RSD employs to measure emissions means that these low values may be recorded as negative concentrations. While in reality there is no such thing as a negative concentration, provided the RSD's quality assurance criteria are met, the negative concentration values produced are valid data as they reflect the uncertainty in the measurements. The negative values recorded are a useful indicator of the "noise" that is contained within the data that the RSD instrument produces.

In this report, all valid negative data have been included in the data analyses and the subsequent calculations of mean, and median values etc. However, for ease of display and interpretation, the box plots which show the emission measurements only show the positive data.

[2] A non-parametric one-way analysis of variance is a test which does not rely on having to know the distribution of data in advance.

3 Features of the sampled diesel vehicle fleet

This section profiles the features of the sampled diesel vehicle fleet. In total, approximately 9,400 individual diesel vehicles were monitored during the 2004 and 2005 measurement campaigns, yielding a dataset of approximately 10,000 valid measurements due to several vehicles being monitored more than once.

3.1 Vehicle type

Vehicle type is one of the primary factors that determines the quantity of pollutants discharged. For example, light duty diesel (LDD) vehicles typically have small engines because their gross vehicle mass is less than <3,500 kg. Heavy duty diesel (HDD) buses and trucks, because of their requirement to carry significant loads in either passengers or freight, require much larger engines. The HDD fleet is broken down by either trucks or buses according to the vehicle classification in the motor vehicle register. A total of 7,719 diesel vehicles were monitored, including 247 buses, 988 trucks and 6,484 light duty vehicles. Twenty vehicles in other categories (13 of which were motor caravans) were excluded from all subsequent analyses.

3.2 Year of manufacture

Year of manufacture is another key determinant of emissions. For example, the type of emissions control technology that is installed tends to be associated with the year of manufacture of a vehicle. Year of manufacture is also important for profiling the age of the monitored fleet.

Table 3.1 summarises the average year of manufacture and age of each vehicle type at the time of monitoring. Figure 3.1 shows the detailed breakdown of year of manufacture of the sampled vehicles by vehicle type. Because of the low number of vehicles sampled that were manufactured before 1985, vehicles older than this have been grouped with the 1985 vehicles.

Table 3.1 Average year of manufacture and age of the sampled diesel fleet by vehicle type

Vehicle Type	LDD	HDD	Truck	Bus
Average year of manufacture	1996	1995	1995	1995
Average age of vehicle	8.9 years	9.3 years	9.3 years	9.3 years

Table 3.1 and Figure 3.2 show that the average age of sampled light diesel vehicles was 8.9 years. By comparison, the average age of vehicles in Auckland's light duty diesel commercial fleet and light duty diesel passenger fleet in mid 2005 was 9.2 years and 11.0 years respectively (NZTA, 2009). Given that light diesel commercial vehicles travel approximately 1.37 times further on average than light diesel passenger vehicles, this translates to an approximate overall light diesel vehicle age of 10.2 years. The difference between the ages of the sampled (8.9 years) and total (10.2 years) light diesel fleets in Auckland is not surprising.

Newer vehicles tend to be driven a greater number of kilometres each year than do older vehicles (MoT, 2010). Hence they have a greater chance of driving through a monitoring site than older vehicles that do fewer kilometres. Another possible explanation is that monitoring was undertaken in principally urban areas where the average age of vehicles may be lower than the region wide average which includes smaller towns and rural areas, where older vehicles may be more commonly used. Table 3.2 presents the 2005 light diesel vehicle registration statistics for Auckland by TLA confirming a wide variation in average vehicle ages across the region (NZTA, 2009).

Table 3.2 Variation in average age of the light diesel vehicles across Auckland in 2005

TLA	Rodney District	North Shore City	Waitakere City	Auckland City	Manukau City	Papakura District	Franklin District
Average age of light commerial diesel vehicles	11.0 years	8.9 years	10.7 years	8.0 years	8.8 years	10.9 years	11.1 years
Average age of light passenger diesel vehicles	11.2 years	10.5 years	11.7 years	10.5 years	11.2 years	11.1 years	11.3 years

Table 3.3 and Figure 3.1 show that the average age of the sampled HDDs, trucks and buses was approximately 9.3 years.

Figure 3.1 shows that year of manufacture of LDD, HDDs and trucks is distributed bi-modally with peaks occurring in 1995-1996 and 2003-2004. This pattern is due to the two points where vehicles enter the fleet. The first peak (1995-1996) is generated by Japanese imported used vehicles entering the New Zealand fleet at around seven years of age. The second peak (2003-2004) indicates the effect of new vehicles entering the fleet. Note that the monitoring campaign was undertaken in mid 2005 and hence the full influence of vehicles manufactured in that year is not evident in Figure 3.1. The age profile for buses is less clear, although there does seem to be a significant number of old (pre 1985) buses still travelling on the road.

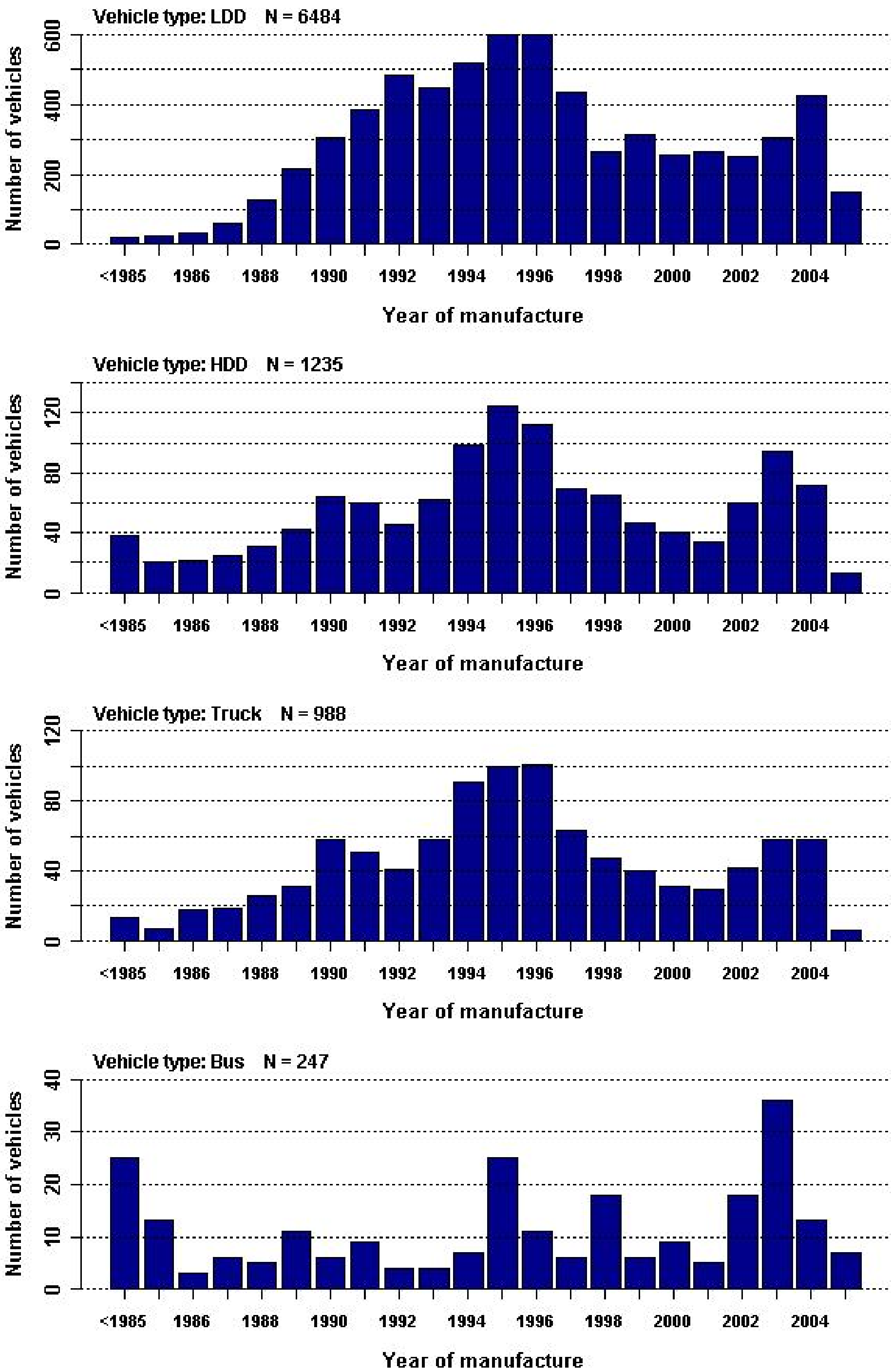


Figure 3.1 Year of manufacture profile of the sampled diesel fleet by vehicle type

3.3 Mileage or odometer reading

Mileage also influences emissions. As vehicles travel a greater number of kilometres, engines and emission control systems begin to wear and pollutant emissions tend to increase. For those vehicles built to emissions standards, many of these standards have durability limits. This means that vehicles are only guaranteed to meet a particular standard until the mileage exceeds a certain number of kilometres, e.g. Euro 4 for LDDs applies up to 100,000 km.

Table 3.3 summarises the average odometer reading by vehicle type at the time of monitoring. Figure 3.3 presents a more detailed breakdown of average odometer reading by vehicle type and year of manufacture.

Table 3.3 Average odometer reading of the sampled diesel fleet by vehicle type

Vehicle type	LDD	HDD	Truck	Bus
Average odometer reading (in '000s of km)	144	217	194	310

Table 3.3 shows that the average odometer reading for HDDs was approximately 50 per cent higher than for LDDs, and that on average buses travelled 45 per cent further than trucks.

Figure 3.3 shows that the average odometer reading increases as the LDDs get older, with the highest average at just over 200,000km for vehicles manufactured in 1988. The rate of odometer reading increase is greater for newer LDDs (manufactured between 1998 and 2005) than for older LDDs (manufactured between 1989 and 1998). This indicates that newer LDDs tend to be driven further each year than older vehicles. The opposite trend (lower odometer readings for older vehicles) is observed for LDDs manufactured before 1987. While this result may appear to be counter-intuitive, it can be explained. Vehicles are designed and built to drive a maximum number of kilometres before the maintenance requirements become prohibitive. Once they travel that number of kilometres, they are worn out and are typically retired from the fleet. A vehicle's useful life can be extended by good maintenance, but not usually indefinitely. Therefore the older vehicles that are still operational tend to be those that have travelled a relatively low number of kilometres and have not yet reached the end of their useful working life.

For HDDs, Figure 3.2 shows that there is a steep rise in odometer reading for the first six years that trucks and first 11 years that buses are operated. Beyond those initial periods, there is no clear pattern in odometer reading.

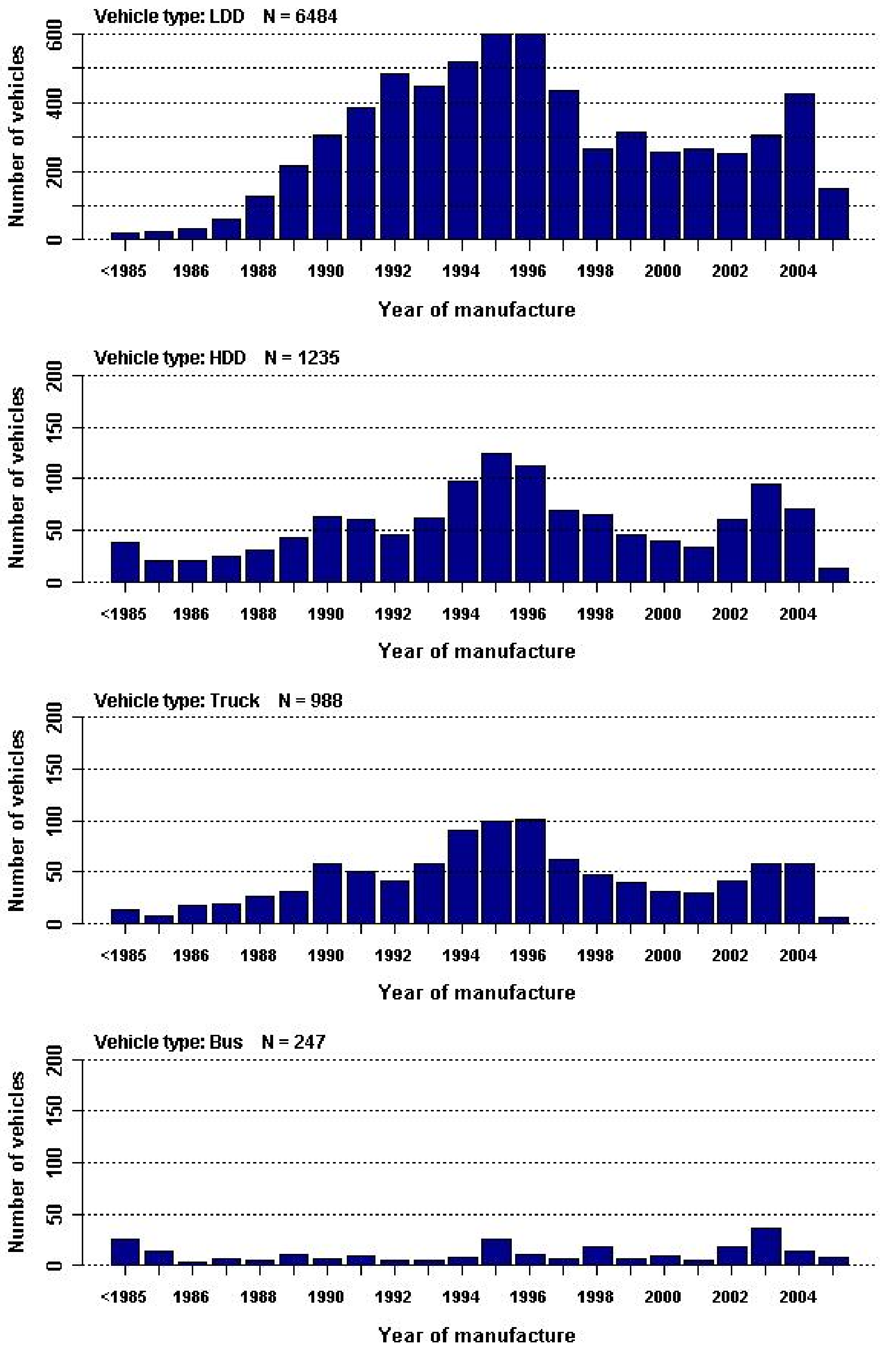


Figure 3.2 Odometer reading of the sampled diesel fleet by vehicle type and year of manufacture

3.4 Vehicle weight

Vehicle weight, usually referred to as gross vehicle mass (GVM), can have a significant effect on vehicle emissions. Heavier vehicles tend to have larger engines and must work harder to move larger loads. Vehicle weight is often linked to vehicle type but even within a vehicle type, e.g. trucks, GVM can vary widely. Figure 3.3 shows the GVM profile of the sampled vehicles by vehicle type.

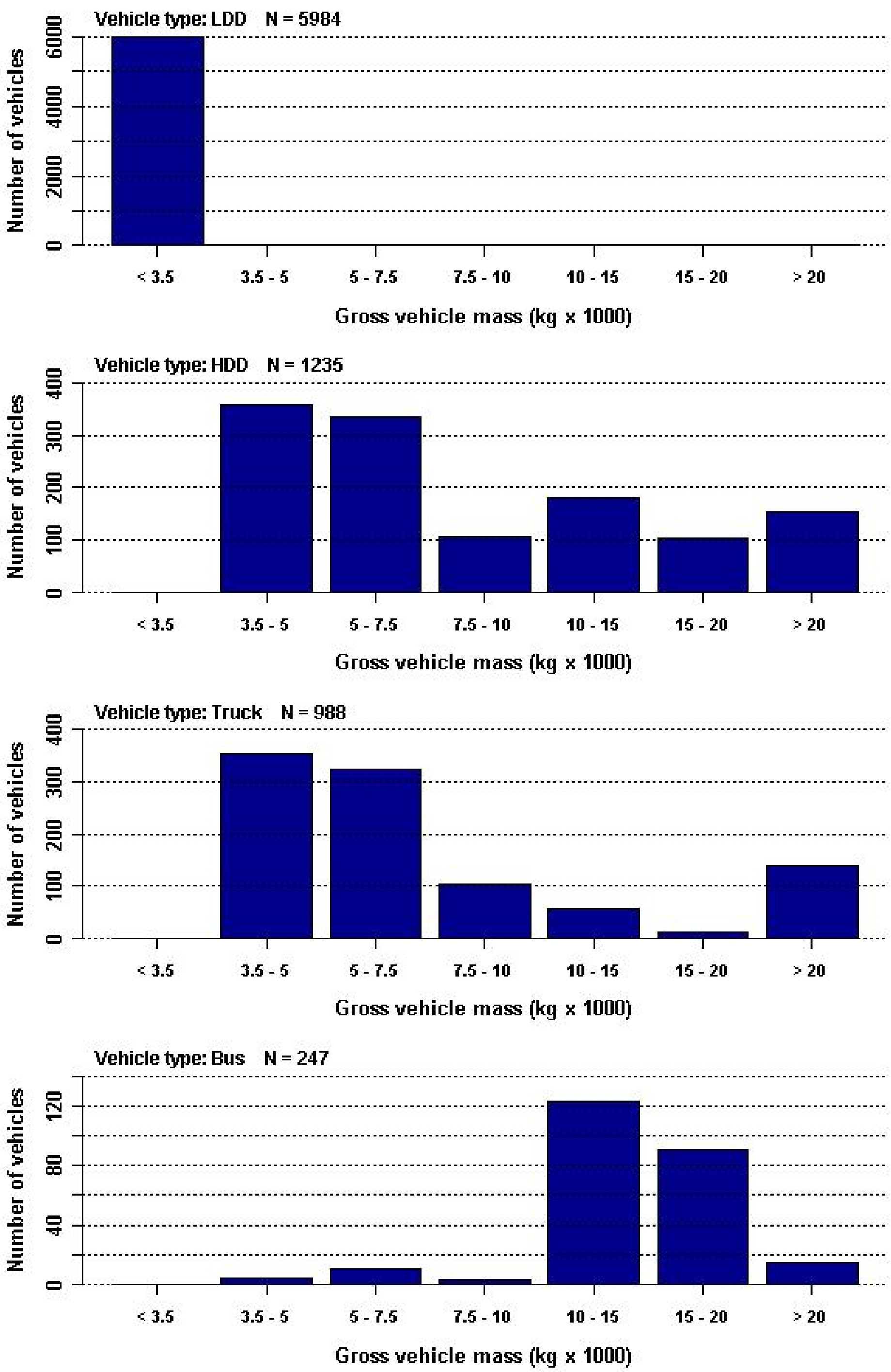


Figure 3.3 Gross vehicle mass profile of the sampled diesel fleet by vehicle type

Figure 3.3 shows that:

- Approximately 66 per cent of HDD trucks have GVM between 3,5 and 7.5 tonnes and nearly 16 per cent are heavier than 20 tonnes; and
- Approximately 80 per cent of HDD buses have GVM between 10 and 15 tonnes.

3.5 Country of first registration

Relative to other countries, New Zealand has an unusual vehicle fleet in that it is split almost evenly between imported new and imported used vehicles. Vehicles are typically manufactured to meet the emission control specifications in the country where they are intended to be registered for the first time and these specifications differ depending on the country. Prior to 2003, New Zealand did not have any regulations for vehicle exhaust emissions and therefore imported new vehicles were not required to have emission control equipment. However imported used vehicles were generally sourced from countries, primarily Japan, with existing vehicle emissions standards. Consequently, country of first registration (which is recorded in the motor vehicle register for every vehicle) is a critical parameter in understanding a vehicle's emissions performance.

Figure 3.4 shows the country of first registration of the sampled fleet broken down by vehicle type.

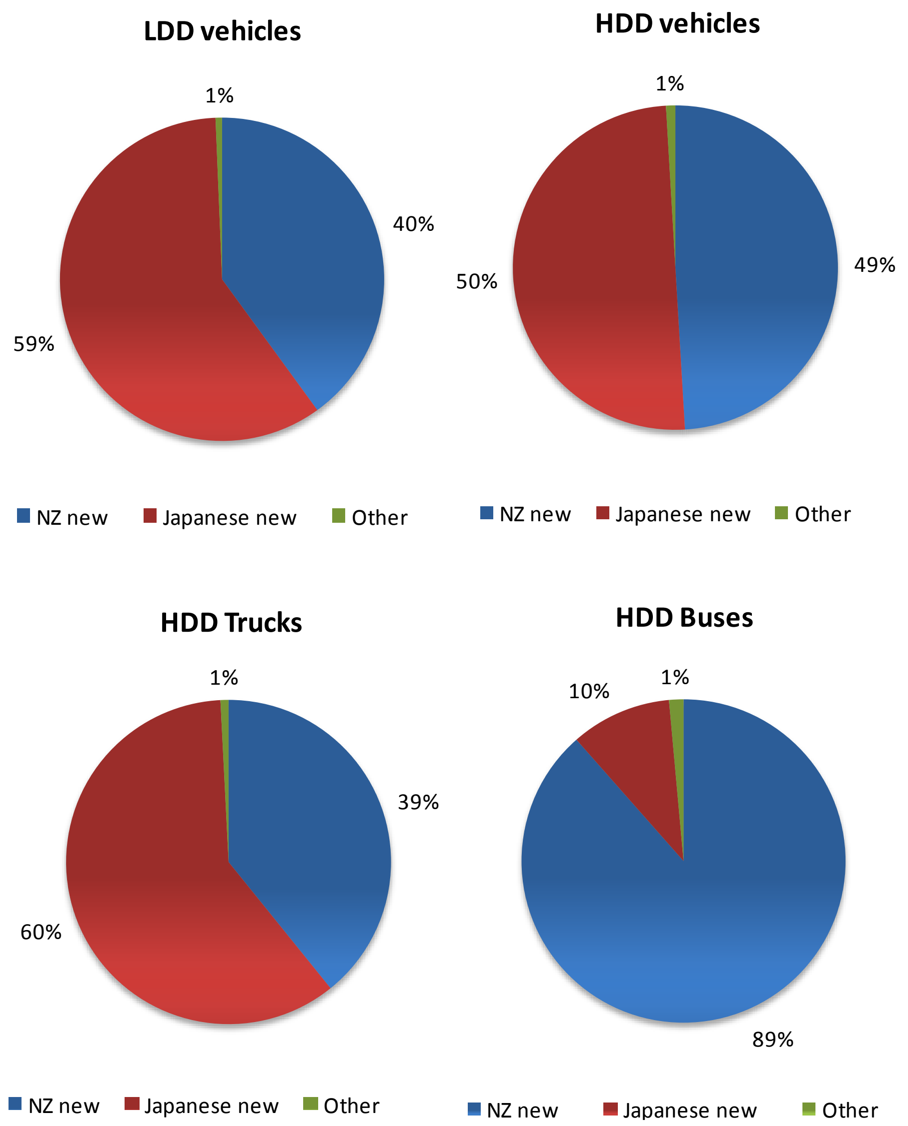


Figure 3.4 Country of first registration of sampled fleet by vehicle type

The vast majority of imported used vehicles come from Japan. The vehicles imported from other countries are mainly imported from Australia and Great Britain. Almost 60 per cent of the LDDs are vehicles imported used from Japan. Approximately 49 per cent of the total HDDs are New Zealand new vehicles and 50 per cent imported used from Japan. However the split for the trucks and buses, which make up the HDD fleet, is signficantly different. Sixty per cent of the trucks are imported used from Japan, while only 10 per cent of the buses are imported used from Japan.

Table 3.4 summarises the average year of manufacture of each vehicle type in the sampled fleet by country of first registration. Figure 3.5 shows the detailed breakdown of country of first registration of the sampled vehicles by year of manufacture, but only for New Zealand new and Japanese used imported vehicles. Profiles for used imported vehicles from other countries have not been included.

Table 3.4 Average year of manufacture of each vehicle type by country of first registration

Vehicle Type	LDD		HDD		Truck		Bus	
Country of first registration	NZN	JPN	NZN	JPN	NZN	JPN	NZN	JPN
Average year of manufacture	2000	1993	1997	1993	1997	1993	1995	1990
Average age of vehicle	4.9 yrs	11.6 yrs	7.0 yrs	11 8 yrs	6.5 yrs	11.7 yrs	8.2 yrs	14.8 yrs

Table 3.4 and Figure 3.5 show that Japanese imported vehicles are on average considerably older than New Zealand new vehicles. The average year of manufacture for Japanese imported LDDs is 1993 compared to 2000 for NZ new LDDs. The average year of manufacture for Japanese imported HDDs is 1993 compared to 1997 for NZ new vehicles. Similar trends exist for the age differences between the imported used and New Zealand new trucks and buses, but buses are older on average than trucks.

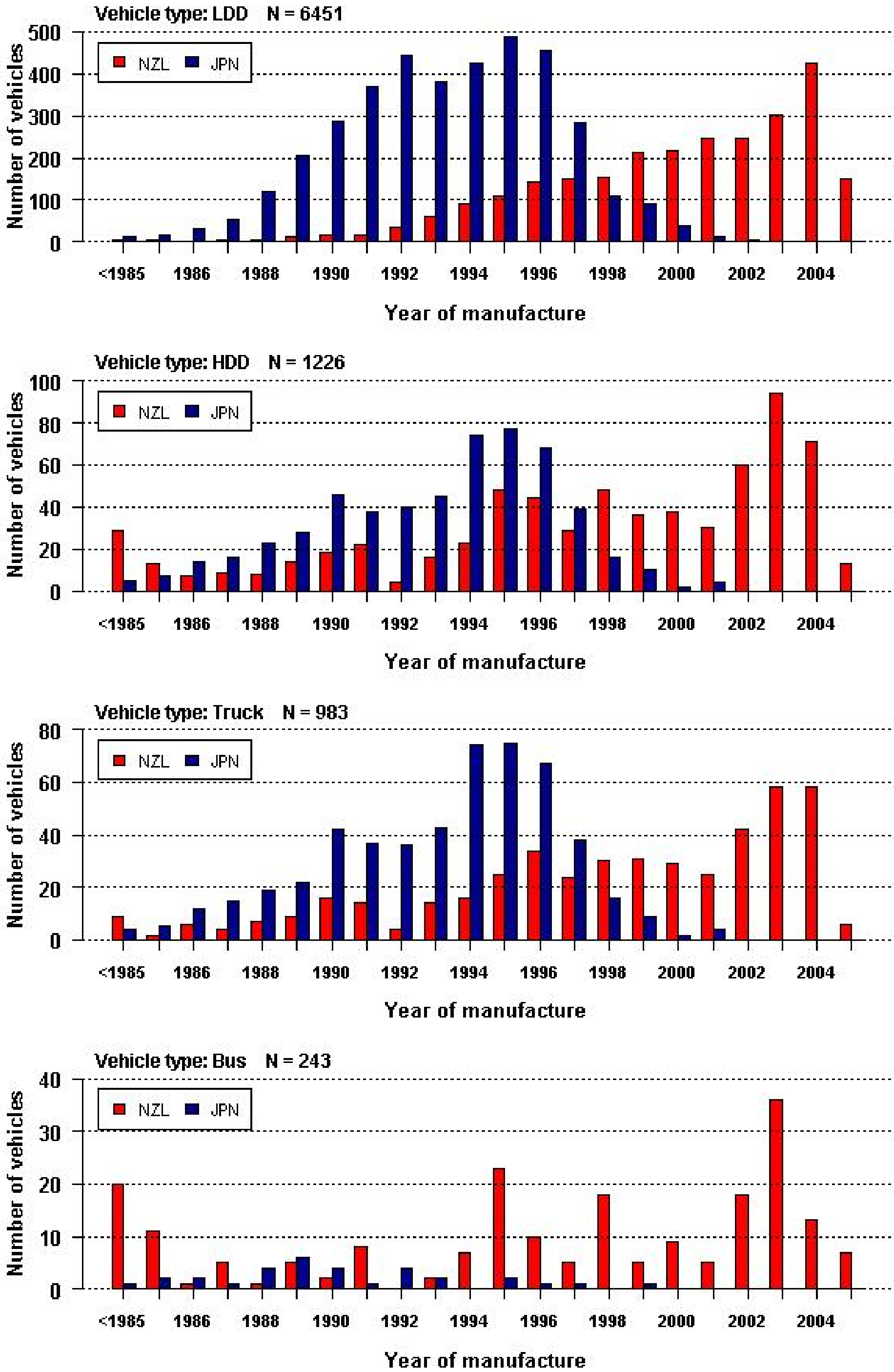


Figure 3.5 Country of first registration by vehicle type and year of manufacture

4 Factors that influence diesel emissions

This section explores the factors that have the most influence on light duty and heavy duty diesel emissions. The individual vehicles that make up the HDD fleet are quite diverse and contain different types of vehicles (buses and trucks), weights, engine size, country of origin and emission control technology, all of which may have an influence on emissions. Therefore the trends observed in HDD emissions with variables should be treated with some caution due to the number of additional variables that could be influencing the observed trends.

4.1 Vehicle type

Table 4.1 and Figure 4.1 compare the emissions of the four measured pollutants by vehicle type for the sampled diesel fleet. In Figure 4.1 (and in all other box plots through-out the report) the median values are indicated by the lines that run horizontally through the box. The inter-quartile (25th to 75th percentile) range is noted by the lower and upper edges of the box respectively. The whiskers extend to the 5th and 95th percentile values. Any values outside this range (outliers) are denoted by empty circles. The mean values are indicated by red dots. Negative data are not displayed on the plots but are included in the calculation of all values.

Table 4.1 Median (and mean) emissions by vehicle type

Vehicle Type	LDD	HDD	Truck	Bus	Highest Average Emitter Type	Lowest Average Emitter Type
CO (%)	0.016 (0.036)	0.049 (0.077)	0.048 (0.070)	0.058 (0.103)	HDD*	LDD
HC (ppm)	63 (97)	228 (318)	222 (286)	265 (447)	HDD*	LDD
NO (ppm)	404 (451)	1047 (1178)	1007 (1108)	1316 (1466)	Bus	LDD
uvSmoke	0.106 (0.165)	0.203 (0.265)	0.208 (0.274)	0.169 (0.231)	Truck	LDD

Table 4.1 and Figure 4.1 together with the results of the K-W tests[3] show that, on average, LDD vehicles emit significantly less of all four pollutants than HDD vehicles. They also demonstrate that, on average, buses emit significantly more NO than trucks and on average trucks emit significantly more uvSmoke than buses. While the median and mean values suggest there is a difference between emissions of HC and uvSmoke emissions from trucks and buses, these differences are not statistically significant.

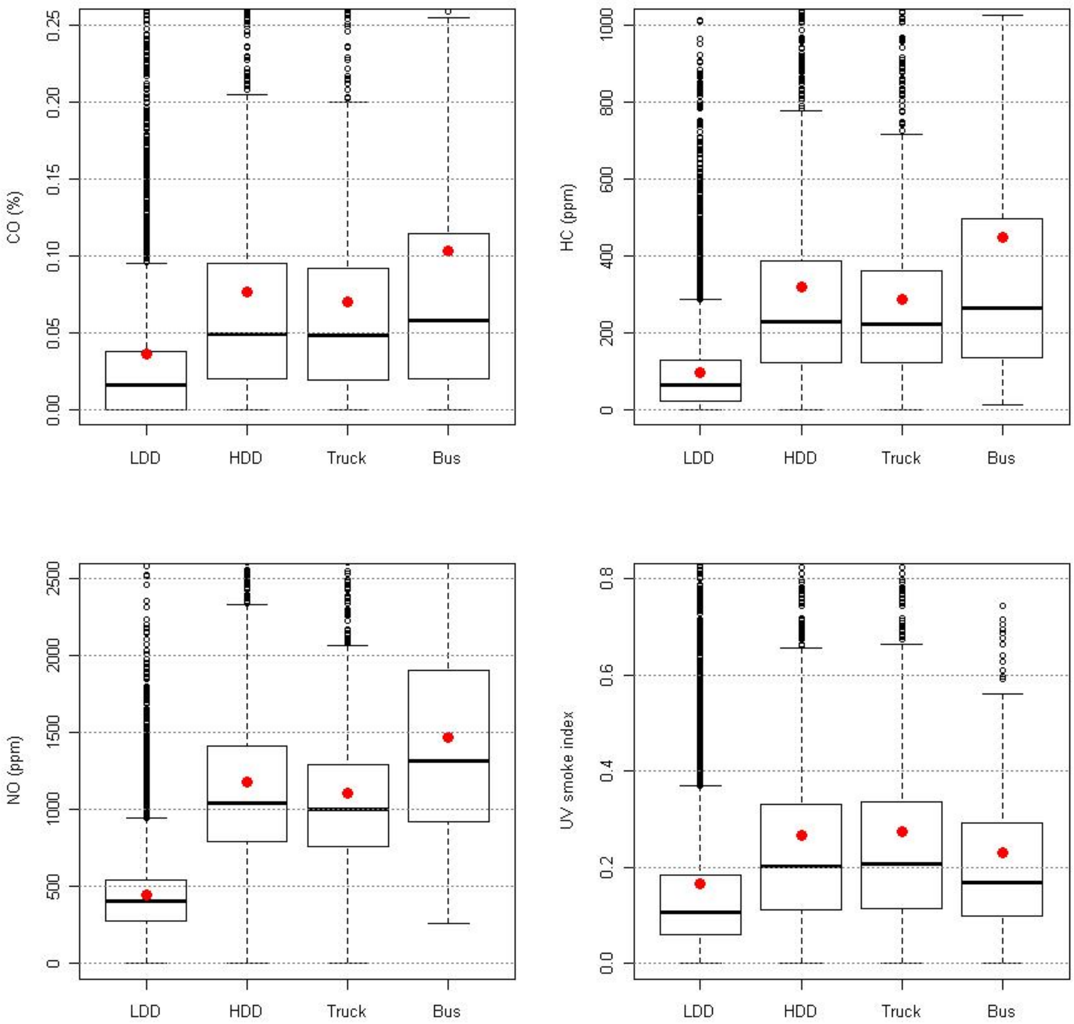


Figure 4.1 Emissions of the four pollutants by vehicle type

*No significant difference between bus and truck emitters

[3] An example of results from the Kruskal-Wallis test for significant differences is provided in Appendix 3

4.2 Year of manufacture

4.2.1 Light duty diesel vehicles

Table 4.2 compares the median and mean emissions of the four measured pollutants for LDD vehicles manufactured in 1985, 1995 and 2005 to highlight the influence of vehicle year of manufacture. More detailed results are presented in Figure 4.2 which shows the emissions from the LDD vehicle fleet by individual year of manufacture.

Table 4.2 Median (and mean) emissions for LDDs manufactured in 1985, 1995 and 2005

Year of Manufacture	1985	1995	2005
CO (%)	0.041 (0.216)	0.017 (0.038)	0.005 (0.022)
HC (ppm)	174 (220)	58 (95)	38 (60)
NO (ppm)	408 (511)	379 (393)	387 (482)
uvSmoke	0.263 (0.444)	0.104 (0.177)	0.063 (0.082)

Table 4-2 and Figure 4.2 together with the results of the K-W tests show that:

- CO emissions decrease slowly but steadily with year of manufacture. CO emissions from LDDs manufactured pre-1998 are significantly higher than those manufactured post 2002;
- HC emissions decrease slowly but steadily with year of manufacture. HC emissions from LDDs manufactured pre-1994 are significantly higher than those manufactured post 2002;
- NO emissions from LDDs do not exhibit an obvious trend with year of manufacture; and
- uvSmoke emissions decrease steadily with year of manufacture. uvSmoke emissions from LDDs manufactured pre-1995 are significantly higher than those manufactured post 2000.

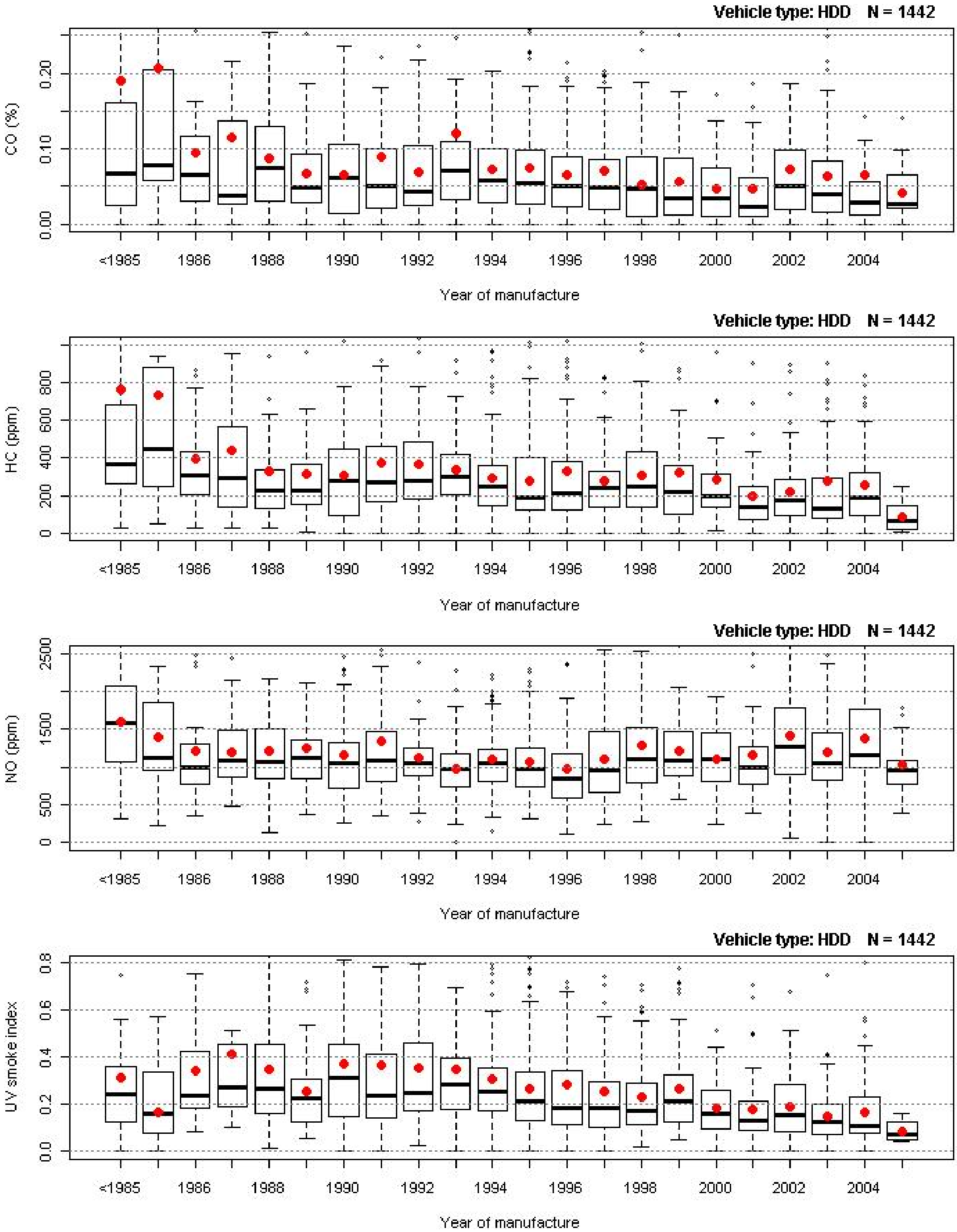


Figure 4.2 LDD fleet emissions by year of manufacture

4.2.2 Heavy duty diesel vehicles

Table 4.3 compares the median and mean emissions of the four measured pollutants for HDD vehicles manufactured in 1985, 1995 and 2005 to highlight the influence of vehicle year of manufacture. More detailed results are presented in Figure 4.3 which shows the emissions from the HDD vehicle fleet by individual year of manufacture.

Table 4.3 Median (and mean) emissions for HDDs manufactured in 1985, 1995 and 2005

Year of Manufacture	1985	1995	2005
CO (%)	0.079 (0.206)	0.054 (0.075)	0.026 (0.041)
HC (ppm)	444 (732)	191 (277)	67 (86)
NO (ppm)	1125 (1401)	974 (1061)	950 (1035)
uvSmoke	0.163 (0.166)	0.213 (0.264)	0.075 (0.086)

Table 4.3 and Figure 4.3 together with the results of the K-W tests show:

- CO emissions decrease gradually with year of manufacture. This gradual downward trend results in a number of years of manufacure post-2000 having significantly lower CO emissions than some years of manufacture pre-1996;
- HC emissions decrease steadily with year of manufacture. HC emissions from HDDs manufactured pre-1994 are significantly higher than those manufactured post 2000;
- NO emissions from HDDs do not exhibit an obvious trend with year of manufacture; and
- uvSmoke emissions decrease steadily with year of manufacture from about 1988 onwards. uvSmoke emissions from HDDs manufactured pre-1999 are significantly higher than those manufactured post 2000.

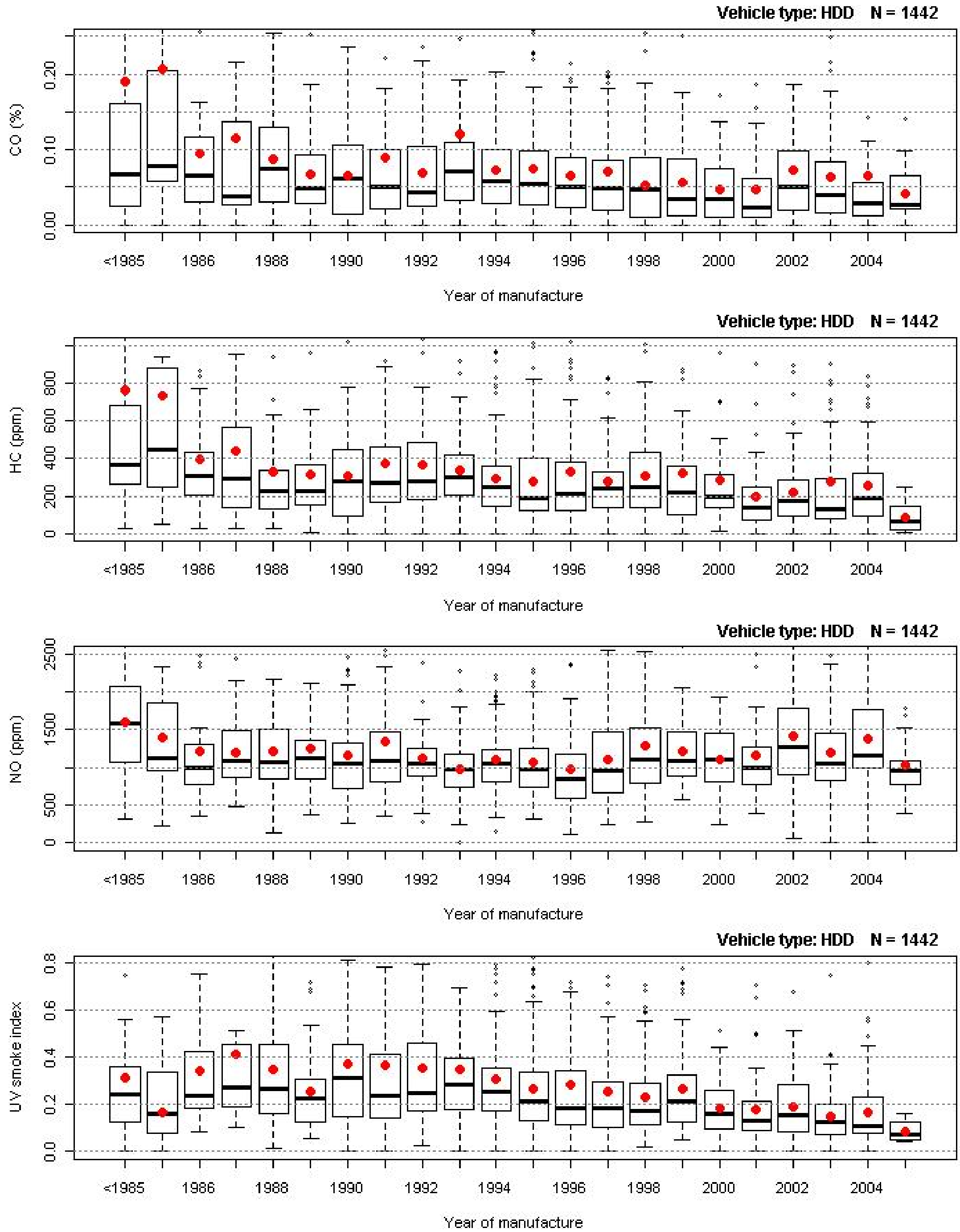


Figure 4.3 HDD fleet emissions by year of manufacture

4.2.3 HDD trucks

Table 4.4 compares the median and mean emissions of the four measured pollutants for HDD trucks manufactured in 1985, 1995 and 2005 to highlight the influence of vehicle year of manufacture. More detailed results are presented in Figure 4.4 which shows the emissions from the HDD truck fleet by individual year of manufacture.

Table 4.4 Median (and mean) emissions for HDD trucks manufactured in 1985, 1995 and 2005

Year of Manufacture	1985	1995	2005
CO (%)	0.059 (0.081)	0.053 (0.073)	0.029 (0.04)
HC (ppm)	285 (261)	194 (269)	119 (124)
NO (ppm)	934 (837)	939 (1020)	948 (834)
uvSmoke	0.156 (0.262)	0.225 (0.269)	0.103 (0.110)

Table 4-4 and Figure 4.4 together with the results of the K-W tests show:

- CO emissions from HDD trucks do not exhibit an obvious trend with year of manufacture;
- HC emissions from HDD trucks do not exhibit an obvious trend with year of manufacture;
- NO emissions from HDD trucks do not exhibit an obvious trend with year of manufacture; and
- uvSmoke emissions decrease steadily with year of manufacture from about 1990 onwards. uvSmoke emissions from HDD trucks manufactured pre-1994 are significantly higher than those manufactured 2000 to 2004.

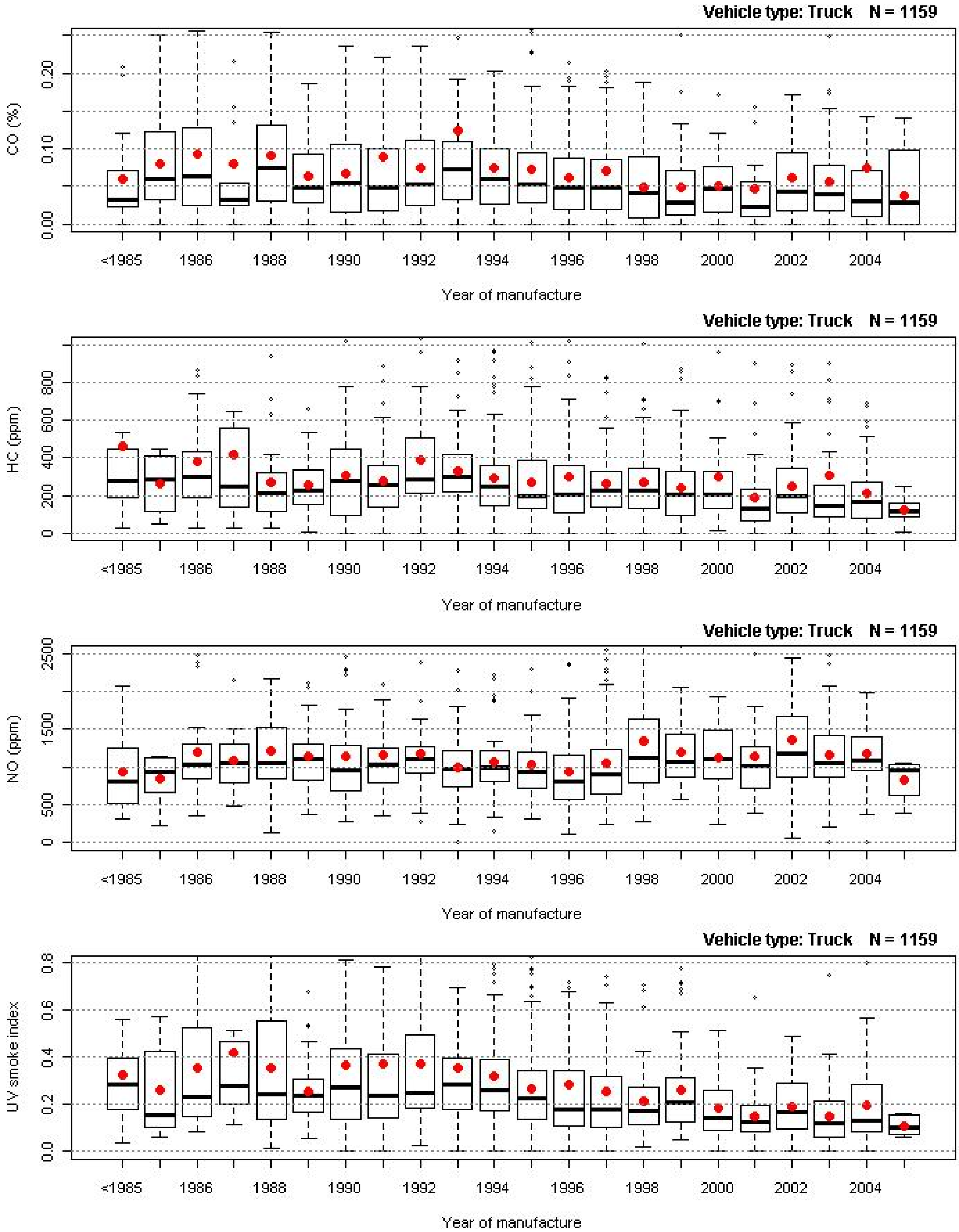


Figure 4.4 HDD truck emissions by year of manufacture

4.2.4 HDD buses

Table 4.5 compares the median and mean emissions of the four measured pollutants for HDD buses manufactured in 1985, 1995 and 2005 to highlight the influence of vehicle year of manufacture. More detailed results are presented in Figure 4.5 which shows the emissions from the HDD bus fleet by individual year of manufacture.

Table 4.5 Median (and mean) emissions for HDD buses manufactured in 1985, 1995 and 2005

Year of Manufacture	1985	1995	2005
CO (%)	0.082 (0.273)	0.057 (0.081)	0.026 (0.043)
HC (ppm)	803 (986)	179 (308)	25 (54)
NO (ppm)	1702 (1704)	1162 (1218)	1078 (1208)
uvSmoke	0.169 (0.114)	0.173 (0.247)	0.049 (0.065)

Table 4-5 and Figure 4.5 together with the results of the K-W tests show:

- CO emissions from HDD buses do not exhibit an obvious trend with year of manufacture;
- HC emissions from HDD buses do not exhibit an obvious trend with year of manufacture;
- NO emissions from HDD buses do not exhibit an obvious trend with year of manufacture; and
- uvSmoke emissions from HDD buses do not exhibit a significant trend with year of manufacture. However, uSmoke emissions from HDD buses manufactured post-2002 are significantly lower than those manufactured pre-2000.

Note that there are a relatively low number of buses (<10) manufactured in 13 of the 21 years considered in this analysis (See Figure 3.2 for detail). Therefore the trends observed in HDD bus emissions with year of manufacture should be treated with some caution as each year may not contain a representative sample of buses.

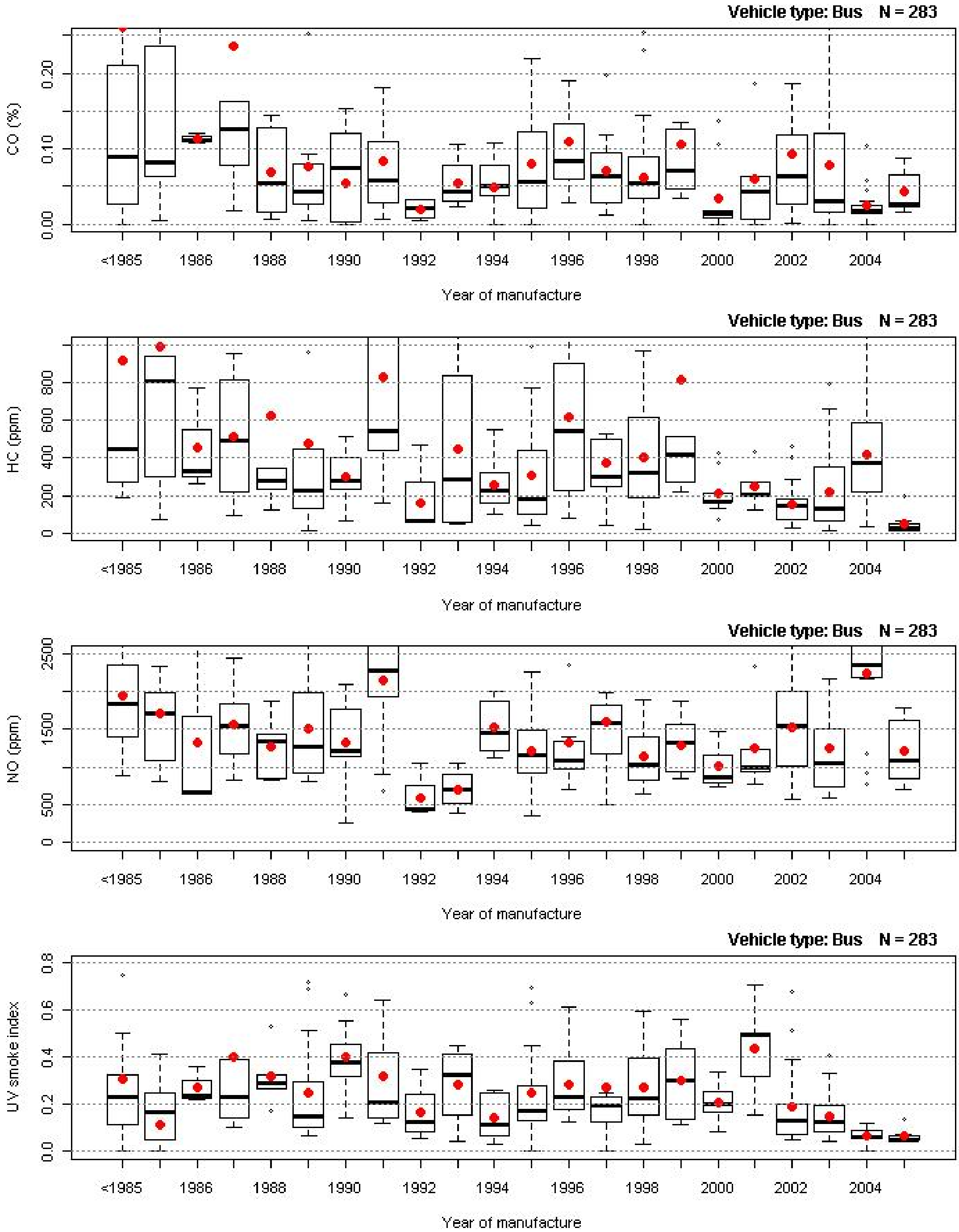


Figure 4.5 HDD bus emissions by year of manufacture

4.3 Mileage or odometer reading

4.3.1 Light duty diesel vehicles

Table 4.6 compares the median and mean emissions of the four measured pollutants for LDD vehicles that have travelled less than 50,000 km with those that have travelled between 150,000 to 200,000 km and more than 300,000 km to highlight the influence of mileage. More detailed results are presented in Figure 4.6 which shows the emissions from the LDD vehicle fleet by individual odometer reading.

Table 4.6 Median (and mean) emissions for LDDs by low, medium and high odometer reading

Odometer Reading (km)	<50,000	150,000 to 200,000	>300,000
CO (%)	0.009 (0.023)	0.018 (0.035)	0.019 (0.055)
HC (ppm)	47 (78)	67 (104)	69 (120)
NO (ppm)	403 (459)	407 (464)	454 (519)
uvSmoke	0.079 (0.109)	0.117 (0.186)	0.116 (0.201)

Table 4-6 and Figure 4.6 together with the results of the K-W tests show:

- CO emissions tend to increase with odometer reading. CO emissions from LDDs with odometer readings <50,000 km are significantly lower than for LDDs that have travelled between 50,000 – 1000,000 km. However, there is no significant difference between the other kilometre bands (as shown in Figure 4.6) This suggests a step change up in CO emissions after the LDDs have travelled >50,000 km;
- HC emissions tend to increase with odometer reading. HC emissions from LDDs with odometer readings <50,000 km are significantly lower than for LDDs that have travelled further. This suggests a step change up in HC emissions after the LDDs have travelled >50,000 km;
- NO emissions from LDDs do not exhibit an obvious trend with odometer reading; and
- uvSmoke emissions increase steadily increase with mileage. uvSmoke emissions from LDDs with odometer readings <100,000 km are significantly lower than for LDDs that have travelled >150,000 km. In addition, the mean emissions seem to be increasing at a faster rate than the median emissions

which suggests a greater proportion of gross uvSmoke emitters at the higher odometer readings.

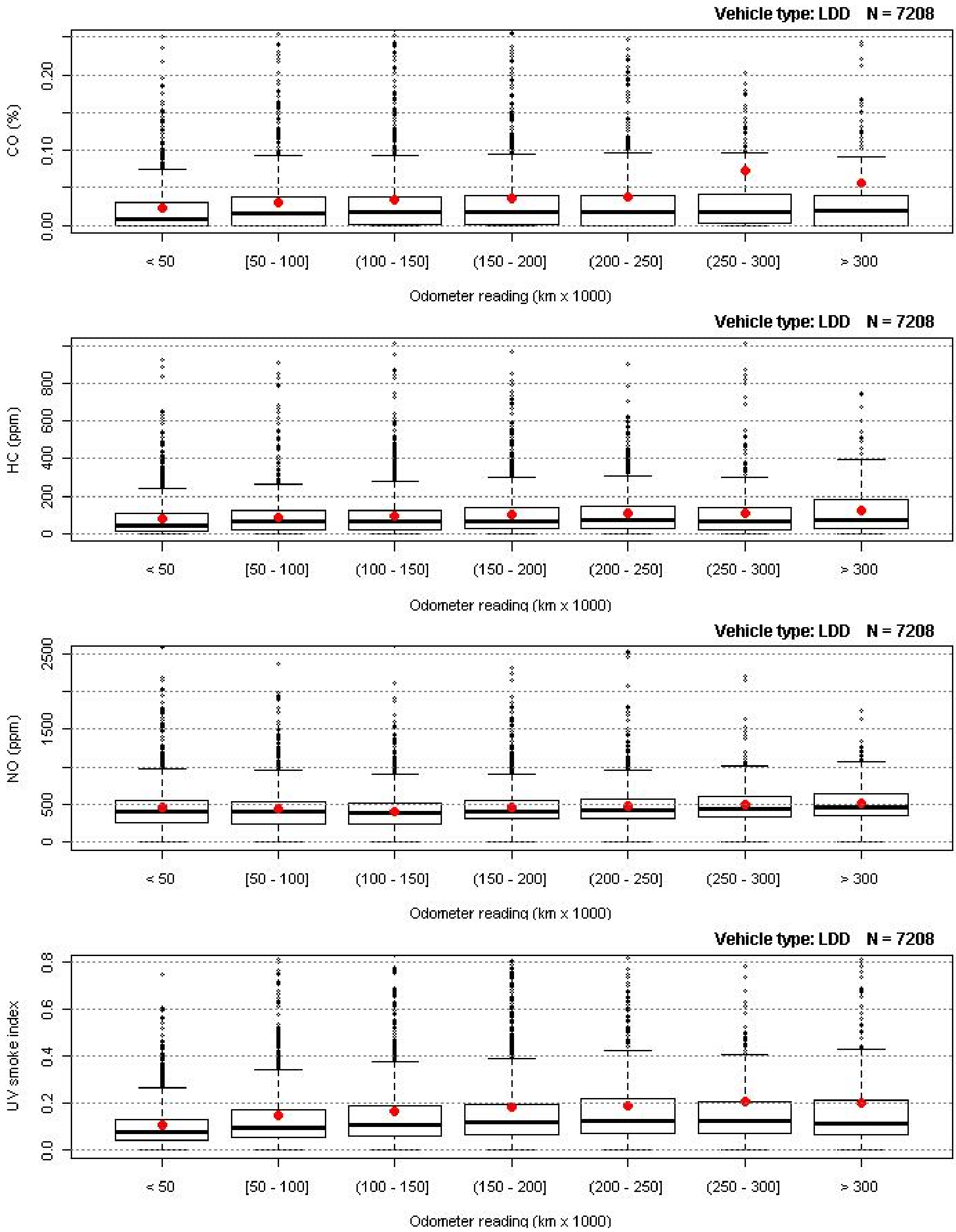


Figure 4.6 LDD fleet emissions by odometer reading

4.3.2 Heavy duty diesel vehicles

Table 4.7 compares the median and mean emissions of the four measured pollutants for HDD vehicles that have travelled less than 50,000 km with those that have travelled between 150,000 to 200,000 km and more than 300,000 km. More detailed results are presented in Figure 4.7 which shows the emissions from the HDD vehicle fleet by individual odometer reading.

Table 4.7 Median (and mean) emissions for HDDs by low, medium and high odometer reading

Odometer Reading (km)	<50,000	150,000 to 200,000	>300,000
CO (%)	0.041 (0.082)	0.046 (0.061)	0.056 (0.088)
HC (ppm)	203 (315)	226 (266)	275 (421)
NO (ppm)	1079 (1291)	980 (1052)	1238 (1428)
uvSmoke	0.153 (0.202)	0.220 (0.275)	0.218 (0.302)

Table 4.7 and Figure 4.7 together with the results of the K-W tests show:

- CO emissions from HDDs do not exhibit an obvious trend with mileage;
- HC emissions apear to not change greatly for the first 250,000 km travelled. HDDs with odometer readings >300,000 km are significantly higher than for HDDs that have travelled <250,000 km indicating a small step change in emissions of HC occurs after the vehicle has travelled more than 250,000 km;
- NO emissions from HDD vehicles with odometer readings >300,000 are significantly higher than for HDDs that travelled between 150,000 to 300,000km. However emissions from HDDs with low odometer readings (<50,000 km) are relatively and unexpectedly high; and
- uvSmoke emissions tend to increase with mileage. uvSmoke emissions from HDD vehicles with odometer readings <100,000 are significantly lower than for HDDs that have travelled further indicating a step change in uvSmoke emissions occurs after the vehicle has traveleld more than 100,000 km.

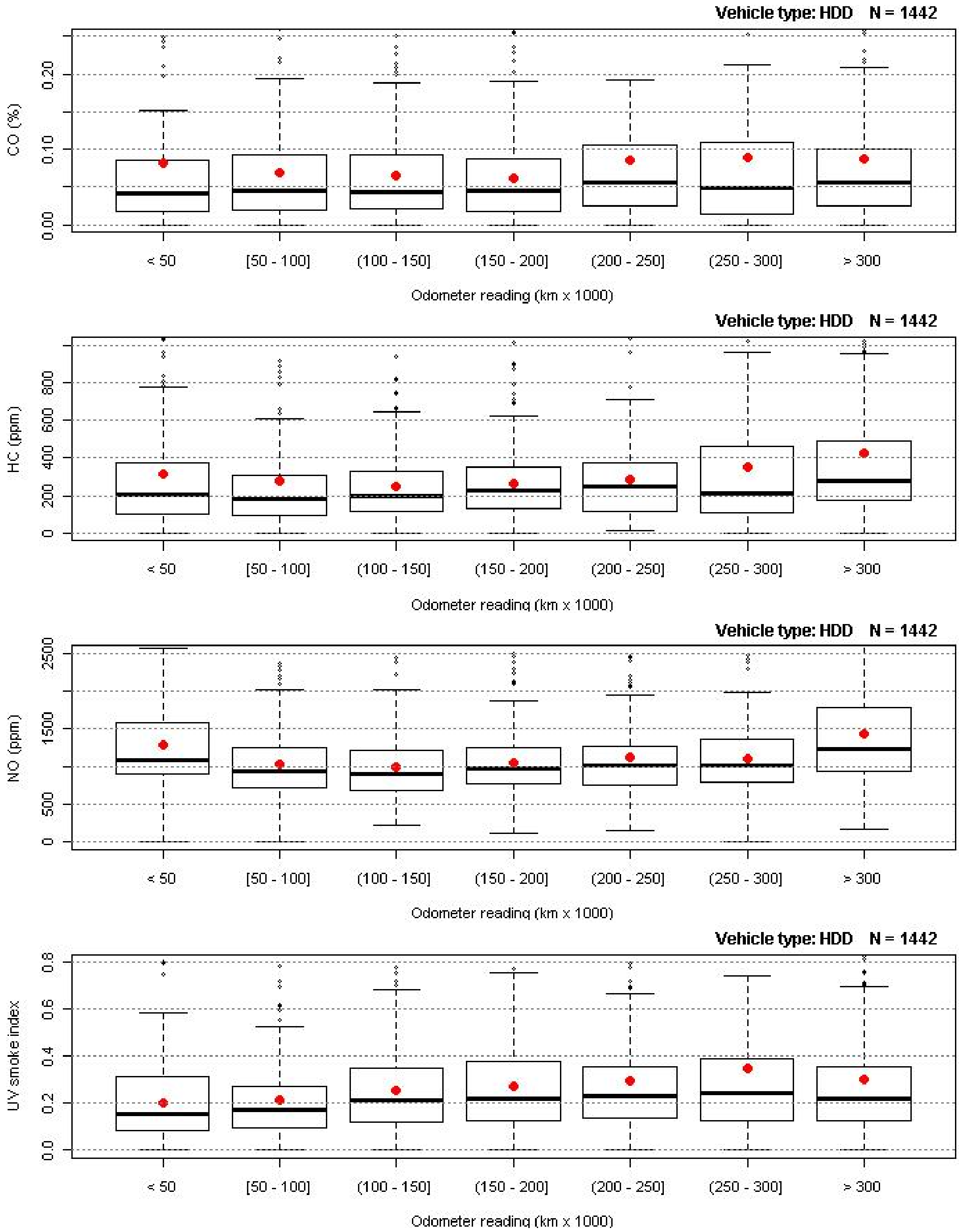


Figure 4.7 HDD fleet emissions by odometer reading

4.3.3 HDD trucks

Table 4.8 compares the median and mean emissions of the four measured pollutants for HDD trucks that have travelled less than 50,000 km with those that have travelled between 150,000 to 200,000 km and more than 300,000 km. More detailed results are presented in Figure 4.8 which shows the emissions from the HDD truck fleet by individual odometer reading.

Table 4.8 Median (and mean) emissions for HDD trucks by low, medium and high odometer reading

Odometer Reading (km)	<50,000	150,000 to 200,000	>300,000
CO (%)	0.037 (0.072)	0.047 (0.061)	0.051 (0.081)
HC (ppm)	177 (261)	233 (273)	267 (351)
NO (ppm)	1034 (1123)	965 (1020)	1183 (1387)
uvSmoke	0.170 (0.214)	0.221 (0.275)	0.230 (0.324)

Table 4.8 and Figure 4.8 together with the results of the K-W tests show:

- CO emissions from HDD trucks do not exhibit an obvious trend with odometer reading;
- HC emissions from HDD trucks increase with odometer readings. HC emissions from HDD trucks with odometer readings >300,000 km are significantly higher than for HDD trucks that have travelled <150,000 km;
- NO emissions from HDD trucks increase slightly with odometer readings 50,000 to 300,000 km. NO emissions from HDD trucks with odometer readings >300,000 km are significantly higher than for HDD trucks that have travelled between 50,000 to 250,000 km; and
- uvSmoke emissions increase with odometer reading. uvSmoke emissions from HDD trucks with odometer readings >150,000 km are significantly higher than for HDD trucks that have travelled less than 100,000 km.

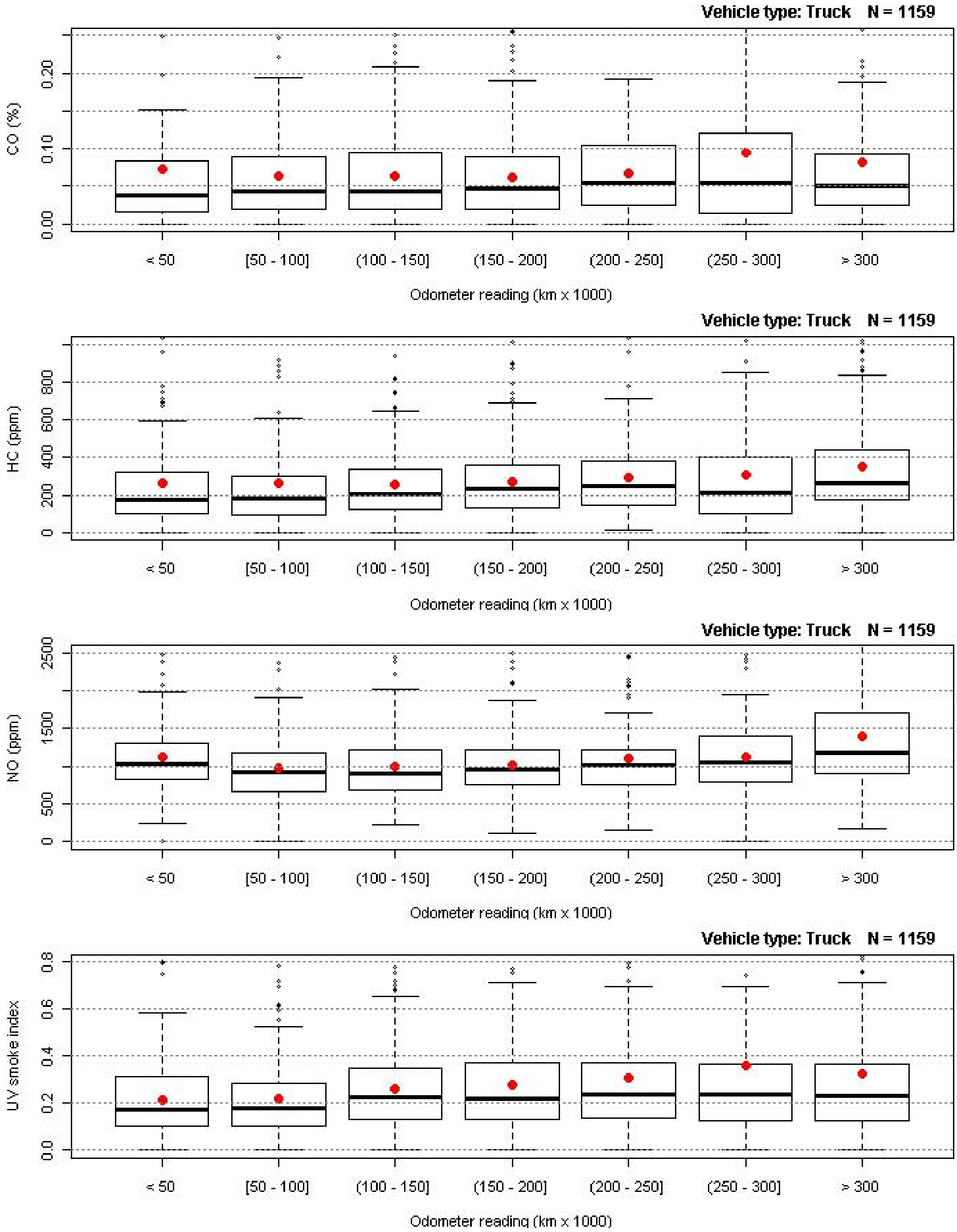


Figure 4.8 HDD truck emissions by odometer reading

4.3.4 HDD buses

Table 4.9 compares the median and mean emissions of the four measured pollutants for HDD buses that have travelled less than 50,000 km with those that have travelled between 150,000 to 200,000 km and more than 300,000 km. More detailed results are presented in Figure 4.9 which shows the emissions from the HDD bus fleet by individual odometer reading.

Table 4.9 Median (and mean) emissions for HDD buses by low, medium and high odometer reading

Odometer Reading (km)	<50,000	150,000 to 200,000	>300,000
CO (%)	0.058 (0.113)	0.032 (0.006)	0.067 (0.101)
HC (ppm)	358 (487)	189 (220)	324 (547)
NO (ppm)	1722 (1834)	1076 (1268)	1387 (1501)
uvSmoke	0.089 (0.163)	0.204 (0.272)	0.217 (0.263)

Table 4-9 and Figure 4.9 together with the results of the K-W tests show:

- CO emissions from HDD buses do not exhibit an obvious trend with mileage;
- HC emissions from HDD buses do not exhibit an obvious trend with mileage. However, HC emissions from HDD buses with odometer readings >250,000 km are significantly higher than vehicles that have not travelled between 50,000 to 250,000 km. HC emissions from HDD buses that have travelled less than 50,000 km are relatively and unexpectedly high;
- NO emissions from HDD buses do not exhibit an obvious trend with mileage; and
- uvSmoke emissions from HDD buses do not exhibit an obvious trend with mileage. However, uvSmoke emissions from HDD buses with odometer readings >300,000 km are significantly higher than for HDD buses that have travelled <100,000 km.

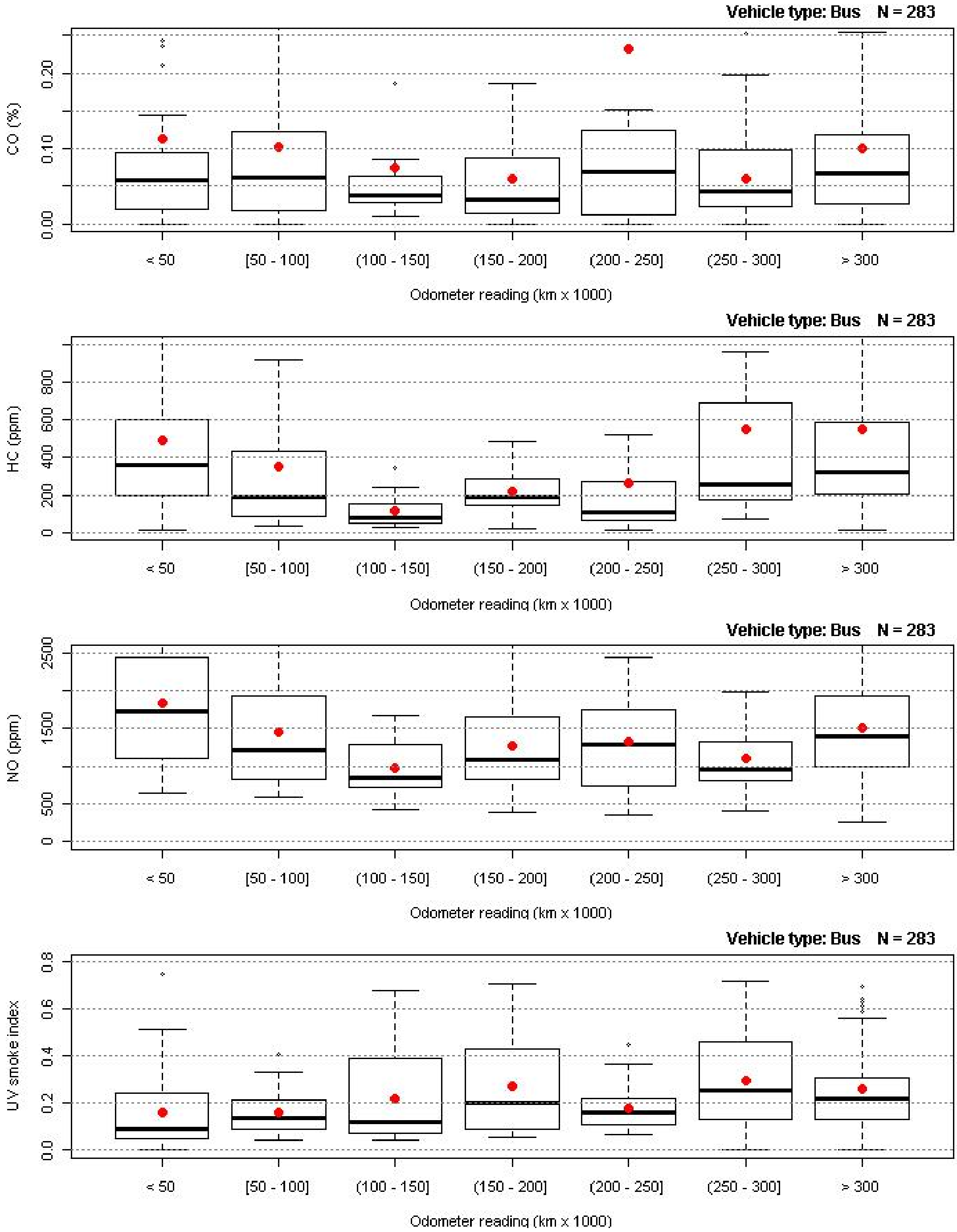


Figure 4.9 HDD bus emissions by odometer reading

4.4 Vehicle weight

Gross vehicle mass (GVM) is used as the indicator of vehicle weight. This section only considers the effect of GVM on the HDD and HDD truck subset of the monitored fleet. This is because very limited GVM data was available for LDD vehicles and the great majority of HDD buses fall within a very narrow band of GVM values.

4.4.1 Heavy duty diesel vehicles

Table 4.10 compares the median and mean emissions of the four measured pollutants for HDD vehicle fleet that have a GVM of 3.5-5.0 tonnes with those with a GVM of 10 to 15 tonnes and more than 20 tonnes. More detailed results are presented in Figure 4.10 which shows the emissions from the HDD fleet by individual GVM value.

Table 4.10 Median (and mean) emissions for HDDs by low, medium and high gross vehicle mass

Gross Vehicle Mass (tonnes)	3.5 to 5.0	10 to 15	> 20
CO (%)	0.039 (0.058)	0.059 (0.088)	0.049 (0.083)
HC (ppm)	193 (258)	267 (372)	229 (355)
NO (ppm)	860 (870)	1304 (1376)	1498 (1640)
uvSmoke	0.198 (0.254)	0.205 (0.267)	0.131 (0.231)

Table 4.10 and Figure 4.10 together with the results of the K-W tests show:

- CO emissions from HDD vehicles do not exhibit an obvious trend with GVM.
- HC emissions from HDD vehicles increase with GVM from 3.5 to 15 tonnes. HC emissions from HDDs with GVMs from 5 to 7.5 tonnes and 10 to 15 tonnes are significantly higher than the preceding GVM classes.
- NO emissions from HDD vehicles increase with GVM.
- uvSmoke emissions from HDD vehicles do not exhibit an obvious trend with GVM.

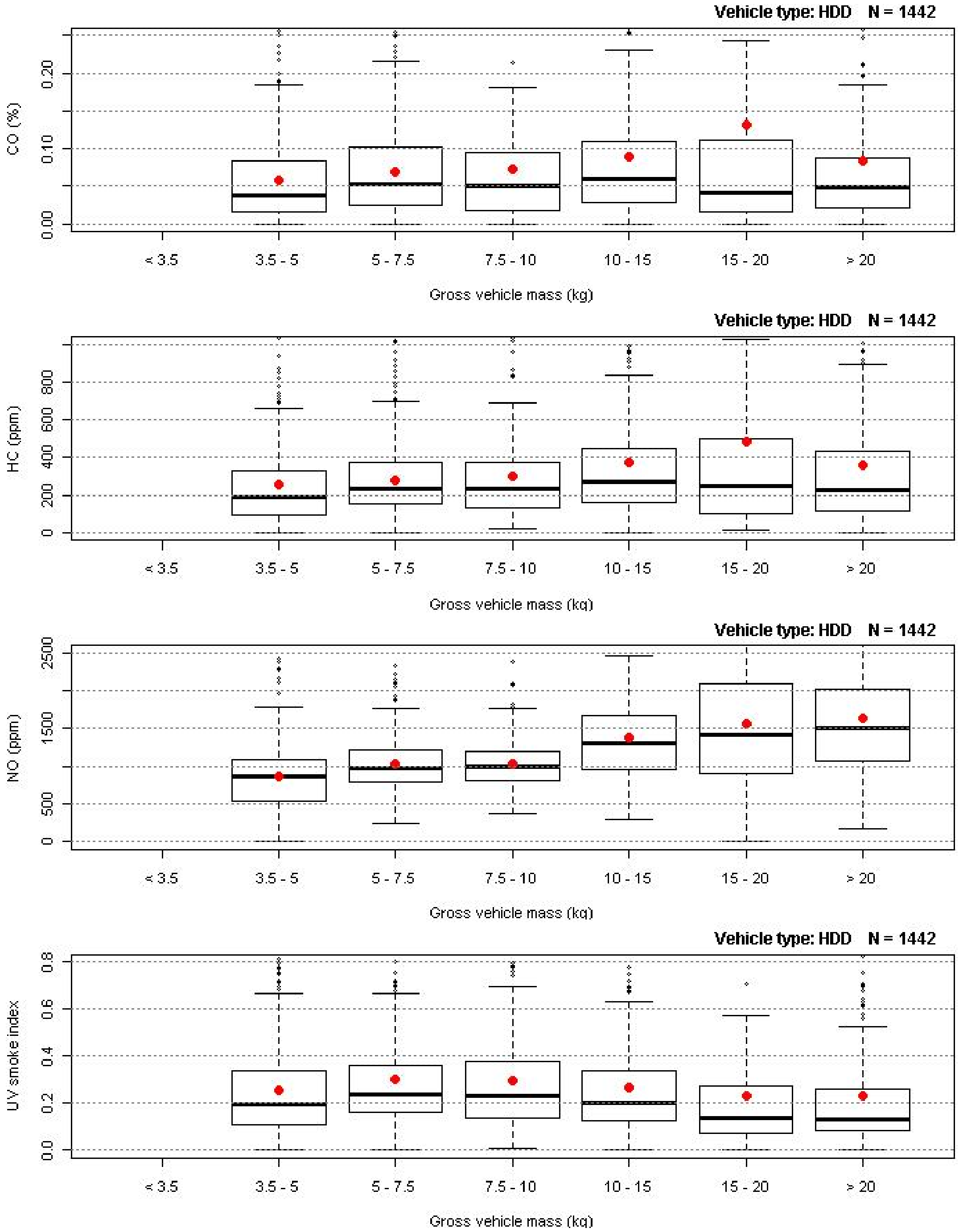


Figure 4.10 HDD fleet emissions by GVM

4.4.2 HDD trucks

Table 4.11 compares the median and mean emissions of the four measured pollutants for HDD trucks that have a GVM of 3.5-5.0 tonnes with those with a GVM of 10 to 15 tonnes and more than 20 tonnes. More detailed results are presented in Figure 4.11 which shows the emissions from the HDD truck fleet by individual GVM value.

Table 4.11 Median (and mean) emissions for HDD trucks by low, medium and high gross vehicle mass

Gross Vehicle Mass (tonnes)	3.5 to 5.0	10 to 15	> 20
CO (%)	0.039 (0.058)	0.050 (0.083)	0.049 (0.083)
HC (ppm)	195 (259)	259 (329)	219 (328)
NO (ppm)	860 (869)	1461 (1468)	1428 (1575)
uvSmoke	0.199 (0.254)	0.207 (0.287)	0.129 (0.233)

Table 4.11 and Figure 4.11 together with the results of the K-W tests show:

- CO emissions from HDD trucks do not exhibit an obvious trend with GVM;
- HC emissions from HDD trucks do not exhibit an obvious trend with GVM;
- NO emissions from HDD vehicles increase significantly as GVM increases from 3.5 to 15 tonnes. An increase in NO emissions is observed with HDD trucks with GVMs > 20 tonnes but these are not significantly higher than for the lighter GVM classes; and
- uvSmoke emissions from HDD trucks do not exhibit an obvious trend with GVM.

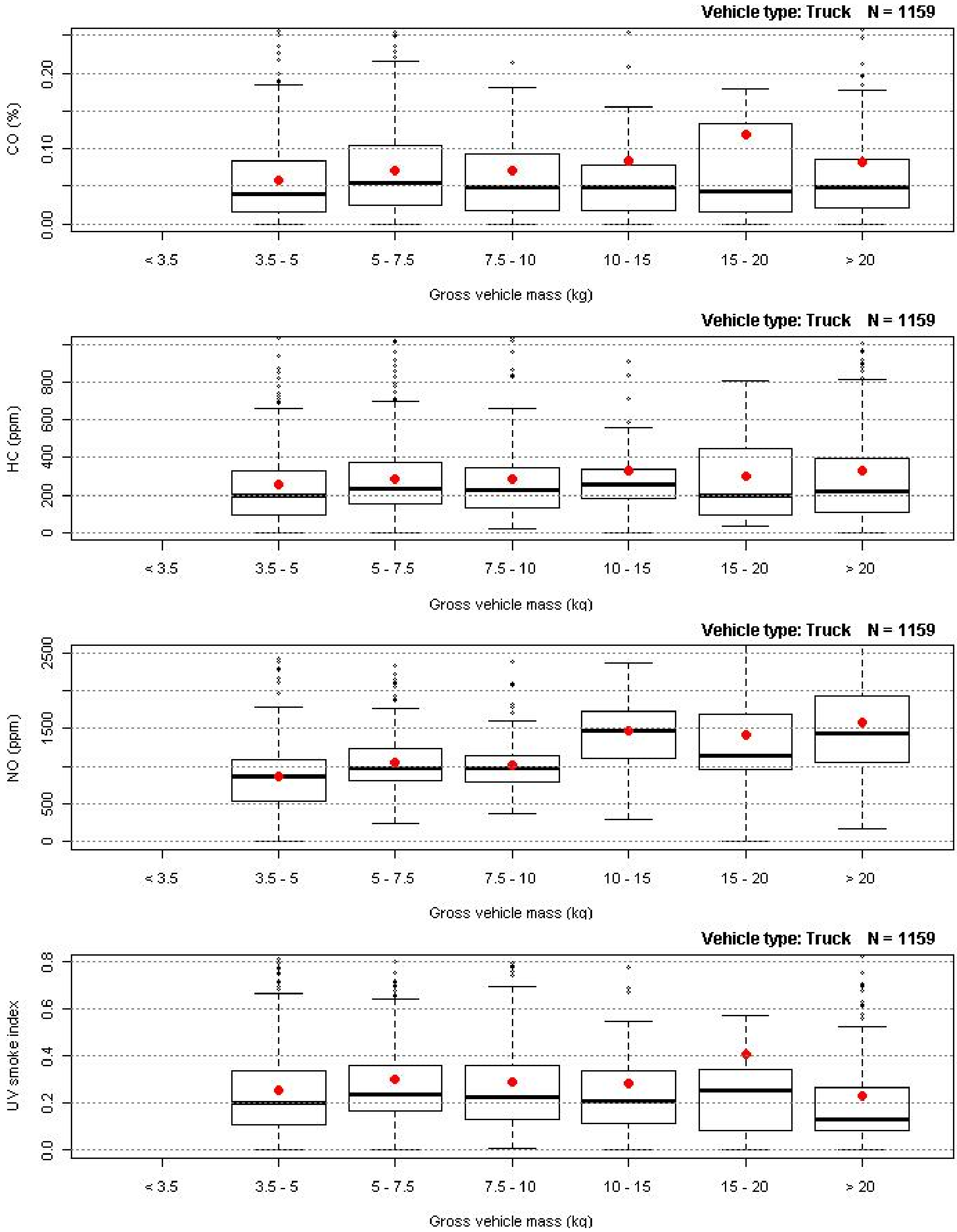


Figure 4.11 HDD truck emissions by GVM

4.5 Country of first registration

This section investigated whether there is any difference between the emissions of vehicle with different countrues of first registration. Only LDD and HDD trucks manufactured between the years of 1990 and 2000 were considered for this comparison because they were the only types with sufficient numbers of New Zealand new (NZN) and Japanese used (JPN) imported vehicles for robust statistical analyses.

4.5.1 Light duty diesel vehicles

Table 4.12 and Figure 4.12 compare the median and mean emissions of the four measured pollutants for LDD vehicles manufactured between 1990 and 2000 by country of first registration.

Table 4.12 Median (and mean) emissions for LDDs by country of first registration

Country of First Registration	JPN	NZN	Highest
CO (%)	0.018 (0.035)	0.016 (0.039)	~
HC (ppm)	64 (96)	63 (98)	~
NO (ppm)	369 (387)	507 (576)	NZN
uvSmoke	0.113 (0.175)	0.105 (0.159)	~

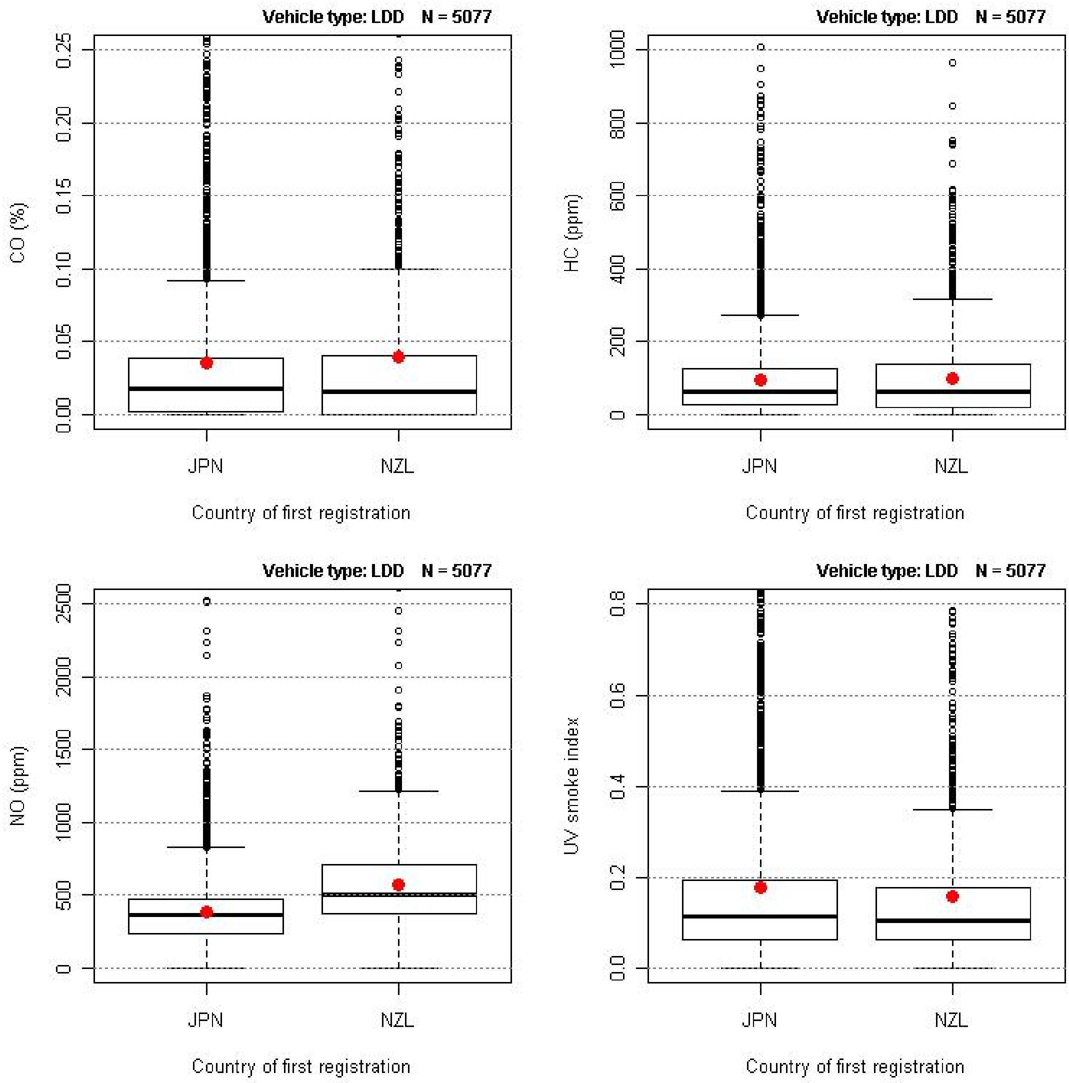


Figure 4.12 Emissions for LDD NZN and JPN vehicles manufactured between 1990 and 2000

Table 4.12 and Figure 4.12 together with the results of the K-W tests show that overall:

- There are no significant differences in CO, HC, and uvSmoke emissions, on average, between the NZN LDD vehicle fleet and the JPN LDD vehicle fleet; and
- NO emissions, on average, from the NZN LDD vehicle fleet are significantly higher than emissions from JPN LDD vehicle fleet.

However, the age profiles of the two fleets are quite different as shown in Figure 4.13. The average ages of NZN and JPN LDD vehicles in this subset are approximately 8 and 11 years respectively. Also, there are many more JPN (~4,000) than NZN (~ 1,500) vehicles in this group.

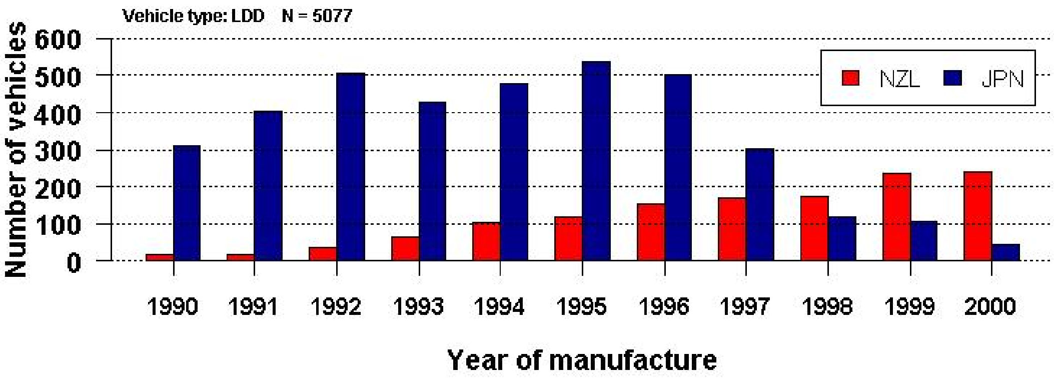


Figure 4.13 LDD fleet by year of manufacture (1990-2000) and country of first registration

Table 4.13 compares the median and mean emissions of the four measured pollutants for NZN and JPN LDD vehicles manufactured in the years 1990, 1995 and 2000. More detailed results are presented in Figure 4.14 which compares the emissions for each individual year of manufacture from 1990 to 2000.

Table 4.13 Median (and mean) emissions for NZN and JPN LDD vehicles manufactured in the years 1990, 1995 and 2000

Year of Manufacture	1990		1995		2000	
Country	JPN	NZN	JPN	NZN	JPN	NZN
CO (%)	0.019 (0.057)	0.034 (0.32)	0.017 (0.042)	0.012 (0.025)	0.011 (0.012)	0.015 (0.032)
HC (ppm)	72 (114)	97 (206)	57 (92)	62 (108)	21 (29)	62 (94)
NO (ppm)	399 (431)	603 (611)	344 (350)	540 (583)	448 (447)	442 (520)
uvSmoke	0.136 (0.224)	0.131 (0.153)	0.104 (0.179)	0.103 (0.166)	0.037 (0.044)	0.093 (0.147)

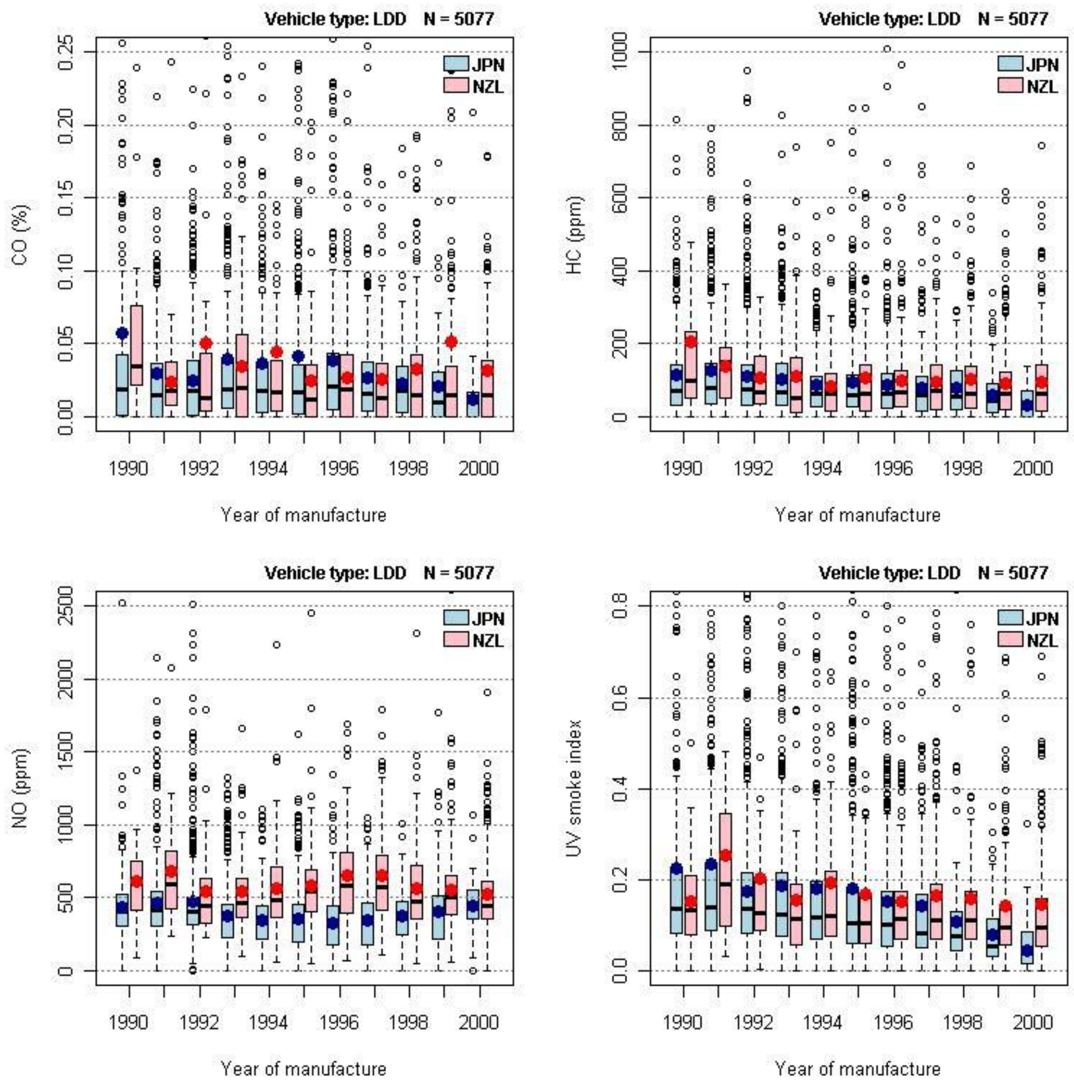


Figure 4.14 LDD emissions by country of first registration and year of manufacture

Table 4.13 and Figure 4.14 together with the results of the K-W tests show:

- CO emissions are not signficantly different between NZN and JPN LDD vehicles for the same year of manufacture;
- HC emissions are generally similar for NZN and JPN LDD vehicles for the same year of manufacture. However for 1990, 1999 and 2000, HC emissions from NZN vehicles are significantly higher than for JPN vehicles;
- NO emissions are higher for NZN than JPN LDD vehicles for the same year of manufacture. The differences observed are statistically significant, except for 1992 and 2000; and

- uvSmoke emissions are not significantly different between NZN and JPN LDD vehicles for those manufactured between 1990 and 1996. However, uvSmoke emissions emissions from NZN LDDs manufactured between 1997 and 2000 are significantly higher than JPN LDDs of the same year of manufacture.

Figure 4.14 also shows:

- Very little change in emissions of CO, HC, NO or uvSmoke from NZN LDDs with year of manufacture; and
- Very little change in emissions of CO or NO but a general decrease in emissions of HC and uvSmoke from JPN LDDs with year of manufacture.

4.5.2 HDD trucks

Table 4.14 and Figure 4.15 compare the median and mean emissions of the four measured pollutants for HDD trucks manufactured between 1990 and 2000 by country of first registration.

Table 4.14 Median (and mean) emissions for HDD trucks by country of first registration

Country of First Registration	JPN	NZN	Highest
CO (%)	0.055 (0.074)	0.046 (0.067)	JPN
HC (ppm)	247 (290)	225 (298)	~
NO (ppm)	892 (923)	1161 (1333)	NZN
uvSmoke	0.241 (0.312)	0.181 (0.271)	JPN

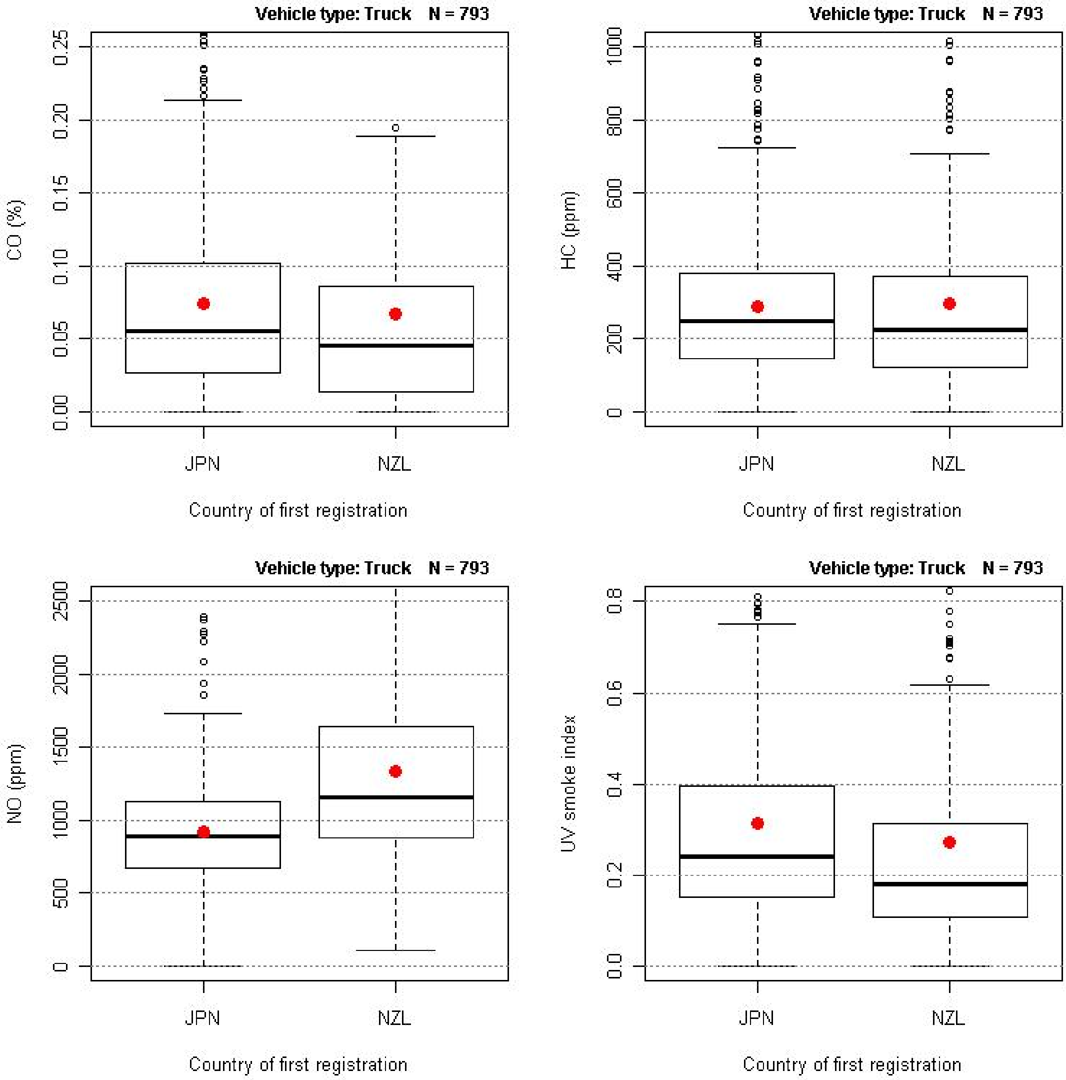


Figure 4.15 Emissions for HDD NZN and JPN trucks manufactured between 1990 and 2000

Table 4.14 and Figure 4.15 together with the results of the K-W tests show:

- CO emissions, on average, from JPN HDD trucks are significantly higher than emissions from NZN HDD trucks;
- HC emissions from NZN and JPN HDD trucks are not significantly different;
- NO emissions, on average, from the NZN HDD trucks are significantly higher than emissions from JPN HDD trucks; and
- uvSmoke emissions, on average, from JPN HDD trucks are significantly higher than from NZN HDD trucks.

However, as with LDD vehicles, the age profiles of the two HDD truck fleets are quite different as shown in Figure 4.16. The average ages of NZN and JPN HDD vehicles in this subset are approximately 9 and 11 years respectively. Also, there are more JPN (~600) than NZN (~350) vehicles in this group.

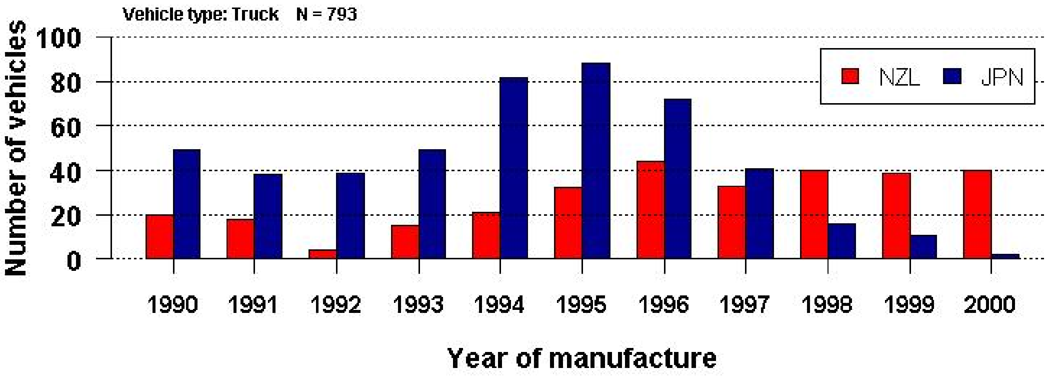


Figure 4.16 HDD truck fleet by year of manufacture (1990-2000) and county or first registration

Table 4.15 compares the median and mean emissions of the four measured pollutants for NZN and JPN HDD trucks manufactured in the years 1990, 1995 and 2000. More detailed results are presented in Figure 4.17 which compares the emissions for each individual year of manufacture from 1990 to 2000.

Table 4.15 Median (and mean) emissions for NZN and JPN HDD trucks manufactured in the years 1990, 1995 and 2000

Year of Manufacture	1990		1995		2000	
Country	JPN	NZN	JPN	NZN	JPN	NZN
CO (%)	0.064 (0.076)	0.051 (0.045)	0.053 (0.079)	0.051 (0.057)	0.016 (0.016)	0.050 (0.052)
HC (ppm)	325 (350)	110 (201)	213 (261)	184 (292)	41 (41)	212 (314)
NO (ppm)	1065 (1125)	778 (1157)	847 (877)	1146 (1414)	322 (322)	1112 (1155)
uvSmoke	0.318 (0.419)	0.158 (0.244)	0.225 (0.259)	0.190 (0.294)	0.066 (0.066)	0.148 (0.187)

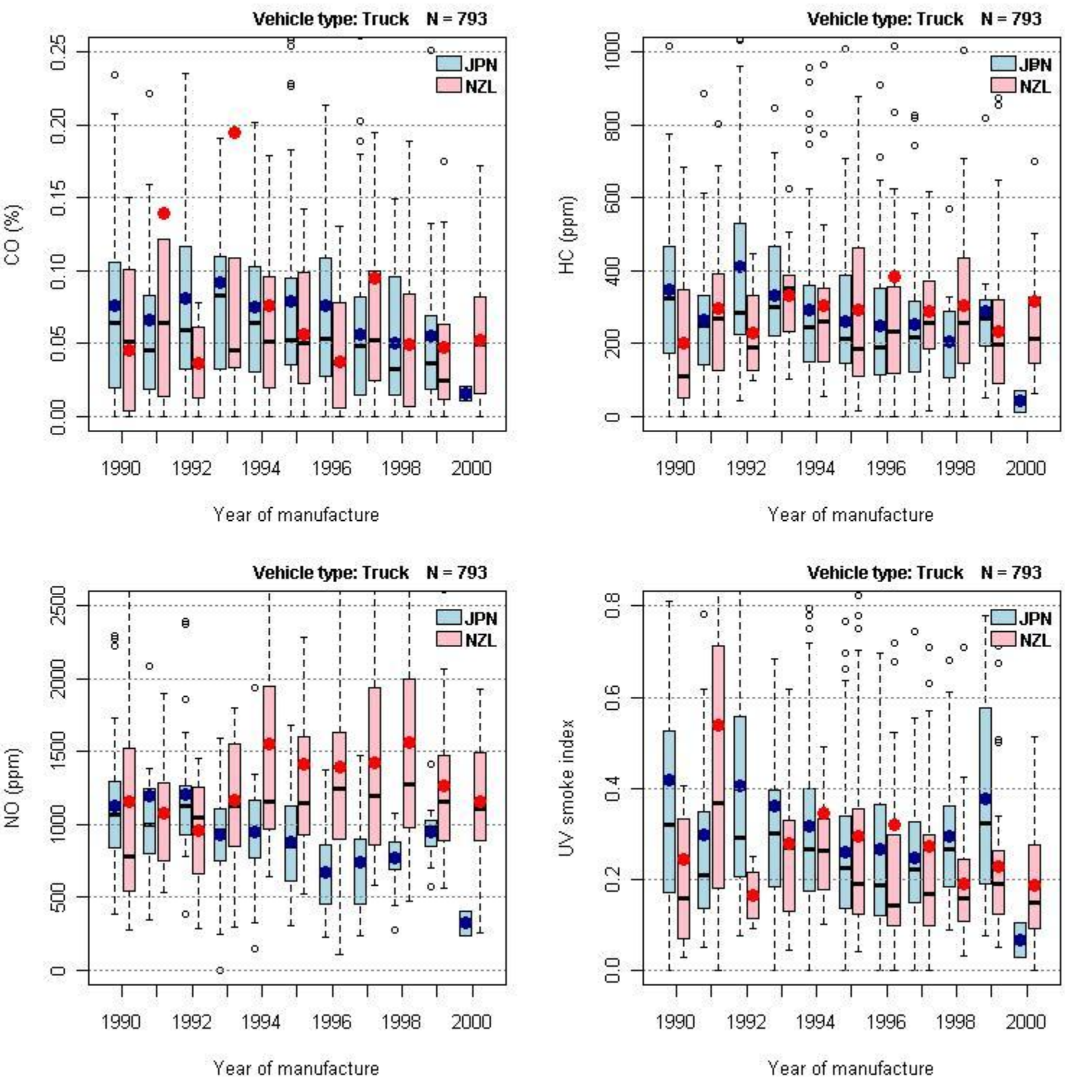


Figure 4.17 HDD truck emissions by country of first registration and year of manufacture

Table 4.15 and Figure 4.17 together with the results of the K-W tests show:

- CO and HC emissions are not significantly different for NZN and JPN HDD trucks for the same year of manufacture;
- NO emissions are higher for NZN than JPN HDD trucks for the same year of manufacture. The differences observed are statistically significant, except for 1990, 1991 and 1992; and
- uvSmoke emissions are generally similar for NZN and JPN HDD trucks for the same year of manufacture.. However, uvSmoke emissions emissions from JPN HDD trucks manufactured in 1990, 1992 and 1998 are significantly higher than NZN HDD trucks of the same year of manufacture.

Figure 4.17 also shows:

- No or very little change in emissions of CO or HC from NZN and JPN HDD trucks with year of manufacture;
- A general decrease in emissions of NO from JPN HDD trucks with year of manufacture, but no change for NZN HDD trucks; and
- Some reduction in uvSmoke emissions with later years of manufacture for NZN and JPN HDD trucks.

5 Effect of emission standard on bus emissions

This section evaluates the effect of emission standard on measured emissions for a total of 91 buses.

Figure 5.1 shows the distribution of emission standards of the monitored buses, for which this information was available, with the emissions standards shown from worst on the left to best on the right of this graph.

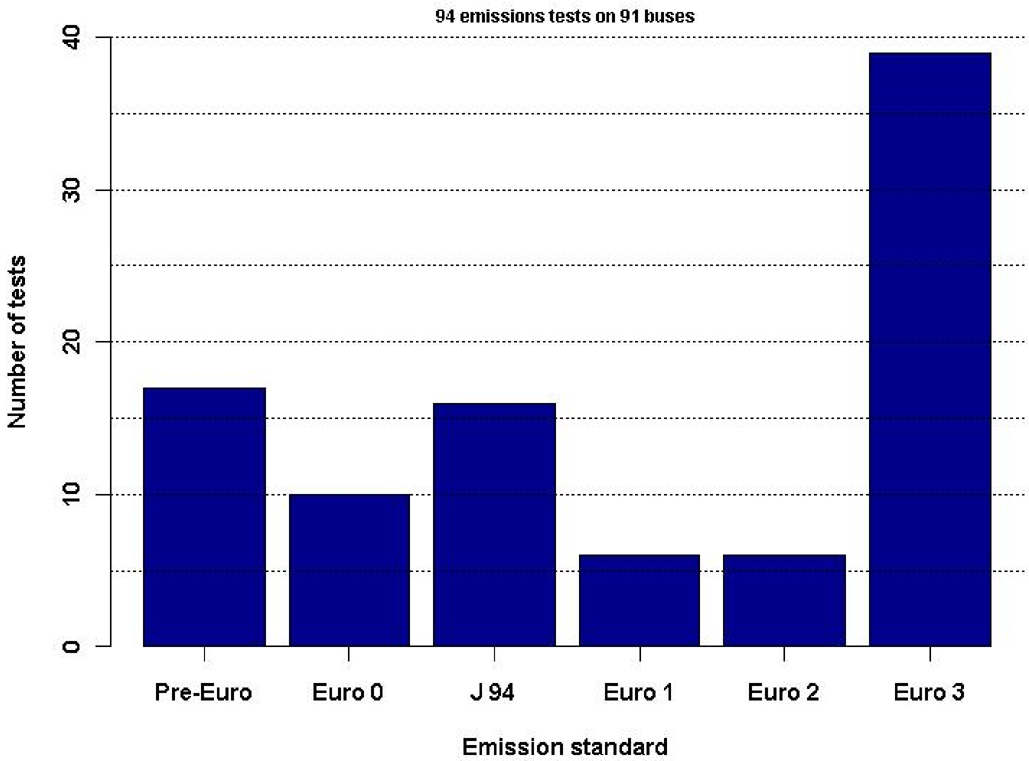


Figure 5.1 HDD bus fleet by emission standard

More than 90 of the buses were built to European emission standards with only 16 built to Japanese standards (e.g. J94). It is important to note that the test cycles used to assess the compliance of a heavy duty diesel vehicle relative to its emission standard are different between Japan and Europe and therefore there is no direct equivalency between the standards. However, looking at the limits for each pollutant J94 can be positioned approximately between the Euro 0 and Euro 1 limits.

Table 5.1 compares the typical weighted emission factors for the range of bus emission standards, taken from the ARC's Bus Emission Prediction Model assuming an average speed of 30 km/hr (ARC, 2005). These factors are for slightly different pollutants than those measured by the RSD system but are indicative of the expected emissions reductions with improved emission standards.

Table 5.1 Emission factors for HDD buses at 30 km/hr by emission standard

Emission Standard	Pre Euro	Euro 0	J94	Euro 1	Euro 2	Euro 3
CO (g/km)	11.6	5.6	3.5	2.0	1.8	1.3
NMHC (g/km)	3.92	1.04	1.17	0.73	0.69	0.34
NO_X (g/km)	16.5	11.4	7.1	7.7	7.9	5.1
PM (g/km)	1.53	0.73	0.80	0.36	0.25	0.17

Table 5.2 compares the median and mean emissions of the four measured pollutants for HDD buses manufactured to the range of different emission standards. More detailed results are presented in Figure 5.2.

Table 5.2 Median and (mean) emissions for HDD buses by emission standard

Emission Standard	Pre-Euro	Euro 0	J94	Euro 1	Euro 2	Euro 3
CO (%)	0.107 (0.138)	0.075 (0.092)	0.089 (0.109)	0.008 (0.000)	0.009 (0.051)	0.030 (0.061)
HC (ppm)	800 (1029)	742 (919)	616 (701)	289 (449)	270 (281)	147 (252)
NO (ppm)	1973 (2170)	2268 (2356)	1184 (1310)	899 (1042)	789 (1003)	1465 (1523)
uvSmoke	0.212 (0.202)	0.208 (0.257)	0.231 (0.278)	0.523 (0.479)	0.280 (0.349)	0.114 (0.167)

Table 5.2 and Figure 5.2 together with the results of the K-W tests show:

- CO emissions from buses built to Pre-Euro are significantly higher than those for buses built to Euro 1, Euro 2 or Euro 3 standards;
- HC emissions from buses built to Pre-Euro, Euro 0 and J94 and are significantly higher than those for buses built Euro 3 standards;
- NO emissions from buses built to Pre-Euro and Euro 0 are significantly higher than those for buses built to J94, Euro 1, Euro 2 or Euro 3 standards; and

❑ uvSmoke emissions from buses built to Euro 3 had the lowest median and mean values but were only statistically significantly lower that uvSmoke emissions from buses built to J94 or Euro 1 standards.

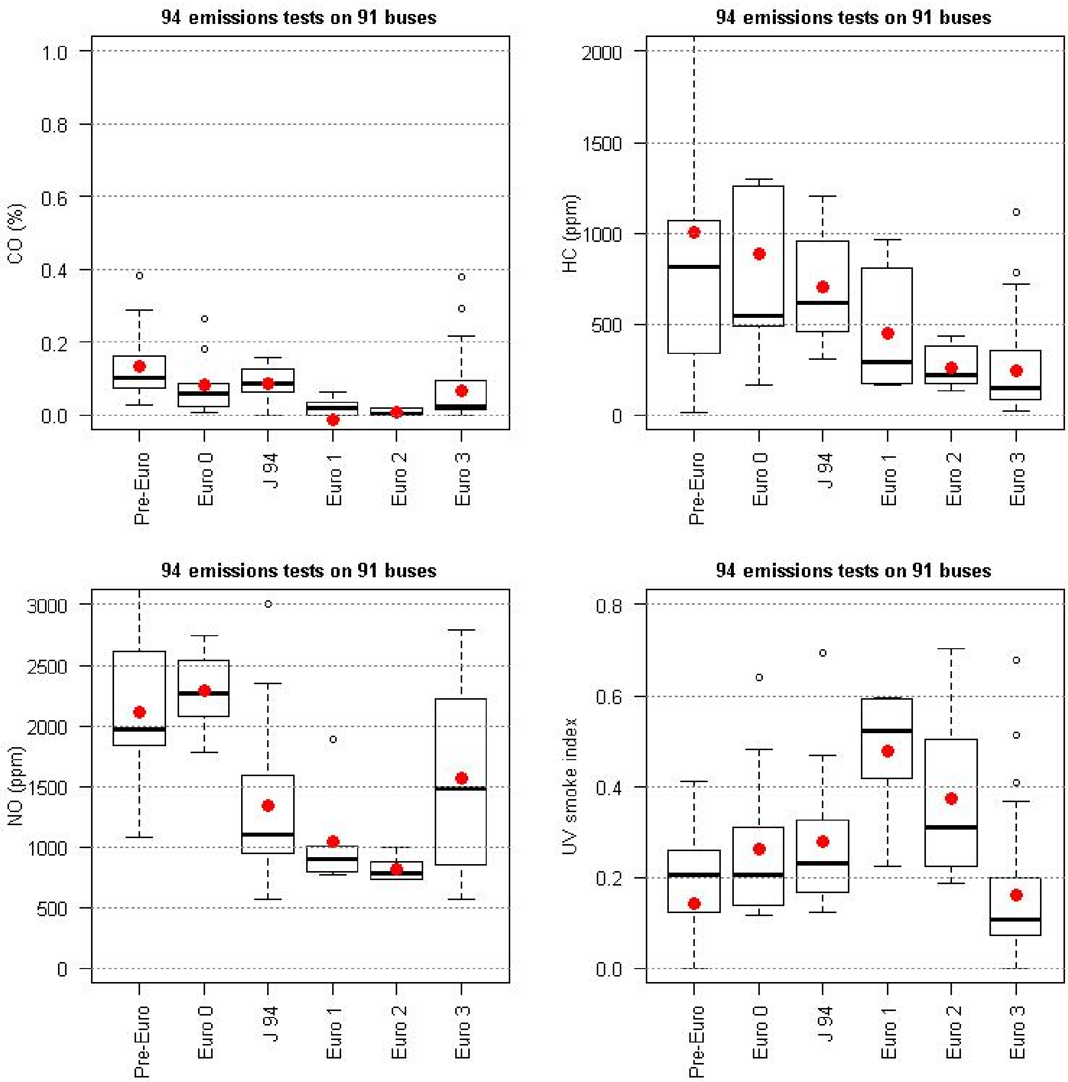


Figure 5.2 HDD bus emissions by emission standard

Overall, the measured emissions of all pollutants (except uvSmoke) generally trend in the *expected direction* of the bus emission standard improvement but do not necessarily mirror the *expected full reduction* in emissions. This is not surprising given that the compliance testing procedure for HDD buses involves a full cycle of driving events whilst the remote sensing only captures a single instant and the limited number of buses considered within the analysis.

6 Emissions from light and heavy duty diesel "gross emitters"

The total emissions from the fleet are frequently disproportionately influenced by a relatively small number of vehicles that discharge relatively high levels of pollutants. This small number of high polluting vehicles are referred to as "gross emitters". Typically in a New Zealand vehicle fleet approximately half of the total emissions are discharged from just 10 per cent of the fleet (ARC, 2003). This section of the report presents the distribution of emissions from the monitored diesel vehicles and quantifies the effect that gross emitting diesel vehicles have on total emissions.

Figure 6.1 compares the cumulative emissions curves for the four pollutants for each vehicle type and demonstrates the influence of gross emitting vehicles on the cumulative emissions produced by the sampled diesel fleet. Table 6.1 shows the percentage of total emissions produced by the highest emitting 10 per cent of the fleet –the "gross emitters". As the effect of gross emitters lessens, the cumulative curves become more linear.

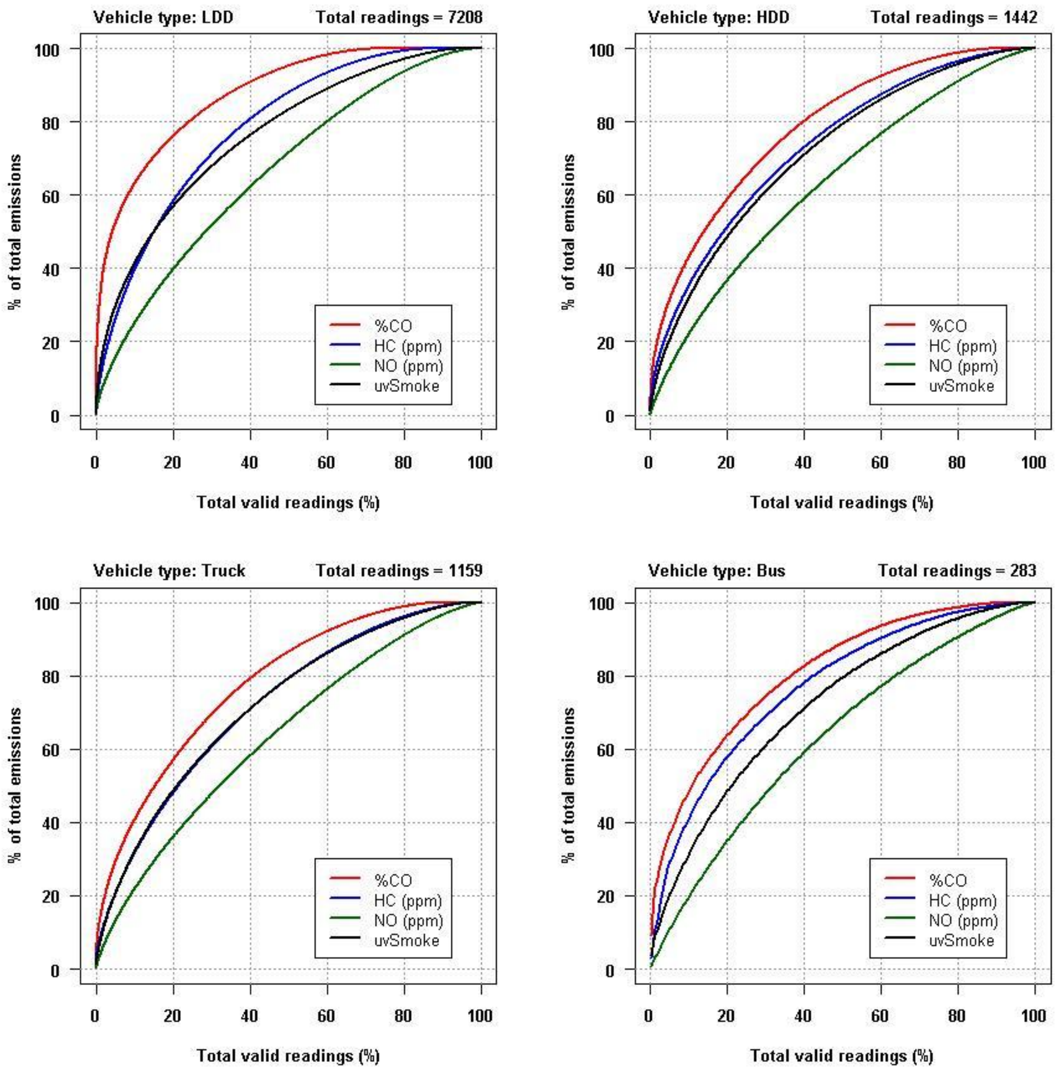


Figure 6.1 Cumulative emission curves by diesel vehicle type

Table 6.1 Percentage of total emissions produced by the "gross emitters" by diesel vehicle type

Vehicle Type	LDD	HDD	HDD Truck	HDD Bus
CO	63	43	41	46
HC	39	35	32	41
NO	25	22	22	20
uvSmoke	42	33	33	34

Figure 6.1 and Table 6.1 show:

- The pollutant most strongly influenced by gross emitting diesel vehicles is CO;
- The pollutant least affected by gross emitting diesel vehicles is NO;
- CO emissions from LDD vehicles are more strongly influenced by "gross emitters" than CO emissions from HDD vehicles. The percentages of the fleet total CO emissions produced by LDD and HDD gross emitting vehicles are 63% and 43%, respectively; and
- NO emissions from all diesel vehicle types is affected similarly, with 10% of the vehicles emitting 20%-25% of the fleet total NO emissions.

The results presented in Figure 6.1 and Table 6.1 show that the highest emitting diesel vehicles do contribute disproportionately to the total fleet emissions.

As a comparison, the data from the 2003 Auckland on-road vehicle emission study demonstrated that the highest emitting 10% of the light duty fleet overall (both petrol and diesel vehicles) was responsible for discharging 53%, 51% and 39% of the total CO, HC and NO emissions respectively (ARC 2003)

7 Key Findings

This section presents the key findings from the analysis of the LDD, HDD, truck and bus emission data.

The measurements used in the analysis were from two campaigns – the first undertaken in November/ December 2004 and the second in May/June 2005. Vehicles were sampled at the Ports of Auckland (trucks), five Auckland bus depots (buses), and 20 roadside sites (heavy and light duty vehicles). The pollutants measured in the exhaust gases emitted from the vehicles were: carbon monoxide (CO), hydrocarbons (HC), nitric oxide (NO) and particulates (uvSmoke).

7.1 Light Duty Diesel Vehicles

The monitoring at 20 roadside sites yielded a total of 7,200 valid emission measurements from 6,484 different light duty diesel (LDD) vehicles, with approximately 700 LDDs being monitored more than once. The average year of manufacture for the sampled LDD fleet was 1996, making the average age of the LDD at the time of monitoring 8.9 years. The average odometer reading of the LDD vehicles sampled was 144,000 km.

Approximately 40 per cent of the LDDs were New Zealand new vehicles, the remaining 60 per cent were used vehicles at the time they were imported into New Zealand. The vast majority of these imported used vehicles were sourced from Japan. The average year of manufacture for the New Zealand new fraction of the LDD fleet was 2000 (4.9 years old at the time of monitoring). The average year of manufacture for the Japanese new fraction of the LDD fleet was 1993 (11.6 years old).

LDD vehicles were found to emit significantly less of all four pollutants on average than the heavy duty diesel (HDD) vehicles. Older LDDs emitted significantly more uvSmoke than newer vehicles. The amount of CO and HC discharged from LDDs increased slightly with vehicle age. However, vehicle age did not appear to influence LDD NO emissions. Vehicles with higher odometer readings (>250,000 km) tended to emit more CO, HC and uvSmoke than vehicles with lower odometer readings (<100,000 km). As was the case with vehicle age, odometer reading did not appear to influence LDD emissions of NO.

A comparison of New Zealand new and Japanese new LDDs was undertaken for the vehicles with year of manufacture in the range 1990 to 2000. No significant difference was observed in the fleet average emissions of CO, HC or uvSmoke between New Zealand new and Japanese new LDDs. However, average emissions of NO from New Zealand new LDDs were significantly higher than from Japanese new LDDs. When compared by year of manufacture, emissions of CO and HC from New Zealand new and Japanese new vehicles were very similar. NO emissions from New Zealand new LDDs were significantly higher than Japanese new for all years of manufacture.

uvSmoke emissions from newer (post 1997) New Zealand new LDDs were significantly higher than from equivalent year of manufacture Japanese new LDDs.

The highest emitting 10 per cent (gross emitting) LDD vehicles were found to disproportionately influence the LDD fleet performance by contributing 63 per cent, 39 per cent, 25 per cent and 42 per cent of the total CO, HC, NO and uvSmoke emissions respectively.

7.2 Heavy duty diesel vehicles

Monitoring at the Ports of Auckland, bus depots and 20 roadside sites yielded a total of 1,442 valid emission measurements from 1,235 different heavy duty diesel (HDD) vehicles, with approximately 200 HDDs being monitored more than once. The average year of manufacture for the sampled HDD fleet was 1995, making the average age of HDDs at the time of monitoring 9.3 years. The average odometer reading of the HDD vehicles sampled was 217,000 km. Fifty-five per cent of the HDD fleet had a gross vehicle mass (GVM) of between 3.5 and 7.5 tonnes, with 14 per cent being heavier than 20 tonnes.

Approximately 56 per cent of the HDDs were New Zealand new vehicles, the remaining 44 per cent were used vehicles at the time they were imported into New Zealand. The vast majority of these imported used vehicles were sourced from Japan. The average year of manufacture for the New Zealand new fraction of the HDD fleet was 1997 (7.0 years old at the time of monitoring). The average year of manufacture for the Japanese new sector of the HDD fleet was 1993 (11.8 years old at the time of monitoring).

HDD vehicles were found to emit significantly more of all four pollutants on average than light duty diesel (LDD) vehicles. Older HDDs emitted significantly more CO, HC and uvSmoke than newer vehicles. However, vehicle age did not appear to influence HDD NO emissions. Vehicles with higher odometer readings tended to emit more HC, NO and uvSmoke than vehicles with lower odometer readings. Odometer reading did not appear to influence emissions of CO. HDDs with greater GVMs tended to emit more HC and uvSmoke than lighter vehicles. No trend in CO or NO emissions with GVM was observed.

The highest emitting 10 per cent (gross emitting) HDD vehicles were found to disproportionately influence the HDD fleet performance by contributing 43 per cent, 35 per cent, 22 per cent and 33 per cent of the total CO, HC, NO and uvSmoke emissions respectively.

7.3 HDD trucks and buses

Of the 1,442 valid HDD emission measurements, 1,150 were from trucks and 282 were from buses. A comparison was undertaken between the truck and bus fleet and their respective emissions.

The average year of manufacture for the sampled truck and bus fleets were both 1995, making the average age of the buses and trucks at the time of monitoring 9.3 years.

The average odometer readings of the trucks and buses sampled were 194,000 and 310,000 km respectively. Sixty six per cent of the truck fleet had a GVM between 3.5 and 7.5 tonnes, with 16 per cent of the trucks being heavier than 20 tonnes. In comparison, 80 poer cent of buses had GVMs between 10 and 20 tonnes.

Approximately, 39 per cent of the trucks and 89 per cent of the buses were New Zealand new vehicles. The average year of manufacture for New Zealand new and Japanese new trucks were 1997 and 1993 respectively. The average year of manufacture for New Zealand new and Japanese new buses were older at 1995 and 1990 respectively.

Buses, on average, emitted significantly more NO than trucks. However, trucks, on average, emitted significantly more uvSmoke than buses. There was no significant difference between the average emissions of CO or HC from trucks or buses.

A comparison of New Zealand new and Japanese new trucks was undertaken for the vehicles with year of manufacture in the range 1990 to 2000. On average, the New Zealand new trucks were considerably newer than Japanese new trucks (6.5 years vs 11.7 years). Fleet average emissions of CO and uvSmoke from Japanese new trucks were significantly higher than from New Zealand new trucks. Conversely, average emissions of NO from New Zealand new trucks was significantly higher than from Japanese new trucks. No significant difference was observed in the fleet average HC emissions. When compared by year of manufacture, emissions of CO, HC and uvSmoke from New Zealand new and Japanese new trucks were similar. NO emissions from New Zealand new trucks were significantly higher than Japanese new trucks for most years of manufacture.

A comparison of bus emissions by emission control technology showed that the measured emissions of all pollutants (except uvSmoke) generally trended downward with improving emission standard. However, the relative improvement in the measured emissions was not as great as the expected relative improvement based on emissions standards. The highest emitting 10 per cent (gross emitting) of these vehicles were also found to disproportionately influence their fleet performance, with "truck gross emitters" contributing 41 per cent, 32 per cent, 22 per cent and 33 per cent and "bus gross emitters" 46 per cent, 41 per cent, 20 per cent and 34 per cent of the total CO, HC, NO and uvSmoke emissions respectively.

8 Discussion and Recommendations

This section describes the potential science and policy implications of the findings and outlines recommendations for future emission monitoring projects.

8.1 Potential scientific and policy implications

The data collected and key findings from this project have valuable scientific and policy implications for the Auckland Regional Council. These include (but are not limited to):

- Evaluation of the potential benefits of implementing different diesel emission control strategies;
- Assisting with the development of targeted diesel vehicle emission reduction strategies;
- Providing benchmark data to assess changes in fleet characteristics of and emissions from diesel vehicles over time;
- Assessing the likelihood that ARC's vehicle emission reduction targets will be met; and
- Refining and/or validating vehicle emission models (e.g. VEPM and BEPM) and improving confidence in ARC's emission inventory data.

8.2 Recommendations for future monitoring

In addition to the roadside sampling, this project included ten days of monitoring, which was undertaken at the Ports of Auckland and five regional bus depots to target heavy duty diesel emissions. On average, the depot monitoring yielded 32 bus or 40 truck emissions measurements per day. By comparison, the roadside monitoring yielded five bus and 39 truck emission measurements per day. Roadside monitoring was almost as effective as depot monitoring at sampling trucks and provided a dataset of light duty measurements. However, the number of bus measurements collected at roadside sites was relatively low. Although the number of sampled HDD vehicles may be similar with each method, depot monitoring provides other benefits that roadside monitoring does not, such as the:

- Relative ease to collect repeat measurements from the same vehicle;
- Ability to target specific sectors of the HDD fleet (e.g. trucks over 20 tonnes at the Ports of Auckland); and
- Opportunity to perform "under-bonnet" checks to verify emission control equipment

Therefore, it is recommended that plans for future diesel emission monitoring projects include an assessment of the cost and benefits of including depot type monitoring for the heavy vehicles.

9 Conclusions

This section summarises the outcomes of the diesel vehicle emissions measurement campaign which was undertaken between 2003 and 2005 in Auckland.

The main conclusions from this study were that:

- Approximately 40 per cent of the LDDs were New Zealand new vehicles, the remaining 60 per cent were used vehicles were imported from Japan. For HDDs, approximately 56 per cent of the HDDs were New Zealand new vehicles, the remaining 44 per cent were used vehicles were imported from Japan. This proportion of HDDs varied significantly depending on whether vehicles were trucks or busses, with 39 per cent of the trucks and 89 per cent of the buses were New Zealand new vehicles;
- Light duty diesel (LDD) vehicles were found to emit significantly less NO, CO, HC, and uvSmoke on average than the heavy duty diesel (HDD) vehicles. However, uvSmoke emissions from newer (post 1997) New Zealand new LDDs were significantly higher than from equivalent year of manufacture Japanese new LDDs;
- Fleet average emissions of CO and uvSmoke from Japanese new trucks were significantly higher than from New Zealand new trucks. Conversely, average emissions of NO from New Zealand new trucks were significantly higher than from Japanese new trucks;
- The amount of CO, HC, and uvSmoke discharged from LDDs and HDDs increased with vehicle age and odometer readings. However, vehicle age and odometer readings did not appear to influence NO emissions;
- HDDs with greater gross vehicle masses tended to emit more HC and uvSmoke than lighter vehicles. No trend in CO or NO emissions with gross vehicle mass was observed;
- Buses, on average, emitted significantly more NO than trucks. However, trucks, on average, emitted significantly more uvSmoke than buses. There was no significant difference between the average emissions of CO or HC from trucks or buses;
- The highest emitting 10 per cent LDD and HDD vehicles (gross emitters) were found to disproportionately influence the fleet performance. LDD gross emitters contributed 63 per cent, 39 per cent, 25 per cent and 42 per cent of the total CO, HC, NO and uvSmoke emissions respectively. HDD gross emitters contributed 43 per cent, 35 per cent, 22 per cent and 33 per cent of the total CO, HC, NO and uvSmoke emissions respectively.
- A comparison of bus emissions by emission control technology showed that the measured emissions of all pollutants (except uvSmoke) generally trended downward with improving emission standard. However, the relative

improvement in the measured emissions was not as great as the expected relative improvement based on emissions standards.

The results of this diesel emissions programme has already proved invaluable for the identification and assessment of the key trends that influence the emissions performance of the fleet and its principal components. Consequently, the principal recommendation of this work is to continue with regular roadside remote sensing, perhaps once every two years.

10 References

ARC (2003). *On-Road Remote Sensing of Vehicle Emissions in the Auckland Region* Report prepared by G. Fisher, J. Bluett, S. Xie and G Kuschel for Auckland Regional Council, ARC Technical Report, TP198, August 2003.

ARC (2005). *Bus Emission Prediction Model, Version 1.0*, CD-ROM of model and supporting documentation prepared by G. Kuschel, J. Metcalfe and S. Elder for Auckland Regional Council, 31 May 2005.

ARC (2006). *Auckland Air Emission Inventory: 2004*. Report prepared by J. Metcalfe, G. Fisher, M. Sherman, and G. Kuschel for Auckland Regional Council, ARC Technical Publication 292, February 2006

ARC (2010). *Remote Sensing of Vehicle Emissions 2005: "The Big Clean Up "Tune Your Car" Campaign*. Report prepared by J. Bluett, K. Dey, and G. Kuschel for Auckland Regional Council, ARC Technical Report No. 2010/028, July 2010

Bishop G.; Stedman D. (2005). *On-Road Remote Sensing of Automobile Emissions in West Los Angeles: Year 4,* available from www.feat.biochem.du.edu/assets/databases/Cal/LaBrea_Year_4_CRC_2005.pdf, 4 October 2005

California Air Resources Board (CARB), (2008). *Evaluation of Remote Sensing for Improving California's Smog Check Program*, Final Report, available from www.arb.ca.gov/msprog/smogcheck/march08/rsd_study_final_report.pdf, 3 March 2008

DEFRA (2003). *Air Quality Expert Group: Report on Nitrogen Dioxide in the United Kingdom.* Prepared for Department of Environment, Food, and Rural Affairs, UK

MoT (2010). *The New Zealand Vehicle Fleet: Annual Fleet Statistics 2009*. Report prepared by the Ministry of Transport, March 2010

NZTA (2009). Motor Vehicle Register, Data provided by New Zealand Transport Agency. November 2009.

Pokharel S.; Stedman D.; Bishop G. (2000). *RSD versus IM240 Fleet Average Correlations*. Technical report, available from www.feat.biochem.du.edu/assets/reports/RSD IM1240 comparison.,pdf

Pokharel S.; Stedman D.; Bishop G. (2002). An On-road Vehicle Emissions Inventory for Denver, an Efficient Alternative to Modelling. *Atmospheric Environment* **36**: 5177-5184, 2002

Stedman D.H. and Bishop G.A. (2002). *Opacity Enhancement of the On-Road Remote Sensor for HC, CO and NO*. Technical Report E056-2 available from www.feat.biochem.du.edu/assets/reports/E56_report_2002.pdf

Walsh P.A.; Sagebiel J.C.; Lawson D.R.; Knapp K.T.; Bishop G.A. (1996). Comparison of Auto Emissions Measurement Techniques, *Science of the Total Environment* **189/190:** 175-180, 1996

Williams M.; Bishop G.; Stedman D. (2003). *On-Road Remote Sensing of Automobile Emissions in the LaBrea Area: Year 2*. Technical report available from www.feat.biochem.du.edu/assets/databases/Cal/La_Brea_Year_2_CRC_2001.pdf

11 Glossary

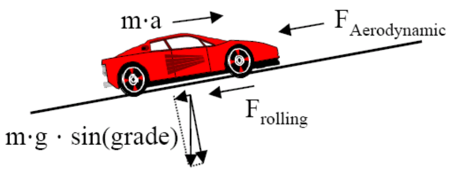
Terms	Definition
ARC	Auckland Regional Council
CO	Carbon monoxide, a type of air pollutant
CoF	Certificate of Fitness, a mandatory check to ensure the roadworthiness of commercial vehicles
CO_2	Carbon dioxide, a type of greenhouse gas
Gross emitter	Vehicle whose emissions fall in the top 10 per cent of the readings for the fleet it is part of
GVM	Gross vehicle mass, kg
HC	Hydrocarbons, a type of air pollutant
HDD	Heavy duty diesel vehicle, usually with a GVM over 3,500kg
IM240	The IM240 test is a chassis dynamometer schedule used in the USA for emission testing of in-use light duty vehicles in inspection & maintenance programs.
IR	Infrared light, includes wavelengths in the range 750 nm and 100 µm
K-W test	Kruskall-Wallis test of significant difference
LDD	Light duty diesel vehicle, usually with a GVM under 3,500kg
MoT	NZ Ministry of Transport
NIWA	National Institute of Water and Atmospheric Research Ltd
NO	Nitric oxide, a precursor to the formation of NO_2
NO_2	Nitrogen dioxide, a type of air pollutant
Opacity	A measure of the ability of a plume to absorb and scatter light, sometimes referred to as smokiness and used as a proxy for PM emissions
PM	Particulate matter
PM_{10}	Fine particles less than 10 microns in diameter, a type of air pollutant
ppm	Parts per million

RSD	Remote sensing device
TARE weight	The weight of the unloaded vehicle.
UV	Ultraviolet light, includes wavelengths in the range 10 nm to 400 nm
uvSmoke	A measure of the opacity but in the UV spectrum, sometimes used as a proxy for PM emissions
VSP	Vehicle specific power, a measure indicating whether a vehicle is operating within an accepted power range
WoF	Warrant of Fitness, a mandatory check to ensure the roadworthiness of private vehicles

Appendix 1: Calculation of vehicle specific power

A1.1 Definition of VSP

In remote sensing studies, vehicle specific power (VSP) is a useful performance measure for determining whether a vehicle is operating within an acceptable power range to get representative data from the RSD. 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 as shown in the following diagram.



$$
\begin{aligned}
VSP = \frac{\text{Power}}{\text{Mass}} &= \frac{\frac{d}{dt}(E_{\text{Kinetic}} + E_{\text{Potential}}) + F_{\text{Rolling}} \cdot v + F_{\text{Aerodynamic}} \cdot v + F_{\text{internal friction}} \cdot v}{m} = \\
&\approx v \cdot a \cdot (1+\varepsilon_i) + g \cdot \text{grade} \cdot v + g \cdot C_R \cdot v + \frac{1}{2}\rho_a C_D \frac{A}{m}(v+v_w)^2 \cdot v + C_{if} \cdot v = \\
&\approx 1.1 \cdot v \cdot a + 9.81 \cdot \text{grade} + 0.213 \cdot v + 0.000305 \cdot (v+v_w)^2 \cdot v
\end{aligned}
$$

Where:

v is the vehicle speed assuming no headwind (m/s)

a is the vehicle acceleration (m/s^2)

grade is the road grade at the monitoring location (%)

v_w is the windspeed at the monitoring location (m/s)

VSP is the vehicle specific power (kW/tonne)

VSP is a convenient measure that can be used directly to predict emissions and is a common metric for remote sensing, inspection and maintenance test, drive cycles, and emissions models. It allows comparison of results of different methods and conditions, such as IM240 drive cycle tests and remote sensing.

A1.2 Use of VSP to validate the HDD/LDD results

As discussed in section 2.1.4, the emissions dataset from a vehicle is only considered valid if its VSP falls between zero and 40 kW/tonne. This subsection presents the results for the monitored diesel fleet to confirm that the emissions data analysed in the body of the report were generated from vehicles with valid VSP readings.

Figure A1.1 displays the profile of VSP by vehicle type of the monitored diesel fleet and shows that all of the readings are within the valid range of 0 to 40 kW/tonne.

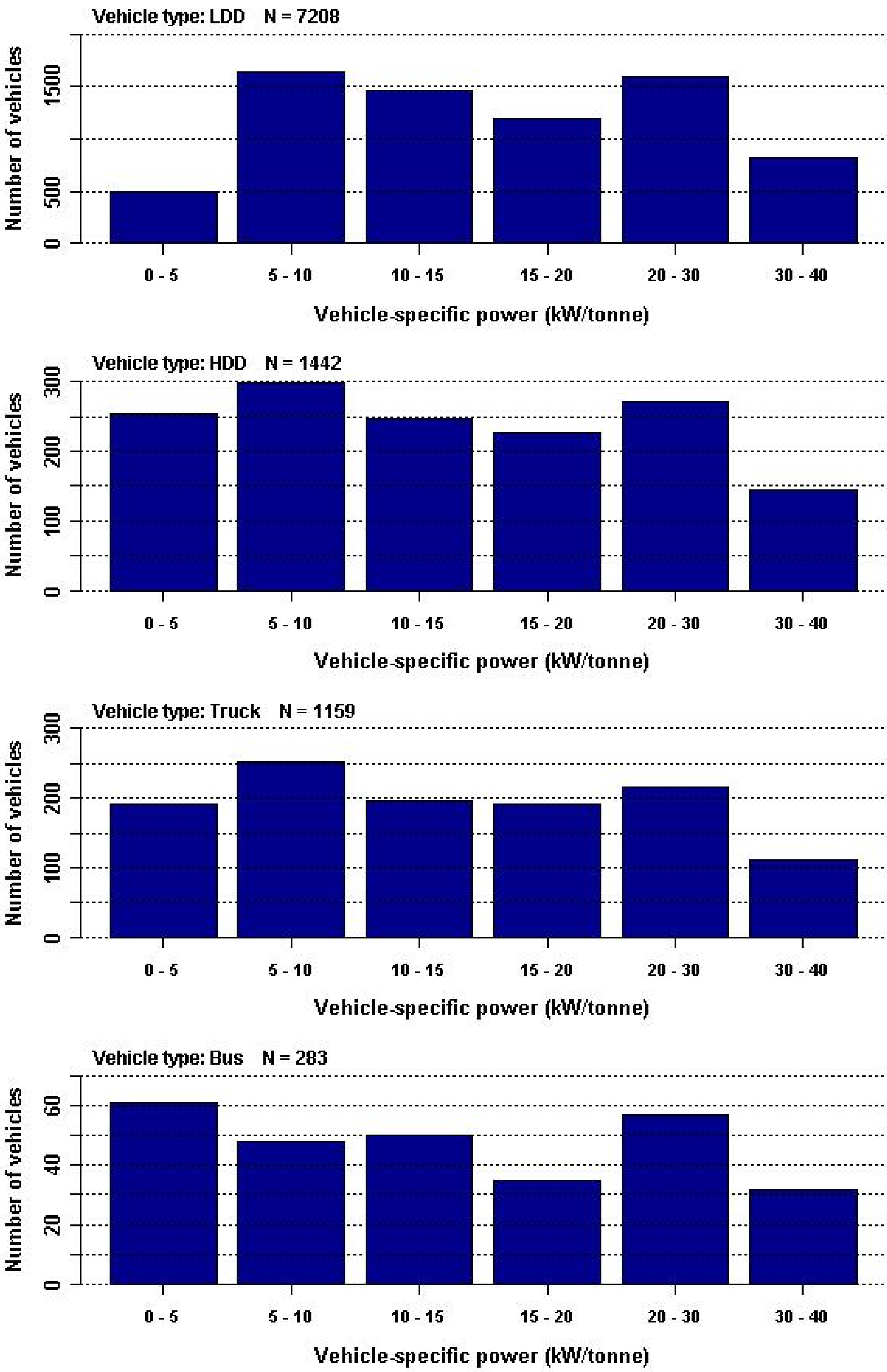


Figure A1.1 Profile of VSP by vehicle type

A1.2.1 Light duty vehicles

Figure A1.2 compares the emissions from the LDD vehicle fleet by VSP and confirms that:

- Emissions of CO, HC and NO are largely independent of VSP for LDD vehicles; and
- uvSmoke emissions increase slightly with VSP. Uvsmoke emissions for VSP (30-40 kW/tonne are significantly higher than for VSP <15 kW/tonne.

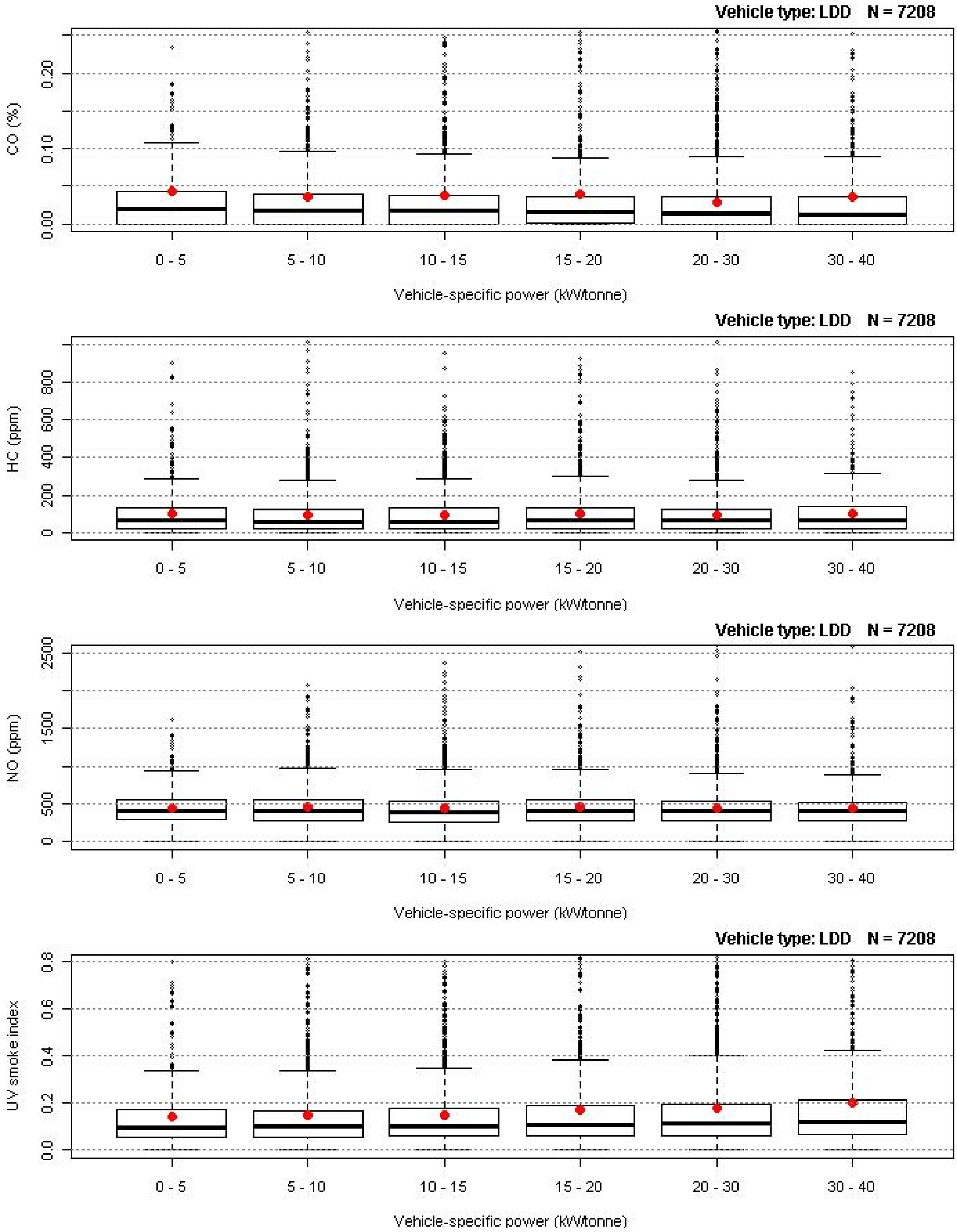


Figure A1.2 Comparison of emissions from the LDD vehicle fleet by vehicle specific power

A1.2.2 Heavy duty vehicles

Figure A1.3 compares the emissions from the HDD vehicle fleet by VSP and confirms that:

- Emissions of CO, HC and NO are largely independent of VSP for HDD vehicles.
- uvSmoke emissions increase slightly with VSP. . Uvsmoke emissions for VSP 30-40 kW/tonne are significantly higher than for VSP <15 kW/tonne.

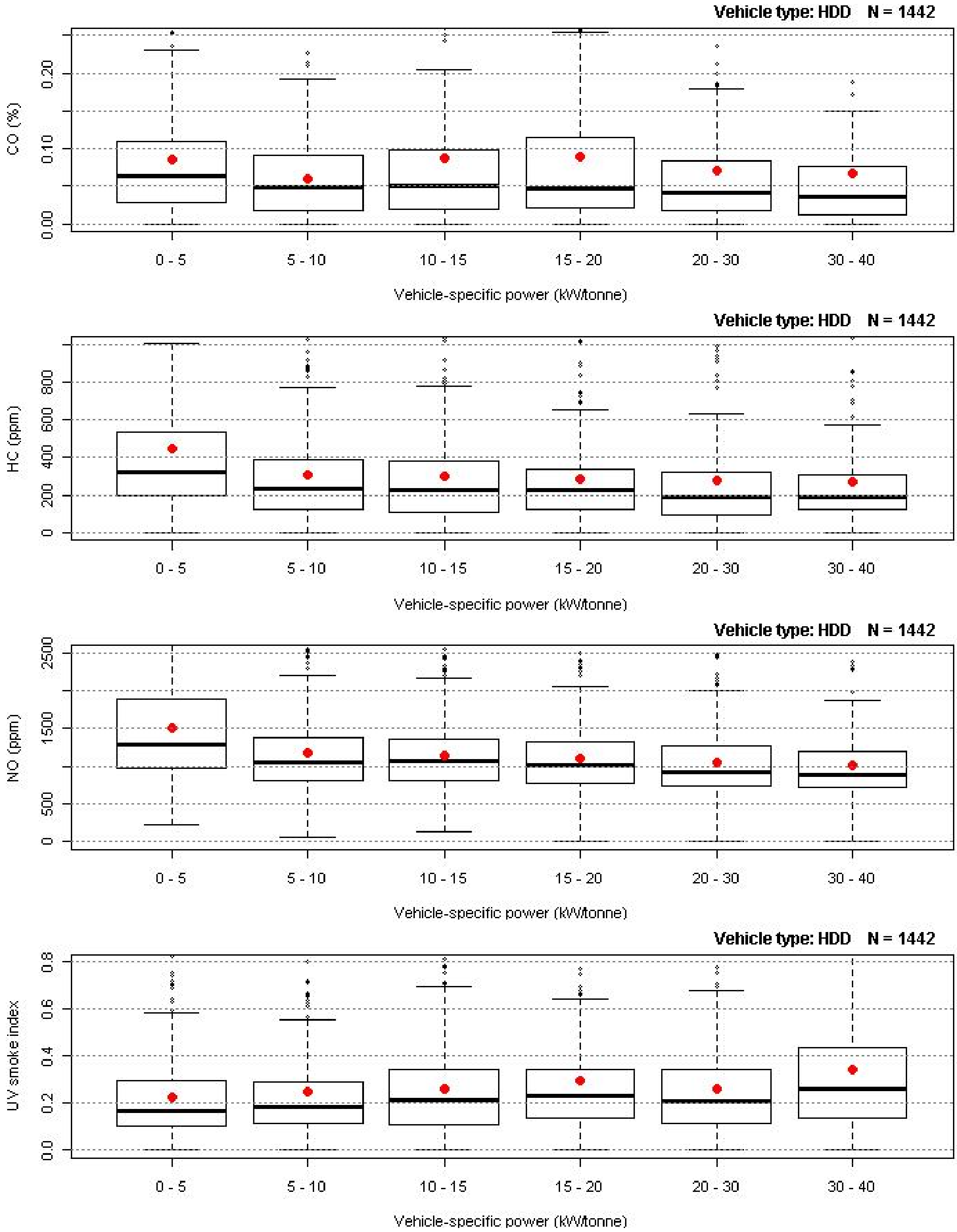


Figure A1.3 Comparison of emissions from the HDD vehicle fleet by vehicle specific power

Appendix 2: Skewed (non-normal) nature of vehicle emission data

This appendix discusses the skewed nature of the of the RSD vehicle emission data, (i.e. it does not form a normal distribution) and why we need to use non-parametric statistical methods to analyse the data.

Figure A1.1 shows a typical box plot of carbon monoxide (CO) emissions from petrol and diesel vehicles measured in the 2005 roadside monitoring campaign. The horizontal red line shows the median (50th percentile), the horizontal blue lines of the box are the quartiles (25th and 75th percentiles). The whiskers extend to 1.5 times the inter-quartile range. Red + signs mark statistical outliers. The long stream of outliers above each box confirms that the data are skewed to the right (i.e. towards high values).

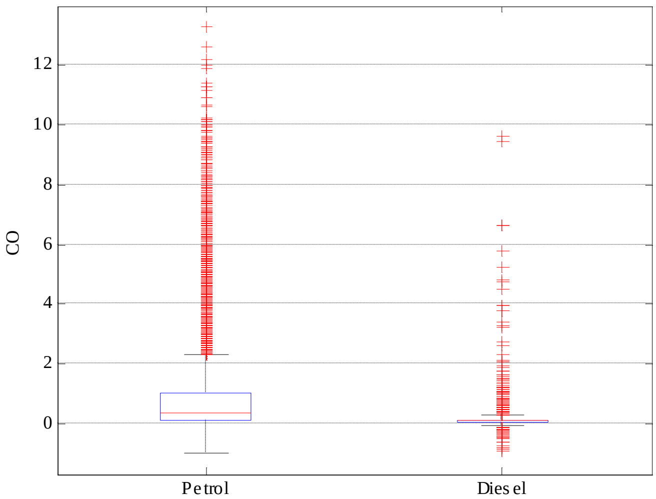


Figure A2.1 Box and whisker plot of CO emissions from petrol and diesel vehicles

Figure A1.2 shows a normal probability plot for the CO emissions from petrol cars. A normal probability plot is a statistical way of comparing the actual distribution of the data to a normal distribution. If the data are normally distributed then the blue crosses should line up along the red line. For this dataset, the blue crosses deviate far from the red line so the data are not normally distributed.

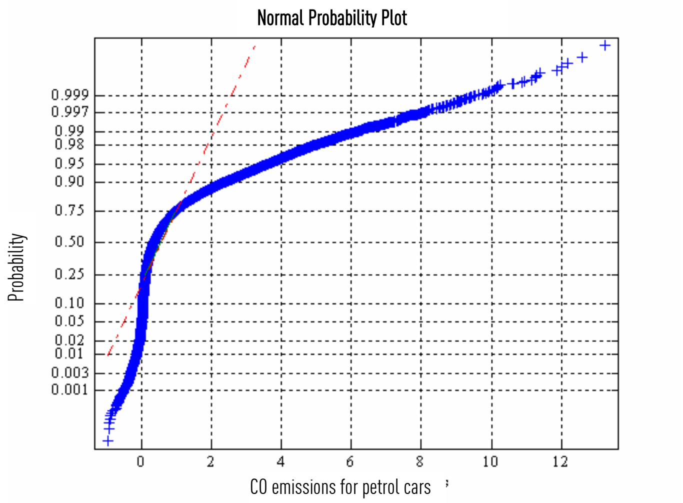


Figure A2.2 Normal probability plot of CO emissions from petrol vehicles

A histogram is another way to show graphically the distribution of the data. Figure A2.3 shows a histogram for the CO emissions from petrol vehicles. The red line shows where the tops of the blue bars should come to if the data were normally distributed. The dataset peaks well to the left of centre of the normal distribution and has a long tail to the right. The distribution of the data is very different from a normal distribution.

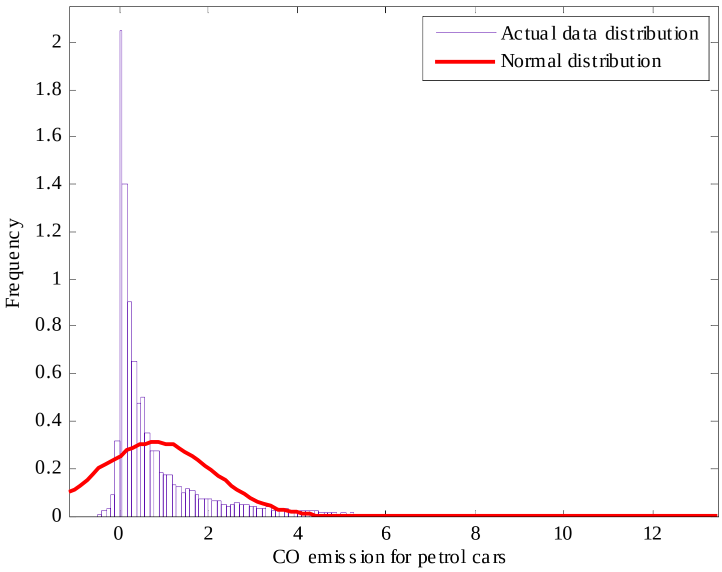


Figure A2.3 Histogram of CO emissions from petrol vehicles

The Lilliefors test is another statistical test of whether data are normally distributed or not. It evaluates the hypothesis that X has a normal distribution with unspecified mean and variance, against the alternative that X does not have a normal distribution. The

Lilliefors test confirms that the vehicle emissions data are definitely not normally distributed.

Skewed datasets can be analysed using the Kruskal-Wallis (K-W) test (a non-parametric[4] one-way analysis of variance). This test does not assume that the data come from a *normal* distribution (though it does assume that all data come from the *same* distribution). The routine converts all values to ranks before analysis, thereby creating a uniform distribution. Therefore the K-W test is an appropriate and useful tool to analyse highly skewed data sets, such as real-life vehicle emissions.

The routine tests the hypothesis that all samples have the same median rank, against the alternative that the median ranks are different. The routine returns a *p*-value for the likelihood that the observed differences could occur purely by chance.

A set of example results for the K-W test for significant differences is provided in Appendix 3.

[4] A parametric test is a statistical test that depends on an assumption about the distribution of the data, e.g., that the data are normally distributed. Therefore a *non*-parametric test does not rely on having to know the distribution of the data in advance.

Appendix 3: Example results for the Kruskal-Wallis test for significant differences

In the body of this report, the Kruskall-Wallis (K-W) test has been applied to each analysis to establish whether the results presented are indeed significantly different or not. However, for the sake of brevity, the actual K-W analysis for each is not presented in the report. This appendix takes one example and shows what the corresponding K-W analysis looks like to indicate how the conclusions in the text have been reached.

Figure A3.1 repeats Figure 4.1 and compares various emissions by vehicle type.

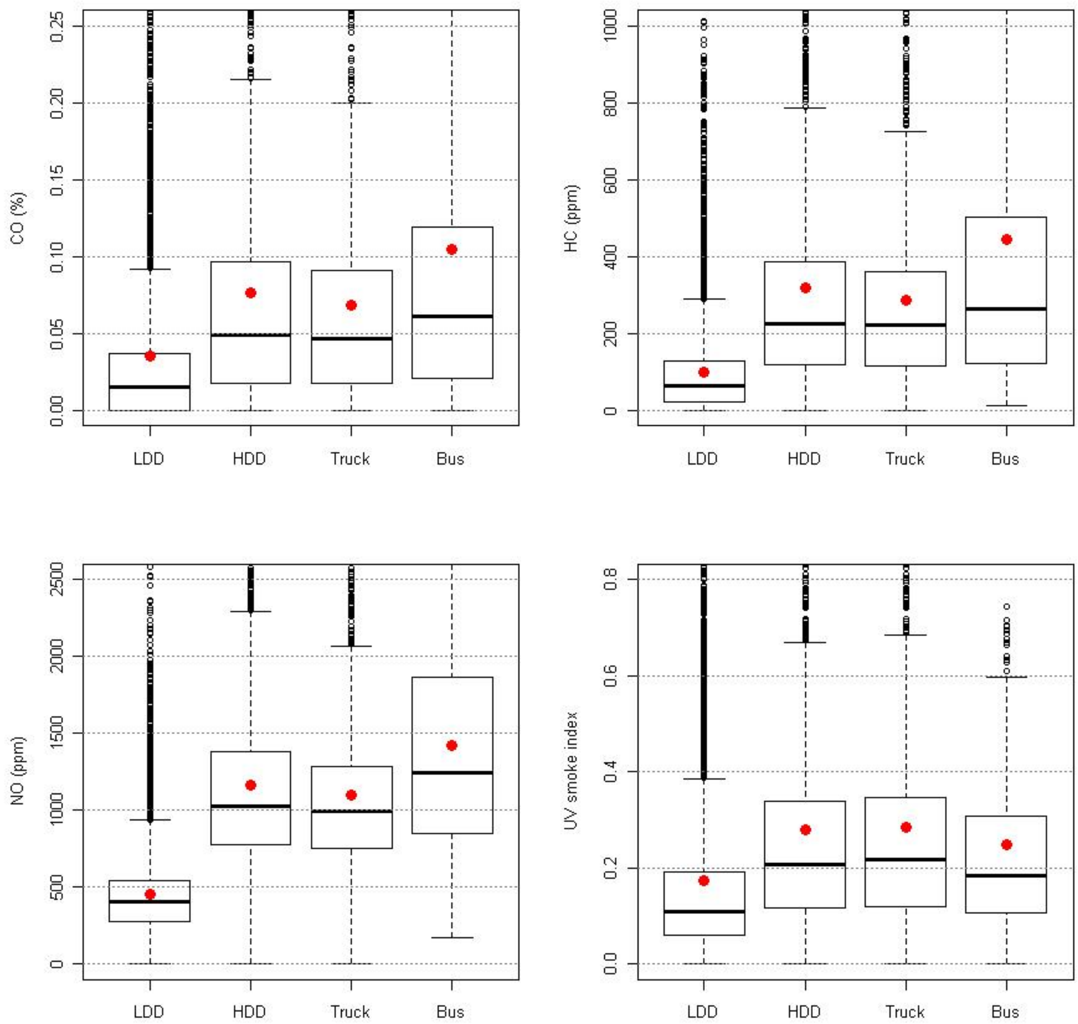
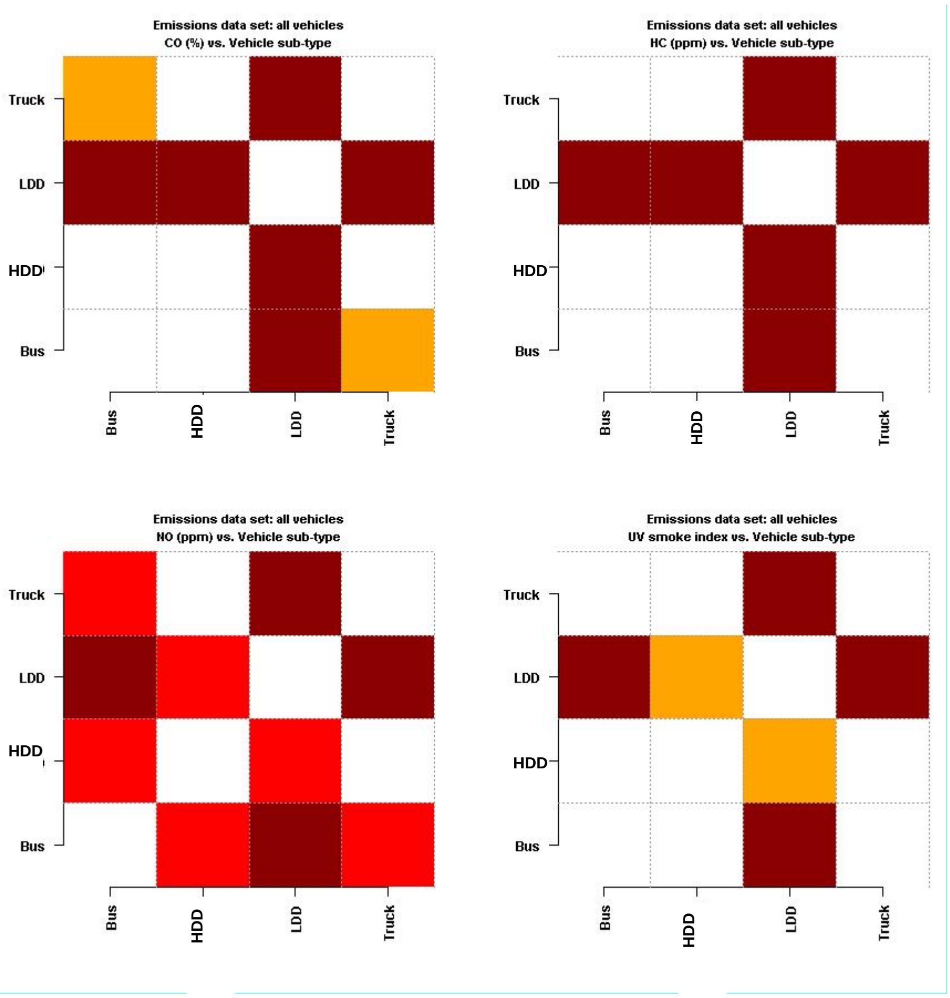


Figure A3.1 Pollutant emissions by vehicle type

The results presented *suggest* that emissions from heavy duty diesel vehicles are significantly worse than those from light duty diesel vehicles for all pollutants, with buses being particularly bad for all except possibly uvSmoke.

In order to test whether these apparent differences are *statistically significant*, the data are subjected to the Kruskal-Wallis test, as shown in the matrix plots summarised in Figure A3.2.

Figure A3.2 K-W significant difference matrix plot for vehicle type



Each of the four plots presents the results for the different pollutants (CO, HC, NO and uvSmoke). The *x* and *y* axes show the vehicle types[5] considered in the comparison. Note that the top half of each matrix is a mirror image of the bottom half and therefore is redundant. Each cell in the matrix compares two vehicle types. If the cell is uncoloured, the difference between vehicle types is not significant a the 95%

[5] Note that in Figure A3.2, "HDD (other)" covers large diesel motor homes, of which there were less than ten in the entire dataset, and these were not considered in the analysis.

confidence interval (CI). If the cell is colour coded "orange", the difference between the two vehicles types is significant at the 95% CI,. "Red" indicates a difference at the 99% CI and "deep red/brown" a difference at the 99.9% CI.

Referring back to Figure A3.1, Figure A3.2 confirms that the emissions of CO from:

- HDD Trucks and HDD Buses are indeed significantly different (higher) from LDDs at the 99.9% CI
- HDD Buses are indeed significantly different (higher) from HDD Trucks at the 95% CI