Testing New Zealand vehicles to measure real-world fuel use and exhaust emissions

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Executive summary

Research overseas has found that vehicles on the road consume more fuel and produce higher exhaust emissions under real-world driving conditions than the values to which they are type approved when manufactured. New Zealand vehicles enter the fleet either as new vehicles or as used vehicles imported from a range of countries as we do not manufacture vehicles here. While exhaust emissions standards are regulated at the border, New Zealand does not currently regulate fuel economy. Consequently, the fleet is strongly influenced by international requirements and trends, with vehicles arriving that meet a diverse range of standards, including Japanese, European and Australian. The NZ Transport Agency's Vehicle Emission Prediction Model (VEPM) is used to model emissions and fuel consumption of New Zealand vehicles for assessing environmental impacts and fleet trends. However, the diversity of standards in use and the subsequent real-world performance can introduce considerable uncertainty into the prediction.

The purpose of this project was to improve our understanding of real-world fuel consumption and vehicle exhaust emissions from the New Zealand fleet. A key outcome was to provide real-world data for a separate future review and update (if appropriate) of VEPM emissions factors to better reflect actual fuel consumption and emissions.

The research commenced in 2016 with a literature review and desktop fuel consumption study of previous international and New Zealand studies. This uncovered considerable uncertainty about real-world fuel consumption and exhaust emissions from diesel vehicles, in particular, which influenced the selection of test vehicles.

The second stage in 2017 focussed on developing a suitable methodology for robustly measuring the real-world emissions of a representative cross-section of the New Zealand fleet. A range of testing methods were assessed with portable emissions monitoring systems (PEMS) offering the best solution. A purpose built system was designed to measure key pollutants, including carbon dioxide (CO_2), oxides of nitrogen (NO_X), nitrogen dioxide (NO_2) and fine particulate matter ($PM_{2.5}$), together with speed, acceleration, gradient and other vehicle operating conditions. Preliminary testing was undertaken to trial the equipment and to identify a suitable real-world test route in Auckland that simulated the range of typical New Zealand road conditions.

Testing commenced in earnest in early 2018 using vehicles selected to represent the most common and influential sectors of the New Zealand fleet. PEMS measurements were gathered for thirty two vehicles in total, comprising six light duty petrol vehicles, 20 light duty diesel vehicles and six heavy duty diesel vehicles, and covering years of manufacture from 1996 to 2014 with both New Zealand-new vehicles and Japanese-used imports.

The key findings were:

- Real-world NO_x emissions were generally higher than regulated emission standards, with results approximately 4.6 times higher on average (ranging from two to nearly eight times the limit). Real-world $PM_{2.5}$ emissions for light duty vehicles were similar to the regulated emissions standards and real-world CO_2 emissions were on average 17% higher than type-approval fuel consumption figures.
- Little improvement was seen in real-world emissions of NO_x with improving emissions standards (up to and including Euro 5/V). However, $PM_{2.5}$ emissions were dramatically reduced in late model diesel vehicles (reflecting the effectiveness of the diesel particulate filters fitted to these vehicles).
- There was little evidence of fuel consumption improvements over time, with real-world CO_2 emissions typically in the range of 200 g/km to 300 g/km, irrespective of duty or fuel type.

- Our real-world results were consistent with those from recent studies undertaken in Europe and Australia.

We compared emissions factors from this PEMS study with those from VEPM and found:

- There were differences, sometimes significant, between VEPM emissions factors and those derived from the PEMS results. These differences were observed for all vehicles tested, throughout the speed bins analysed, and were generally not unexpected as they reflected the difference between real-world emissions and an emissions model. An emissions model is intended to represent average emissions from an average vehicle at a specified speed.
- VEPM does a reasonable job of estimating the effects of uphill gradient on emissions. However, it appears to over-estimate the reduction in emissions when vehicles travel downhill.
- Comparisons with cold start emission ratios in VEPM suggest VEPM would under-estimate average emissions from our test vehicles over the first 3 km of the trip.

Several recommendations are made to improve VEPM's ability to predict real-world harmful emissions from New Zealand vehicles including:

- Discussing the discrepancy between real-world emission factors and emission factors in VEPM with the developers of the European emission factors (on which VEPM is based).
- Reviewing VEPM emissions factors based on the findings of this study and other New Zealand and international evidence, and updating VEPM factors as appropriate.
- Investigating real-world $PM_{2.5}$ emissions from heavy duty diesel vehicles further to confirm whether VEPM is under-estimating these emissions and, if so, by how much.
- Reviewing vehicle classifications in VEPM to improve predictions of real-world emissions from large diesel SUVs for a range of pollutants - NO_X, $PM_{2.5}$ and CO_2.
- Investigating in more detail the impact of vehicle types, loads (laden vehicle mass), speed and route characteristics on real-world fuel consumption and emissions of heavy duty diesel vehicles.
- Assessing whether the Ministry of Transport real-world fuel consumption factors for New Zealand could be incorporated into VEPM to better predict CO_2 emissions.
- Combining remote sensing data with PEMS data to develop adjustment factors for VEPM (if appropriate) to account for unique features of the New Zealand fleet (especially Japanese-used vehicles and the prevalence of large/heavy vehicles compared with Europe).

Abstract

The purpose of the research was to better understand real-world fuel consumption and vehicle exhaust emissions from the New Zealand fleet and use this knowledge to improve the ability of the Transport Agency's Vehicle Emissions Prediction Model (VEPM) to predict actual emissions.

A portable emissions monitoring system (PEMS) was developed to measure real-world emissions from a range of typical New Zealand vehicles on a route typical of New Zealand conditions. Testing was undertaken in Auckland between January and May 2018 on six light duty petrol vehicles, 20 light duty diesel vehicles and six heavy duty diesel vehicles, including New Zealand-new and Japanese-used imported vehicles manufactured between 1996 and 2014.

As expected, our testing found that real-world emissions of most pollutants were higher than regulated standards (up to eight times). The real-world NO_x results were comparable to real-world emissions from Europe and Australia for similar vehicles.

Although based on real-world factors, VEPM emissions factors were found to be different from those derived from the PEMS results in this study for all vehicles tested and all speed bins analysed.

Recommendations have been made to improve and update VEPM utilising the results of this study and other international and New Zealand evidence. Additional testing of heavy duty diesel vehicles is recommended to better predict emissions and fuel consumption from this class of vehicles.

1 Introduction

1.1 Research purpose

The purpose of this research project was to improve understanding of both real-world fuel consumption and real-world emissions from the New Zealand vehicle fleet.

This improved understanding was intended to be translated into improved emissions factors for incorporation in the NZ Transport Agency’s (the Transport Agency) Vehicle Emission Prediction Model (VEPM) to enable the model to better reflect the current state and more reliably assess the impacts of future trends/interventions on harmful emissions and fuel consumption from New Zealand vehicles.

1.2 Research objectives

The objectives of this research were to:

1. Develop a New Zealand on-road vehicle exhaust and fuel consumption testing methodology outlining:
    a. testing/monitoring techniques and equipment
    b. parameters to be monitored
    c. number and type of vehicles to be tested, and how these represent the New Zealand vehicle fleet
    d. operating conditions under which the vehicles would be tested
    e. how test vehicles will be obtained.
2. Carry out real-world testing on typical New Zealand vehicles under typical New Zealand driving conditions for the key air pollutants of concern:
    a. fuel consumption/carbon dioxide (CO_2)
    b. fine particulate matter ($PM_{2.5}$)
    c. oxides of nitrogen (NO_X which is made up of NO and NO_2).
3. Investigate the reasons for differences between expected results (based on the outcomes of the literature review, emission factors in VEPM and type-approval values) and the actual findings.
4. Develop revised emissions factors for later incorporation into VEPM, where appropriate, based on the outcomes of the research to enable the model to better reflect real-world fuel consumption and emissions from the New Zealand fleet.

1.3 Method overview

The key steps involved in the project included:

1. Reviewing published literature on real-world testing.
    a. Was there real-world fuel consumption and emissions data available from overseas for vehicles commonly found in the New Zealand fleet? What were the key data gaps?
    b. What real-world fuel consumption and emissions data was already available in New Zealand?

2 Conducting a desktop study of real-world fuel consumption in New Zealand.
   a How well did VEPM predict real-world fuel consumption?
   b Could we identify vehicle types where VEPM was less realistic?
3 Designing a robust methodology for a suitable portable emissions measurement system (PEMS) testing programme.
4 Trialling the PEMS equipment and comparing results obtained for a vehicle tested on-road with results from a chassis dynamometer.
5 Undertaking PEMS testing on-road for a full subset of vehicles, representative of the New Zealand fleet.
6 Reviewing the results and reporting key findings.

1.4 Project outputs

The project commenced in October 2016, with trials conducted in November 2017, on-road PEMS testing undertaken in Auckland between January and April 2018, and data analysis/reporting completed by August 2018.

The deliverables from this project consisted of the following outputs:

1 A review and assessment of New Zealand and overseas literature.
2 A brief (peer-reviewed) report recommending a comprehensive methodology for on-road monitoring of fuel consumption and emissions in New Zealand.

   Note: After discussion with the Steering Group, deliverables 1 and 2 above were combined into a single report and presented at a meeting in December 2016. The key findings are summarised in this research report.

3 A comprehensive final report outlining the project objectives, methodology, findings and implications, including:
   a an assessment of on-road fuel consumption and exhaust emissions by vehicle type and driving conditions
   b discussion of the reasons for any differences between predicted and real-world results
   c comparison of the project findings with published literature.
4 An electronic database of all on-road measurements (including fuel consumption, emissions, speed acceleration, gradient and other vehicle operating conditions) for the vehicles tested.
5 A set of powerpoint slides explaining the research and its findings (presented to the Steering Group).

1.5 Report structure

The report is structured as follows:

- Chapter 2 gives a background to the research.
- Chapter 3 discusses the findings from the literature review and desktop fuel consumption study.
- Chapter 4 describes the methodology employed for the testing including:

  - design of the equipment
  - selection of representative vehicles
  - identification of a suitable real-world route
  - development of the on-road procedure
  - description of the data quality assurance and analysis protocols.
- Chapter 5 presents the results.
- Chapter 6 presents the overall conclusions and recommendations.

A series of technical appendices is located at the end, including a glossary (appendix F).

2 Background to the research

2.1.1 Which air pollutants are associated with vehicle emissions?

Urban air pollution is a complex mixture of gases and particles, with pollutants typically split into harmful air pollutants (which cause adverse human health effects and impact locally) and greenhouse gases (which contribute to global warming and impact globally).

For vehicles, the pollutants of most concern include:

- Particulate matter smaller than 10 µm in diameter (PM_{10}) and particulate matter smaller than 2.5 µm in diameter ($PM_{2.5}$). PM_{10} and $PM_{2.5}$ impact respiratory and cardiovascular systems, with effects ranging from reduced lung function to increased use of medications to more hospital admissions through to reduced life expectancy and death.
- Nitrogen oxides (NO_X). NO_X includes nitric oxide (NO) and nitrogen dioxide (NO_2). NO_2 is a gas that causes increased susceptibility to infections and asthma. It reduces lung development in children and has been associated with increasingly more serious health effects, including reduced life expectancy.
- Hydrocarbons (HCs). HCs include a wide range of chemicals, some of which are carcinogenic to humans. HCs can also react with NO_x in the presence of sunlight to form ozone (O_3), which is a lung irritant.
- Carbon dioxide (CO_2). CO_2 is the primary contributor to global warming.

Motor vehicle emissions result largely from the combustion of fossil fuels but can also occur from road abrasion and tyre and brake pad wear as well as fuel evaporation.

2.1.2 How are vehicle emissions regulated in New Zealand?

2.1.2.1 Exhaust emissions standards for vehicles entering the fleet

In New Zealand, vehicles enter the fleet either as new vehicles or as used vehicles imported from a range of countries because we do not manufacture vehicles here.

Prior to 2003, New Zealand did not regulate emissions standards at the border. However, this changed with the introduction of the Vehicle Exhaust Emissions Rule in 2004, which has since been regularly amended to incorporate improved standards as they have become available (NZ Transport Agency 2016a). The rule specifies minimum emissions standard requirements for used and new vehicles entering the fleet, further broken down by fuel type and vehicle weight. The entry regulations are set by the Ministry of Transport (MoT) but administered by the Transport Agency.

The European or ‘Euro’ standards are among the most common standards specified, although the United States, Japan and Australia also have their own standards. For the Euro standards, higher numbers mean better (more strict) limits. In addition, the standards use Arabic numerals (eg Euro 3 or Euro 5) to indicate they apply to light duty (less than 3.5 tonnes) vehicles and Roman numerals (eg Euro III or Euro V) to indicate they apply to heavy duty vehicles.

From 1 November 2016, all new light and heavy vehicles (irrespective of fuel type) entering the New Zealand fleet were required to meet Euro 5/V emissions standards (or near equivalent from other jurisdictions). All imported used light and heavy vehicles have been required to meet Euro 4/IV (or near equivalent from other jurisdictions) since 1 January 2012. The current Vehicle Exhaust Emissions Rule does not include Euro 6/VI requirements for new vehicles or Euro 5/V requirements for used imports.

New Zealand does not currently regulate vehicle fuel economy or set CO_2 standards (which are a function of fuel consumption). Consequently, the fleet is strongly influenced by international requirements and trends, with vehicles arriving that meet a diverse range of standards, including Japanese, European and Australian.

2.1.2.2 Rules for performance of in-service vehicles

Regulation of in-service emissions was first introduced in 2001 with a 10-second rule for excessive smoke from on-road vehicles. This rule was later updated and extended by the following land transport rules:

- The Road User Rule 2004 prohibits a vehicle from emitting visible smoke for 10 or more seconds while being driven on the road (NZ Transport Agency 2005). This is enforced by the Police.
- The Vehicle Exhaust Emissions Rule 2007 prohibits removal of, or tampering with, a vehicle's emissions control equipment and requires a vehicle to pass a five-second visible smoke check during a warrant of fitness or certificate of fitness inspection (NZ Transport Agency 2016a).

2.1.3 Why do 'real-world' emissions matter?

Studies carried out overseas and in New Zealand have found that vehicles on the road generally emit more in the 'real world' (ie when being driven on real roads experiencing real traffic conditions) than the emissions standards to which they are 'type approved' (ie being driven in a laboratory according to test conditions designed to simulate real-world driving).

The International Council on Clean Transportation (ICCT) reviewed various fuel consumption studies and found that vehicles in Europe are emitting significantly more CO_2 in the real world than their official CO_2 values and that this gap is growing (Tietge et al 2015, Tietge et al 2017). New Zealand trends are similar (Wang et al 2015).

For harmful emissions, the gap between real world and type approval is even more pronounced. In 2014, the ICCT published an analysis of the results from testing using PEMS of 15 different late model diesel passenger cars (Franco et al 2014). The authors found average, real-world emission levels of NO_x to be seven times higher than the emission standard.

Effective management of the impacts of motor vehicles, especially in urban areas, requires good understanding of real-world emissions. Emissions information is critical for assessing the environmental effects of transport projects. It is also vital for monitoring fleet trends and for evaluating the effectiveness of interventions. Modelling emissions based on type-approval limits rather than real-world performance can result in considerable under-estimation of impacts.

In New Zealand, the Transport Agency's VEPM is the principal tool used to model harmful emissions and fuel consumption of vehicles (NZ Transport Agency 2018). It was developed by the Transport Agency and Auckland Council to predict emissions from vehicles in the New Zealand fleet under typical road, traffic and operating conditions. VEPM is a speed-based model with emission factors taken from international emissions databases designed to reflect the real world (eg the European Environment Agency (EEA) 2016). However, the diversity of standards in use in New Zealand and the subsequent real-world performance can introduce considerable uncertainty into future predictions.

2.1.4 How can real-world emissions be measured?

Internationally, common methods for measuring emissions from individual vehicles include chassis dynamometer testing, remote sensing and portable emissions monitoring. Each method has its advantages and limitations depending on the purpose of the testing.

2.1.4.1 Chassis dynamometer testing

Historically, 'type-approval testing' (ie confirming a vehicle model complies with its regulated emissions standard) has been performed under controlled conditions using a chassis dynamometer (see figure 2.2).

Figure 2.2 Vehicle undergoing chassis dynamometer testing at the Energy and Fuels Research Unit, University of Auckland

During chassis dynamometer testing, the test vehicle is driven on a set of rollers that simulate driving resistances according to a standard time/velocity profile known as a 'drive cycle' (Franco et al 2014). The emissions of the test vehicle are collected and then compared with the exhaust (harmful) emission standard (eg Euro 5) or the applicable fuel consumption limit. The standard drive cycles used for type-approval testing include a prescribed set of typical driving events (eg cold start, warm start, accelerations, decelerations and steady state driving) but typically under-represent real-world emissions.

However, if real-world drive cycles are used, dynamometer testing can be invaluable for developing emission factors and testing the influence of individual parameters such as vehicle speed (Franco et al 2013). Emission factors in VEPM are based primarily on the European COPERT emission factors (EEA 2016). These factors have been developed by compilation of data across Europe from chassis dynamometer emission tests over real-world drive cycles. These drive cycles are designed to represent real-world driving conditions and cover a much wider range of operating conditions compared with type-approval drive cycles. European COPERT emission factors have been validated in Europe in several studies by comparison with real-world measurements (Kousoulidou et al 2013).

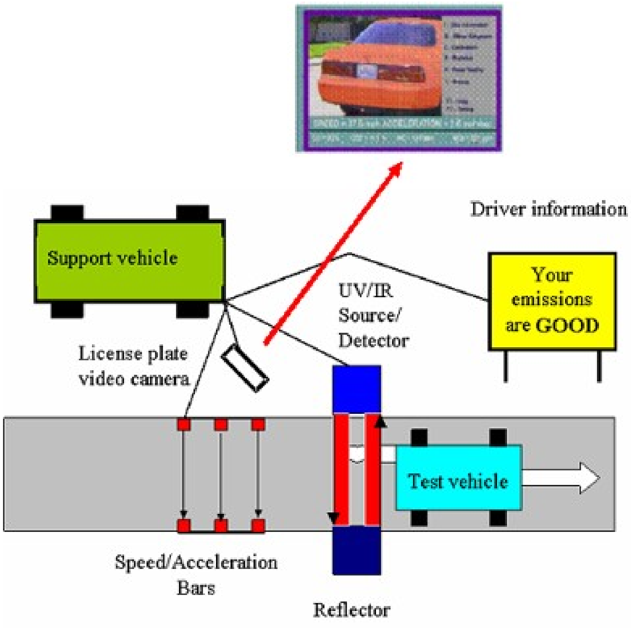
2.1.4.2 Remote sensing devices

Remote sensing refers to measuring vehicle exhaust emissions as the vehicle passes using equipment located on the roadside (known as a remote sensing device or RSD). Unlike chassis dynamometer or PEMS equipment, RSDs do not need to be physically connected and therefore do not interfere with the operation of the vehicle. Infrared (IR) and ultraviolet (UV) light are directed across the road through the exhaust plume then reflected back to detectors (see figure 2.3). Because different pollutants absorb at different wavelengths, the returned light can be analysed and converted into concentrations of the pollutants of interest after background levels are subtracted.

Most commercially available RSD systems incorporate speed and acceleration detectors together with a digital camera. This allows the licence plate details, the vehicle driving conditions and the exhaust emissions data to be simultaneously recorded. This data is sensed and stored, with each remote sensing test taking less than one second.

Remote sensing provides snapshots of emission rates from thousands of individual vehicles, as they are driven on actual roadways by their owners, relatively easily and cost effectively versus other methods. It provides information on trends in fleet and subfleet emissions (if sufficient numbers of vehicles are sampled) and can be used to identify potential 'gross emitters' (ie vehicles that emit considerably more than their type on average due to poor maintenance or tampering). However, while remote sensing is valuable as a screening method, it cannot be used for type approval or compliance because it records only a small fraction of a drive cycle.

Figure 2.3 Schematic diagram showing the remote sensing system in operation (Bluett et al 2011)



2.1.4.3 Portable emissions monitoring systems

The use of PEMS involves carrying a full set of instruments on board the test vehicle to record instantaneous measurements of emissions, engine operating conditions and road conditions while the vehicle drives a real-world route (see figure 2.4).

Figure 2.4 Passenger car instrumented with PEMS (Franco et al 2014)

PEMS equipment has undergone considerable development over the past two decades, with improved gas measurement principles and significant reductions in size, weight and overall complexity (Franco et al 2014). Compared with a chassis dynamometer facility, PEMS are relatively simple and inexpensive to purchase and maintain. PEMS are now used for regulatory purposes in both the United States and Europe to verify the in-service conformity of particular vehicles with the applicable emissions standards.

The results of real-world monitoring techniques are typically less repeatable than those of chassis dynamometer studies, due to the absence of a standard test cycle and the presence of additional sources of variability such as environmental or traffic conditions, driver behaviour or highly transient operation (Franco et al 2013). However, PEMS can cover a wide range of operating conditions that would otherwise be impractical to test in the laboratory.

2.1.4.4 New Zealand vehicle emissions measurements

Both chassis dynamometer testing and remote sensing have been used to measure emissions from New Zealand vehicles previously – most notably reported in Fisher et al (2003), Campbell et al (2006), Bluett and Dey (2007), Bluett et al (2010a), Bluett et al (2010b), Bluett et al (2011) and Bluett et al (2016). However, most of these studies have focused on light duty vehicles, with only limited measurements of heavy duty vehicle emissions due to a lack of suitable facilities.

Prior to this research project, PEMS had not been deployed in New Zealand. PEMS offers significant advantages over the previously used methods for:

1 Assessing the influence of real-world driving on emissions

2 Covering a wide range of operating conditions that would otherwise be impractical to test in the laboratory

3 Testing heavy duty vehicles over realistic drive cycles.

3 Literature review and desktop study findings

This chapter summarises the key findings from the literature review and the desktop study of real-world fuel consumption in New Zealand undertaken in the first phase of the project to inform the development of the methodology.

3.1 Literature review

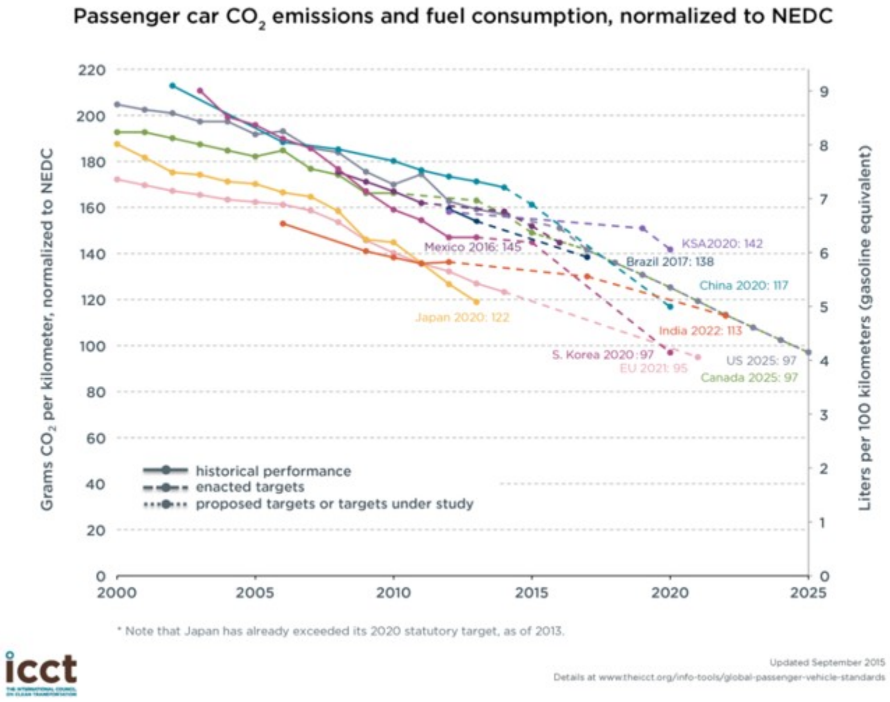
The literature review was undertaken in the initial phase of the project to inform the design and direction. Key questions for the review to address were:

- What information is available on real-world fuel consumption internationally and in New Zealand?
- What information is available on real-world exhaust emissions internationally and in New Zealand?
- Are there any international examples of PEMS test results being used to develop or validate emission factors?

3.1.1 What information is available on real-world fuel consumption internationally?

New Zealand does not have fuel economy standards for vehicles entering the fleet. This means the fuel economy of vehicles entering the fleet is influenced by international requirements and trends. Vehicle fuel consumption standards and targets, as shown in figure 3.1, have required significant improvements in fuel consumption and reduction in carbon dioxide (CO_2) emissions from the light duty vehicle fleet globally. The trends are based on the values to which vehicles are type approved when manufactured. This means the fuel consumption and CO_2 emissions are derived from the results of testing in controlled laboratory conditions over a regulatory (type-approval) drive cycle.

Figure 3.1 International CO_2 emission standards and targets, where NEDC = New European Driving Cycle (ICCT 2015)

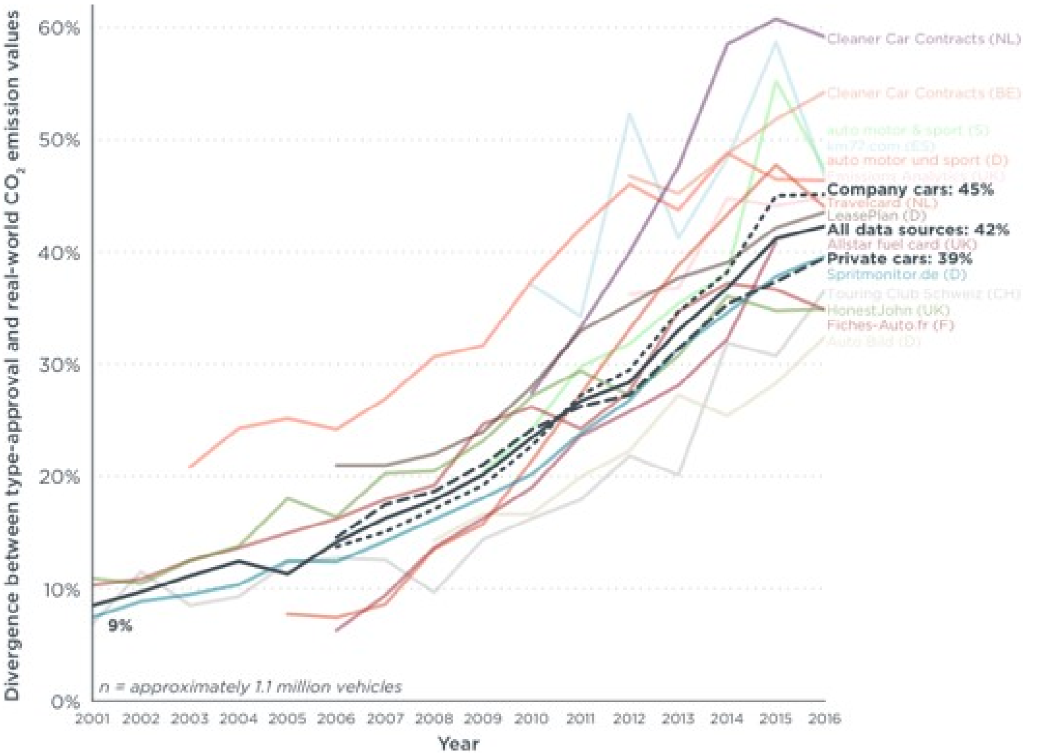


* Note that Japan has already exceeded its 2020 statutory target, as of 2013.

Updated September 2015
Details at www.theicct.org/info-tools/global-passenger-vehicle-standards

Studies carried out overseas have found that vehicles on the road generally consume more fuel than the fuel consumption values they are type approved to when manufactured. Research in Europe has shown this gap between real-world and type-approved fuel consumption is growing (Tietge et al 2015, Tietge et al 2017) as illustrated in figure 3.2.

Figure 3.2 Gap between real world and official CO_2 emission values from various studies (Tietge et al 2017)



Real-world fuel consumption is the average fuel consumption of vehicles operating in the real world under all different driving conditions. It can be estimated from a variety of sources including fuel cards, corporate fleet data and self-reporting websites (eg honestjohn.co.uk). The real-world fuel consumption estimates shown in figure 3.2 are based on a diverse range of vehicles, driving conditions and data sources. The spread in the data shows that real-world fuel consumption factors are not necessarily precise. However, these real-world estimates are the best way to understand how vehicles are performing outside of the laboratory. According to Tietge et al (2015):

> *driving styles and conditions vary widely, rendering elusive a precise technical definition of real-world driving. Nevertheless, aggregating large datasets reveals clear trends in the real-world performance of cars.*

3.1.2 What information is available on real-world fuel consumption in New Zealand?

Real-world fuel consumption factors for diesel and petrol vehicles in New Zealand have been estimated by the Ministry of Transport using fuel consumption and travel data from a large data set of fuel card transactions (Wang et al 2015). These estimates have been used to develop New Zealand real-world fuel consumption factors for vehicles manufactured after 2012, and for all vehicle classes in VEPM (Metcalfe and Sridhar 2016). These factors have been used by the Ministry of Transport to estimate fuel consumption at a national level and have provided reasonable agreement with national fuel sales figures (S Badger, pers comm).

Some key assumptions and limitations of the New Zealand real-world fuel consumption factors are:

- The real-world fuel consumption factors are based on analysis of corporate vehicles, with the majority being manufactured after 2010. There is no real-world fuel consumption data for privately owned or older vehicles in New Zealand (Wang et al 2015). Research has found that corporate vehicles generally consume more fuel than their private counterparts, as shown in figure 3.2 (Tietge et al 2017).
- The fleet analysed to develop New Zealand real-world fuel consumption estimates did not include hybrid or plug-in hybrid vehicles. Real-world fuel consumption factors have been estimated for these vehicles based on the New Zealand real-world fuel consumption factor for the equivalent internal combustion engine, and international data on the relative fuel consumption of hybrid and plug-in hybrid vehicles (Metcalfe and Sridhar 2016).

Finding 3.1

Overall there is good information on average real-world fuel consumption internationally and in New Zealand. Data gaps for the New Zealand fleet are:

- There is no real-world fuel consumption data for privately owned or older vehicles in New Zealand (Wang et al 2015).
- Real-world fuel consumption factors for hybrid and plug-in hybrid vehicles in New Zealand are based on international data on the relative fuel consumption of hybrids and plug-in hybrids versus conventional vehicles.

3.1.3 Real-world emission test methods

Vehicle emission factors are usually developed on the basis of experimental data collected from vehicle emission tests. Emissions can be measured under controlled conditions in laboratories, or in real-world conditions using remote sensing (RSD), tunnel studies, on road (chase) measurements or on board measurements such as PEMS (Franco et al 2013).

3.1.3.1 Chassis dynamometer

During chassis dynamometer testing, the vehicle under test remains stationary on a set of rollers that simulate driving resistance, and its emissions are collected and analysed as it is driven according to a standard time/velocity profile known as the drive cycle (Franco et al 2014).

Emission factors in VEPM are based primarily on the European COPERT emission factors (EEA 2016). These factors have been developed by compilation of data across Europe from chassis dynamometer emission tests over real-world drive cycles. These drive cycles are designed to represent real-world driving conditions and cover a much wider range of operating conditions compared with type-approval drive cycles.

3.1.3.2 Remote sensing

Remote sensing measures the concentration of pollutants in vehicle exhausts as they drive past the measurement device. This provides a snap shot of emissions at a particular location on the road, so it cannot realistically measure emissions over a whole drive cycle. However, remote sensing is valuable because it provides measurements from a large number of real-world vehicles in an on-road situation and it provides complementary information that can be used to check and validate emission factors (NZ Transport Agency 2013).

3.1.3.3 Portable emission monitoring systems

PEMS is a relatively new technology that has developed over the last two decades. PEMS are complete sets of emissions measurement instruments that can be carried on board the vehicle to record instantaneous emission rates of selected pollutants with levels of accuracy that are comparable to laboratory systems. They are a popular tool for scientific studies, and in recent years have also been applied for regulatory purposes (Franco et al 2014).

Key limitations of PEMS are as follows:

- The range of pollutants that can be measured is limited in comparison with laboratory measurements.
- The added mass of the PEMS system may bias the measurement.
- Repeatability is reduced due to real-world sources of variability.

3.1.4 What information is available on real-world exhaust emissions internationally?

In recent years, international research has highlighted the importance of understanding harmful emissions under real-world conditions.

Carslaw et al (2011) analysed monitoring results from RSD to investigate why recent concentrations of NO_x and NO_2 in the UK had not decreased as anticipated. This study found that NOx emissions from light duty diesel vehicles were not decreasing, whereas emission models predicted significant reductions.

PEMS measurements were undertaken by the European Commission's Joint Research Centre (Weiss et al 2011) to investigate the difference between on road and laboratory emissions. This measurement campaign confirmed NO_x emissions from light duty diesel vehicles were substantially above emission standards.

Extensive PEMS measurement campaigns have since been undertaken to investigate high NO_x emissions from modern light duty diesel vehicles. The ICCT published an analysis of the results from PEMS testing of 15 different modern diesel passenger cars (Franco et al 2014). This found that the average, on road NO_x emissions were seven times higher than the emission standard.

The UK Government more recently published another emission testing programme on modern diesel cars (Department for Transport 2016). One of the aims of this programme was to investigate whether manufacturers other than Volkswagen were using software or any other system that causes engines to behave differently during emissions tests compared with real-world driving. The test programme included Euro 5 and 6 vehicles with a total of 56 different vehicle types in Germany and 37 vehicle types in the UK. The study found no evidence of other manufacturers using any similar system to that used by Volkswagen. However, the study found average on road NO_x emissions from Euro 5 and 6 vehicles were over six times higher than the legislative NEDC laboratory test limits. The Australian Automobile Association undertook similar tests on around 30 modern diesel vehicles in Australia with similar findings (Australian Automobile Association 2017).

High NO_x emissions from Euro IV and V trucks and buses have also been reported by the ICCT (Lowell and Kamakaté 2012). This study is based on analysis of chassis dynamometer test results from real-world drive cycles.

It has only recently become feasible to measure particulate emissions accurately with PEMS technology and we have found limited real-world measurements of particulate. However, modern vehicles fitted with diesel particulate filters are expected to perform well, with regards to particulate emissions, in real-world conditions. For example, extensive testing of two Euro 6 diesel vehicles in Europe found particulate mass emissions were well below legislative limits except during regeneration of the filter. This study included real-world measurements as well as chassis dynamometer tests with various drive cycles (May et al 2014).

There are limited published studies of real-world emissions from older vehicles. The European Joint Research Council study (Weiss et al 2011) included 12 light duty diesel and gasoline vehicles that comply with Euro 3 to Euro 5 emission standards. The study found that on road emissions of NO_x from petrol vehicles, and CO and hydrocarbons from both petrol and diesel vehicles are generally within the emissions limits. Kousoulidou et al (2013) published an example of the use of PEMS measurements for development and validation of COPERT emission factors. This study measured on road emissions of CO, HC and NO_x emissions from six passenger cars ranging from Euro 3 to Euro 5. The study found reasonably good agreement between PEMS measurements and COPERT with the exception of NO_x from diesel vehicles.

PEMS measurements of 268 trucks and 77 buses in China found no significant reduction in real-world NO_x emissions between Euro 0 and Euro IV vehicles. Significant reductions in real-world emissions of other pollutants, including particulate were found (Zhang 2013).

Finding 3.2

High NO_x emissions from diesel cars have prompted significant research into real-world NO_x emissions. There is a substantial body of evidence that real-world NO_x emissions are higher than legislative limits for light duty and heavy duty vehicles.

Finding 3.3

There is extensive PEMS test data available internationally for light duty Euro 5 and Euro 6 diesel vehicles. There is an opportunity to capitalise on overseas research by comprehensively testing a small sample of Euro 5 (light duty) vehicles. This would provide a benchmark for the validation of VEPM in New Zealand.

Finding 3.4

There is limited data available internationally for real-world emissions from older vehicles. However, the data that is available indicates there is reasonable agreement between emission factors and real-world emissions for all pollutants except for NO_x.

3.1.5 What information is available on real-world exhaust emissions in New Zealand?

3.1.5.1 Ambient air quality monitoring

The Transport Agency monitors ambient NO_2 as a proxy for vehicle-related air pollution. Monitoring is undertaken at approximately 130 sites across New Zealand using passive samplers to measure NO_2.

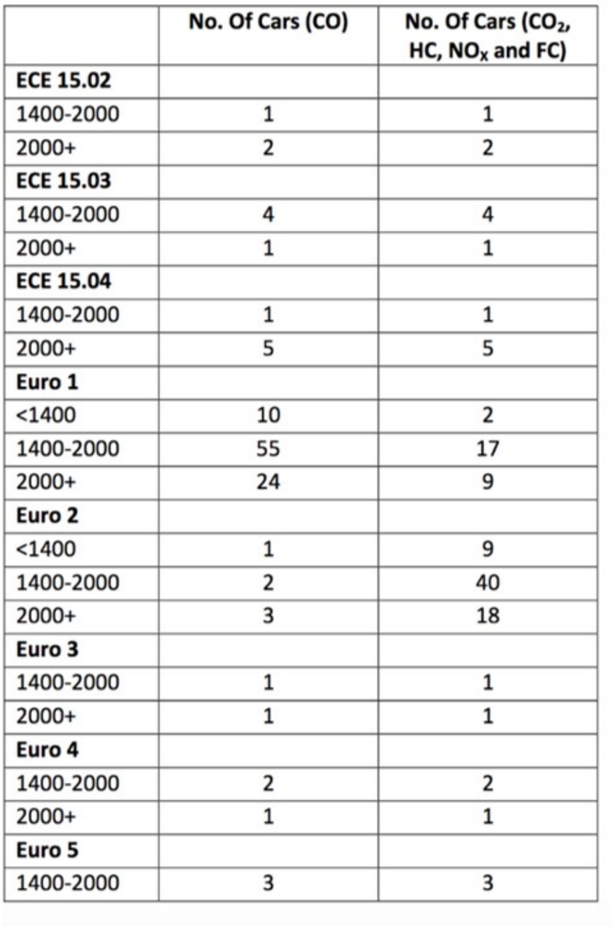
In 2015, annual average NO_2 concentrations across 36 sites that have operated since 2007 were 17% higher on average than in 2007 (individual sites range from 10% lower to almost 55% higher than concentrations measured in 2007). However, levels have only increased by 1% per annum between 2010 and 2015 on average (with individual sites ranging from approximately 20% lower to 30% higher than in 2010) (NZ Transport Agency 2016b).

3.1.5.2 Chassis dynamometer tests

Another valuable source of data is the NZ Vehicle Emissions Test Database (Graham and Jones 2012). The database collates results from emission testing of 117 light duty petrol and 25 light duty diesel on the chassis dynamometer facility at the Auckland University Energy and Fuels Research Unit, including testing drive cycles that have been designed to represent real-world New Zealand conditions. The database includes real-world drive cycle results for 45 New Zealand-new and 24 Japanese-used import petrol light duty vehicles. The Japanese-used imports are all older vehicles manufactured between 1983 and 1999. Most of the test results for light duty diesel vehicles are based on regulatory drive cycles.

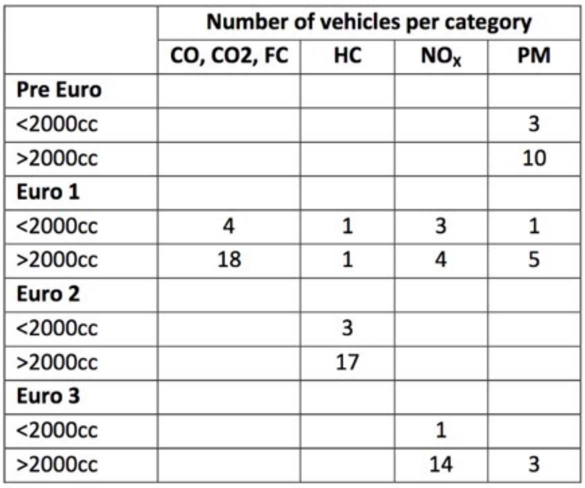
Tables 3.1 and 3.2 show the number of test results in the database for light duty vehicle categories in VEPM. In these tables, Japanese-used imports have been assigned to the equivalent Euro emission standard that is assumed in VEPM.

Table 3.1 Number of petrol vehicle test results in the NZ emission factor database for each category (Graham and Jones 2012)



	No. Of Cars (CO)	No. Of Cars (CO_2, HC, NO_X and FC)
ECE 15.02		
1400-2000	1	1
2000+	2	2
ECE 15.03		
1400-2000	4	4
2000+	1	1
ECE 15.04		
1400-2000	1	1
2000+	5	5
Euro 1		
<1400	10	2
1400-2000	55	17
2000+	24	9
Euro 2		
<1400	1	9
1400-2000	2	40
2000+	3	18
Euro 3		
1400-2000	1	1
2000+	1	1
Euro 4		
1400-2000	2	2
2000+	1	1
Euro 5		
1400-2000	3	3

Table 3.2 Number of diesel vehicle test results in the NZ emission factor database for each category (Graham and Jones 2012)



	Number of vehicles per category			
	CO, CO2, FC	HC	NO_X	PM
Pre Euro				
<2000cc				3
>2000cc				10
Euro 1				
<2000cc	4	1	3	1
>2000cc	18	1	4	5
Euro 2				
<2000cc		3		
>2000cc		17		
Euro 3				
<2000cc			1	
>2000cc			14	3

The emission test results in the database were compared with VEPM where possible (Graham and Jones 2012). This comparison found in general:

- There is very good agreement between the database and VEPM results for fuel consumption.
- VEPM emission factors agree reasonably well with the database results for CO and HC. In general, the output from VEPM is lower that the results in the database.
- For NO_x emissions, there is poor agreement between VEPM emissions factors and the database.

3.1.5.3 Remote sensing

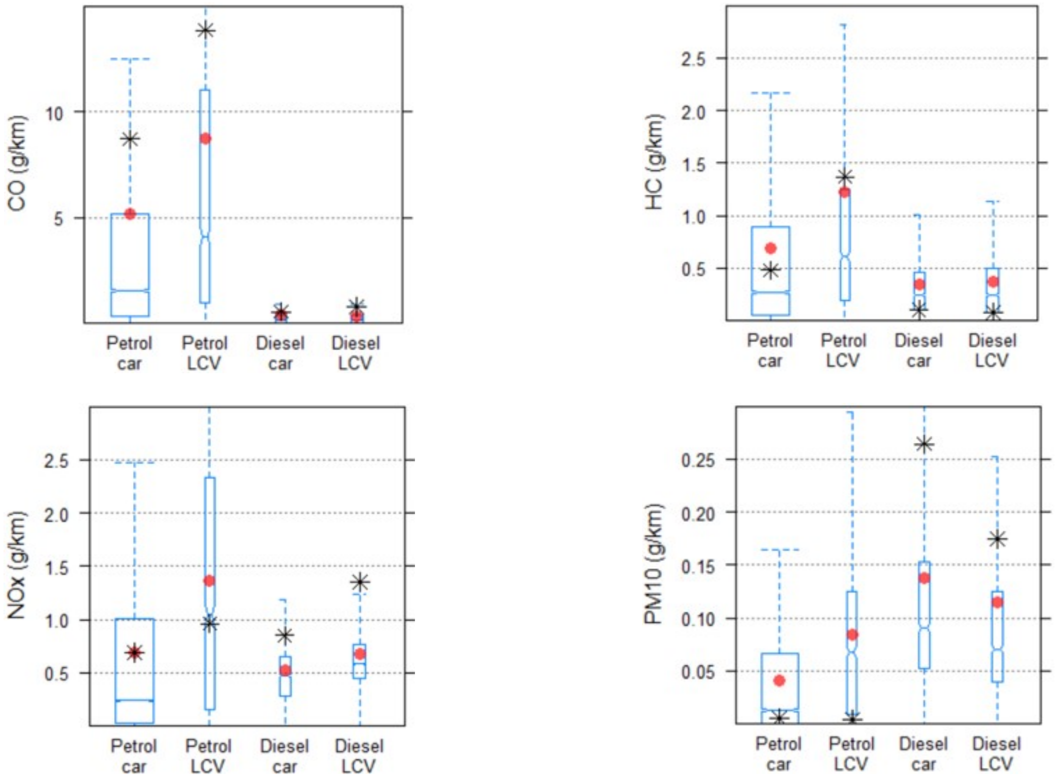
Regular monitoring with the remote sensing device (RSD) has provided a proxy measure of real-world vehicle emission trends in New Zealand. The RSD measures the concentration of pollutants in the exhaust stream including CO (%), HC (ppm) and NO (ppm). A smoke index measured using UV light (uvSmoke) is used to estimate particulate emissions. RSD monitoring has been undertaken in 2003, 2005, 2009, 2011 and 2015 at seven sites in Auckland. Exhaust concentrations from more than 100,000 light vehicles have been collated into a RSD database.

RSD concentrations can be converted to emission factors (in g/km) with some significant assumptions including:

- The conversion of concentrations to g/km emission factors relies on estimated fuel consumption rates.
- The RSD measures instantaneous emission concentrations at a particular point on the road, generally on motorway on or off ramps, arterial roads or one way street. Although many measurements are collected at each location, they may not be representative of average emissions over a full drive cycle.
- The fraction of NO_2 in the exhaust has to be estimated to derive NO_X from NO.
- uvSmoke only provides an indication of likely particulate matter concentration.

The results of the 2011 remote sensing campaign have been used to derive light duty vehicle emission factors for CO, HC and NOx for comparison with VEPM (Golder 2014). Subject to the limitations and assumptions in the method, the report concludes there is reasonable agreement between VEPM and RSD-derived emission factors for most combinations of vehicle type and pollutant. The results are shown in figure 3.3.

Figure 3.3 Comparison of RSD emission factors (shown as box and whisker with red circle showing the mean) and VEPM emission factors (shown as black asterisk) (Golder 2014)



The charts in figure 3.3 show VEPM emission factors as black asterisks and represent RSD results with box and whisker plots. The red circles show the mean of the RSD measurements, while the median is represented by a ‘belt’ across the box.

The most recent RSD report (Bluett et al 2016) concludes that between 2011 and 2015, average emissions of NO for light duty diesel vehicles have continued to increase. The report also concludes that an average heavy duty vehicle emitted similar levels of NO in 2015 relative to 2003. These findings from New Zealand RSD monitoring are consistent with international findings.

The 2016 report identifies the three most significant gaps in the current RSD database as:

- emissions from heavy duty vehicles
- particulate matter emissions
- emissions of NO_2 (the RSD measures NO).

Comparison of trends in VEPM versus RSD results has found good agreement between fleet average trends predicted by VEPM and measured trends in average vehicle emissions for the overall light duty fleet between 2003 and 2011 (Metcalfe et al 2013). However, the comparison found that:

- The trend in measured NO emissions (increasing) is contrary to the trend in predicted NOx emissions factors (reducing) from diesel vehicles.
- The measured reduction in uvSmoke (an indication of particulate emissions) is less than the predicted reduction in PM emissions factors, especially for diesel vehicles.

Finding 3.5

The New Zealand emission test database provides good information for fuel consumption and emissions from light duty vehicles, including Japanese used imports. There is good agreement between VEPM and database results for fuel consumption and reasonable agreement for CO and HC. However:

- For diesel vehicles there is limited data, and no results from ‘real-world’ drive cycles.
- Most of the vehicles in the database are Euro 2 or older.

Finding 3.6

There is good information on vehicle emission trends in New Zealand from remote sensing campaigns. There is good agreement between fleet average trends predicted by VEPM and measured RSD trends for the overall light duty fleet except:

- The trend in measured NO emissions (increasing) is contrary to the trend in predicted NO_x emissions factors (reducing) from diesel vehicles.
- The measured reduction in uvSmoke emissions is less than the predicted reduction in PM emissions factors, especially for diesel vehicles.

Finding 3.7

The RSD database is a valuable source of real-world data for a large sample of the fleet. However, three significant data gaps are:

- emissions from heavy duty vehicles
- particulate matter emissions
- emissions of NO_2 (the RSD measures NO).

Finding 3.8

There is limited information about real-world exhaust emissions from heavy duty vehicles in New Zealand.

Finding 3.9

There is significant uncertainty about real-world emissions of PM and NO/NO_2 from light duty diesel vehicles in New Zealand.

3.1.6 Are there examples of PEMS being used to develop or validate emission factors?

PEMS comprise complete sets of instruments that can be carried on board the vehicle to record instantaneous emission rates of selected pollutants with levels of accuracy that are comparable to laboratory systems. However, the results of real-world monitoring techniques are typically less repeatable than those of chassis dynamometer studies, due to the absence of a standard test cycle and the presence of additional sources of variability such as environmental or traffic conditions, driver behaviour or highly transient operation (Franco et al 2013).

The real-world variability of PEMS test results is illustrated by the results of on-road testing of Euro 5 and 6 vehicles in the UK, as shown in figures 3.4 and 3.4 (Department for Transport 2016). In these charts the average NO_x emissions of all vehicles is shown by the red line, while the horizontal dotted black line is the type-approval limit. The Department for Transport (2016) report states that the results are not directly comparable to each other as the test conditions varied from test to test.

The results show there is significant variation between vehicles built to the same emission standard. However, comparing figure 3.5 with figure 3.4 shows NO_x emissions from Euro 6 vehicles are generally lower than Euro 5 vehicles.

Figure 3.4 Real-world NO_X emissions from Euro 5 vehicles (Department for Transport 2016)

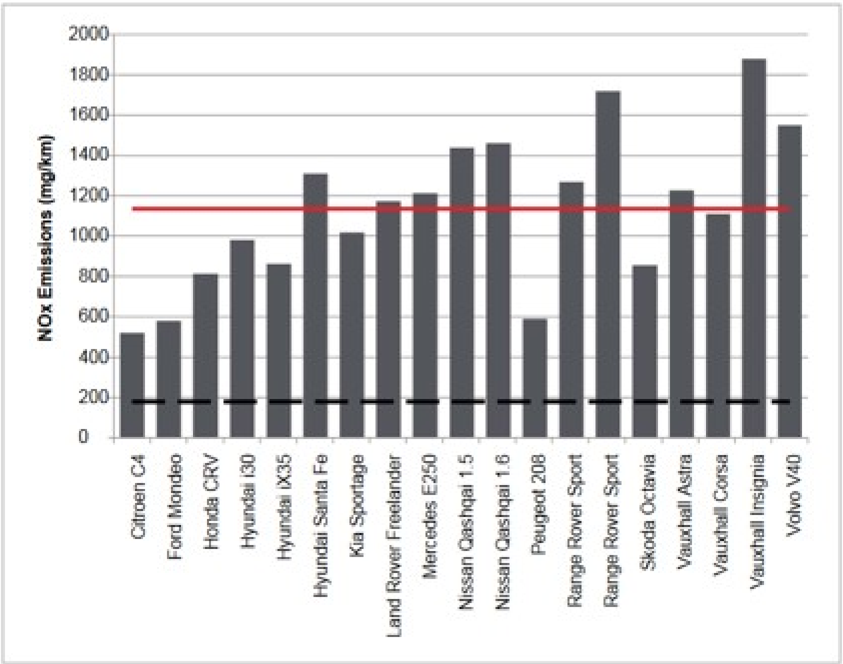
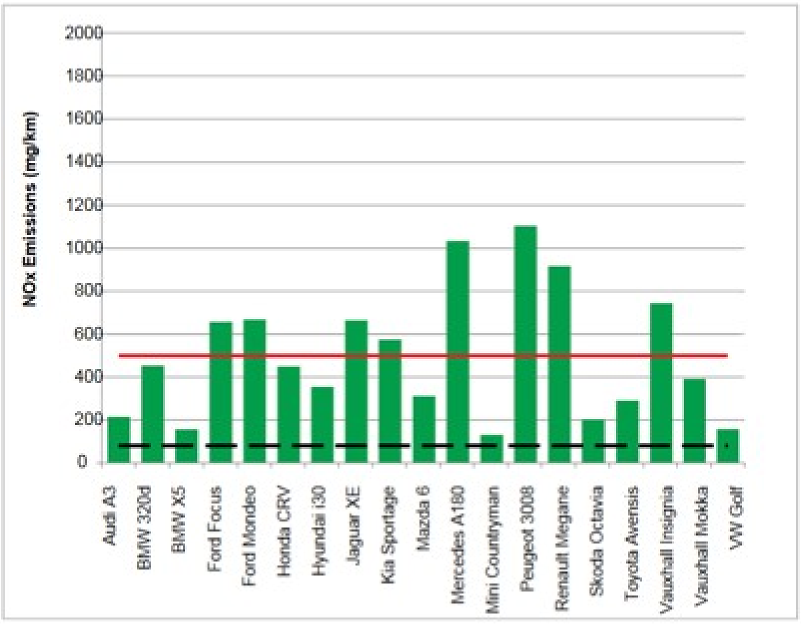


Figure 3.5 Real-world NO_X emissions from Euro 6 vehicles (Department for Transport 2016)



Capturing this effect of real-world variables on emissions is the key advantage of PEMS tests. Chassis dynamometer tests are an artificial way of measuring emissions, and their results may differ from the actual on road emissions. Franco et al (2014) conclude that chassis and engine dynamometer testing can be expected to remain the main source of emission factor data for the years to come. However, given their inherent inability to capture the full range of real-world driving parameters (even when real-world drive cycles are used) these should not be the only source of data. Real-world measurement techniques are valuable for emission factor validation, investigation of off cycle emissions, characterisation of trends and identification of high emitters (Franco et al 2013).

COPERT emission factors have been validated in Europe in several studies by comparison with real-world measurements (Kousoulidou et al 2013). More recently, PEMS data has been used to provide data for updated Euro 5 and Euro 6 NO_x emission factors in COPERT (Ntziachristos et al 2016).

Two locations where PEMS data has been used to validate and calibrate local emission factors are China and Hong Kong.

In Hong Kong, the vehicle emission model (EMFAC-HK) is based on US emissions factors. The model has been updated regularly based on the results of a regular PEMS monitoring programme. PEMS monitoring has been undertaken on more than 200 vehicles since 2008 (Environmental Protection Department 2016).

In China, local emission factors were developed for trucks and buses built to Euro standards. The factors were based on analysis of real-world PEMS measurements of 268 trucks and 77 buses (Zhang 2013). This study compared the rate of emission reduction predicted by emission inventories (including inventories based on COPERT emission factors) with measured emission reductions. Figures 3.6 and 3.7 illustrate the comparison of emission inventory estimates (shown as points) and fleet-weighted average emissions based on PEMS measurements (shown as solid lines) for NO_x and $PM_{2.5}$. The Chinese study concludes that it is useful and necessary to conduct vehicle emission measurements in China and to develop emission models based on local measurement data.

Figure 3.6 Comparison of NO_X emission factors derived from various emission inventories (shown as points) with those calculated from PEMS measurements (shown as lines) for heavy duty truck and buses in China (Zhang 2013)

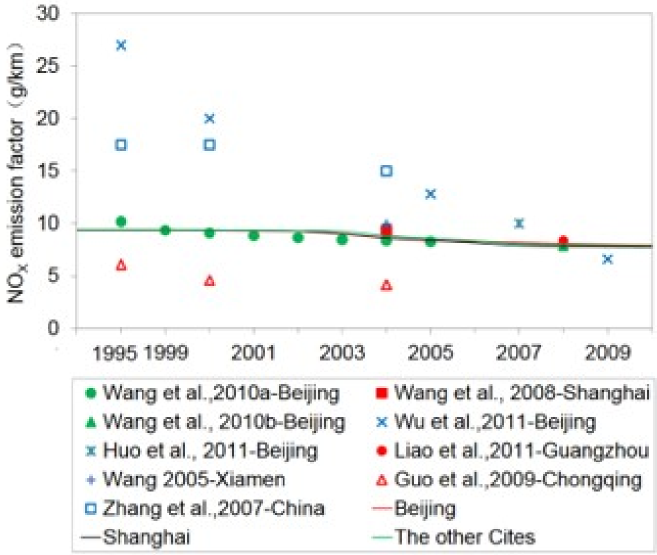
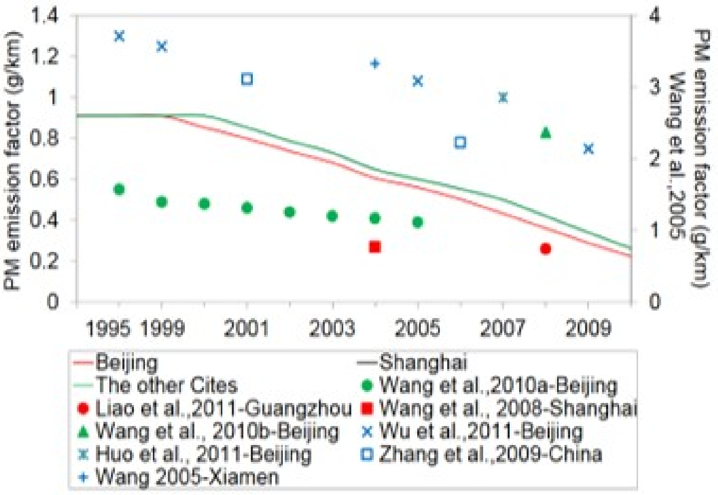


Figure 3.7 Comparison of PM emission factors derived from various emission inventories (shown as points) with those calculated from PEMS measurements (shown as lines) for heavy duty truck and buses in China (Zhang 2013)



Finding 3.10

PEMS can measure emission rates with levels of accuracy that are comparable to laboratory systems. However, the results of real-world monitoring techniques are typically less repeatable than those of chassis dynamometer studies because of real-world factors. This means care is needed when comparing

Finding 3.11

PEMS captures a wide range of driving parameters and is useful for validation of emission factors under local conditions.

Finding 3.12

COPERT emission factors are intended to represent real-world emissions and have been updated to incorporate the results of real-world emission measurements (eg Ntziachristos et al 2016). This means COPERT should, in general, be reasonably representative of real-world emissions in Europe.

Finding 3.13

Studies have shown it is important and appropriate to use local emission measurements to validate and, if appropriate, calibrate international emissions factors.

3.2 Desktop study of real-world fuel consumption in New Zealand

A desktop study of real-world fuel consumption was undertaken in the initial phase of the project to compare fuel consumption predicted by VEPM with real-world fuel consumption for New Zealand vehicles. Key questions the study was to address were:

- How well does VEPM predict real-world fuel consumption?
- Can we identify vehicle types where VEPM is less realistic for estimation of real-world fuel consumption?

3.2.1 Average real-world fuel consumption in New Zealand

The majority of vehicles imported into New Zealand new (‘New Zealand-new’ vehicles) are built to European standards and the majority of vehicles imported used (‘Japanese-used imports’) are built to Japanese domestic standards. Figure 3.8 shows the trends in type-approval CO_2 emissions from New Zealand-new light vehicles (Metcalfe and Sridhar 2016). This shows that New Zealand-new light vehicles have higher CO_2 emissions (and fuel consumption) on average compared with European and Japanese vehicles. However, the overall rate of reduction in type-approval CO_2 emissions is similar in all regions.

Figure 3.9 compares the average type-approval CO_2 emissions and estimated real-world CO_2 emissions for new light duty vehicles in New Zealand and Europe. The real-world estimates are from the MoT (Wang et al 2015) and are compared with type-approval information for vehicles entering the New Zealand fleet (MoT 2016a) and European data (ICCT 2015).

This comparison shows that type-approval fuel consumption and real-world fuel consumption of new vehicles in New Zealand are higher than Europe. The overall rates of improvement in type-approval fuel consumption and real-world fuel consumption are similar in New Zealand compared with Europe (Metcalfe and Sridhar 2016).

The New Zealand vehicle fleet is different from the European fleet, so this difference is not unexpected. For example, the average engine size of vehicles entering the New Zealand fleet is around 2300cc (MoT 2016b) compared with 1300cc in Japan and 1700cc in the UK (OECD/IEA 2016). However, a benchmarking exercise undertaken for the MoT (Metcalfe and Sridhar 2016) found that engine size does not account for all of the difference between New Zealand and European fuel consumption. This study found:

> *…even for vehicles with equivalent engine size, the estimated real-world CO_2 emissions and fuel consumption for average new vehicles in New Zealand is approximately 18% higher, compared with average new vehicles in Europe. This difference may be due to New Zealand having heavier vehicles, and a higher proportion of SUVs on average compared with Europe. However, further investigation would be required to confirm this.*

This is important because VEPM characterises vehicles based on engine size, and it is based on European fuel consumption and emission factors. This means that VEPM could be under-estimating fuel consumption.

Figure 3.8 Trends in average type-approval CO_2 emissions from New Zealand–new vehicles compared with Europe, Japan and Australia. All results are normalised to the New European driving cycle (NEDC). (Metcalfe and Sridhar 2016)

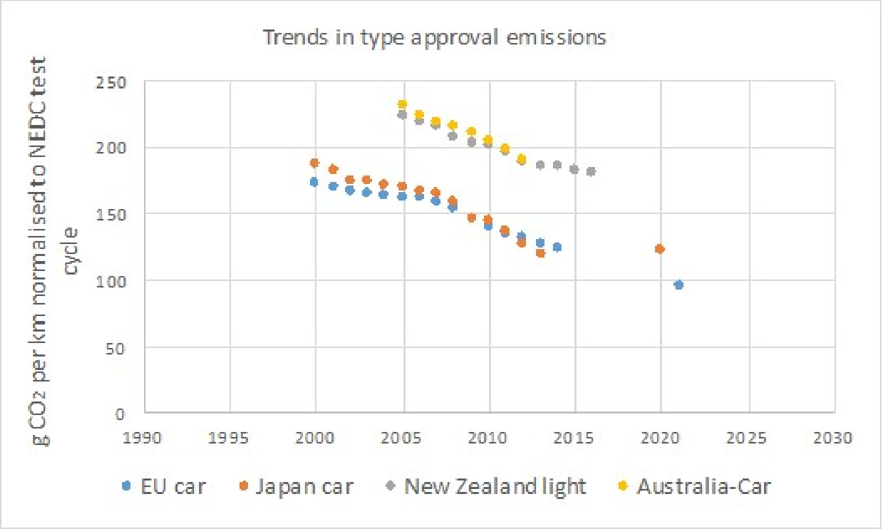
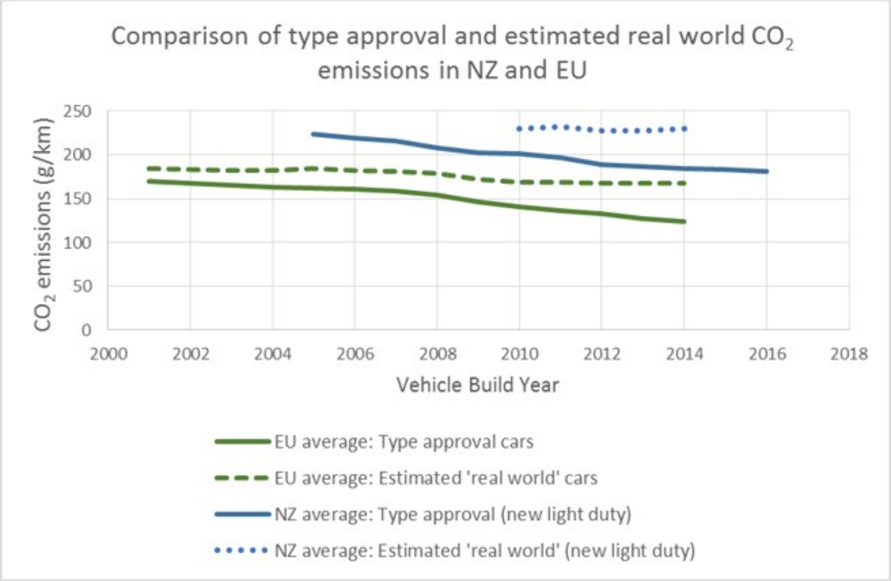


Figure 3.9 Comparison of type-approval and estimated real-world CO_2 emissions in New Zealand and Europe (Wang et al 2015, MoT 2016b and ICCT 2015)



3.2.2 How well does VEPM predict real-world fuel consumption?

The recent development of New Zealand-specific real-world fuel consumption factors by the MoT provides an opportunity to find out how well VEPM predicts fuel consumption. Real-world fuel consumption estimates for New Zealand-new vehicles (Wang et al 2015, Metcalfe and Sridhar 2016) were compared with fuel consumption factors for the equivalent vehicle from VEPM.

The objectives of this were to address the questions:

- How well does VEPM predict real-world fuel consumption for New Zealand?
- Can we identify vehicle types where VEPM is less realistic (ie predicts poorly)?

3.2.2.1 Assumptions for VEPM versus real-world fuel consumption

The MoT real-world fuel consumption estimates were compared with fuel consumption factors from VEPM that were equivalent to the average fuel consumption estimated in the Auckland Air Emissions Inventory (Sridhar et al 2014).

In the Auckland inventory, emission factors from VEPM are used to calculate emissions and fuel consumption from each link in the network for each hour of the day. Each VEPM emission factor is based on the average speed (including intersection delays) over the link for that time period. This means that the inventory takes into account the effects of congestion on emissions and fuel consumption. The inventory covers the whole region, so it includes a mix of urban and open road driving. Fuel consumption factors that are equivalent to the Auckland inventory may not be representative of the whole country. However, the intention is primarily to determine whether VEPM performs better for some vehicle types relative others.

The 'Auckland equivalent' fuel consumption factors for Euro 4 vehicles were developed from VEPM 5.2 for 2012 and an average speed of 40 km/h. All other parameters in VEPM were left as the 'default' settings.

3.2.2.2 Light duty vehicles

Table 3.3 compares the MoT real-world fuel consumption estimates with fuel consumption predicted by VEPM for Euro 4 vehicles at an average speed of 40 km/h. Based on these assumptions, the weighted average fuel consumption across all engine size categories show:

- VEPM predictions are approximately 1% lower than real-world fuel consumption estimates for petrol passenger cars.
- VEPM predictions are approximately 20% lower than real-world fuel consumption estimates for diesel cars.
- VEPM predictions are approximately 13% higher than real-world fuel consumption estimates for petrol light commercial vehicles.
- VEPM predictions are approximately 24% lower than real-world fuel consumption estimates for diesel light commercial vehicles.

This analysis is subject to significant assumptions and limitations. However, the good agreement between real-world petrol consumption estimates and VEPM petrol consumption factors is consistent with previous research, providing some confidence in the assumptions and methodology. There is very good agreement between VEPM fuel consumption factors and fuel consumption measured for New Zealand drive cycles on the chassis dynamometer (Graham and Jones 2012). Regional emissions inventories in Auckland and Canterbury have also found good agreement between regional fuel sales data and estimated petrol consumption based on detailed traffic models and VEPM fuel consumption factors (Sridhar et al 2014, Sridhar and Metcalfe 2014).

Table 3.3 Comparison of MoT real-world fuel consumption estimates with VEPM fuel consumption predictions for Euro 4 vehicles at an average speed of 40 km/hour

Vehicle type	Engine size	MoT real-world estimates		VEPM factors	
		Fuel consumption (l/100km)	Category weighted fuel consumption (l/100km)	Fuel consumption (l/100km)	Category weighted fuel consumption (l/100km)
Petrol passenger car	<1350cc	8.1	8.8	6.5	8.8
	1350 - <1600cc	7.8		7.8	
	1600 - <2000cc	8.5			
	2000 - <3000cc	9.7		11.3	
	>3000cc	11.4			
Diesel passenger car	<1350cc	7.4	9.3	5.6	7.6
	1350 - <1600cc	7.1			
	1600 - <2000cc	7.6			
	2000 - <3000cc	9.3		7.8	
	>3000cc	10.3			
Petrol light commercial	<1350cc	8.1	9.4	10.8	10.8
	1350 -<1600cc	7.8			
	1600 - <2000cc	10.2			
	2000 - <3000cc	9.9			
	>3000cc	11.4			
Diesel light commercial	<1350cc	7.4	10.1	8.1	8.1
	1350 - <1600cc	7.1			
	1600 - <2000cc	9.5			
	2000 - <3000cc	10.2			
	>3000cc	10.3			

For diesel cars, the results of this comparison suggest VEPM under-estimates real-world fuel consumption by 20%. The difference between VEPM predictions and New Zealand real-world fuel consumption estimates for diesel vehicles could be influenced by a number of factors including:

- VEPM fuel consumption factors are based on the European fleet, which is different from the New Zealand fleet.
- VEPM fuel consumption factors are based on European driving conditions, which could be different from New Zealand conditions.
- New Zealand real-world fuel consumption factors are based on corporate fleet data. Research has found corporate vehicles generally consume more fuel than their private counterparts (Tietge et al 2015, Tietge et al 2017).

Overall, it is likely that the difference between New Zealand real-world and VEPM predictions of fuel consumption is primarily due to different types of vehicles in the fleet, because:

- There is good agreement between VEPM and real-world fuel consumption for petrol vehicles, which are driven in the same real-world conditions as diesel vehicles in New Zealand.

- The vast majority of New Zealand-new diesel vehicles are SUVs or utes, which have higher fuel consumption than passenger cars with the same size engine. In contrast, diesel passenger cars are common in Europe.

Figure 3.9 shows New Zealand-new vehicles have similar CO_2 emissions and fuel consumption to vehicles in Australia. An Australian version of COPERT has recently been developed (Smit and Ntziachristos 2013). The vehicle classification in COPERT Australia includes a number of vehicle categories that do not have specific fuel consumption or emission factors in VEPM (which is based on the European COPERT) but are nonetheless relatively common in the New Zealand light duty diesel fleet, such as large passenger cars with engine capacities > 3 litres, compact SUVs with engine capacity ≤ 4 litres, and large SUVs with engine capacity ≤ 6 litres. The results of this comparison suggest these vehicle categories should be included in VEPM.

The comparison of light commercial vehicles highlights an inconsistency between VEPM and the MoT fleet classifications. In VEPM, light vehicles are classified as either cars or light commercial vehicles. This is based on the European COPERT model where the classification 'light commercial' vehicles is dominated by vans. In MoT fleet data, the commercial classification is based on body type. This means light commercial vehicles may include vans, and light trucks/utes. Currently VEPM assumes that all vehicles classified as light commercial in the New Zealand fleet are 'light commercial vehicles' (effectively small vans). This inconsistency should be investigated and addressed.

Finding 3.14

On average, VEPM provides very good estimates for indicated real-world fuel consumption of light duty petrol vehicles in New Zealand.

Finding 3.15

On average, VEPM underestimates real-world fuel consumption for light duty diesel vehicles. This underestimation is likely to be explained by differences in the fleet (bigger heavier vehicles in New Zealand) compared with Europe.

Finding 3.16

VEPM does not include specific fuel consumption or emission factors for vehicles that are common in the New Zealand light duty diesel fleet including utes and SUVs. These vehicles are included in COPERT Australia, so this may be a valuable source of data.

Finding 3.17

The current classification of light commercial vehicles in VEPM needs to be reviewed.

3.2.3 Heavy duty vehicles

Table 3.3 (in the previous section) shows that VEPM under-estimates real-world fuel consumption based on the default settings for light duty vehicles. While this under-estimation could be due to differences in the New Zealand fleet compared with Europe or differences in vehicle loading, gradient effects could also be significant.

Sensitivity analysis undertaken for the Auckland motor vehicle emissions inventory (Sridhar et al 2014) found that heavy duty vehicle emissions were particularly sensitive to assumptions about gradient. The report concludes that, given Auckland's undulating terrain, gradient effects could have a significant effect on emissions. The report recommends further work to develop a method for consideration of gradient in the inventory.

Table 3.4 shows that the agreement between VEPM fuel consumption factors for heavy vehicles and real-world fuel consumption estimates improves if the gradient is assumed to be 2%.

Table 3.4 Comparison of MoT real-world fuel consumption estimates with VEPM fuel consumption predictions for Euro IV vehicles at an average speed of 40 km/hour for two different gradients

Fuel	Vehicle weight	MoT real-world fuel consumption (l/100km)	VEPM @ 0% gradient		VEPM @ 2% gradient	
			Fuel consumption (l/100km)	Difference VEPM vs real-world	Fuel consumption (l/100km)	Difference VEPM vs real-world
Diesel heavy duty	<5 t	15.9	11.0	-31%	15.9	0%
	5- <7.5 t	16.0		-32%		-1%
	7.5 - <10 t	22.2	16.9	-24%	25.5	15%
	10 - <12 t	24.9		-32%		2%
	12 - <15 t	30.8	18.4	-40%	28.6	-7%
	15 - <20 t	33.3	22.6	-32%	35.1	5%
	20 - <25 t	44.2	28.6	-35%	46.1	4%
	25 - <30 t	48.8	30.5	-38%	49.1	1%
	>=30 t	50.6	34.8	-31%	58.0	15%

Finding 3.18

VEPM with default settings underestimates the real-world fuel consumption of heavy duty vehicles in New Zealand. However, the effect of gradient may be substantial and has not been investigated.

4 Methodology

This chapter describes the methodology employed for the real-world testing of New Zealand vehicles, in response to the findings of the literature review and desktop study (summarised in chapter 3).

This chapter discusses the:

- design and validation of the PEMS equipment
- selection of representative test vehicles
- identification of a suitable real-world route
- development of the on-road test procedure
- description of the data quality assurance and analysis protocols.

4.1 PEMS equipment

The original intention was to buy or hire commercially available PEMS equipment for the testing. Five systems were identified as suitable, with one system – the Axion RS+ – in the lead. However, shortly after the research project started in October 2016, the manufacturer changed the specifications so the preferred system no longer met the project requirements. Unfortunately, the other systems on the list were also ruled out because they were significantly more expensive and/or required unacceptably lengthy lead times. As a way forward, the project team opted to build a PEMS from separate commercially available modules.

4.1.1 Design

Figure 4.1 shows the PEMS equipment as built, with a schematic of all components in figure 4.2. The equipment used for the on-road testing comprises five different systems in order to measure exhaust flow rate, particulate (as $PM_{2.5}$), gases (CO_2, NO_2, NO_x), other operating parameters and fuel usage (see appendix A for details).

The three main components are:

4.1.1.1 The exhaust flow measurement system

This system uses high-quality commercial pressure sensors to measure the differential pressure at a frequency of 10 Hz. This measurement was converted to a flow rate which was then corrected for temperature and pressure. However, we also recorded the air/fuel ratio using a lambda meter to enable mass conversion. The flow measurement system was calibrated using a high precision laminar flow element from Meriam Process Technologies which has National Institute of Standards and Technology (NIST) certification.

4.1.1.2 The particle sub sampling system

This system samples the exhaust at a known rate and then mixes the exhaust gas with clean dilution air at a set ratio of between five and 50 times dilution. For ‘clean’ exhausts that met Euro 5 requirements, we typically used a low five times dilution rate to maximise the sensitivity to emission variation. The concentration of particulate in the mixed air was measured using a TSI DustTrak sampler, which was the same unit used by the University of Auckland chassis dynamometer. The sampled particulates were also collected on a particle filter for subsequent analysis. This enabled us to correct the real-time continuous data to gravimetric equivalent.

Figure 4.1 The PEMS equipment used in the on-road testing

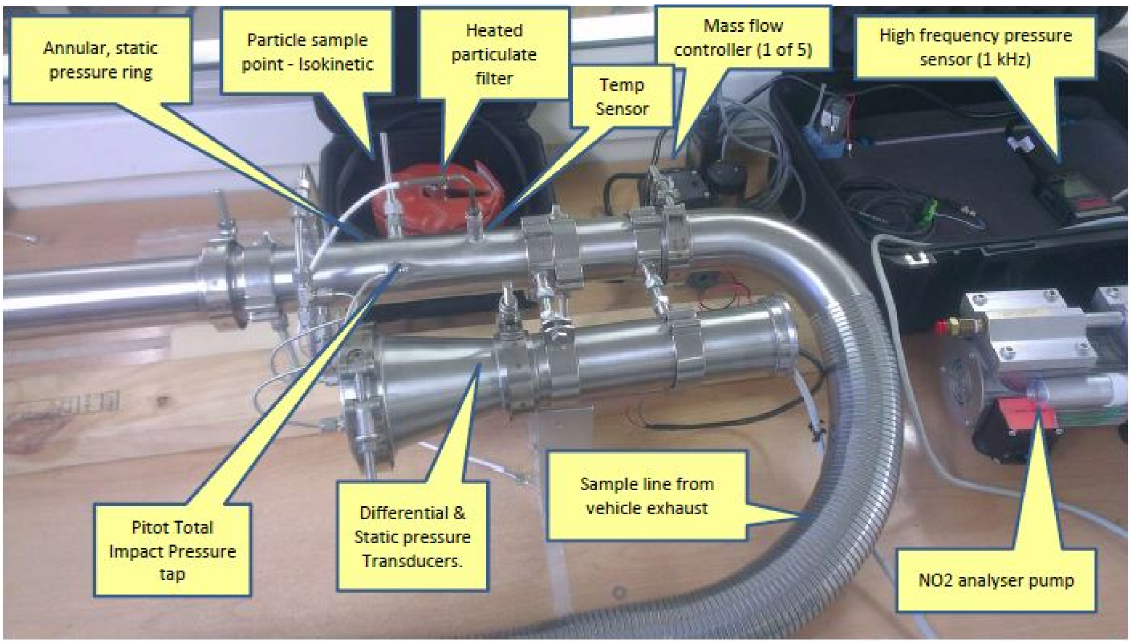
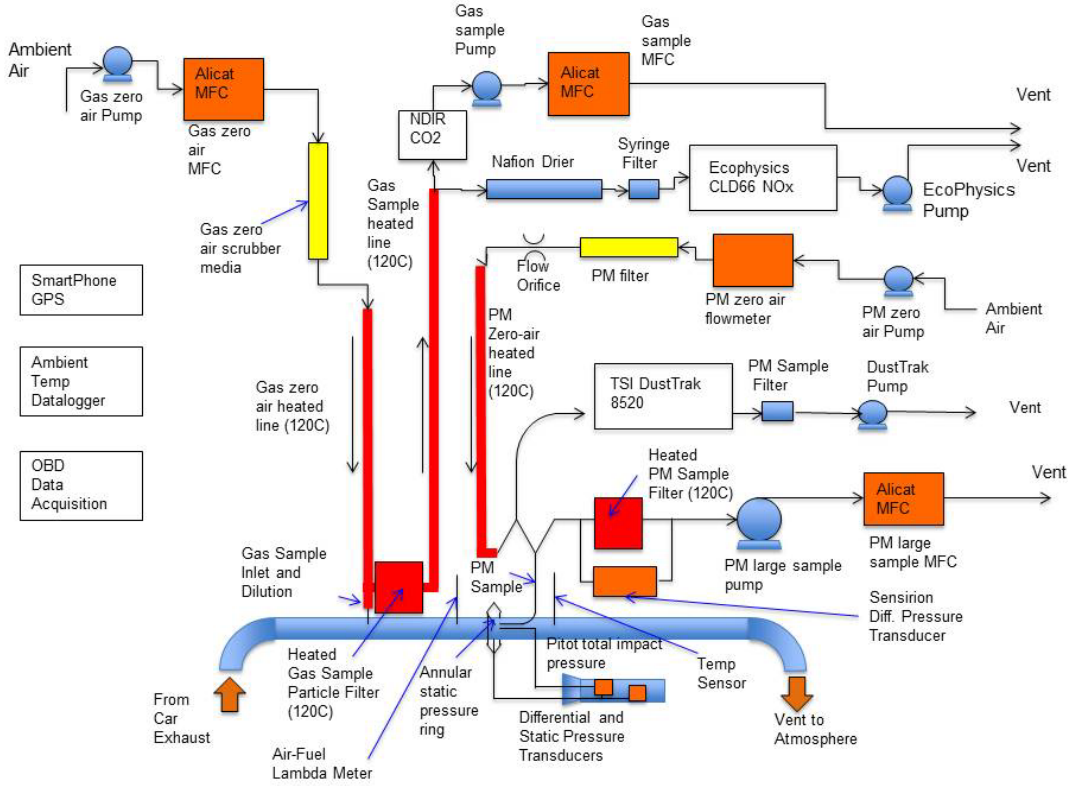


Figure 4.2 Schematic of the PEMS equipment used in the on-road testing



4.1.1.3 The gas sub sampling system

This system samples the exhaust at a known rate and then mixes the exhaust gas with clean dilution air at a set ratio of between five and 50 times dilution. This dilution rate was able to be varied independently of the particle measurement subsystem. This enabled us to assess vehicles with low particulate emissions but high NO_x emissions and vice versa. The concentration of NO_x in the diluted air was then measured using an Ecophysics CLD 60 instrument. The Ecophysics analyser is a high precision instrument that measures NO and NO_x at a frequency of about 10 Hz. This frequency is considerably higher than for traditional chemiluminescent analysers and is necessary to capture the rapid changes in gas exhaust concentrations that occur during normal vehicle driving.

Note: The PEMS was designed to measure $PM_{2.5}$, NO_X, and NO_2 as these are key/indicator road-transport harmful pollutants. While CO_2 was also measured, carbon monoxide was not monitored as it is no longer considered a significant road-transport pollutant in New Zealand.

4.1.2 Validation

The PEMS equipment was assembled into an operating system in June 2017 to undergo a three-stage validation.

4.1.2.1 Phase 1– laboratory testing

Laboratory testing was undertaken in June/July 2017 to validate the flow, dilution and thermal control of the modular components and then calibrate and test the analysers.

All equipment parameters (eg instrument responses) were confirmed to be operating within the manufacturer's specifications.

4.1.2.2 Phase 2 – chassis dynamometer comparison

Testing was undertaken in September/October 2017 to compare results from the PEMS equipment with those from the chassis dynamometer facility at the University of Auckland, which operates the following equipment:

- Schenck chassis dynamometer, rated to 200km/h, 230kW, with fully programmable load and inertia simulation
- Beckman constant volume sample system for certification type emission testing
- Laboratory grade exhaust gas analysers for CO_2, total hydrocarbons and NO_X
- Two stage particulate dilution tunnel for diesel vehicle particulate emission measurement.

The two systems were operated simultaneously during testing of a Holden Omega Euro 5 petrol car (see figure 4.3).

Figure 4.3 Simultaneous measurements being taken by the PEMS and the chassis dynamometer equipment

The car was driven to a test cycle involving step changes in speed followed by a series of acceleration/deceleration events to simulate a range of typical driving conditions. Comparison of the flowrate, $PM_{2.5}$ and NO_x data confirmed the PEMS measurements were generally consistent with those measured by the chassis dynamometer.

The volumetric flow measurement compared well across the test drive cycle, with the average exhaust flow measured by the university at 9.202 litres per second versus that measured by the PEMS of 9.201 litres per second. Figure 4.4 compares the two sets of exhaust flow measurements in more detail. The two different systems not only yielded comparable averages but both tracked the same events very closely during the test cycle.

Figure 4.4 Comparison of volumetric exhaust flow measurements from the two systems during the test cycle

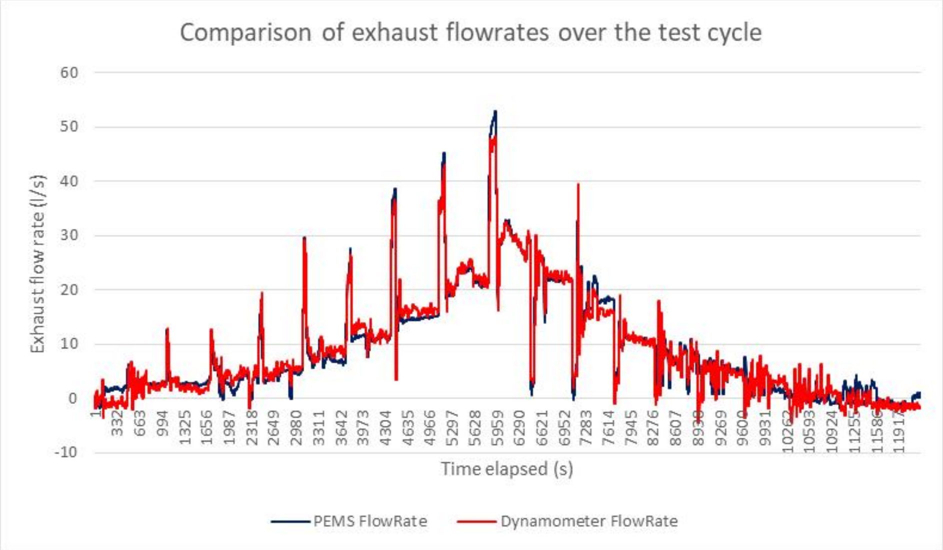


Figure 4.5 shows the variation in $PM_{2.5}$ concentrations during the test cycle. As can be seen, concentrations significantly increased each time the vehicle speed increased. The data from both the PEMS and the chassis dynamometer was generally consistent. Figure 4.6 expands the main part of the test cycle to more clearly compare the particulate measurements to confirm the good agreement between the two datasets.

Figure 4.5 Comparison of particle measurements from the two systems during the test cycle

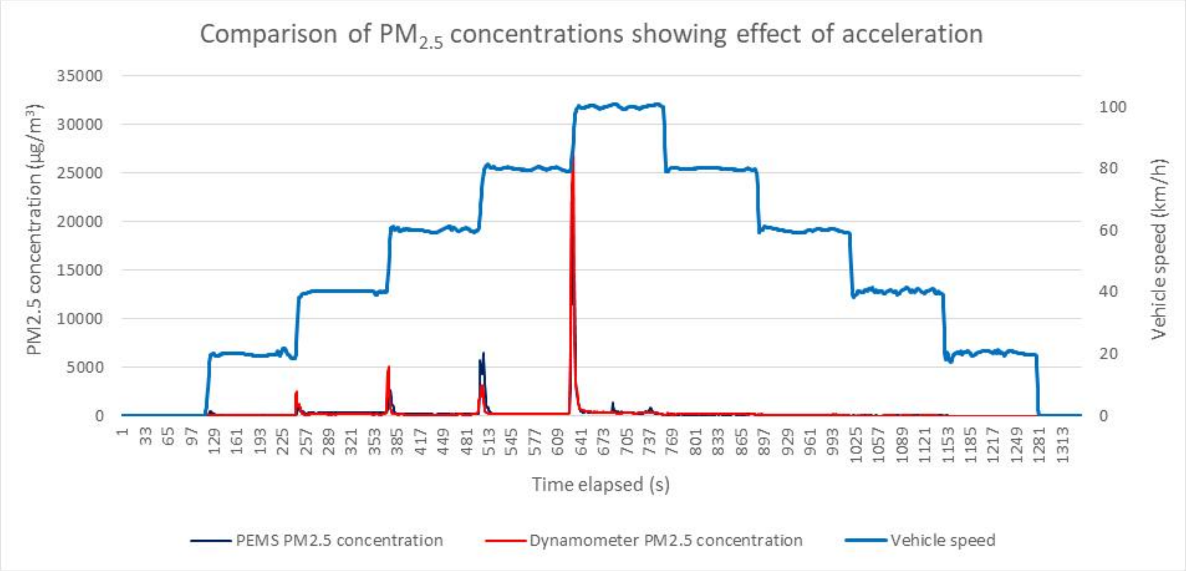
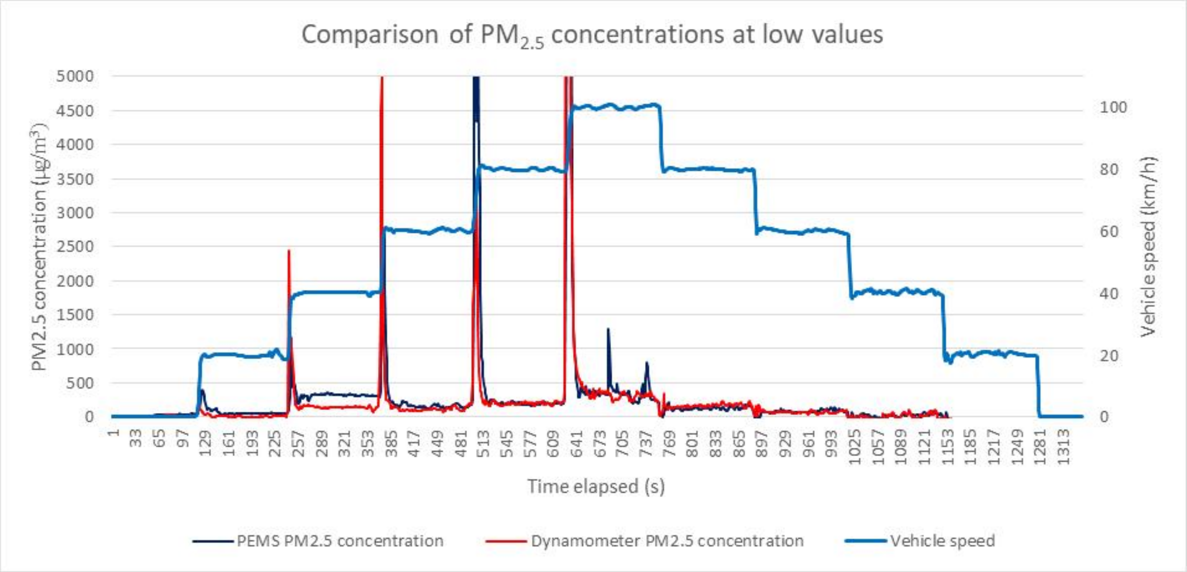


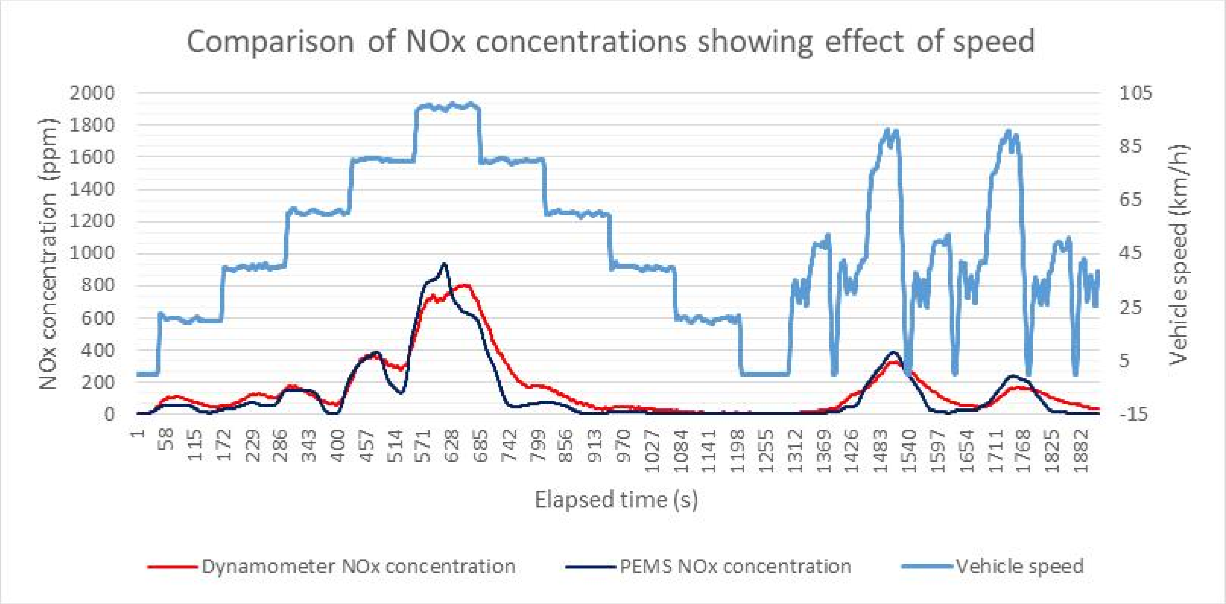
Figure 4.6 Comparison of particle measurements from the two systems at low concentrations



The two systems used very different chemiluminescent analysers for the measurement of NO_x concentrations. The Ecophysics unit in the PEMS had a much faster response than the chassis dynamometer analyser. Furthermore, the averaging period of the university instrument (several seconds) was considerably longer. In addition, the university data suggested a 10-second delay between the engine output and a corresponding change in NO_x concentration. This delay was removed and both datasets were averaged over the same period to enable direct comparison.

Figure 4.7 shows that despite the significant differences in equipment characteristics, both sets of measurements were generally in agreement.

Figure 4.7 Comparison of NO_X measurements from the two systems during the test cycle



The overall conclusion was that all PEMS measurements were robust and directly comparable with existing emission measurements for New Zealand vehicles undertaken using the University of Auckland chassis dynamometer.

4.1.2.3 Phase 3 – on-road testing

Final testing was undertaken in late November 2017 to demonstrate that the PEMS performed equally well on-road.

The test vehicle was a 2013 LWB Ford Transit Van (2198 cc diesel) with an odometer reading of 104,000 km. It was sourced from a vehicle rental company and had been serviced in accordance with the manufacturer's instructions. The rental company advised us the vehicle had been purchased new by them and they had not performed any modifications to the engine, transmission or exhaust system. This was confirmed by a visual inspection of the vehicle.

The on-board diagnostic logging tool was unable to communicate sufficiently to log all parameters. However, we found no evidence of alarms or engine warnings. Vehicle speed was logged using a geographical positioning system (GPS). The equipment was calibrated and heated prior to switching over to battery.

Two test routes were initially considered to capture a combination of both urban and motorway driving.

Test route 1 (shown in figure 4.8) departed from George Street in Mt Eden and proceeded down Dominion Road before turning onto SH 20. The route continued along the motorway, through the Waterview tunnel before returning back into town, exiting via the Newton Road off-ramp and returning to George Street.

Test route 2 (shown in figure 4.9) included congested driving and sloping terrain. The route commenced at George Street, proceeded along Dominion Road into Nelson Street, before continuing up Hobson Street. The route then entered the motorway via the Wellington Street on-ramp continuing over the Auckland Harbour Bridge before exiting at Onewa Road then returning back onto the motorway, exiting at the Cook Street off-ramp and returning to George Street.

$PM_{2.5}$ measurements were collected for both test routes and concentrations generally remained well below 500 micrograms per cubic metre (µg/m³), except when rapidly increasing speed (sharp spikes). Figure 4.10 shows the typical results (in this case for a test run using route 1), with a description of the test phases shown beneath.

In general, $PM_{2.5}$ concentrations remained reasonably constant during idle or driving at constant speed. Significant increases in concentration generally related to rapid increases (and sometimes decreases) in speed. One transient spike event did not correlate with a change in speed and may have been due to diesel particulate filter cleaning.

Figure 4.8 Proposed test route 1

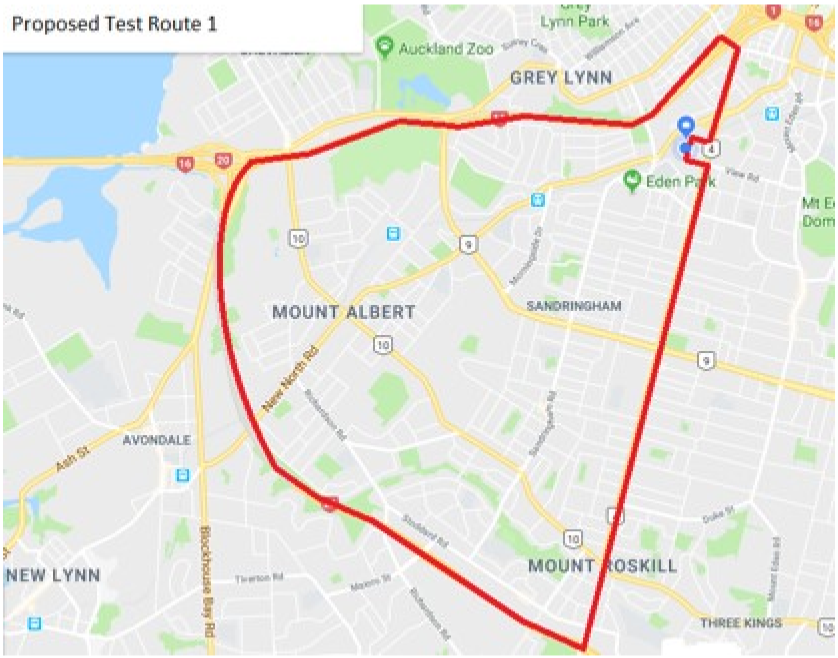


Figure 4.9 Proposed test route 2

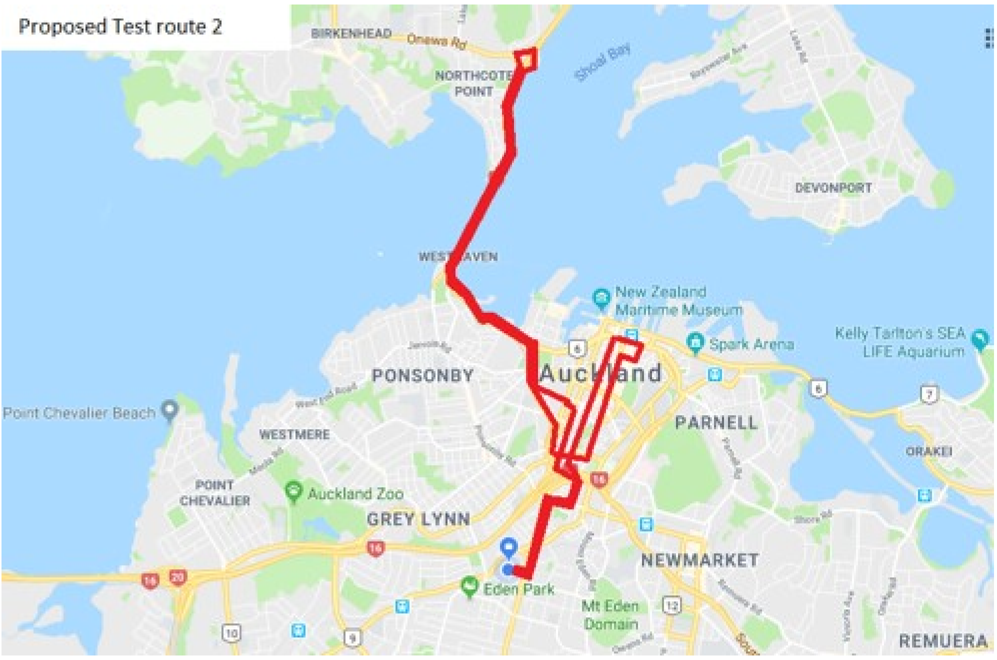
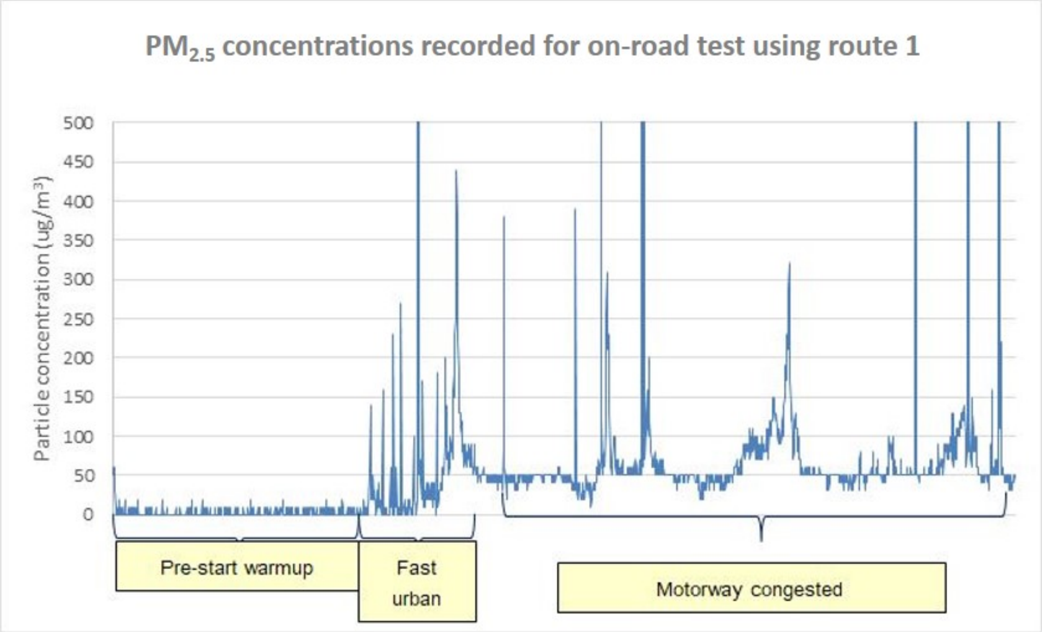


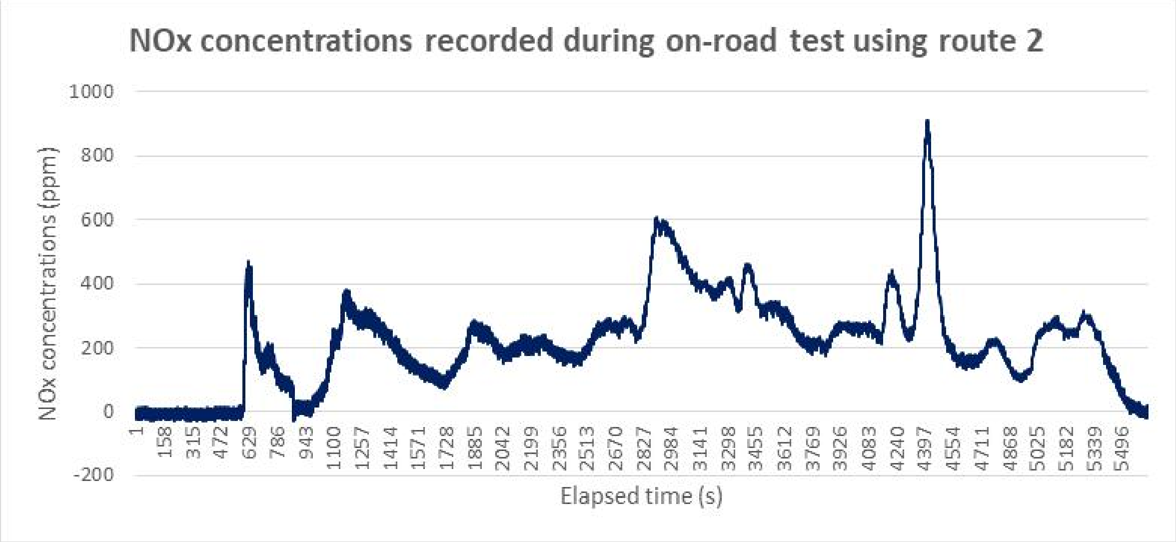
Figure 4.10 Particulate matter concentrations during the on-road test (route 1) indicating the responsiveness of the equipment



The gravimetric filter collected 150.0 milligrams of particulate during the test. This corresponded with an optical mass from the DustTrak of 142.9 milligrams over the same period and confirmed the continuous measurements were comparable with the gravimetric measurement (k factor of 1.049 = 150.0/142.9).

Figure 4.11 presents an example of the NO_x data (in this case collected for test route 2). Concentrations varied considerably during the on-road test with periods of high NO_x generally coinciding with periods of rapid acceleration. High NO_x concentrations were associated with high speed (>80 km/h) motorway driving, in particular.

Figure 4.11 NOx concentrations during the on-road test (route 2) indicating the responsiveness of the equipment



Unfortunately, in this example, an incident on the motorway during the on-road test resulted in considerable congestion and limited the length of time we were able to drive at 80 km/h. This increased congestion may have impacted the overall result. This highlighted the importance of checking road conditions prior to commencing any test and scheduling tests to avoid the commuter peak periods, where possible.

4.2 Representative test vehicles

The team identified nine broad categories from which test vehicles would be selected (shown in table 4.1), based on:

- their estimated contribution towards exhaust emissions of CO_2, $PM_{2.5}$ and NO_X from the overall New Zealand fleet using VEPM 5.1 for a default 2017 fleet and an average speed of 42 km/h. This speed was estimated to be the average speed across urban areas in New Zealand in 2017
- their contribution toward total fleet vehicle kilometres travelled(%VKT) using VEPM 5.1
- the availability of existing data on real-world emissions for that category.

The categories shown in table 4.1 were intentionally broad, covering multiple emissions standards to enable flexibility in being able to achieve the target numbers of test vehicles.

Test vehicles were obtained from various sources – both private and commercial – to meet these categories. Most vehicles had current vehicle registrations so vehicle metadata was sourced from the Motor Vehicle Register (MVR). However, all of the pre-J98 vehicles were used imports that had just arrived from Japan and were yet to be issued with a licence plate. For these vehicles, the engine plates were photographed and sent to the Vehicle Importers Association, which was able to provide comparable information to that from the MVR.

Table 4.1 Vehicle categories prioritised for testing with their estimated contribution to exhaust emissions and fleet travel

Duty[a] and fuel	Type	Year of manufacture	Emission standards covered [b,c]	%CO_2	%$PM_{2.5}$	%NO_X	%VKT	No. of vehicles to be tested
Light duty petrol	Jap used	2000 onwards	J00 & J05	15%	2%	3%	18%	3
	NZ new	2001-2009	Euro 3 & 4	24%	3%	6%	27%	3
Light duty diesel	Jap used	Pre-1998	Pre J98	2%	11%	2%	2%	5
	NZ new	Pre-2003	≤Euro 2	2%	14%	5%	2%	5
	NZ new	2004-2015	Euro 3 & 4	13%	28%	14%	16%	8
	NZ new	2016 onwards	Euro 5 & 6	1%	0%	1%	1%	2
Heavy duty diesel	Jap used	1997 onwards	J97, J03 & J05	3%	3%	4%	1%	1
	NZ new	2001-2011	Euro III & IV	7%	12%	17%	2%	3
	NZ new	2012 onwards	Euro V & VI	7%	4%	8%	2%	2
			Totals	74%	77%	60%	72%	32

[a] 'Light duty' means any vehicle with a gross vehicle mass less than 3.5 tonnes

[b] The standards of J00 and J05 etc refer to the year the standard was implemented in Japan for new vehicle models, ie 2000 and 2005 respectively. The J00 and J05 standards both include subordinate standards indicating the improvement above the base standard, eg the NO_X and non-methane hydrocarbon limits for the JLA standard are 50% tighter than the limits in the base 2000 (JGH) standard.

[c] See appendix E for a description of all of the relevant emissions standards.

Table 4.2 summarises the metadata for the vehicles that underwent PEMS testing. The relevant emission standards and official type-approval fuel consumption for the vehicles are listed in full in appendix B.

A significant amount of time and effort was required to secure suitable candidate vehicles for PEMS testing. Commercial and heavy duty vehicles were particularly difficult to obtain because businesses depend on them for their day-to-day operations. In many instances, we resorted to renting candidate vehicles, Consequently, there was limited diversity in the makes and models and the vehicles actually tested were not necessarily representative of a broad range of vehicles in their respective classes.

For the diesel vehicles in particular, certain models (eg Toyota Hilux) were represented multiple times in the samples. This meant the results were likely skewed by certain models. However, it did mean we could assess model repeatability in the results.

For the heavy duty diesel vehicles tested, the decision was made to focus on medium-sized delivery trucks (up to a GVM of six tonnes) which are common in urban areas rather than the heavier vehicles which typically travel longer distances. Nonetheless, most of the vehicles tested were those commonly seen on-road in New Zealand.

Note: Heavy vehicles were tested unladen (ie load=0%).

Table 4.2 Metadata for the vehicles that underwent PEMS testing

Vehicle ID	Make and model	Engine size (cc)	Fuel[a]	GVM[b] (kg)	Emission standard	NO_X limit	PM[c] limit	Official [d] CO_2	Exhaust treatment[e]	VEPM class[f]
Light duty petrol						**(g/km)**	**(g/km)**	**(g/km)**		
JLA LPV (Honda Stream)	2002 Honda Stream	1660	91P	1725	J00 (JLA)	0.04	---[g]	178	TWC	LPV
JCBA LPV (Subaru Forester)	2006 Subaru Forester	1990	91P	1695	J05 (JCBA)	0.025	---[g]	204	TWC	LPV
JCBA LPV (Toyota Avensis)	2005 Toyota Avensis	1990	91P	1755	J05 (JCBA)	0.025	---[g]	n/a	TWC	LPV
Eur3 LPV (Mazda 3)	2006 Mazda 3	1998	91P	1655	Euro 3	0.15	---[g]	197	TWC	LPV
Eur3 LPV (Toyota RAV4)	2010 Toyota RAV4	2362	91P	2100	Euro 3	0.15	---[g]	220	TWC	LPV
Eur4 LCV (Great Wall Ute)	2014 Great Wall V240 Ute	2378	95P	2660	Euro 4	0.11	---[g]	245	TWC	LCV
Light duty diesel						**(g/km)**	**(g/km)**	**(g/km)**		
JKC LPV (Toyota L/cruiser)	1996 Toyota Landcruiser	4163	D	3350	J92 (JKC)	0.60	---[g]	n/a	EGR	LPV
JKD LPV (Toyota Prado)	1997 Toyota Prado	2982	D	2185	J95 (JKD)	0.60	0.20	n/a	EGR	LPV
JKD LCV (Toyota Hilux) A	1996 Toyota Hilux	2982	D	2185	J95 (JKD)	0.60	0.20	n/a	EGR	LCV
JKD LCV (Toyota Hilux) B	1996 Toyota Hilux	2982	D	2185	J95 (JKD)	0.60	0.20	n/a	EGR	LCV
JKD LCV (Toyota Hilux) C	1997 Toyota Hilux	2982	D	2185	J95 (JKD)	0.60	0.20	n/a	EGR	LCV
Eur2 LCV (Ford Transit Van)	2005 Ford Transit Van	2402	D	3490	Euro 2	1.60[h]	0.20	237	EGR	LCV
Eur2 LCV (Toyota Hilux DCab) A	2005 Toyota Hilux Double Cab	2982	D	2780	Euro 2	1.60[h]	0.20	216	EGR	LCV
Eur2 LCV (Toyota Hilux DCab) B	2006 Toyota Hilux Double Cab	2982	D	2780	Euro 2	1.60[h]	0.20	216	EGR	LCV
Eur2 LCV (Toyota Hilux DCab) C	2008 Toyota Hilux Double Cab	2982	D	2780	Euro 2	1.60[h]	0.20	216	EGR	LCV
Eur2 LCV (Toyota Hilux SCab)	2004 Toyota Hilux Single Cab	2986	D	2730	Euro 2	1.60[h]	0.20	287	EGR	LCV
Eur4 LPV (Audi A5)	2012 Audi A5	2967	D	2010	Euro 4	0.25	0.025	n/a	EGR	LPV
Eur4 LPV (Toyota Prado) A	2008 Toyota Prado	2982	D	2900	Euro 4	0.39[i]	0.060[i]	242	EGR	LPV
Eur4 LPV (Toyota Prado) B	2009 Toyota Prado	2982	D	2990	Euro 4	0.39[i]	0.060[i]	221	EGR	LPV
Light duty diesel						**(g/km)**	**(g/km)**	**(g/km)**		
Eur4 LPV (Toyota Prado) C	2010 Toyota Prado	2982	D	2990	Euro 4	0.39[i]	0.060[i]	221	EGR	LPV

Vehicle ID	Make and model	Engine size (cc)	Fuel[a]	GVM[b] (kg)	Emission standard	NO_x limit	PM[c] limit	Official[d] CO_2	Exhaust treatment[e]	VEPM class[f]
Eur4 LCV (Ford Transit Van) A	2011 Ford Transit Van	2399	D	3490	Euro 4	0.39	0.060	270	EGR	LCV
Eur4 LCV (Ford Transit Van) B	2011 Ford Transit Van	2399	D	3490	Euro 4	0.39	0.060	270	EGR	LCV
Eur4 LCV (Hyundai iLoad Van)	2014 Hyundai iLoad Van	2477	D	3160	Euro 4	0.39	0.060	229	EGR	LCV
Eur4 LCV (Nissan Urvan)	2008 Nissan Urvan	2953	D	3100	Euro 4	0.39	0.060	284	EGR	LCV
Eur5 LCV (Ford Transit Van)	2012 Ford Transit Van	2198	D	3490	Euro 5	0.28	0.005	206	EGR, DPF	LCV
Eur5 LCV (Merc Sprinter Van)	2016 Mercedes Sprinter Van	2143	D	3490	Euro 5	0.28	0.005	215	EGR, DPF	LCV
Heavy duty diesel						**(g/kWh)**	**(g/kWh)**	**(g/km)**		
J97 (Isuzu Elf 4.5t)	1998 Isuzu Elf 4.5t	4330	D	4500	J97	4.5	0.25	n/a	EGR	HCV
EurIII (Mitsubishi Canter 4.5t) A	2007 Mitsubishi Canter Furn Van 4.5t	3907	D	4495	Euro III	5.0	0.10	n/a	EGR	HCV
EurIII (Mitsubishi Canter 4.5t) B	2007 Mitsubishi Canter Furn Van 4.5t	3907	D	4495	Euro III	5.0	0.10	n/a	EGR	HCV
EurIII (Mitsubishi Canter 4.5t) C	2007 Mitsubishi Canter Furn Van 4.5t	3907	D	4495	Euro III	5.0	0.10	n/a	EGR	HCV
EurV (Mitsubishi Canter 6t) A	2012 Mitsubishi Canter Tipper 6t	2998	D	5995	Euro V	2.0	0.02	n/a	EGR, DPF	HCV
EurV (Mitsubishi Canter 6t) B	2013 Mitsubishi Canter Tipper 6t	2998	D	5995	Euro V	2.0	0.02	n/a	EGR, DPF	HCV

Notes

[a] '91P' is unleaded 91 octane petrol, '95P' is unleaded 95 octane petrol and 'D' is diesel. Vehicles were fuelled according to their manufacturer's specifications.

[b] 'GVM' is gross vehicle mass.

[c] all PM is assumed to be $PM_{2.5}$.

[d] The official CO_2 is derived from the official type-approval fuel consumption figures for each model (see appendix B).

[e] 'TWC' is three-way catalyst, 'EGR' is exhaust gas recirculation and 'DPF' is diesel particulate filter.

[f] 'LPV' is light passenger vehicle, 'LCV' is light commercial vehicle and 'HCV' is heavy commercial vehicle. These are the classes assigned to this vehicle in VEPM.

[g] '---' means no PM limit was set for this emission standard.

[h] For Euro 2 light duty diesel vehicles, the NO_x limit is combined with hydrocarbons so this is the total.

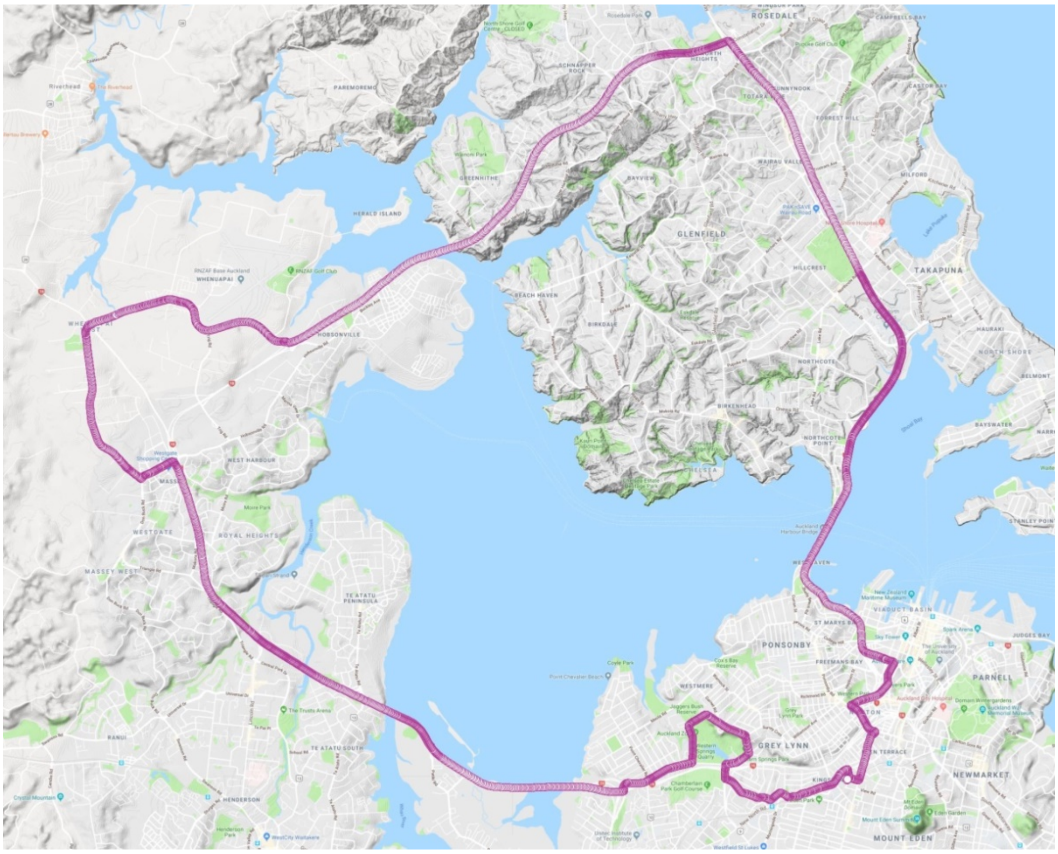
[i] At the Euro 1–4 stages, passenger vehicles heavier than 2500 kg were type approved as Category N_1 (LCV) vehicles.

4.3 Real-world test route

Following the on-road validation testing, the test route was modified to incorporate a greater range of real-world driving conditions encountered in New Zealand. The maximum time for a real driving test was limited to approximately 60 minutes so the route was re-designed to incorporate the widest practicable range of realistic conditions in the time available. The 60-minute limit was imposed based on the amount of battery power available to operate the equipment. Additional batteries could have been deployed for some of the test vehicles but space was limited in the smaller vehicles.

The final real-world route selected for the PEMS testing is shown in figure 4.12 and encompassed a mix of city centre, urban, open road and motorway driving over a total distance of just over 53 km.

Figure 4.12 Final real-world test route for the PEMS testing



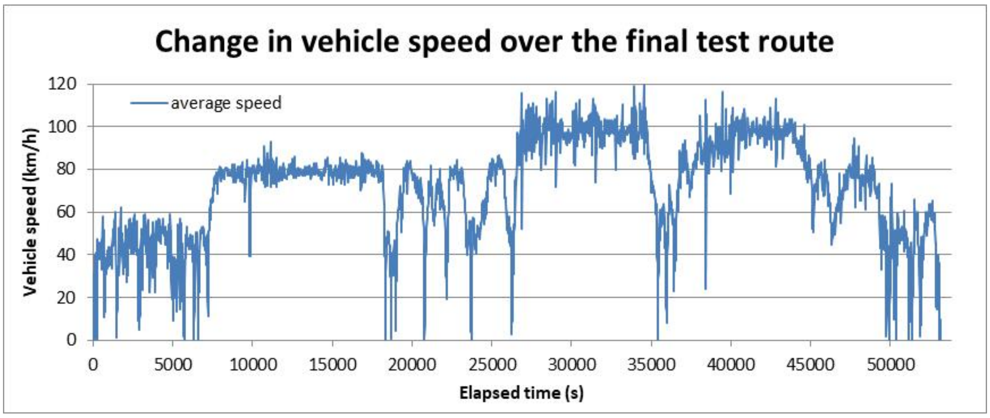
The objective of the testing was to measure real-world emissions and fuel consumption for different operating conditions, including driving speeds, driving styles, traffic/road conditions, gradients and cold starts.

Figure 4.13 shows the change in average speed across the final real-world route as a function of distance (in the graph at the top) and as a function of time (in the graphs on the bottom).

Figure 4.14 shows the change and distribution information for average gradient across the final real-world route.

Both figures (4.13 and 4.14) confirm that the final real-world route selected for the PEMS testing incorporated a reasonable range of average vehicle speeds and gradients.

Figure 4.13 Change in and distribution of average speed across the test route, based on one-second average data



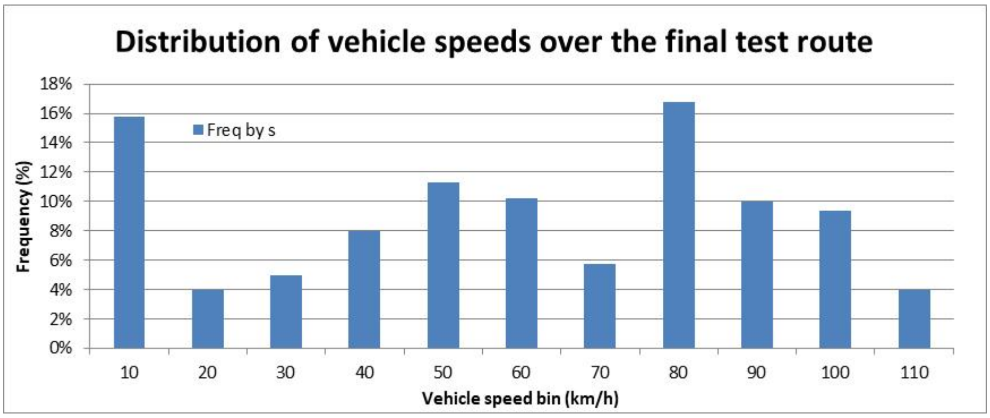
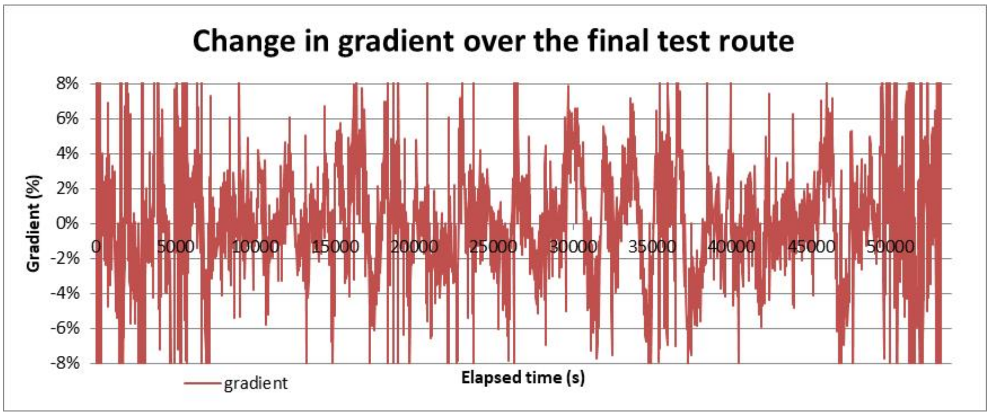
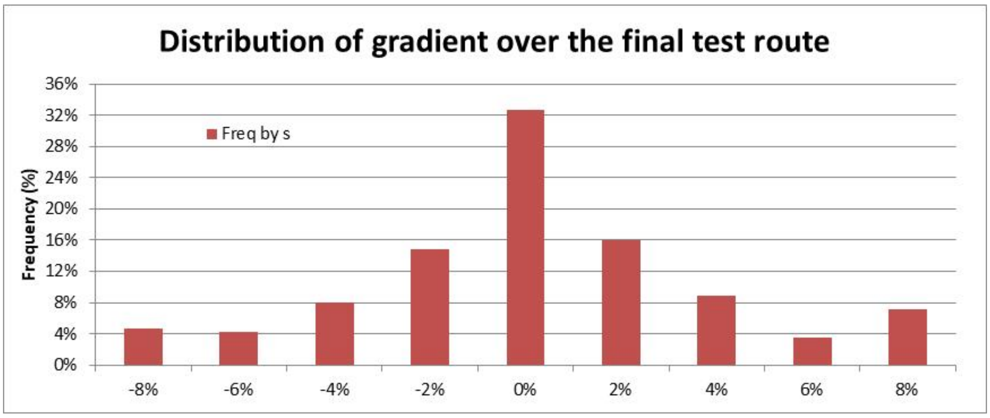


Figure 4.14 Change in and distribution of gradient across the test route, based on 1-second average data





4.4 On-road testing procedure

4.4.1 Initial evaluation and inspection

All potential test vehicles were first assessed on paper (using MVR data and the like) to confirm they met the relevant required emission standard. Following that, vehicles were required to pass a 'gross emitter' inspection before PEMS testing commenced. Some potential vehicles were rejected after failing this initial inspection.

New Zealand does not have an inspection and maintenance programme to identify gross emitters but does require vehicles to pass a five-second visible smoke check during a warrant of fitness or certificate of fitness inspection (NZ Transport Agency 2016a). This smoke check was included in the following protocol applied to the PEMS test vehicles.

4.4.1.1 Protocol for identifying gross emitters

- Do not test if the vehicle has not been serviced within the last 15,000 km (which equates to typical recommended service intervals). If service records are not available, assess the general condition of the engine (eg cam belt stickers, condition of the oil and filters) and do not test if the vehicle appears to be poorly maintained.
- Undertake visual inspection of exhaust and emission control systems to identify any obvious leaks/signs of tampering. Do not test vehicle if the exhaust or emission control system are not in good condition.
- Do not test vehicle if there are obvious signs of aftermarket modifications (eg addition of a turbocharger).
- Visually inspect exhaust emissions in accordance with the New Zealand exhaust emissions rule (visual check with engine at idle for at least five seconds and accelerated to the lower of 2500 rpm or half the maximum engine speed). Do not test if there is visible smoke.

4.4.1.2 Additional step for vehicles with on-board diagnostics (OBD):

- Interrogate OBD. Do not test vehicle if the OBD indicates fault/s with the engine or the emission control systems.

Note: We had access to three different types of OBD scanners – ELM327, MPPS v13.02 and VAG 409.1 – for recording the OBD data. With most vehicles we were able to record some information. However, the critical parameters – exhaust flow, engine temperature and vehicle speed – proved difficult to log at a reasonable frequency. We found our OBD scanners would record intermittently or the refresh rate would change during the test drive. We also observed a noticeable lag in response time – particularly on older vehicles. These issues may have been due to the (generally) older vehicles we tested and/or possibly limitations of the OBD scanners we were using.

4.4.2 Pre-test preparation and fuelling

The following steps were undertaken to prepare for an on-road test once a suitable test vehicle had been confirmed.

- All flow-related equipment was calibrated pre-test using primary flow standards.
- All analysers were assessed for stability, logicality and response.
- All pre-weighed filters were installed in the test rig.

- Vehicles were collected then driven to the Kingsland Gull service station for fuelling.
- The pump nozzle was inserted in the fuel pipe and fuel added until the automatic cut off refused to allow any more fuel to flow. Refuelling was then stopped for 10–30 seconds to allow the fuel level and any foaming/blow back to settle before confirming the tank was 'full'. Efforts were made to use the same pump each time but this was not always possible at a public facility. Regardless, only pumps displaying valid calibration stickers were used for fuelling.
- The vehicle was then driven approximately 500 m to the laboratory (the test start point).

4.4.3 PEMS installation and on-road operation

Back at the laboratory:

- The equipment was installed in the vehicle (see figure 4.15).
- The heated elements were warmed up using mains power.
- The analysers were allowed to stabilise prior to transferring to battery/inverter power.
- The vehicle engine was then started (typically between 20 and 50 minutes after fuelling), all computer systems were installed and final checks were made regarding the operational status of all equipment.
- The vehicle was given a final health and safety assessment against a pre-test checklist and released for testing.

  Note: Our test protocol did not comply with regulatory requirements for measurement of cold start emissions. In particular, the vehicle was driven (to the nearby service station) on the day of the test, and the equipment was typically bypassed for the first 30 to 40 seconds after start up. This means that our test results might under-estimate cold start emissions somewhat compared with a regulatory test. However, the vehicle exhaust temperature was recorded so the amount of cold start could be determined.

  Note: Heavy vehicles were tested unladen (ie load=0%).

Figure 4.15 The PEMS equipment being installed in a test vehicle

Note: TV One news filmed the equipment in operation during the testing in March 2018 (TVNZ 2018).

Once on-road:

- The GPS and ambient temperature measurements were initiated and the vehicle started driving the test route.
- The vehicle was stopped briefly at the end of the first urban driving component of the test route to check the operational status of all equipment and measurement systems.
- The vehicle continued and completed a motorway section of the test, before being stopped briefly to again confirm the operational status of all equipment.
- The vehicle then continued to complete the test route.

4.4.4 Post-test requirements

Upon completion of the on-road test:

- The equipment was removed from the vehicle and post-test flow and analyser checks were undertaken.
- The analysers were transferred to dry, zero air flows to eliminate any deleterious effects of the test environment on the equipment.
- The vehicles were refuelled to maximum levels (according to the procedure outlined in section 3.4.2) and returned to their owners.
- Measurements were downloaded from each of the data loggers covering readings from the:
  - Ecophysics (NO_X/NO/NO_2) analyser
  - mass flow meters
  - Lambda meter
  - exhaust gas temperature sensor
  - static and differential pressure sensors
  - DustTrak $PM_{2.5}$ concentrations
  - GPS logger
  - ambient temperature logger
  - CO_2 sensor.
- Results were then stored in a spreadsheet titled with the vehicle licence plate number and date of test. Vehicle engine number was used for those vehicles not yet been registered.

4.5 Data quality assurance and analysis protocols

4.5.1 Raw parameters measured

The following raw parameters were logged during vehicle tests:

- time
- GPS coordinates
- exhaust temperature

- static pressure and differential pressure (between total impact pressure and static pressure)
- air–fuel ratio (lambda)
- OBD measurements (where available)
- zero air gas flow rate and gas sample flow rate
- zero air PM flow rate and large sample PM flowrate
- NO and NOx
- CO_2
- $PM_{2.5}$
- ambient air temperature.

4.5.2 Data validation and quality assurance

The steps involved in the data quality assurance and validation were as follows:

1. Visual and completeness check
2. Data conversion
3. Removal of anomalous values
4. Data alignment
5. Application of corrections and offsets.

Step 1. The data from each instrument was assessed for completeness and then plotted to ensure the dynamic range was consistent with what would have been expected. Where the full record was incomplete and/or the plotted data did not display the response expected, the test was deemed incomplete and a repeat would be scheduled. Approximately 25% of vehicle tests needed to be repeated – usually due to incomplete data from one or more sensors.

Step 2. The instrument readings (typically logged as voltages) were converted into their relevant parameters (eg temperature, pressure). These conversions were made using the manufacturer's calibration information which was independently verified.

Step 3. Anomalous values were identified and removed. Spurious readings can arise due to electromagnetic interference, physical impact of the sensor or a communication error between the sensor and the data logger. In most cases, the anomaly generated a 'null' value which was simply removed prior to the averaging process. On occasion, the anomaly generated an unrealistic number (eg an exhaust temperature of >10,000°C). These spurious readings were usually very obvious and were removed prior to generating a one-second average. Typically, 'null' values and spurious values comprised less than 0.1% of the dataset.

Step 4. Data from each of the data channels were aligned. Some of the data (eg the pressure sensor) was logged at relatively high frequency (1000 Hz) while other instruments such as the GPS logged values only once per second (1 Hz). Readings from each of the sensors were converted to one-second data by averaging the preceding multiple values in each one-second period. For example, the timestamp at 10:01:01 consists of averaging all readings for the particular sensor taken between 10:00:00 and 10:01:01 and assigning them to the 10:01:01 timestamp.

Step 5. Corrections (where necessary) were applied to the gas analyser data to account for any differences between gas calibrations prior to and after the test. In most instances, the pre and post-test calibrations were virtually identical with any variation falling within the uncertainty of the analyser and diluter. Where differences were found (typically less than 2 ppb), the change in concentration was applied linearly (ramped) across the duration of the test. Corrections to the $PM_{2.5}$ data were made after comparing the optical mass recorded by the DustTrak with the particulate mass collected on the GFA filter installed in the sample line exiting the analyser. This enabled us to apply a gravimetric correction to the continuous results.

Following the corrections, the NO_X and CO_2 data was offset by two seconds to account for the time it took the sample gas to traverse the sample train and reach the gas analysers. For the $PM_{2.5}$ data, the lag was found to be less than the one-second time interval used to record this data. The lags were calculated from the volumetric flowrates, the technical specifications of the mass flow controllers and the analysers, and the physical volume of the gas sample particle filter and the heater sample line tubing as well as the tubing volume beyond the tee to the analyser. The residence time in the main sample line was estimated at <0.2 seconds and the residence time in the analyser line at approximately 1.5 seconds.

4.5.3 Data processing

The corrected data and the validated base data were then transferred to an Excel workbook (one per vehicle test) for data processing. Appendix C lists the sheets and contents, with all assumptions and calculations shown.

The final processed results included:

- time in seconds
- speed (*v*) in km/h and m/s
- distance travelled in m
- acceleration (*a*) in m/s^2
- gradient as a percentage, eg 1% means 1 m increase in elevation per 100 m travelled
- exhaust temperature in °C
- mass of NO, NO_X, NO_2, $PM_{2.5}$ and CO_2 in g
- emission factors for NO_X, NO_2, $PM_{2.5}$ and CO_2 in g/km
- fuel consumption in l/100 km.

4.5.4 Data binning

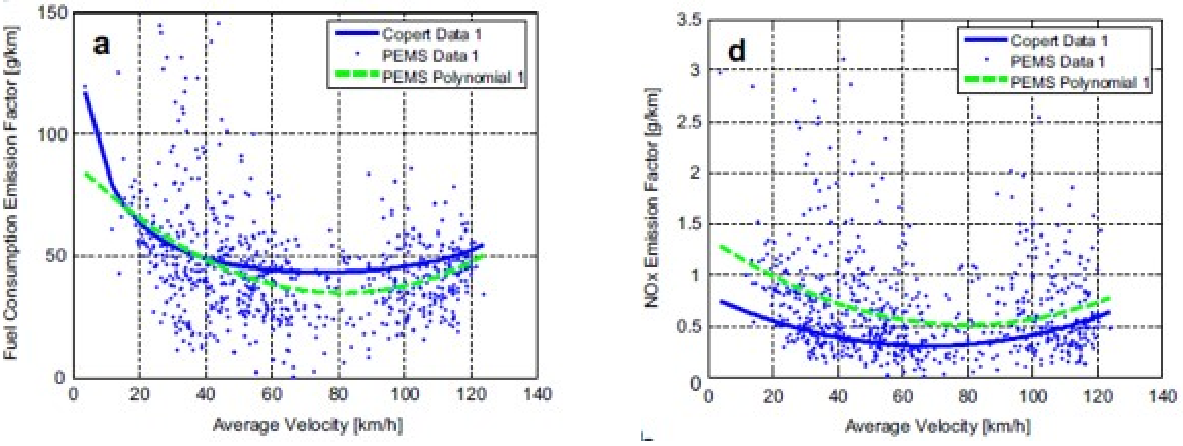
Binning of PEMS data is useful for a number of reasons.

4.5.4.1 Developing speed-based emission factors

Mean speed-based emission factors can be derived from PEMS data by sorting the data into speed ‘bins’ and plotting the corresponding mass emissions against the mean speed of the data bin. This produces a cloud of data points to which a regression curve may be fitted (Franco et al 2013). Figure 4.16 shows an example with PEMS data sorted into 1 km/h speed bins compared with the corresponding COPERT emission factor (Kousoulidou et al 2013).

As part of the data processing, we binned the PEMS data according to average speed so emission factors could be compared directly with speed-based emission factors from VEPM for the corresponding vehicle.

Figure 4.16 Example of a comparison between COPERT and PEMS results for a Euro 5 diesel vehicle showing (a) fuel consumption factors and (d) NOx emission factors by 1 km/h speed bins (Kousoulidou et al 2013)



4.5.4.2 Investigating the effect of real-world variables

Capturing the effect of real-world variables on vehicle emissions is the key advantage of PEMS testing. However, it means that overall results from individual on road tests may not be directly comparable with each other due to the dynamics of the environment. To improve comparability, all one-second test data was 'binned' based on ICCT recommended criteria (Franco et al 2014). These take into account the most significant sources of variability between real-world tests including:

- speed
- gradient
- acceleration * velocity (*a*v*) which approximates instantaneous, mass-specific power and provides an indication how dynamic the driving is.

Note: Franco et al (2014) present results according to time share and distance share of trips. However, we binned our data on time share only of the trip due to the way the data was logged. Regardless, we do not consider this approach affected the interpretation of the results.

In addition to these criteria, we also binned the first 3 km of data to take into account any 'cold start' effect. The first 3 km of the trip was used as the cold start criteria (in preference to ICCT criteria based on exhaust temperature), because this is approximately equivalent to the cold start portion of a trip in VEPM. This allowed for cold start emission factors to be developed for VEPM. This 'cold start' data was excluded from gradient and *a*v* bins to reduce confounding factors. Binning data enabled us to develop 'situation-specific' emission factors for each vehicle so these could be directly compared.

Table 4.3 lists all the binning criteria applied to the PEMS data.

Table 4.3 Binning criteria for PEMS data for the one-second averages

Variable	Binning criteria	Bin descriptor
Acceleration * velocity (approximates instantaneous mass specific power and indicates the degree of dynamic driving)	$a \times v < -9.2\ W/kg$	Strong negative
	$-9.2\ \leq a \times v < 0\ W/kg$	Mild negative
	$0 \leq a \times v < 9.2\ W/kg$	Mild positive
	$a \times v \geq 9.2\ W/kg$	Strong positive
Road gradient	$gradient < -4\%$	Strong downhill
	$-4 \leq gradient < -1\%$	Mild downhill
	$-1 \leq gradient < 1\%$	Pretty flat
	$1 \leq gradient < 4\%$	Mild uphill
	$gradient \geq 4\%$	Steep uphill
Cold start	First 3 km of trip	Cold start

5 Results

This chapter presents the key results from the PEMS testing of the New Zealand vehicles as follows:

- overall real-world results, compared with emissions standards where applicable
- real-world results compared with VEPM predictions
- effects of real-world factors on real-world emissions and fuel consumption
- comparison with international results.

The results broken down by various binning criteria are tabulated in appendix D.

5.1 PEMS test records

Table 5.1 shows the details of the PEMS test records collected for the 32 vehicles. These records were compiled into an electronic database of all on-road measurements (including fuel consumption, emissions, speed, acceleration, gradient and other vehicle operating conditions).

Table 5.1 Details of all PEMS test records

Vehicle descriptor	Date tested	Start time	Start ODO (km)	Ambient temp (°C)	Av speed (km/h)
Light duty petrol					
JLA LPV (Honda Stream)	26-Apr-18	11:28 am	142367	18.1	47.7
JCBA LPV (Toyota Avensis)	27-Apr-18	10:10 am	145532	18.4	42.7
JCBA LPV (Subaru Forester)	2-Feb-18	11:48 am	119898	22.1	43.1
Eur3 LPV (Mazda 3)	1-May-18	4:12 pm	201305	18.3	42.2
Eur3 LPV (Toyota RAV4)	3-May-18	11:19 am	209101	16.5	49.3
Eur4 LCV (Great Wall Ute)	3-May-18	3:21 pm	92450	19.7	43.9
Light duty diesel					
JKC LPV (Toyota L/cruiser)	21-Mar-18	1:24 pm	175091	21.3	45.2
JKD LPV (Toyota Prado)	20-Mar-18	12:15 pm	212039	18.4	48.1
JKD LCV (Toyota Hilux) A	19-Apr-18	4:20 pm	112071	18.4	37.3
JKD LCV (Toyota Hilux) B	19-Mar-18	1:17 pm	137035	22.7	44.1
JKD LCV (Toyota Hilux) C	16-Mar-18	1:38 pm	144090	23.6	39.4
Eur2 LCV (Ford Transit Van)	8-Mar-18	10:36 am	245206	22.1	39.7
Eur2 LCV (Toyota Hilux DCab) A	14-Mar-18	11:01 am	214170	22.3	48.7
Eur2 LCV (Toyota Hilux Dcab) B	26-Apr-18	3:25 pm	270103	18.3	49.1
Eur2 LCV (Toyota Hilux Dcab) C	27-Apr-18	2:32 pm	198511	21.0	43.2
Eur2 LCV (Toyota Hilux Scab)	2-May-18	12:21 pm	128017	18.8	43.4
Eur4 LPV (Audi A5)	1-May-18	12:06pm	77047	18.6	45.9
Light duty diesel					
Eur4 LPV (Toyota Prado) A	8-Mar-18	3:29 pm	129465	22.6	38.6

Vehicle descriptor	Date tested	Start time	Start ODO (km)	Ambient temp (°C)	Av speed (km/h)
Eur4 LPV (Toyota Prado) B	7-Mar-18	2:51 pm	147741	24.7	45.8
Eur4 LPV (Toyota Prado) C	7-Mar-18	10:24 am	119128	21.7	46.8
Eur4 LCV (Ford Transit Van) A	6-Mar-18	2:57 pm	163018	22.4	42.2
Eur4 LCV (Ford Transit Van) B	17-Apr-18	3:46 pm	156782	22.8	41.2
Eur4 LCV (Hyundai iLoad Van)	9-Mar-18	2:39 pm	38381	24.7	33.1
Eur4 LCV (Nissan Urvan)	13-Mar-18	12:07 pm	185047	22.2	48.2
Eur5 LCV (Ford Transit Van)	4-May-18	12:57 pm	153905	18.1	47.6
Eur5 LCV (Merc Sprinter Van) #1	3-Mar-18	10:50 am	15819	21.2	44.0
Eur5 LCV (Merc Sprinter Van) #2	20-Apr-18	1:47 pm	17361	24.8	41.9
Heavy duty diesel					
J97 (Isuzu Elf 4.5t)	30-Apr-18	4:21 pm	225201	21.4	37.1
EurIII (Mitsubishi Canter 4.5t) A	22-Mar-18	12:30 pm	201011	18.5	43.4
EurIII (Mitsubishi Canter 4.5t) B	23-Apr-18	12:57 pm	188098	18.5	43.3
EurIII (Mitsubishi Canter 4.5t) C	26-Mar-18	3:30 pm	202097	25.4	33.1
EurV (Mitsubishi Canter 6t) A	5-Apr-18	2:36 pm	132366	21.4	36.9
EurV (Mitsubishi Canter 6t) B	9-Apr-18	1:40 pm	38125	21.8	45.7

Note: ‘Eur5 LCV (Merc Sprinter Van)’ appears twice in the database (making a total of 33 files for 32 vehicles) because data processing revealed the vehicle’s first test had one set of complete gaseous measurements but incomplete $PM_{2.5}$ measurements and vice versa for the second test. By the time this issue was identified, the vehicle was no longer available for additional testing.

5.2 Overall PEMS results

This section presents the overall (total trip) real-world average emission factors calculated from the PEMS testing and compares them with emission standards and official type-approval fuel consumption figures (see table 4.2) where applicable. Official standards and type-approval figures are based on specific drive cycles and/or conditions that may vary significantly from those in the real world. As such, our results are not expected to match the relevant standards and approvals but rather serve as a point of comparison against real-world New Zealand driving.

Note: Emission standards for heavy duty diesel vehicles are specified in g/kWh not g/km so the PEMS results were converted using a series of assumptions for the comparison in this section. For these vehicles, the total fuel used (taken from the total CO_2 recorded) was converted to a total energy figure based on the calorific value of New Zealand diesel (43.11 MJ/kg). The total energy in MJ was then divided by 3.6 to get the total kWh released from the fuel. This figure was then multiplied by 0.45, assuming only 45% of the energy combusted in a diesel engine is translated to actual vehicle motion, to get the average kWh for each vehicle. Each heavy duty PEMS result (in terms of pollutant mass) was then divided by this average kWh figure to enable an estimate of the actual result to be compared with the standards. These g/kWh estimates were only used in this section – to indicate likely real-world performance against the emissions standards. In section 5.3 onwards, all subsequent analyses for heavy duty vehicles were undertaken using the actual PEMS results in g/km.

5.2.1 NO_x

Figures 5.1 to 5.3 compare the real-world NO_x emission factors for each vehicle by duty and fuel type versus the relevant emissions standards (see table 4.2).

The results show:

- For all vehicle duties and fuel types, real-world NO_x emissions were generally higher than regulated emission standards. Real-world results were 4.6 times higher on average (ranging from two to nearly eight times).
- For light duty petrol vehicles (figure 5.1), NO_x emissions from the Japanese used vehicles were lower than those for the newer Euro 3 and Euro 4 New Zealand-new vehicles that were tested, even though the Japanese-used vehicles were appreciably older. This is likely due to the tighter limits imposed in Japan in the late 1990s to tackle NO_x pollution in urban locations.
- For light duty diesel vehicles (figure 5.2), the results were quite different, with NO_x emissions from the Japanese-used vehicles recording significantly higher emissions than the Euro 2 New Zealand-new vehicles that were tested. NO_x emissions showed little improvement between Euro 2 and Euro 5.
- For the heavy duty diesel vehicles (figure 5.3), the results suggest a possible improvement in NO_x emissions between Euro III and Euro V consistent with the relative improvement in the emissions standards.
- Real-world NO_x emissions for the same types of vehicles (eg JKD Toyota Hilux in figure 5.2) were remarkably consistent, given the results were for different vehicles tested on different days.
- Under the conditions of our tests, real-world NO_x emissions from light duty petrol vehicles irrespective of emission standard (figure 5.1) were less than real-world NO_x emissions from Euro 5 light duty diesel vehicles (figure 5.2).

Figure 5.1 Real-world NO_x emission factors for light duty petrol vehicles compared with relevant emissions standards

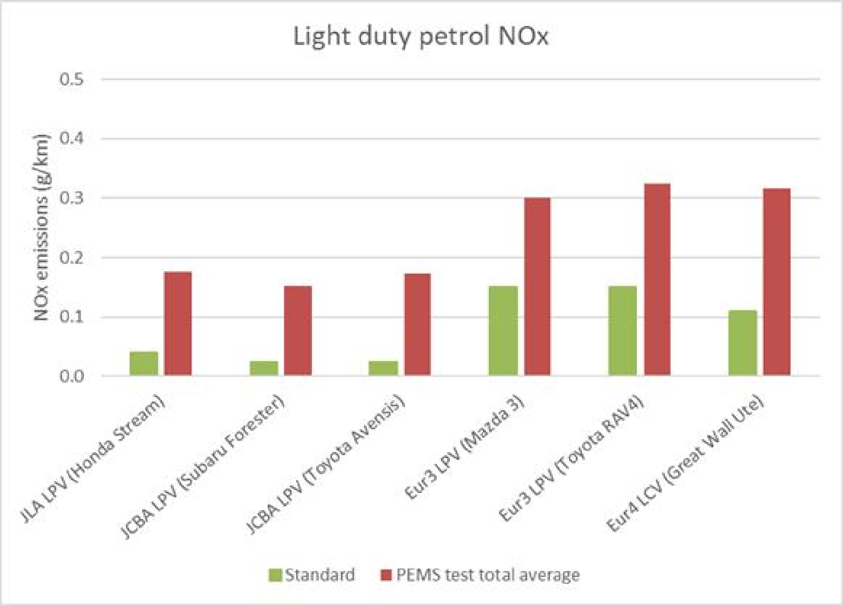
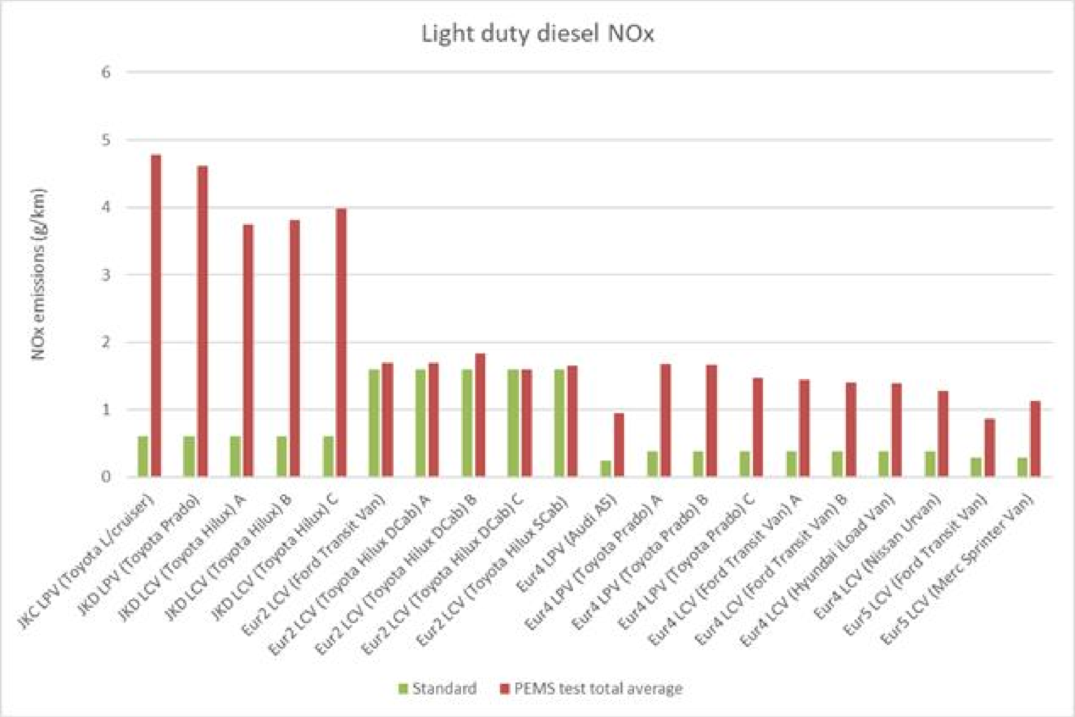
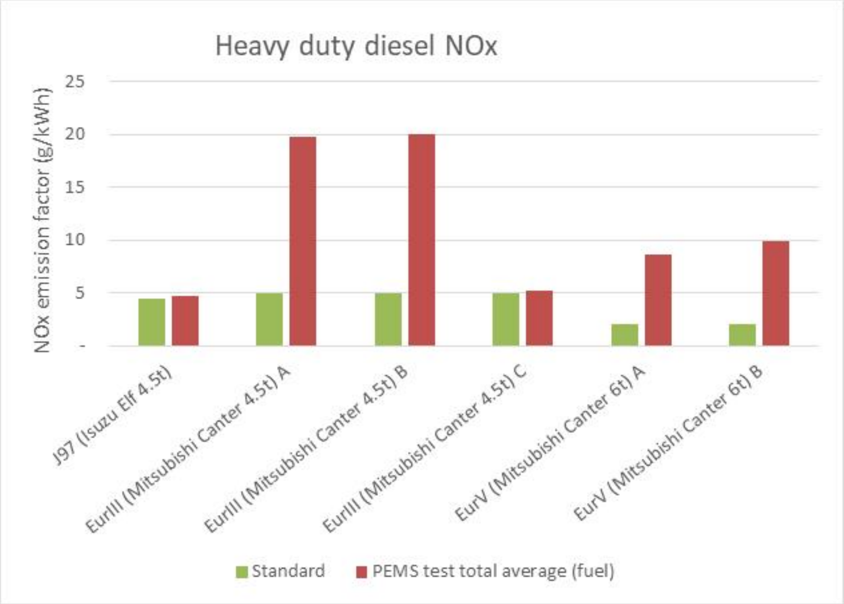


Figure 5.2 Real-world NO_X emissions factors for light duty diesel vehicles compared with relevant emissions standards.



Note: Euro 2 light commercial vehicles have a combined HC & NO_x standard and do not have a separate NO_x standard.

Figure 5.3 Real-world NO_X emission factors for heavy duty diesel vehicles compared with relevant emissions standards.



Note: Broad assumptions were made to convert the real-world g/km to g/kWh so these values should be taken as indicative only.

5.2.2 NO_2

Figures 5.4 to 5.6 show the real-world NO_2 emission factors for each vehicle by duty and fuel type.

Note: There are no regulated emission standards for NO_2 for any of the vehicle duties and fuel types.

The results show:

- For light duty petrol vehicles (figure 5.4), the difference between the Japanese-used vehicles and their later New Zealand-new Euro 3 counterparts was less marked for NO_2 than for NO_x. The major difference seen was for the New Zealand-new Euro 4 Great Wall vehicle which recorded appreciably higher NO_2 emissions than the other light duty petrol vehicles tested.
- For light duty diesel vehicles (figure 5.5), real-world NO_2 emissions from Japanese-used vehicles were generally higher than the more modern New Zealand-new vehicles. However, there was no obvious improvement in NO_2 emissions for the newer Euro 4 and 5 vehicles compared with the older Euro 2 vehicles, with the possible exception of the Euro 5 Mercedes Sprinter Van. None of the vehicles tested used diesel emissions fluid (eg AdBlue) to treat NO_2 emissions.
- For heavy duty diesel vehicles (figure 5.6), the results suggest a possible slight improvement in NO_2 emissions between Euro III and Euro V.
- Real-world NO_2 emissions from light duty petrol vehicles irrespective of emission standard (figure 5.4) were substantially lower than NO_2 emissions from light duty diesel vehicles (figure 5.5) – even with the latter at Euro 5.
- Real-world-NO_2 emissions from light duty petrol vehicles were around 4% of the total NO_x emissions on average (range 3% to 6%) across the vehicles tested. However, the fraction varied much more significantly for diesel vehicles. Light duty diesel vehicles recorded around 17% NO_2 in their NO_x emissions (range 6% to 40%) and heavy duty diesel vehicles were similar at 13% on average (range 7% to 17%).

Figure 5.4 Real-world NO_2 emission factors for light duty petrol vehicles

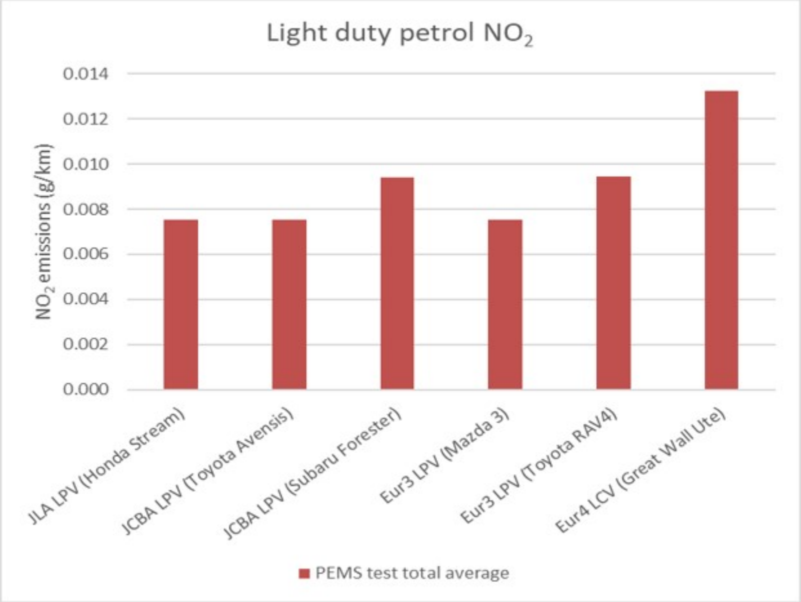


Figure 5.5 Real-world NO_2 emission factors for light duty diesel vehicles

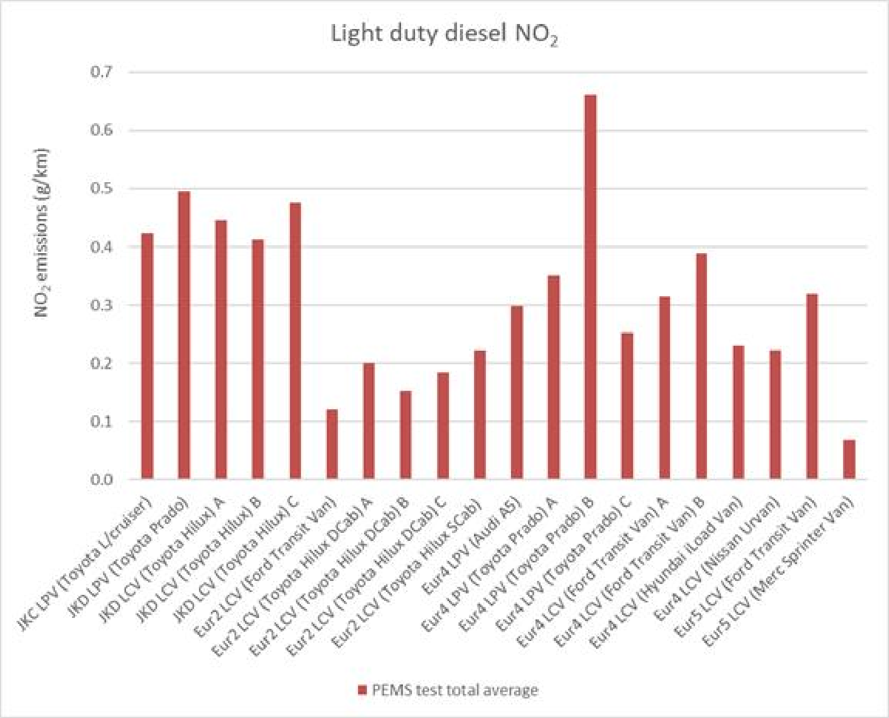
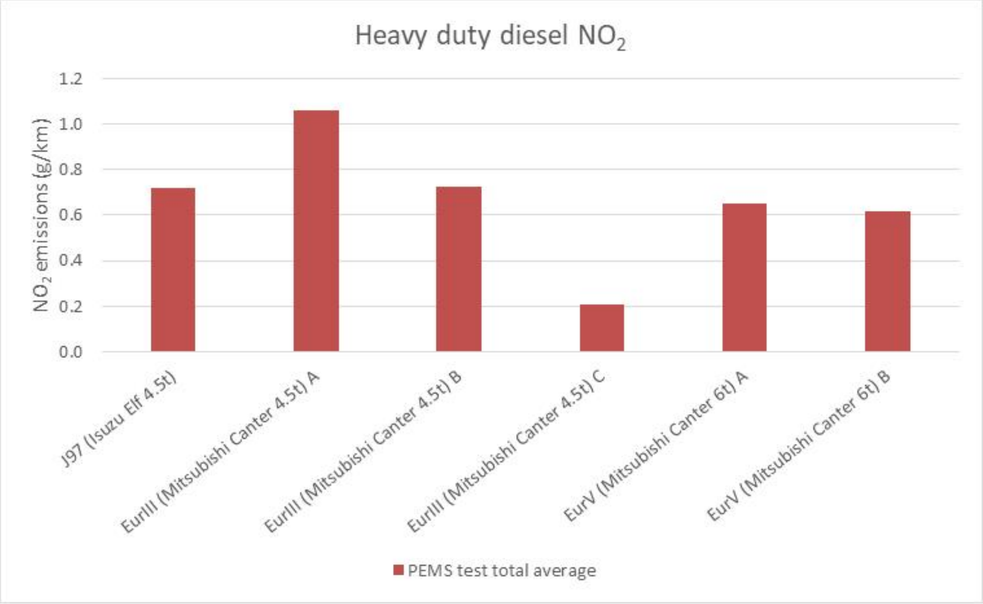


Figure 5.6 Real-world NO_2 emission factors for heavy duty diesel vehicles

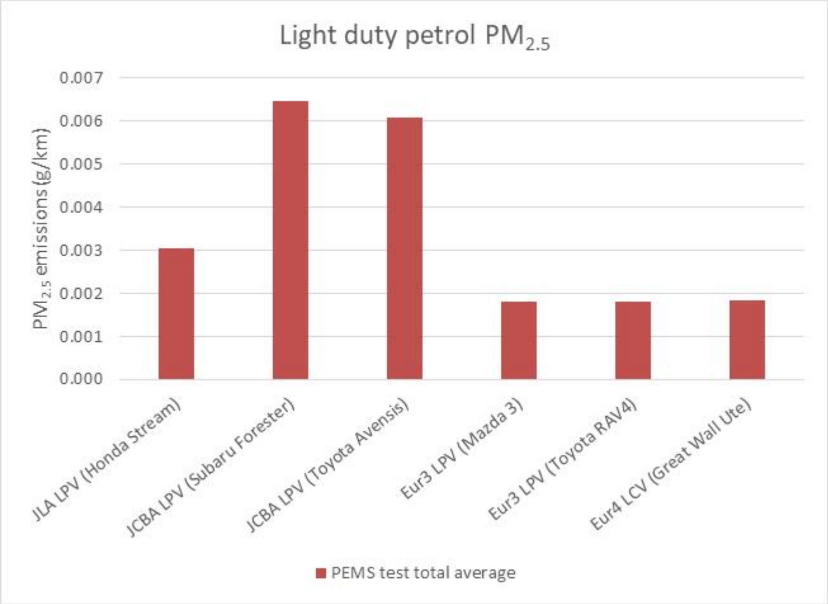


5.2.3 $PM_{2.5}$

Figures 5.7 to 5.9 compare the real-world $PM_{2.5}$ emission factors for each vehicle by duty and fuel type versus the relevant emissions standards (see table 4.2).

- Unlike NO_X, real-world $PM_{2.5}$ emissions were typically the same or only slightly higher than the regulated emissions standards. Real-world results were about equal on average (ranging from half to 1.5 times).
- For light duty petrol vehicles (figure 5.7), $PM_{2.5}$ emissions from the Japanese-used vehicles were higher than those for the newer Euro 3 and Euro 4 New Zealand-new vehicles that were tested. However, $PM_{2.5}$ emissions for light duty petrol vehicles were orders of magnitude lower than for light duty diesel vehicles so the difference between Japanese-used and New Zealand-new Euro 3/4 is somewhat exaggerated.
- For light duty diesel vehicles (figure 5.8), $PM_{2.5}$ emissions from the Japanese-used vehicles were lower than those from the newer Euro 2 light duty diesel vehicles that were tested. However, $PM_{2.5}$ emissions from newer Euro 4 and Euro 5 diesel vehicles were substantially better than emissions from older light duty diesel vehicles.
- The heavy duty diesel vehicles (figure 5.9) also showed marked $PM_{2.5}$ emissions reductions with improved technology. The older Japanese-used vehicle (1998 Isuzu Elf 4.5t) recorded real-world $PM_{2.5}$ emissions of just over four times those for a similarly sized but more modern Euro III vehicle.
- As expected, all four tested vehicles fitted with particulate filters (two Euro 5 and two Euro V diesel vehicles) produced minimal $PM_{2.5}$ emissions. $PM_{2.5}$ emissions from the Euro 5 light duty diesel vehicles tested (figure 5.8) were comparable to those from the light duty petrol vehicles (figure 5.7).

Figure 5.7 Real-world $PM_{2.5}$ emission factors for light duty petrol vehicles.



Note: There are no relevant $PM_{2.5}$ emissions standards set for the vehicles shown.

Figure 5.8 Real-world $PM_{2.5}$ emission factors for light duty diesel vehicles compared with relevant emissions standard limits

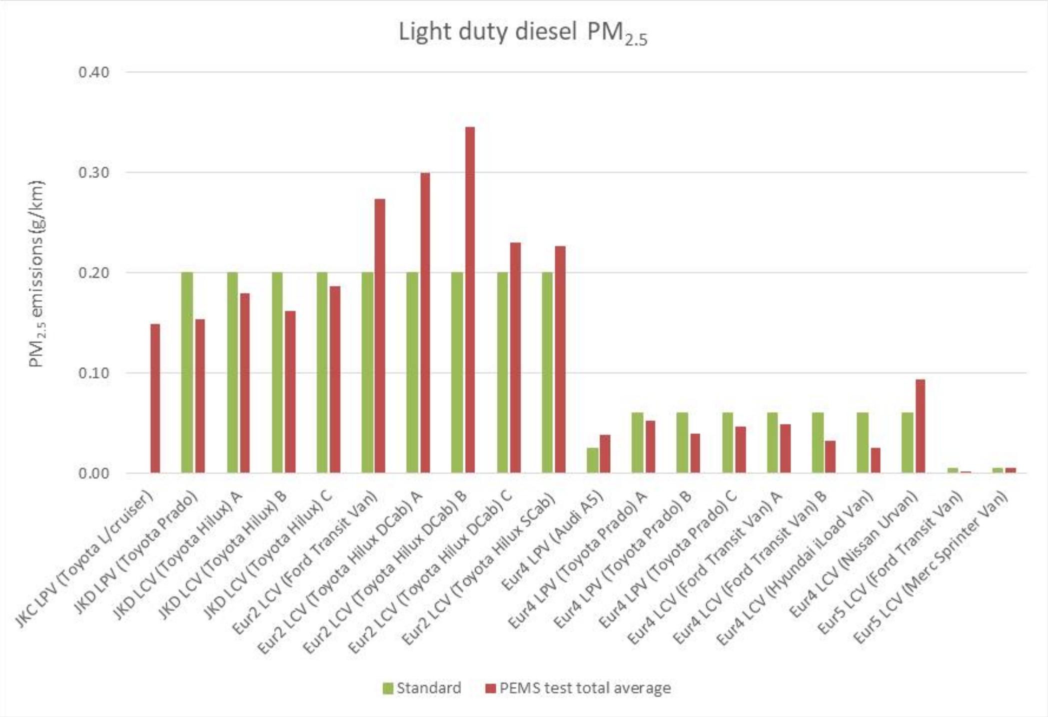
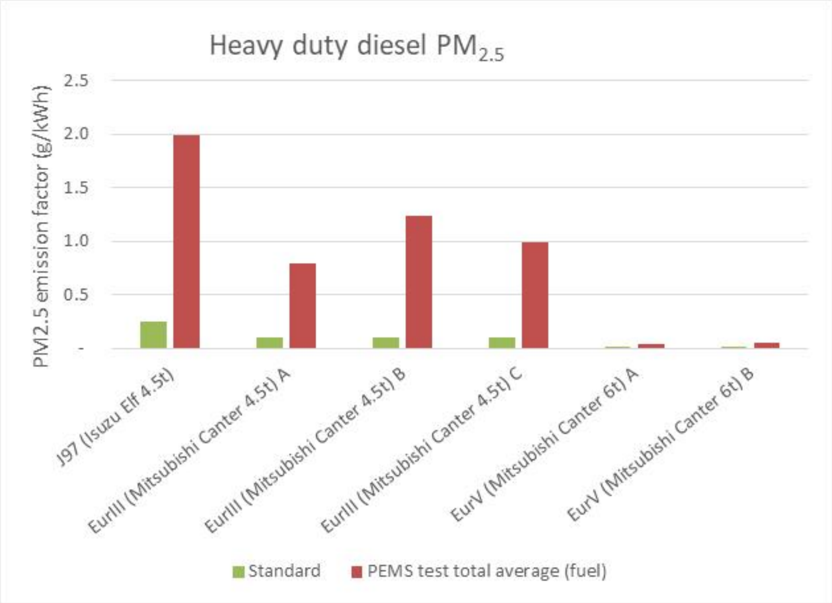


Figure 5.9 Real-world $PM_{2.5}$ emission factors for heavy duty diesel vehicles compared with relevant emissions standards.



Note: Broad assumptions were made to convert the real-world g/km to g/kWh so these values should be taken as indicative only.

5.2.4 CO_2

Figures 5.10 to 5.12 compare the real-world CO_2 emission factors for each vehicle by duty and fuel type versus the relevant official (type-approval) fuel consumption figures for each vehicle (see table 4.2).

Note: These real-world results were taken from the CO_2 measured in the exhaust (not the estimated quantity of fuel used at pump). Difficulties in establishing repeatability of measurements at the service station (a public facility) meant the fuel use at the pump was recorded only as a cross check.

The results show:

- For all vehicle duties and fuel types, real-world CO_2 emissions were typically higher than the CO_2 emissions based on official fuel consumption figures. Real-world results were on average 17% higher. The greatest gap measured between the real-world CO_2 emissions and official type-approval emissions was 40% for the Euro 5 Ford Transit diesel LCV (figure 5.11). The gap between real-world and official fuel consumption is discussed further in section 5.5.
- Real-world CO_2 emissions followed no obvious trend, with results typically in the range of 200 g/km to 300 g/km, regardless of duty or fuel type or emission standard (figures 5.10 to 5.12).
- The light duty diesel CO_2 results included a number of vehicles of the same make and model (eg Ford Transit vans) but with different emissions standards/ages of vehicle (figure 5.11). Interestingly, these models showed little, if any, improvement in CO_2 emissions over time.
- For the heavy duty diesel vehicles (figure 5.12), the older Japanese-used vehicle (1998 Isuzu Elf 4.5t) again recorded significantly higher real-world CO_2 emissions than the New Zealand-new Euro III and Euro V vehicles. However, as was the case with the light duty diesels there was no discernible improvement in the results for the Euro V versus Euro III vehicles tested.

Figure 5.10 Real-world CO_2 emission factors for light duty petrol vehicles compared with official fuel consumption figures

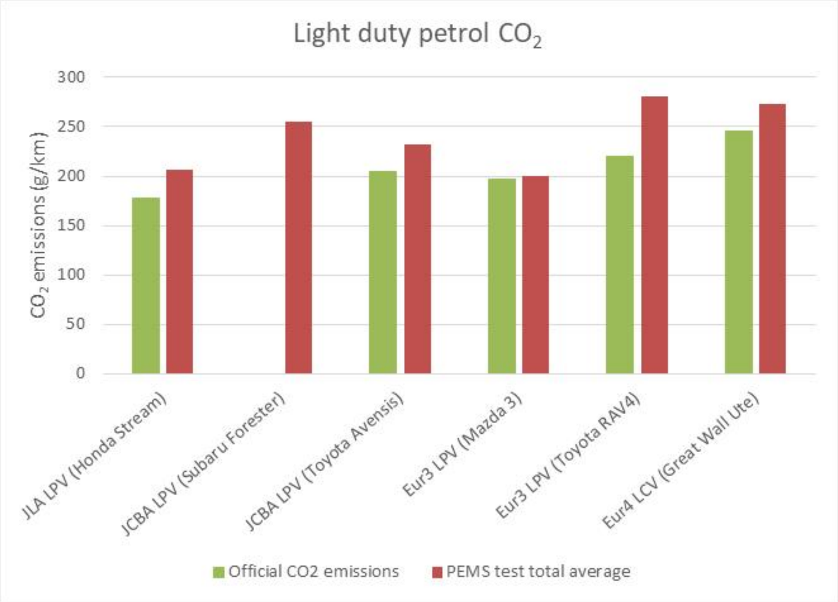
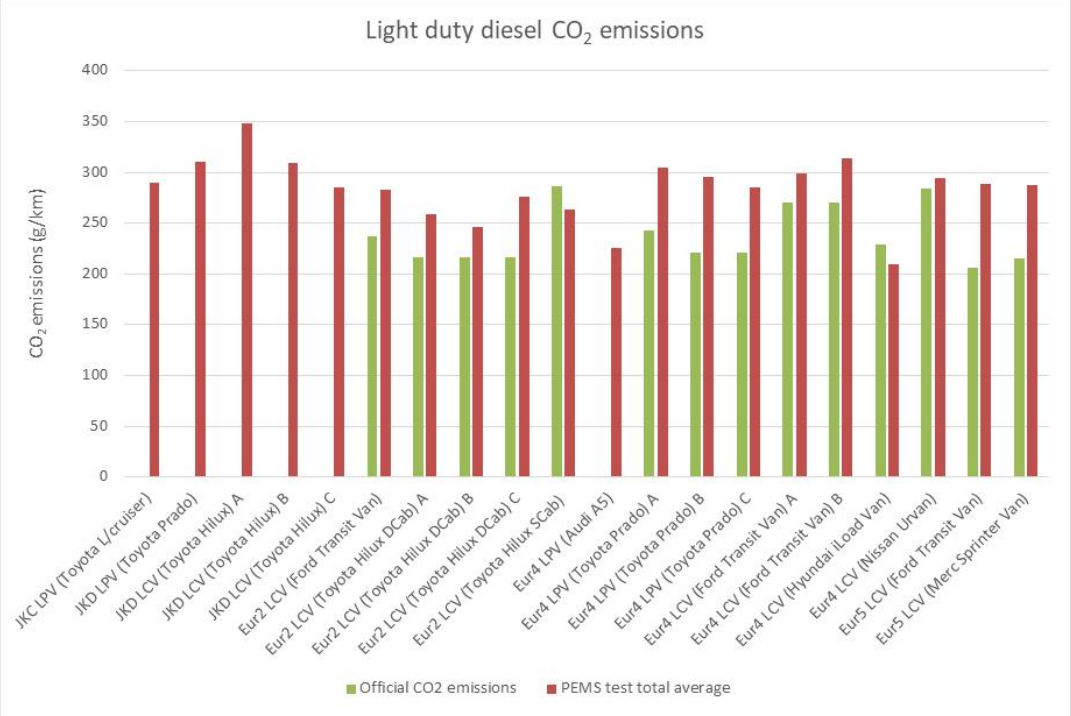
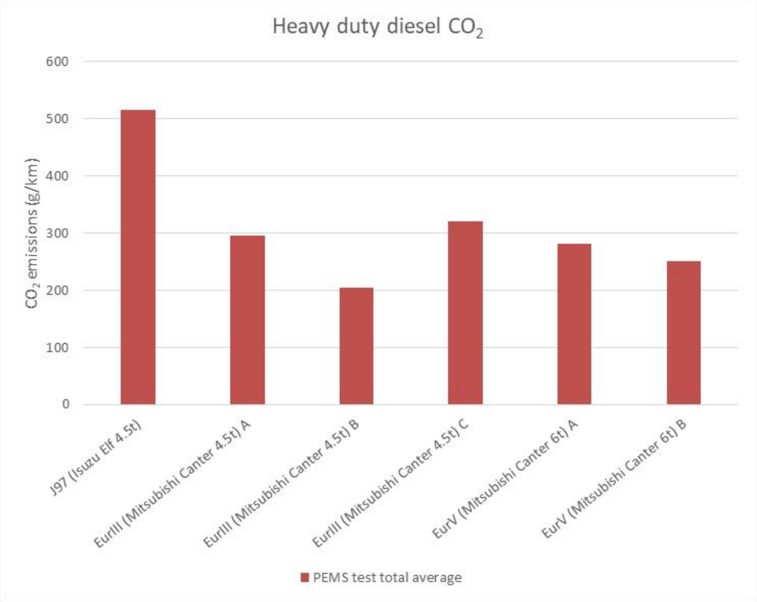


Figure 5.11 Real-world CO_2 emission factors for light duty diesel vehicles compared with official fuel consumption figures.



Note: We were not able to source official type-approval fuel consumption figures for the imported used Japanese light duty diesel vehicles.

Figure 5.12 Real-world CO_2 emission factors for heavy duty diesel vehicles.



Note: We were not able to source official type-approval fuel consumption figures for the heavy duty diesel vehicles. Also the PEMS-derived CO_2 factor for the Euro III (Mitsubishi Canter 4.5t) B vehicle is suspected to be incorrect because it is 29% lower than the CO_2 estimated from fuel consumption measured at pump. We extensively checked the data and concluded the only possible explanation was a leak in the sample line between the NO_x analyser and the CO_2 analyser.

5.3 Comparison with VEPM

A key objective of this project was to investigate differences between expected emissions from VEPM and the actual findings from the PEMS testing. VEPM is intended to represent real-world emissions and this section reviews how well it actually compared.

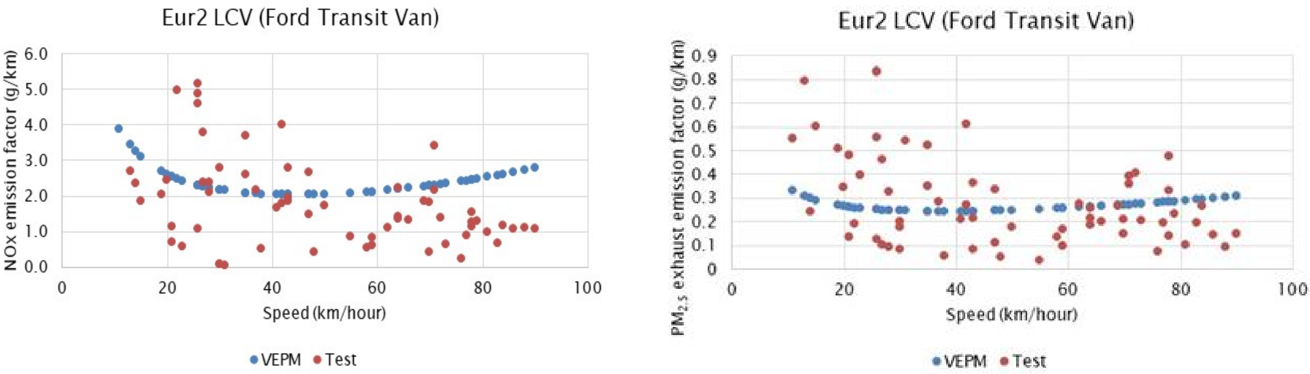
The following procedure was applied to all test data to compare emission factors from the real-world PEMS testing with those from VEPM:

1. Average measured emissions and speed were calculated for fixed one-minute average periods.
2. One-minute average results with an average speed of less than 10 km/h were excluded from the comparison (because the minimum speed in VEPM is 10 km/h). However, it should be noted that the one-minute average results include a substantial portion of individual one-second results below 10 km/h. The results were only excluded from the analysis when the average speed over the entire minute was less than 10km/h.
3. Emission factors were extracted from VEPM for the specific vehicle class/size (eg Euro 3, petrol, passenger car, 1.4 to 2.0 litre).
4. One-minute average measured emissions were compared with the corresponding VEPM emission factor for the corresponding (one-minute average) speed. Note: VEPM emissions factors were not corrected for gradient.

5.3.1 Pollutant emission factors

A comparison of the results for each vehicle and each pollutant are provided in appendix E. A typical example of the comparison is shown in figure 5.13 for the Euro 2 Ford Transit van.

Figure 5.13 Example of VEPM prediction compared with PEMS results for NOx and $PM_{2.5}$ at one-minute resolution



As illustrated in the above example, there were differences, sometimes significant, between VEPM emissions factors and those derived from PEMS results. These differences were observed for all vehicles tested, throughout the speed bins analysed, and were generally not unexpected as they reflect the difference between real-world emissions and an emissions model. An emissions model is intended to represent average emissions from an average vehicle at a specified speed.

The results from this analysis provide real-world data for a separate future review and update (if appropriate) of VEPM emissions factors to better reflect actual fuel consumption and emissions.

5.3.2 NO_2 to NO_x ratios

VEPM emission factors for NO_2 are calculated from VEPM NO_x emission factors based on the ratio of NO_2/NO_x recommended for COPERT (EEA 2016).

Figure 5.14 shows the NO_2/NO_x ratio for each PEMS test against the fraction used in VEPM. The ratios are reasonable for the light duty petrol and heavy duty diesel vehicles but less accurate for the light duty diesel vehicles. For some of the light duty vehicles tested, the VEPM ratios are close to those measured in the PEMS test. However, for the Euro 4 light diesel vehicles the VEPM ratios are too high by a factor of nearly two.

Figure 5.14 Ratio of NO_2 / NO_x expressed as a percentage for each PEMS test

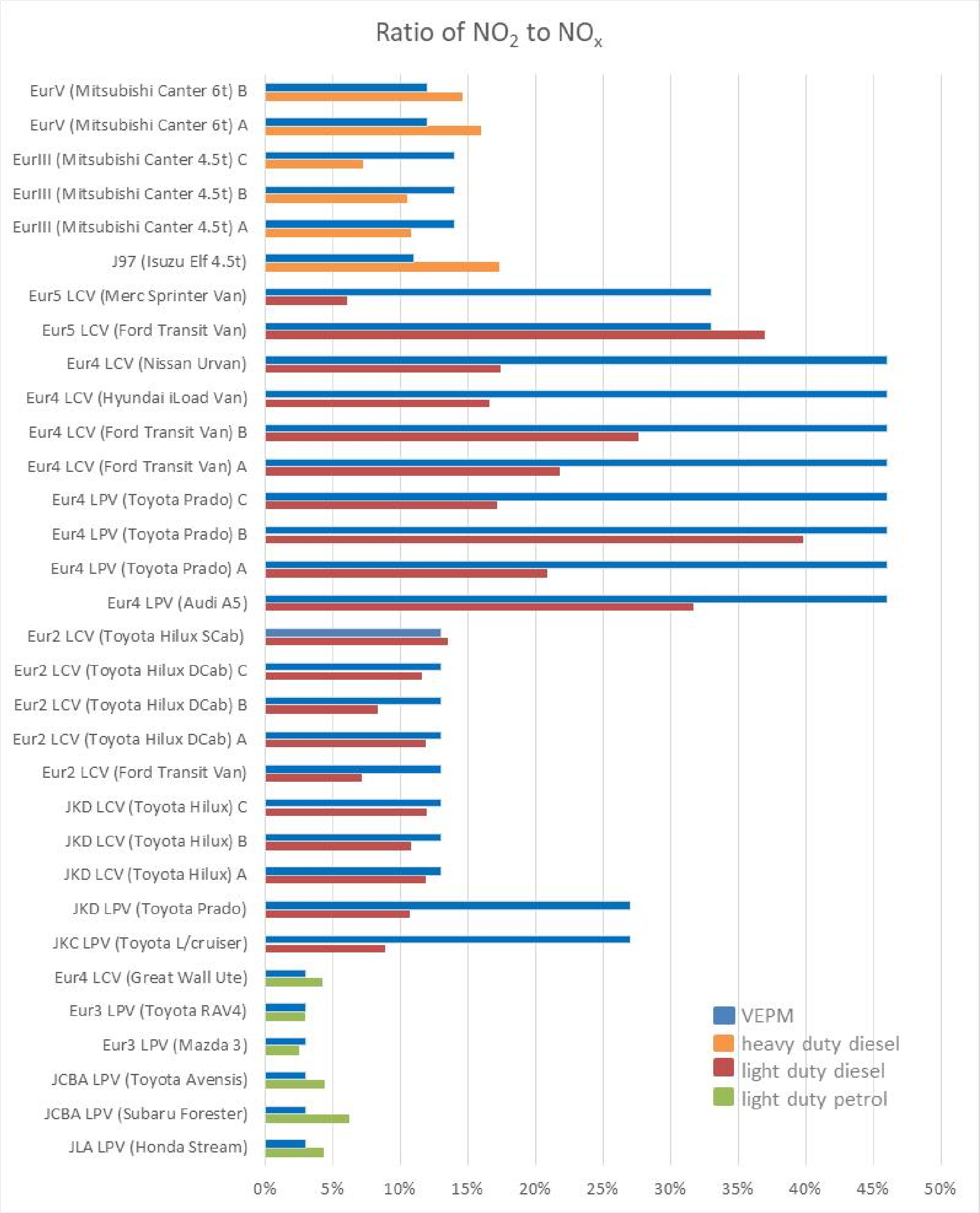


Table 5.2 compares the fractions of NO_2 in NO_x (f-NO_2) from the PEMS test with those utilised in VEPM. The f-NO_2 values in VEPM are based on a relatively small number of emission test results (EEA 2016). Recent work by Carslaw et al (2016), based on remote sensing measurements in the UK, has found lower f-NO_2 values than those used in VEPM. Table 5.2 shows that the average f-NO_2 values from our PEMS tests are generally more consistent with Carslaw's work than VEPM for most vehicle categories.

Table 5.2 Comparison of the fractions of NO_2 in NO_x (f-NO_2) from the PEMS test results (average of all results for the vehicle category and emission standard) with those in VEPM (which are from COPERT) and those reported by Carslaw et al (2016)

		f-NO2		
Vehicle category	**Standard**	**PEMS test results**	**VEPM**	**Carslaw et al (2016)**
Diesel light duty	Euro 1, Euro 2	10%	13%	10% to 15%
	Euro 4	24%	46%	27.6%
	Euro 5	22%	33%	25.5%
Diesel heavy duty	Euro III	9%	14%	10% to 20%
	Euro V	15%	12%	8%

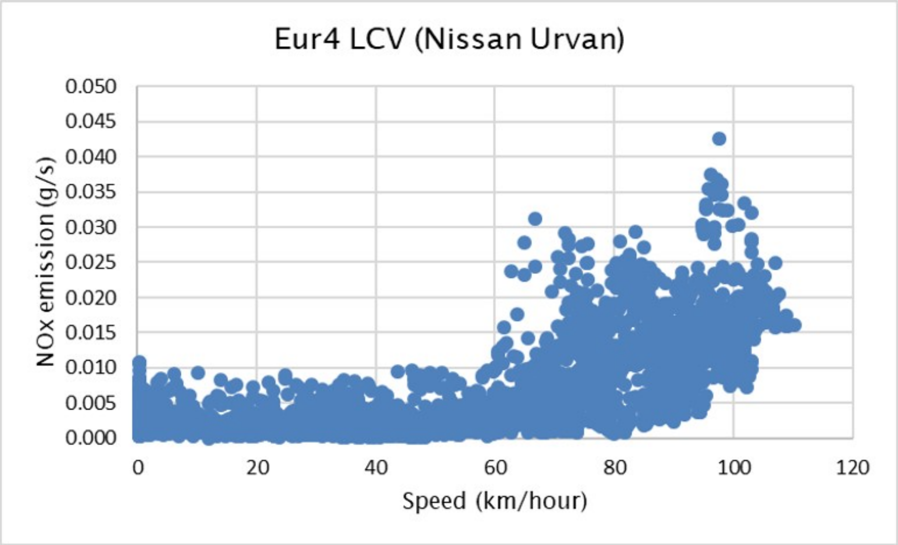
5.3.3 Emission factors at low speed and idle

As highlighted at the beginning of section 5.3, the comparison of the PEMS results with VEPM emission factors *excluded* results with an average speed (over the fixed one-minute average) of less than 10 km/h. This was necessary because VEPM has a minimum valid speed of 10 km/h.

While the PEMS tests included an appreciable proportion of time below 10 km/h on a second by second basis (typically between 20% and 30% as shown in appendix D, table D.1), there were typically only a few full minutes with an average speed of less than 10 km/h. This means that the comparisons earlier in this section included emissions from vehicles travelling slowly and at idle for at least part of their valid one minute averages.

It is worth noting that emissions at idle and at low speeds are typically similar to emissions at 10 km/h on a grams per second (g/s) basis. For example, figure 5.15 shows NO_x emissions in g/s for one of the test vehicles.

Figure 5.15 Real-world NO_X emission rates (g/s) by various average speeds for the Euro 4 Nissan Urvan



5.4 Effect of real-world variables

As discussed in section 4.3, the test route was designed to include a broad range of real-world driving conditions. The effect of these real-world factors is investigated in this section.

5.4.1 Route characteristics

Capturing a broad range of real-world driving situations is a key advantage of PEMS testing. However, a disadvantage is that the results of PEMS tests are not directly comparable with each other because conditions vary from test to test.

For this project, the test to test variability was minimised by following the same route for each test. However, traffic conditions varied considerably. The average speed over the entire test route ranged from 33 km/h to 49 km/h.

To better understand the differences between tests, we adopted ICCT binning criteria (Franco et al 2014) and characterised the trips according to velocity, gradient and *a*v*. The detailed breakdowns for each trip are shown in appendix D.

Unfortunately, no data is available to determine whether the trips undertaken in our real-world testing are ‘typical’ or representative of real-world gradients and *a*v* conditions in New Zealand. However, figure 5.16 provides some context based on overseas data.

Figure 5.16 Time share of ‘strong uphill’ and ‘strong positive’ *a*v*, by test vehicle in ICCT meta-analysis of US and European PEMS test results (Franco et al 2014)

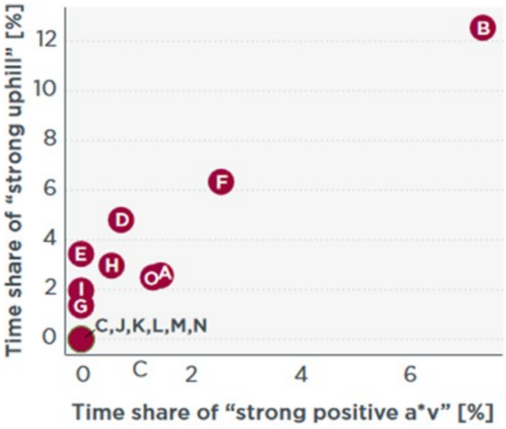


Figure 5.16 presents the trip characteristics from an ICCT meta-analysis of 97 PEMS tests undertaken on 15 individual vehicles in the United States and Europe (Franco et al 2014). This shows that some PEMS tests are performed in an extremely controlled way, with no significant time share of strong positive *a*v* (which provides an indication of how dynamic the driving is).

In comparison, the average time shares recorded across all trips for this project were:

- ‘strong uphill’ (≥4% gradient): approximately 3% on average (ranging from 1.9% to 4.87%)
- ‘strong positive’ (a*v ≥9.2 W/kg): approximately 4% on average (ranging from 0.86% to 6.48%)

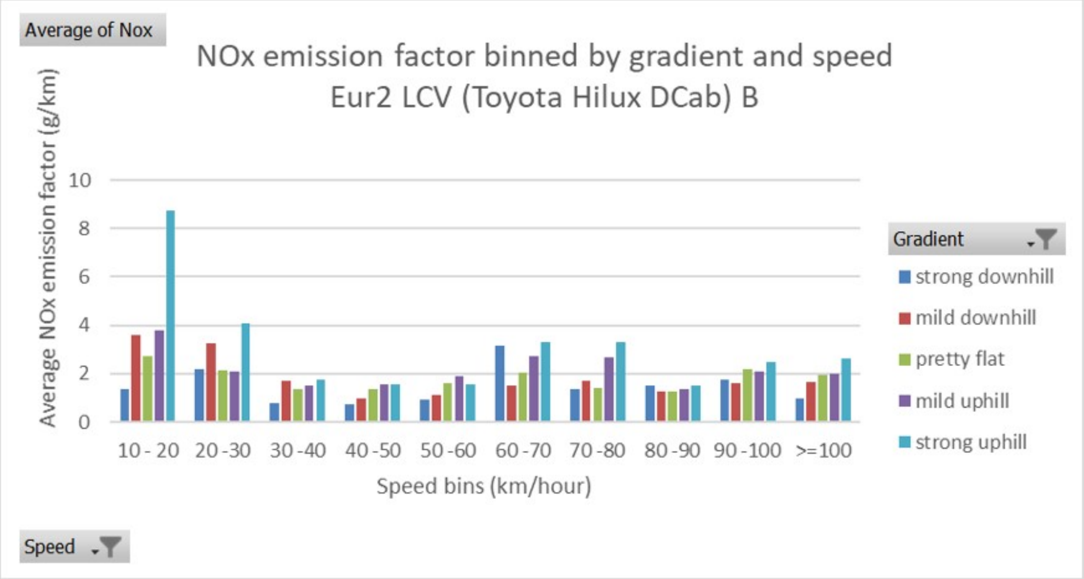
For this project, tests were undertaken in real-world conditions with normal driving and the route was designed to include hills. There is no way to determine whether these conditions were typical of real-world conditions in New Zealand. However, in the context of the international PEMS test results shown in figure 5.16, the trips undertaken for this project include a similar proportion of ‘hilly’ driving but more 'dynamic' driving (with strong positive *a*v*) than is typical for PEMS tests. These two metrics alone do not completely describe the driving conditions that can affect vehicle emissions; however, they indicate the degree of 'demanding' driving conditions.

5.4.2 Gradient and *a*v*

To investigate the effect of gradient and *a*v* on real-world emissions, results were binned according to the criteria described in table 4.3. A typical example of NO_x emission factors binned by gradient and speed is shown in figure 5.17 for the Euro 2 Toyota Hilux Double Cab B.

Average NO_x emission factors (across all speeds) for each gradient and *a*v* 'bin' are provided in appendix D, table D.2.

Figure 5.17 Example of PEMS NO_x emission factors binned by gradient and speed



The effect of gradient on emissions is shown in tables 5.3 to 5.5 for NO_x, $PM_{2.5}$ and CO_2. In these tables, the average ratios of the PEMS factor for each gradient bin relative to the ≥-1 to <1 (pretty flat) gradient bin are compared with the similar ratios using VEPM factors.

As expected, the average NO_x emissions measured with PEMS were higher when vehicles were travelling uphill and lower (but only slightly) when vehicles were travelling downhill (table 5.3). However, VEPM predicted a greater impact of gradient in either direction on emissions, especially for downhill travel.

Table 5.3 The effects of gradient on PEMS NO_x emission factors (averaged across all vehicles in the category) compared with the effects predicted by VEPM (using the default 2018 fleet @ 40 km/h)

	Ratio of PEMS NO_x emission factors for each gradient bin relative to ≥-%1 to <1% gradient bin				Ratio of VEPM NO_x emission factors for specific gradients relative to 0% gradient			
	Gradient (%)				Gradient (%)			
Vehicle category	**<-4**	**≥-4 to<-1**	**≥1to<4**	**≥4**	**-4%**	**-2%**	**+2%**	**+4%**
Petrol light duty	0.96	0.96	1.14	1.63	0.47	0.70	1.42	1.85
Diesel light duty	0.90	0.97	1.20	1.98	0.55	0.74	1.29	1.80
Diesel heavy duty	0.93	1.00	1.08	1.36	0.27	0.59	1.39	1.86

The effect of gradient on average $PM_{2.5}$ emissions measured with PEMS was comparable to the effect on NO_x emissions (table 5.4). However, VEPM's predictions of the effect of gradient on emissions were much closer to what was measured by PEMS.

Table 5.4 The effects of gradient on PEMS $PM_{2.5}$ emission factors (averaged across all vehicles in the category) compared with the effects predicted by VEPM (using the default 2018 fleet @ 40 km/h)

	Ratio of PEMS $PM_{2.5}$ emission factors for each gradient bin relative to ≥-%1 to <1% gradient bin				**Ratio of VEPM $PM_{2.5}$ emission factors for specific gradients relative to 0% gradient**			
	Gradient (%)				**Gradient (%)**			
Vehicle category	**<-4**	**≥-4 to<-1**	**≥1to<4**	**≥4**	**-4%**	**-2%**	**+2%**	**+4%**
Petrol light duty	0.90	0.74	1.33	2.81	0.88	0.93	1.27	1.71
Diesel light duty	1.09	0.97	1.20	1.65	0.90	0.94	1.28	1.74
Diesel heavy duty	0.79	0.74	1.06	1.23	0.70	1.09	1.20	1.40

Similarly, the average CO_2 emissions measured with PEMS were higher when vehicles were travelling uphill and lower (but only slightly) when vehicles were travelling downhill (table 5.5). For heavy duty vehicles, the effect of uphill gradient on emissions predicted by VEPM was similar to the measured effect. However, VEPM predicts significantly lower CO_2 emissions from heavy duty vehicles travelling downhill.

Table 5.5 The effects of gradient on PEMS CO_2 emission factors (averaged across all vehicles in the category) compared with the effects predicted by VEPM (using the default 2018 fleet @ 40 km/h).

	Ratio of PEMS CO_2 emission factors for each gradient bin relative to ≥-%1 to <1% gradient bin				**Ratio of VEPM CO_2 emission factors for specific gradients relative to 0% gradient**			
	Gradient (%)				**Gradient (%)**			
Vehicle category	**<-4**	**≥-4 to<-1**	**≥1to<4**	**≥4**	**-4%**	**-2%**	**+2%**	**+4%**
Petrol light duty	1.05	1.04	1.19	1.31	n/a	n/a	n/a	n/a
Diesel light duty	0.96	0.98	1.11	1.53	n/a	n/a	n/a	n/a
Diesel heavy duty	0.90	1.13	1.49	2.09	0.32	0.68	1.45	1.96

Note: VEPM only estimates the effect of gradient on CO_2 emissions from heavy duty vehicles.

For the vehicles we tested, VEPM seems to do a reasonable job of estimating the effects of uphill gradient on emissions. However, it appears to over-estimate the reduction in emissions when vehicles travel downhill. This might be due to the nature of our route, which was undulating and subject to stop-start traffic (so there might not have been time for the engine load to reduce and stabilise on downhill sections).

At the start of the project we intended using *a*v* to provide a surrogate for engine load and to indicate whether driving was demanding or undemanding. However, the investigation of the situation specific emission factors proved inconclusive. In reality, engine load is influenced by a number of factors including gradient of the road. We suspect our data did not yield a consistent relationship between *a*v* and emissions because our route was quite hilly. A more accurate estimation of vehicle-specific power, including the effect of gradient, may provide a better correlation with emissions. Nevertheless, our analysis of *a*v* provides some basis for comparison of our route characteristics with other PEMS tests as discussed in section 5.4.1

5.4.3 Cold start

The test protocol we used (described in section 4.4) did not comply with regulatory requirements for measurement of cold start emissions. However, we still expected that the majority of cold start emissions were captured in the tests. Average emissions over the first 3 km of each trip were calculated to investigate the effect of cold start conditions and are presented in appendix D, table D.3. The results show t emissions were indeed generally higher during this period of the test trip for the light duty vehicles tested.

Table 5.6 compares the average ratio of PEMS cold start to trip total emissions with the assumed ratio of cold/hot emission factors in VEPM. The average PEMS ratios are generally higher than the VEPM ratios, indicating that VEPM is likely to under-estimate average emissions from these vehicles over the first 3 km of the trip.

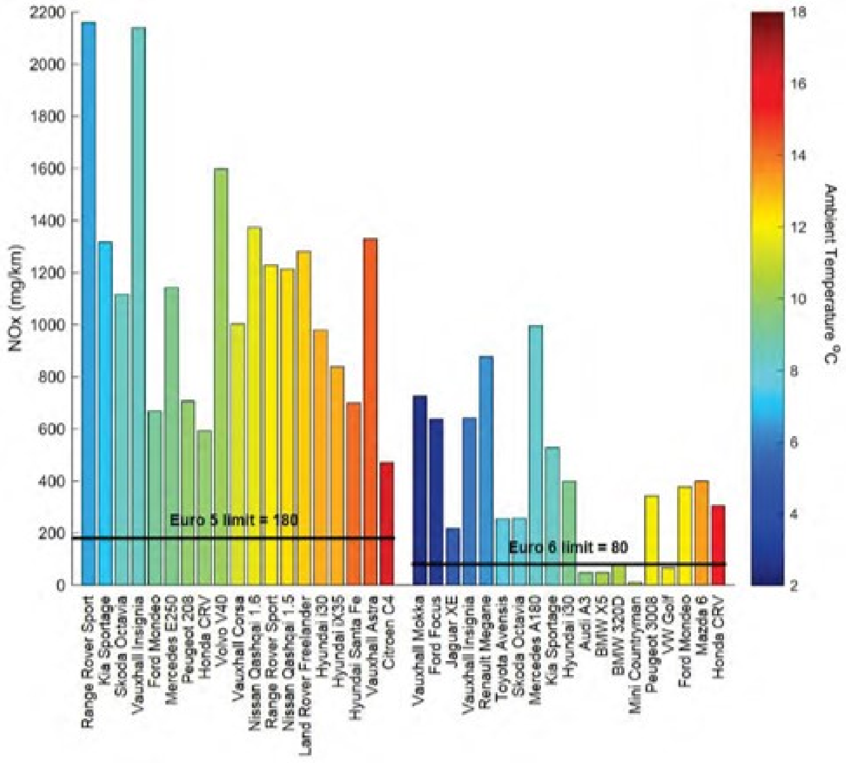
Table 5.6 Average ratio of the cold start/trip total emissions measured by PEMS (across all vehicles in the category) compared with the average ratio of cold/hot emission factors in VEPM

Vehicle category	PEMS ratio of cold start to trip total emissions			VEPM ratio of cold to hot emission factors		
	NO_X	$PM_{2.5}$	CO_2	NO_X	$PM_{2.5}$	CO_2
Petrol light duty	4.6	1.9	2.0	1.8	n/a	1.3
Diesel light duty	1.87	1.4	1.7	1.1	1.45	1.2

5.4.4 Ambient temperature

Ambient temperature is known to affect vehicle emissions, especially NO_x. Figure 5.18, from PEMS testing in the UK, shows that vehicles tested at lower ambient temperatures tend to produce higher NO_x emissions than those tested at higher ambient temperatures (Department for Transport 2016).

Figure 5.18 Effect of ambient temperature on NO_X emissions from PEMS-tested vehicles (Department for Transport 2016)



Our PEMS testing was undertaken at moderate ambient temperatures (between 16°C and 26°C) so the effects of extreme temperatures were not captured. This means NO_x emissions from the vehicles tested could be higher when ambient temperature is low (less than approximately 12°C).

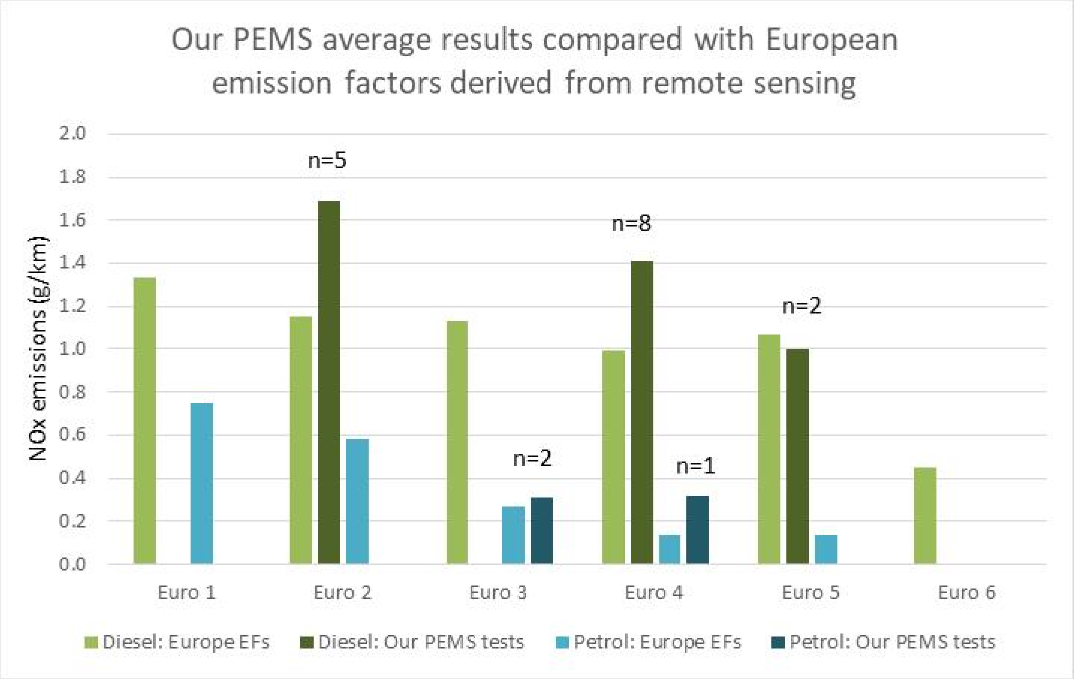
5.5 Comparison with international real-world emission factors

Our literature review (chapter 2) found there was extensive PEMS test data available internationally for Euro 5 and Euro 6 light duty vehicles. However, limited information for older vehicles existed at that time (late 2016). Since then a number of new datasets have been released.

The Real Urban Emissions Initiative (TRUE) has estimated real-world emissions from Euro 2 through to Euro 6 passenger vehicles in Europe (Bernard et al 2018). The TRUE report uses the results of remote sensing to develop real-world NO_x emission factors for individual vehicle ‘families’ (defined as a unique combination of fuel type, Euro standard, manufacturer group and engine displacement). These emission factors are compared with PEMS test results for the same vehicle ‘family’ for Euro 5 and Euro 6 diesel passenger vehicles. Emission factors derived from remote sensing and PEMS have been found to be almost identical for both Euro 5 and Euro 6 vehicles, indicating good agreement between the datasets despite the very different data collection methods.

Figure 5.19 compares our average PEMS results (by fuel type and Euro standard) with the average NO_x emission factors derived from remote sensing in Europe (Bernard et al 2018). Our results are in reasonable agreement with the European results, considering the small number of our test results (indicated by ‘n’ in the figure).

Figure 5.19 Comparison of our average PEMS NO_x emissions (by fuel and Euro standard) with real-world emission factors from Europe derived from remote sensing data (Bernard et al 2018).



PEMS testing has recently been undertaken in Australia. Detailed results from this testing are not publicly available but a summary of results has been published (Australian Automobile Association 2017). The summary report presents the real-world emissions and fuel consumption for the test vehicles as a percentage of the applicable emissions limit or official type-approval fuel consumption.

Figures 5.20 to 5.22 compare our results with the Australian results for vehicle categories (defined by fuel and Euro standard) common to both test campaigns. This comparison shows that emissions measured in New Zealand are remarkably similar to those measured in Australia. The Australian results show more variation in NO_x emissions, which probably reflects a greater diversity of vehicles tested in the Australian campaign.

Figure 5.20 Our PEMS NO_X emissions (by fuel and Euro standard) as a percentage of the applicable emission limit compared with results from Australian PEMS tests (Australian Automobile Association 2017)

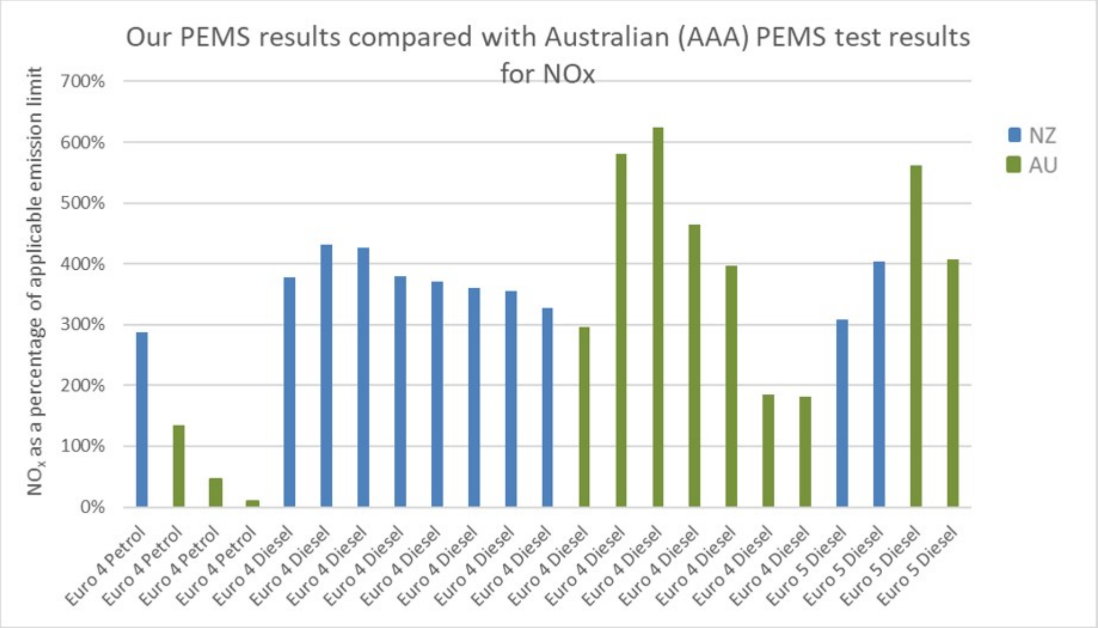
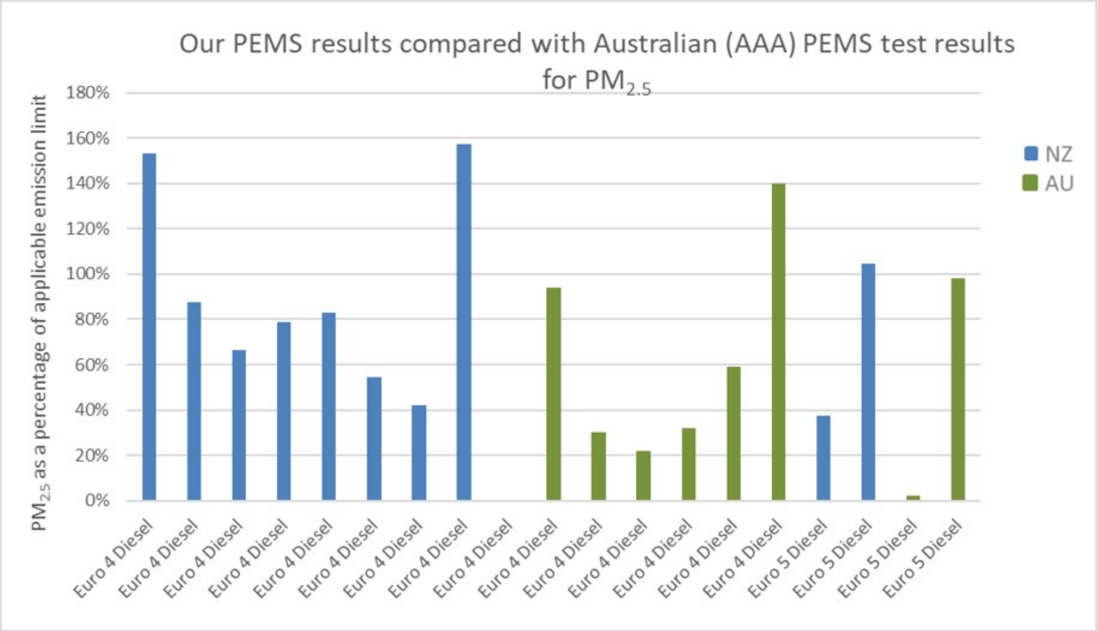


Figure 5.21 Our PEMS $PM_{2.5}$ emissions (by fuel and Euro standard) as a percentage of the applicable emission limit compared with results from Australian PEMS testing (Australian Automobile Association 2017).



Note: The zero value for the Euro 4 diesel vehicles below is correct. It is reported at 0% of the emission standard.

Figure 5.22 Our PEMS fuel consumption (by fuel and Euro standard) as a percentage of the official type-approval fuel consumption figures compared with results from Australian PEMS testing (Australian Automobile Association 2017)

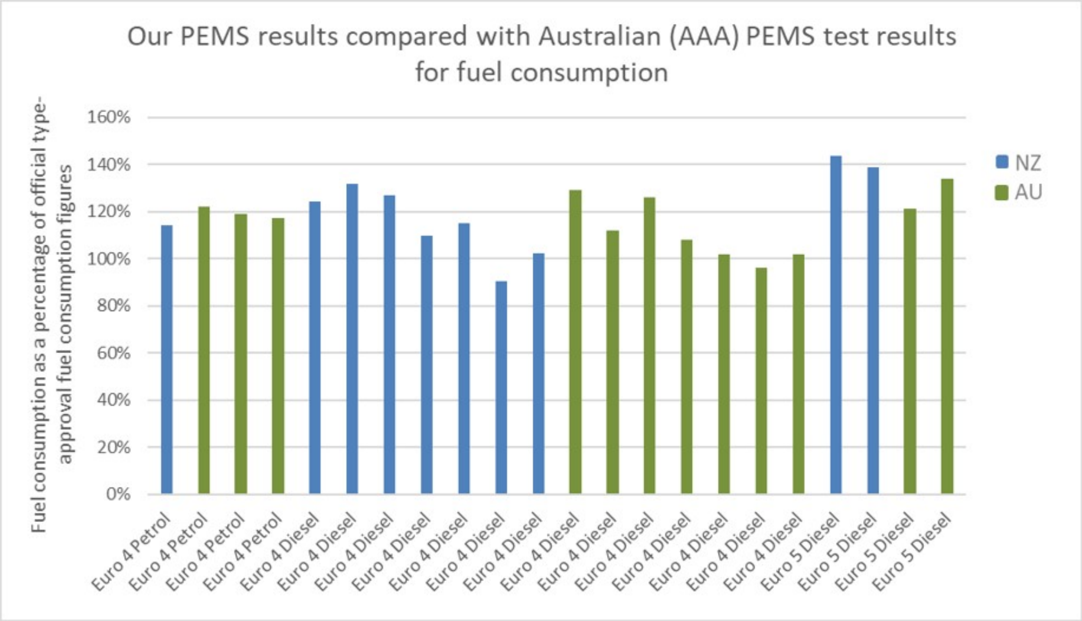
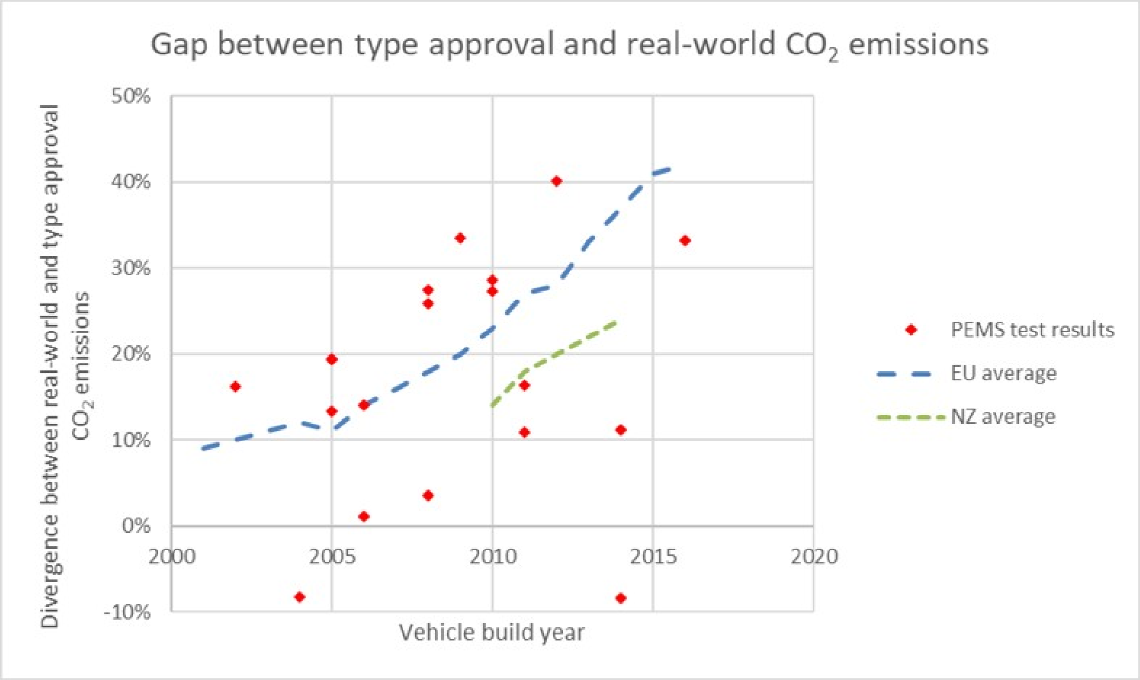


Figure 5.23 compares the gaps between real-world and official type-approval emissions of CO_2 measured for each PEMS-tested vehicle with the estimates for new vehicles in Europe (Tietge et al 2017) and previous estimates for New Zealand (Wang et al 2015). The small number of the PEMS test vehicles is insufficient to make definitive conclusions. However, the results appear to be generally consistent with the trends in Europe and New Zealand.

Figure 5.23 The gaps between official type approval and real-world CO_2 emissions for light duty vehicles PEMS-tested compared with estimates for new light duty vehicles in Europe (Tietge et al 2017) and estimates in New Zealand (Wang et al 2015)



6 Conclusions and recommendations

Research overseas has found that vehicles on the road consume more fuel and produce higher exhaust emissions under real-world driving conditions than the values to which they are type approved when manufactured. New Zealand vehicles enter the fleet either as new vehicles or as used imported vehicles sourced from a range of countries as we do not manufacture vehicles here. While exhaust emissions standards are regulated at the border, New Zealand does not currently regulate fuel economy. Consequently, the fleet is strongly influenced by international requirements and trends, with vehicles arriving that meet a diverse range of standards, including Japanese, European and Australian. The NZ Transport Agency's VEPM was used to model emissions and fuel consumption of New Zealand vehicles for assessing environmental impacts and fleet trends. However, the diversity of standards in use and the subsequent real-world performance can introduce considerable uncertainty into the prediction.

The purpose of this project was to improve our understanding of real-world fuel consumption and vehicle exhaust emissions from the New Zealand fleet. A key outcome was to provide real-world data for a separate future review and update (if appropriate) of VEPM emissions factors to better reflect actual fuel consumption and emissions.

A suitable methodology was developed for robustly measuring the real-world emissions of a representative cross-section of the New Zealand fleet. A range of testing methods was assessed with PEMS offering the best solution. A purpose built system was designed to measure key pollutants, including CO_2, NO_x, NO_2 and ($PM_{2.5}$), together with speed, acceleration, gradient and other vehicle operating conditions. Preliminary testing was undertaken to trial the equipment and to identify a suitable real-world test route in Auckland that simulated the range of typical New Zealand road conditions.

Testing commenced in earnest in early 2018 using vehicles selected to represent the most common and influential sectors of the New Zealand fleet. PEMS measurements were gathered for 32 vehicles in total, comprising six light duty petrol vehicles, 20 light duty diesel vehicles and six heavy duty diesel vehicles, and covering years of manufacture from 1996 to 2014 with both New Zealand-new vehicles and Japanese-used imported vehicles.

6.1 PEMS results and future testing

Comparing the overall PEMS results to emissions standards and type-approval fuel consumption, we found:

- For all duties and fuel types, real-world NO_x emissions were generally higher than regulated emission standards. Real-world results were 4.6 times higher on average (ranging from two to nearly eight times).
- Older used Japanese light duty diesel vehicles had significantly higher NO_x emissions than any of the other light duty vehicles tested. However, NO_x emissions from New Zealand-new light duty diesel vehicles showed little improvement between Euro 2 and Euro 5.
- Under the conditions of our tests, real-world NO_x emissions from light duty petrol vehicles irrespective of emission standard were less than real-world NO_x emissions from Euro 5 light duty diesel vehicles.
- Real-world-NO_2 emissions from light duty petrol vehicles were around 4% of the total NO_x emissions on average (range 3% to 6%) across the vehicles tested. By comparison, light duty diesel vehicles recorded around 17% NO_2 in their NO_x emissions (range 6% to 40%) and heavy duty diesel vehicles were similar at 13% on average (range 7% to 17%).

- Unlike NO_x, real-world $PM_{2.5}$ emissions were similar to the regulated emissions standards for light duty vehicles, with results about equal on average (ranging from half to 1.5 times the limit).
- $PM_{2.5}$ emissions from the newer Euro 4 and Euro 5 light duty diesel vehicles were considerably better than emissions from older light duty diesel vehicles. $PM_{2.5}$ emissions from the Euro 5 light duty diesel vehicles were comparable to the low $PM_{2.5}$ emissions from the petrol vehicles.
- Real-world CO_2 emissions were on average 17% higher than official type-approval fuel consumption figures. The greatest gap between the PEMS and type-approval emissions measured was 40% for a Euro 5 light commercial diesel vehicle.
- Real-world CO_2 emissions showed no obvious trend, with results typically in the range of 200 g/km to 300 g/km, regardless of duty or fuel type. The light duty diesel CO_2 results included a number of vehicles of the same make and model with different emissions standards/age of vehicle. These showed little, if any, improvement in CO_2 emissions over time from comparable vehicles.

It should be noted that official standards and type-approval figures are based on specific drive cycles and/or conditions that may vary significantly from those in the real world. Therefore our PEMS results would not be expected to exactly match the relevant standards and approvals but rather serve as a point of comparison against real-world New Zealand driving. Also, the New Zealand fleet is unique relative to fleets in other countries, especially due to the prevalence of Japanese-used vehicles and many comparatively old/high mileage vehicles. It was not possible to explore the potential effect of fleet differences from the small sample of vehicles test results in our PEMS programme.

Regardless, our results were consistent with those from recent real-world emissions studies undertaken in Europe and Australia. This supports the continued use of European emission factors (for European vehicles) in VEPM.

The real-world test route developed for the PEMS testing incorporated a reasonable range of average vehicle speeds and gradients. Although there was no way to determine whether these conditions were typical of real-world conditions in New Zealand, critical characteristics of our route and driving conditions compared favourably with other test routes used in international PEMS testing.

In terms of the real-world factors investigated:

- The average emissions measured with PEMS were higher (as expected) when vehicles were travelling uphill and lower (but only slightly) when vehicles are travelling downhill. Comparing the effects of gradient on relative emission factors suggests that VEPM does a reasonable job of estimating the effects of uphill gradient on emissions. However, it appears to over-estimate the reduction in emissions when vehicles travel downhill.
- Average emissions over the first 3 km of each trip were calculated to investigate the effect of cold start conditions. The results show that emissions are indeed generally higher during this period of the test trip for the light duty vehicles tested. Comparisons with cold start emission ratios in VEPM suggest VEPM would under-estimate average emissions from our test vehicles over the first 3 km of the trip.
- Ambient temperature is known to affect vehicle emissions, especially NO_x. Our PEMS testing was undertaken at moderate ambient temperatures (between 16°C and 26°C) so the effects of extreme temperatures were not captured. This means that NO_x emissions from the vehicles tested could be higher when ambient temperature is low (less than approximately 12°C).

To improve the representativeness of any future real-world testing, we recommend:

- Undertaking any PEMS testing in close partnership with an agency of business that can guarantee straightforward access to candidate vehicles and increasing the diversity of makes and models being tested.
- Determining typical New Zealand trip characteristics to ensure PEMS tests are representative of New Zealand conditions and testing each vehicle more than once to better quantify the repeatability of the PEMS results.

6.2 VEPM performance and improvements

We compared emissions factors from this PEMS study with those from VEPM and found:

- There were differences, sometimes significant, between VEPM emissions factors and those derived from the PEMS results. These differences were observed for all vehicles tested, throughout the speed bins analysed, and were generally not unexpected as they reflect the difference between real-world emissions and an emissions model. An emissions model is intended to represent average emissions from an average vehicle at a specified speed.
- VEPM does a reasonable job of estimating the effects of uphill gradient on emissions. However, it appears to over-estimate the reduction in emissions when vehicles travel downhill.
- Comparisons with cold start emission ratios in VEPM suggest VEPM under-estimates average emissions from our test vehicles over the first 3 km of the trip.

The results from this analysis will provide real-world data for a separate future review, and update (if appropriate) of VEPM emissions factors to better reflect actual fuel consumption and emissions.

To improve VEPM's ability to predict real-world emissions from New Zealand vehicles, we recommend:

- Discussing the discrepancy between real-world emission factors and emission factors in VEPM with the developers of the European emission factors (on which VEPM is based).
- Reviewing VEPM emissions factors based on the findings of this study and other New Zealand and international evidence, and updating VEPM factors as appropriate.
- Investigating real-world $PM_{2.5}$ emissions from heavy duty diesel vehicles further to confirm whether VEPM is significantly under-estimating these emissions and, if so, by how much. PEMS testing would be a cost-effective method to consider.
- Reviewing vehicle classifications in VEPM to improve predictions of real-world emissions from large diesel SUVs for a range of pollutants - NO_x, $PM_{2.5}$ and CO_2.
- Investigating in more detail the impact of vehicle types, loads (laden vehicle mass), speed and route characteristics on real-world fuel consumption and emissions of heavy duty diesel vehicles.
- Assessing whether the Ministry of Transport real-world fuel consumption factors for New Zealand could be incorporated into VEPM to better predict CO_2 emissions.
- Combining remote sensing data with PEMS data to develop adjustment factors for VEPM (if appropriate) to account for unique features of the New Zealand fleet (especially Japanese-used vehicles and the prevalence of large/heavy vehicles compared with Europe).

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Appendix A: PEMS equipment list

The PEMS equipment used for the on-road testing incorporated five different measurement systems as follows:

- exhaust flow measurement system
- particle measurement system
- gas measurement system
- GPS and other measurements
- fuel usage.

This appendix lists the equipment details for each of the above.

The AC power supply consisted of four lead acid (12V, 130Ah) batteries powering a 1000W and a 2000W x 230V inverter.

A.1 Exhaust flow measurements

A.1.1 Equipment

- Alicat Scientific digital differential pressure sensor (0-1 PISD-D)
- Druck PTX 600 series precision pressure transmitter (static pressure)
- Thermometrics PT200 RTC exhaust gas high temperature sensor
- Race Technologies PLX digital lambda meter
- Measurement Computing data acquisition system

A.1.2 Calibration

- Meriam Z50MH10-3 laminar flow element
- Druck DPI 705 differential and absolute pressure reference instruments
- Vaisala PTU307 temperature and humidity reference instrument

A.1.3 Operation

- The exhaust flow measurements were undertaken using a pitot tube/differential pressure measurement. The flow measurement was calibrated in the flow tube by inter-comparison with a laminar flow element under standard, controlled conditions.
- The differential pressure measurements were sampled at 1000 Hz to determine the instantaneous average exhaust gas flow rate and mitigate pulsating flow measurement issues.
- The measurement (at 1 Hz) of static pressure in an annular ring, temperature and air-fuel ratio allowed the mass flow rate to be accurately determined.

A.2 Particle measurements

A.2.1 Equipment

- TSI DustTrak 8520 aerosol monitor
- Honeywell AWM5000 Series microbridge mass airflow sensor
- Ankersmid Sampling BVBA heated sample lines AHL016 with 120°C self-regulation
- Apex Instruments compact heated filter assembly (120°C)
- Hargraves fluidic diaphragm miniature pumps
- Lennox Laser stainless steel flow orifices
- Measurement Computing data acquisition system
- KNF N816K large sampling pump
- Alicat Scientific 25SLPM mass flow controllers
- Sensirion differential-pressure sensor
- ¼” stainless steel tube, Brechtel stainless steel flow splitters
- 80mm and 37mm GFA filters

A.2.2 Calibration

- OHAUS analytical balance

A.2.3 Operation

- Isokinetic particle sampling was undertaken using an averaged instantaneous differential pressure measurement of the pitot tube to calculate the exhaust flow and provide a proportionate control signal to the large mass flow controller (MFC) controlling the flow of the 16 litres per minute (LPM) pump line.
- The particle sample line was diluted prior to the TSI DustTrak aerosol analyser with a stable, 120°C, 1.8 LPM particle-free source. The diluent flow rate was measured using a Honeywell flow meter to confirm it was constant over the test.
- The aerosol analyser was modified to incorporate a 37 mm filter immediately after the optical engine to allow the optical measurements to be referenced against gravimetric measurements.
- The aerosol analyser flow rate was determined at the beginning and end of each test to confirm the flow rate was consistent and stable.
- Glass fibre A (GFA) filters were conditioned and weighed using an analytical balance, prior to and after each test.
- The optical aerosol measurements were integrated over the test and then adjusted to match the gravimetric test measurements.

A.3 Gas measurement

A.3.1 Equipment

- Eco-Physics CDL 66 NO/NOx analyser
    - detection limit 0.5ppb NO_x, range 0 to 25000ppb NO_x, flow rate 100SCCM
- Dynament Premier IR CO_2 0-2% Vol CO_2 = 0-1V
    - detection limit 0.01% (100ppm) CO_2 or 42.7µV, range 0 to 2% vol CO_2
- Alicat Scientific 5 standard litres per minute (SLPM) and 10 SLPM mass flow controllers
- Ankersmid Sampling BVBA heated sample lines AHL016 with 120°C self-regulation
- Apex Instruments compact heated filter assembly (120°C)
- Hargraves fluidic diaphragm miniature pumps
- Measurement Computing data acquisition system
- Activated alumina, activated carbon, molecular sieve 4A, desiccant
- Stainless steel, thick wall PTFE and Nafion (drying) tubing was used with Swagelok ¼", 6mm and 1/8" compression fittings.

A.3.2 Calibration

- Mesa Drycal primary gas flow calibrators
- Environics 6103 and Ecotech GasCal 1100 gas diluters
- Ecotech 8301 zero air generator
- Coregas reference calibration NO gas

A.3.3 Operation

- The exhaust gas sample was diluted (typically between 10 and 30 times using 120°C zero air) to avoid damage to the instruments and possible partitioning of an aqueous phase.
- The diluent zero air flow was controlled by a mass flow controller at a flow rate slightly below the sample line and analyser flow rates. The latter were controlled by a MFC and a flow orifice respectively. The MFC values were recorded with the data acquisition system. The flow rate of the analyser was checked before each test using a primary flow standard.
- Particles were removed from the gas stream using a 3 micron GFA heated filter and a secondary 1 micron GFA filter was used to protect the analysers.
- The main gas sample flow was approximately 3 LPM with a residence time from sample point to MFC of 0.2 seconds.
- The analyser gas sample flow was 0.1 LPM with a calculated residence time of 1.45 seconds in heavy wall 1/8" polytetrafluororethylene (PTFE) tube.
- Data was acquired from the NDIR CO_2 analyser every second, ie at a sampling rate of 1 Hz.

- The Eco-Physics NO_x analyser sampled at a frequency of 10Hz, with measurement data reported every second. The analyser was programmed to toggle between nitric oxide (NO) and nitrogen oxides (NO_x) every two seconds.
- The total carbon dioxide (CO_2) produced during each test was compared against the predicted CO_2 production based on the total actual fuel used during the test.
- The Eco-Physics NO_x analyser and NDIR CO_2 analyser were calibrated against reference calibration gases across the measurement range regularly.
  - Zero air was applied every day to dry out the units and confirm zero.
  - Span reference gas calibrations were undertaken every two to three weeks or as required following servicing.
  - The NO_x flow rate was checked before and after every test.
  - A bump CO_2 test was performed before each test.

A.4 GPS and other measurements

A.4.1 Equipment

- GPS –- via smart phone (various)
- OBD – OBDLink SX, Foseal OBDII Wifi interface
- Lascar temperature logger.

A.4.2 Operation

- Global positioning system (GPS) measurements were recorded using various smart phones using GPS logger.
- On-board diagnostic (OBD) parameters were logged where possible. However, this was infrequently because of the poor refresh rates and connection issues with various vehicle brands.

A.5 Fuel usage

A.5.1 Equipment and operation

- All pre-test and post-test fuel measurements were made using the Gull Kingsland Service Station fuel pump meters.

Appendix B: Relevant standards

This appendix lists the relevant exhaust emission standards from Japan and Europe and the official (type-approval) fuel consumption figures that applied to the vehicles being PEMS tested.

B.1 Japanese exhaust emissions standards

B.1.1 Passenger vehicles

Table B.1 Japanese exhaust emission standards for gasoline passenger vehicles (in g/km)

Date (standard)	Test mode	CO mean (max)	NMHC mean (max)	NO_X mean (max)	PM mean (max)
2000 (JGH)	10–15 mode	0.67 (1.27)	0.08 (0.17)	0.08 (0.17)	—
2000 (JTA)		0.67	0.06	0.06	—
2000 (JLA)		0.67	0.04	0.04	—
2000 (JUA)		0.67	0.02	0.02	—
2005 (JABA)	10–15 mode + 11 mode	1.15 (1.92)	0.05 (0.08)	0.05 (0.08)	—
2005 (JCBA)		1.15	0.025	0.025	—
2005 (JDBA)		1.15	0.0125	0.0125	—
2008	10–15 mode + JC08C	1.15 (1.92)	0.05 (0.08)	0.05 (0.08)	—
2009	JC08H+C	1.15 (1.92)	0.05 (0.08)	0.05 (0.08)	0.005 (0.007)

Table B.2 Japanese exhaust emission standards for diesel passenger vehicles (in g/km)

Date (Standard)	Test mode	CO mean (max)	NMHC mean (max)	NO_X mean (max)	PM mean (max)
Curb weight ≤ 1250 kg[a]					
1990 (JX)	10–15 mode	2.1 (2.7)	0.40 (0.62)	0.50 (0.72)	—
1994 (JKD)		2.1 (2.7)	0.40 (0.62)	0.50 (0.72)	0.20 (0.34)
1997 (JKE)		2.1 (2.7)	0.40 (0.62)	0.40 (0.55)	0.08 (0.14)
2002		0.63	0.12	0.28	0.052
Curb weight > 1250 kg[a]					
1992 (JKC)	10–15 mode	2.1 (2.7)	0.40 (0.62)	0.60 (0.84)	—
1994 (JKD)		2.1 (2.7)	0.40 (0.62)	0.60 (0.84)	0.20 (0.34)
1998 (JKH)		2.1 (2.7)	0.40 (0.62)	0.40 (0.55)	0.08 (0.14)
2002 (JKN)		0.63	0.12	0.3	0.056

[a] Equivalent inertia weight (EIW) = vehicle weight of 1265kg.

BC.1.2 Light commercial vehicles

Table B.3 Japanese exhaust emission standards for diesel light commercial vehicles (in g/km)

Date	Test mode	CO mean (max)	NMHC mean (max)	NO_X mean (max)	PM mean (max)
Curb weight ≤ 1700 kg					
1993	10-15 mode	2.1 (2.7)	0.40 (0.62)	0.60 (0.84)	0.20 (0.34)
1997		2.1 (2.7)	0.40 (0.62)	0.40 (0.55)	0.08 (0.14)
2002		0.63	0.12	0.28	0.052
Curb weight > 1700 kg					
1993	10-15 mode	2.1 (2.7)	0.40 (0.62)	1.30 (1.82)	0.25 (0.43))
1997[a]		2.1 (2.7)	0.40 (0.62)	0.70 (0.97)	0.09 (0.18)
2003		0.63	0.12	0.49	0.060

[a] 1997 for manual transmission vehicles and 1998 for automatic transmission vehicles.

B.1.3 Heavy commercial vehicles

Table B.4 Japanese exhaust emission standards for diesel heavy duty commercial vehicles (in g/kWh)

Date	Test mode	CO mean (max)	NMHC mean (max)	NO_X mean (max)	PM mean (max)
1994	13 mode	7.40 (9.20)	2.90 (3.80)	DI: 6.00 (7.80) IDI: 5.00 (6.80)	0.70 (0.96)
1997[a]		7.40 (9.20)	2.90 (3.80)	4.50 (5.80)	0.25 (0.49)
2003[b]		2.22	0.87	3.38	0.18

[a] 1997 for GVM ≤ 3500 kg; 1998 for 3500 kg < GVM ≤ 12000 kg; 1999 for GVM > 12000 kg

[b] 2003 for GVM ≤ 12000 kg; 2004 for GVM > 12000 kg

B.2 European exhaust emissions standards

B.2.1 Passenger vehicles

Table B.5 European exhaust emission standards for gasoline passenger vehicles (in g/km)

Date	Standard	CO	HC	HC+NO_X	NO_X	PM
1996.01	Euro 2	2.2	–	0.5	–	–
2000.01	Euro 3	2.3	0.2	–	0.15	–
2005.01	Euro 4	1	0.1	–	0.08	–
2009.09[a]	Euro 5	1	0.10[b]	–	0.06	0.005[c]

Note: At the Euro 1-4 stages, passenger vehicles > 2,500 kg were type approved as Category N1 vehicles

[a] 2011.01 for all models

[b] With NMHC = 0.068 g/km

[c] Applicable only to vehicles using DI engines

Table B.6 European exhaust emission standards for diesel passenger vehicles (in g/km)

Date	Standard	CO	HC	$HC+NO_X$	NO_X	PM
1996.01	Euro 2, IDI	1	–	0.7	–	0.08
1996.01	Euro 2, DI	1	–	0.9	–	0.1
2000.01	Euro 3	0.64	–	0.56	0.5	0.05
2005.01	Euro 4	0.5	–	0.3	0.25	0.025
2009.09[a]	Euro 5	0.5	–	0.23	0.18	0.005

Note: * At the Euro 1-4 stages, passenger vehicles > 2,500 kg were type approved as Category N1 vehicles

[a] 2011.01 for all models

B.2.2 Light commercial vehicles

Table B.7 European exhaust emission standards for light commercial N1, Class III, >1760kg gasoline vehicles (in g/km)

Date	Standard	CO	HC	$HC+NO_X$	NO_X	PM
1998.01	Euro 2	5	–	0.8	–	–
2001.01	Euro 3	5.22	0.29	–	0.21	–
2006.01	Euro 4	2.27	0.16	–	0.11	–
2010.09[a]	Euro 5	2.27	0.16[b]	–	0.082	0.005[c]

[a] 2012.01 for all models; [b] With NMHC = 0.108 g/km; [c] Applicable only to vehicles using DI engines

Table B.8 European exhaust emission standards for light commercial N1, Class III, >1760kg diesel vehicles (in g/km)

Date	Standard	CO	HC	$HC+NO_X$	NO_X	PM
1998.01	Euro 2, IDI	1.5	–	1.2	–	0.17
1998.01	Euro 2, DI	1.5	–	1.6	–	0.2
2001.01	Euro 3	0.95	–	0.86	0.78	0.1
2006.01	Euro 4	0.74	–	0.46	0.39	0.06
2010.09[a]	Euro 5	0.74	–	0.35	0.28	0.005

[a] 2012.01 for all models

B.2.3 Heavy commercial vehicles

Table B.9 European exhaust emission standards for diesel heavy duty commercial vehicles (in g/kWh)

Date	Standard	Test	CO	HC	NO_X	PM	Smoke (m^{-1})
1996.10	Euro II	R-49	5	–	0.8	–	–
1998.10			5.22	0.29	–	0.21	–
2000.10	Euro III	ESC & ELR	2.1	0.66	5	0.1 (0.13[a])	
2005.10	Euro IV	ESC & ELR	1.5	0.46	3.5	0.02	0.5
2008.10	Euro V	ESC & ELR	1.5	0.46	2	0.02	0.5

[a] For engines of less than 750cc swept volume per cylinder and a rated power speed of more than 3000 min^{-1}

B.3 Official type-approval fuel consumption figures

Official type-approval fuel consumption figures (l/100 km) were obtained from the MoT motor vehicle register, where available for the individual vehicle models tested.

Note: For Japanese vehicles, the motor vehicle register includes fuel consumption values based on Japanese test cycles as well as estimated equivalent fuel consumption data normalised to the European NEDC test cycle. For these vehicles, we used the estimated fuel consumption normalised to the European NEDC test cycle.

The fuel consumption values were then converted into official CO_2 emissions rates (g/km) using the following factors (MoT 2016b):

- Diesel CO_2 (g/km) = 26.05 x diesel fuel consumption (l/100km)
- Petrol CO_2 (g/km) = 22.961 x petrol consumption (l/100km)

The official fuel consumption figures and corresponding CO_2 emissions rates are shown in table B.10.

Table B.10 Official fuel consumption tested according to the NEDC and CO_2 emissions

Vehicle descriptor	Fuel consumption (l/100 km)	CO_2 emissions (g/km)
Light duty petrol		
JLA LPV (Honda Stream)	7.76	178
JCBA LPV (Toyota Avensis)	8.94	204
JCBA LPV (Subaru Forester)	No data	-
Eur3 LPV (Mazda 3)	8.60	197
Eur3 LPV (Toyota RAV4)	9.60	220
Eur4 LCV (Great Wall Ute)	10.68	245
Light duty diesel		
JKC LPV (Toyota L/cruiser)	No data	-
JKD LPV (Toyota Prado)	No data	-
JKD LCV (Toyota Hilux) A	No data	-
JKD LCV (Toyota Hilux) B	No data	-
JKD LCV (Toyota Hilux) C	No data	-
Eur2 LCV (Ford Transit Van)	9.10	237
Eur2 LCV (Toyota Hilux DCab) A	8.30	216
Eur2 LCV (Toyota Hilux DCab) B	8.30	216
Eur2 LCV (Toyota Hilux DCab) C	8.30	216
Eur2 LCV (Toyota Hilux SCab)	11.00	287
Eur4 LPV (Audi A5)	No data	-
Eur4 LPV (Toyota Prado) A	9.30	242
Eur4 LPV (Toyota Prado) B	8.50	221
Eur4 LPV (Toyota Prado) C	8.50	221
Eur4 LCV (Ford Transit Van) A	10.36	270
Eur4 LCV (Ford Transit Van) B	10.36	270
Eur4 LCV (Hyundai iLoad Van)	8.78	229
Eur4 LCV (Nissan Urvan)	10.90	284
Eur5 LCV (Ford Transit Van)	7.91	206
Eur5 LCV (Merc Sprinter Van)	8.26	215

Appendix C: Data processing workbook

This appendix describes the Excel workbook created to process data for the PEMS tests, which included sheets for:

- raw data
- one-second averages
- 10-second averages
- one-minute averages
- full test data
- data binning
- VEPM comparisons.

One workbook was created for each vehicle test and the raw data were passed through a number of steps (see the formulae and assumptions which follow) to arrive at the final processed results.

C.1 Raw data sheet

This contains all data initially logged by the GPS unit, instrumentation and the onboard diagnostics (where available).

Time column

- actual time (date-hh:mm:ss) from the start of the test to the finish of the test in sequential one-second intervals

GPS columns

- GPS time (mm:ss.s)
- longitude and latitude in signed degrees format (+/-DDD.ddd), eg -170.6417
- altitude in metres above sea level, eg 65.7 m
- vehicle speed in m/s and km/h
- cumulative distance (cumDist) from the start of the test in metres, calculated from speed (m/s) and actual time (date-hh:mm:ss) from the start of the test to the finish of the test in sequential one-second intervals

Notes:

1 Altitude was derived from GIS terrain based on the GPS longitude and latitude coordinates. While the GPS unit did record altitude values, these data proved unreliable for robust calculations of gradient.

2 The ‘power save’ mode for the GPS unit meant values were sometimes only logged when a vehicle was moving. Therefore, gaps sometimes appeared for the time periods in between (when we assumed the speed was 0 km/h with no change to cumulative distance) which we later interpolated.

3 The GPS unit occasionally had difficulty locking onto satellites and gave a spurious reading until it found sufficient satellites. Data showed obvious outliers which were corrected by interpolating between other confirmed points.

Exhaust columns

- GPS time (mm:ss.s)
- exhaust temperature (°C)
- static pressure, absolute pressure and differential pressure (all in Pa)
- lambda (**λ**) which indicates the ratio between the amount of oxygen actually present in a combustion chamber versus the amount that should have been present to obtain perfect combustion, eg $\lambda > 1.0$ = lean and $\lambda < 1.0$ = rich
- fuel fraction (**yf**), molecular mass (MM) of the exhaust gas (g/mol), density of exhaust gas (g/cm3)
- exhaust flowrate (l/s)
- dilution ratio (10:1 up to 50:1) for dilution gas to exhaust
- venturi flowrate (l/s)
- CO_2 (ppm) in the diluted stream with mass concentration (mg/m^3) calculated from:

  $$mg/m^3 = ppm * (MW / 22.41) * (273.15 / (exhaust\ T + 273.15))$$

  where MW = molecular weight and CO_2 = 44.01 g/mol
- NO (ppb) and NO_X (ppb) in the diluted stream measured directly and NO_2 (ppb) calculated by the instrument, with mass concentrations (µg/m^3)calculated from:

  $$\mu g/m^3 = ppb * (MW / 22.41) * (273.15 / (exhaust\ T + 273.15))$$

  where MW = molecular weight and NO = 30.01 and NO_2 = 46.01 g/mol (but NO_X in NO_2 equivalents)
- $PM_{2.5}$ in the diluted stream (µg/m^3)
- CO_2 (g/s), NO_X (g/s), NO_2 (g/s), NO (g/s), $PM_{2.5}$ (g/s) in the exhaust calculated from:

  $$g/s = \mu g/m^3 * dilution\ ratio * flowrate\ (l/s) * 0.001\ m^3/l * 0.000001\ g/\mu g$$

Other columns

- ambient temperature (°C) but only logged every minute

OBD columns

- instantaneous fuel consumption (FC) in l/h or l/s or l/km
- instantaneous lambda (λ) recorded by the OBD separately
- instantaneous engine speed in RPM
- instantaneous vehicle speed (km/h)
- instantaneous throttle position (unit depends on OBD system) ambient temperature (°C) but only logged every minute

Not all vehicles have OBD available and for those that do the sampling interval can range from 1 to 30 seconds

C.2 One-second average sheet

This sheet contains all data/calculations collated into one-second averages (based on the raw data but offset for any equipment lags).

All GPS data are ‘parsed’, ie aligned to the actual relevant one-second reading, with gaps shown (if necessary) in the raw data to compensate for when the vehicle may have been stationary.

All exhaust parameters are time-corrected as per the *RDE test procedure (EU Commission Regulation 2016/427)* to ensure all ‘events’ are in alignment.

Time column

- actual time (date-hh:mm:ss) from the start of the test to the finish of the test in sequential 1 second intervals (same as in the raw data sheet)

GPS columns

- vehicle speed in km/h and m/s (v) (same as in raw data sheet)
- acceleration (a) in m/s^2 calculated from difference between sequential vehicle speeds
- cumulative distance (cumDist) from the start of the test in m (same as in raw data sheet)
- altitude in m (same as in raw data sheet)

Exhaust columns

- exhaust temperature, T_{ex} (K) (same as in raw data sheet but time-corrected)
- CO_2 (g), NO_X (g), NO_2 (g) and $PM_{2.5}$ (g) (same as in raw data sheet but time-corrected)

Binning columns

- average mass specific power (a*v) for each one-second period
- gradient as a %, to reduce noise this is calculated from the difference in altitude over the previous 20 seconds divided by the distance travelled over the previous 20 seconds, eg

  *(alt@time-alt@time-20s)/(cumDist@time-cumDist@time-20s)*100*

- speed in km/h (same as GPS column)

PEMS emission factor columns

- total distance travelled for each one-second period, calculated from speed
- emission factors (g/km) for NOx, NO_2, $PM_{2.5}$ and CO_2, calculated from mass of each pollutant divided by the distance travelled for each one-second period
- fuel consumption (FC) in l/100 km, calculated from CO_2 and fuel type

Data for comparison with VEPM columns

These columns are for charts showing estimated emissions compared with VEPM emissions.

- speed is rounded to the nearest whole number and set to zero if less than 10 km/h
- emission factors are the same as emission factor columns – except results less than 10 km/h set at zero
- VEPM emission factors – looked up for speed from the VEPM sheet

Data for binning analysis columns

These columns are the same as earlier columns (binning criteria and emission factors) – repeated so data can be analysed in pivot tables.

- all columns exclude results with speed less than 10 km/hour and (cold start) first 3 km of trip

Data check and cold start columns

- test totals calculated for consistency check with the full test data sheet
- test totals excluding results <10 km/hour calculated for information
- cold start emission factor (g/km) calculated as total emissions over first 3 km divided by 3

Other column

- ambient temperature (°C) but only logged every minute

OBD columns

- as available but typically logged at longer intervals.

C.3 10-second average sheet

This sheet contains all 10-second fixed (not rolling) averages or totals (calculated from the one-second average data).

The 10-second values are the ‘finest resolution’ values we compare with VEPM and represent increments of ~149.5 m travelled on average.

As per New Zealand ambient AQ data standards, averages are only calculated for periods with 75% or more valid data points, ie for a 10-second average we need at least 8 x 1-second averages.

All columns are as per the 1 second average sheet – except averaged in fixed 10-second time increments.

C.4 One-minute average sheet

This sheet contains all one-minute fixed (not rolling) averages or totals (calculated from the one-second average data).

The one-minute values are the ‘medium resolution’ values we compare with VEPM and represent increments of ~897 m travelled on average.

As per New Zealand ambient AQ data standards, averages are only calculated for periods with 75% or more valid data points, ie for a one-minute average we need at least 5 x 10-second averages.

All columns are as per the one-second average sheet – except averaged in fixed one-minute time increments.

C.5 Full test data sheet

This sheet contains the results for the full test.

The full test values are the ‘coarsest resolution’ values we compare with VEPM and represent increments of ~53,139m travelled total.

GPS columns

- average vehicle speed in km/h and in m/s (*v*) over the full test

- total distance in m travelled over the full test.

Exhaust columns

- average exhaust temperature in °C over the full test
- total mass (g) of NO, NO_X, NO_2, $PM_{2.5}$ and CO_2 for the full test.

PEMS EF columns – for VEPM comparison

- average vehicle speed in km/h (same as in the GPS column)
- total distance travelled (same as in the GPS column)
- emission factors (g/km) for CO_2, NO_X, NO_2, and $PM_{2.5}$ calculated from total mass of each pollutant divided by the total distance travelled
- fuel consumption (FC) in l/100km, calculated from CO_2 and fuel type
- cross check – compares fuel consumption with the measured amount of fuel used.

Situation specific emission factors

- cold start emission factors (g/km) for CO_2, NO_X, NO_2 and $PM_{2.5}$ calculated (in one-second average sheet) for first 3km of trip
- Acceleration * velocity columns show the average emission factor for each *a*v* binning criteria (from bins sheet)
- Gradient columns show the average emission factor for each gradient binning criteria (from bins sheet).

C.6 Bins sheet

This sheet provides pivot tables and pivot charts to show situation specific emission factors (bins) from one-second average sheet.

C.7 VEPM comparisons sheet

This sheet shows the VEPM emission factor (by speed) for the vehicle class.

Appendix D: Analysis of PEMS trips

This appendix tabulates the analyses of the PEMS results for:

- trip total average emission factors and time share under different driving conditions by vehicle
- NO_x emission factors for gradient and $a*v$ binning criteria
- cold start emission factors (first 3 km of trip).

Note: All heavy vehicles were unladen (ie load=0%).

Table D.1 Trip total average emission factors and time share under different driving conditions by vehicle

Vehicle	Trip total emission factor				Trip percentage (by time)												
	(g/km)				$a * v$ (W/kg)				Gradient (%)					Velocity (km/h)			
	NOx	NO_2	$PM_{2.5}$	CO_2	< -9.2	≥-9.2 to <0	≥0 to <9.2	≥9.2	< -4%	≥-4 to < -1	≥-1 to <1	≥1 to <4	≥4	<10	≥10 to <50	≥50 to <90	≥90
Light duty petrol																	
JLA LPV (Honda Stream)	0.18	0.01	0.00	207	5%	31%	37%	5%	3%	14%	46%	14%	2%	21%	28%	47%	3%
JCBA LPV (Toyota Avensis)	0.17	0.01	0.01	233	6%	27%	33%	6%	2%	11%	45%	9%	3%	28%	29%	34%	9%
JCBA LPV (Subaru Forester)	0.15	0.01	0.01	255	3%	35%	39%	3%	3%	15%	44%	14%	2%	22%	36%	38%	5%
Eur3 LPV (Mazda 3)	0.30	0.01	0.00	200	7%	28%	32%	6%	2%	14%	39%	14%	4%	26%	32%	30%	11%
Eur3 LPV (Toyota RAV4)	0.32	0.01	0.00	281	6%	30%	36%	6%	3%	12%	48%	13%	3%	21%	28%	37%	14%
Eur4 LCV (Great Wall Ute)	0.32	0.01	0.00	273	4%	32%	36%	5%	2%	11%	49%	11%	3%	24%	32%	38%	6%
Light duty diesel																	
JKC LPV (Toyota L/cruiser)	4.78	0.42	0.15	289	3%	33%	35%	4%	2%	16%	43%	12%	3%	24%	28%	44%	3%
JKD LPV (Toyota Prado)	4.61	0.50	0.15	310	5%	30%	37%	6%	2%	13%	46%	13%	4%	22%	28%	39%	11%
JKD LCV (Toyota Hilux) A	3.74	0.45	0.18	348	5%	32%	38%	4%	4%	17%	42%	14%	3%	20%	47%	30%	3%
JKD LCV (Toyota Hilux) B	3.81	0.41	0.16	310	4%	27%	36%	3%	2%	14%	40%	11%	3%	30%	33%	28%	9%
JKD LCV (Toyota Hilux) C	3.98	0.48	0.19	285	5%	28%	35%	5%	3%	11%	45%	13%	3%	26%	29%	34%	11%
Eur2 LCV (Ford Transit Van)	1.66	0.22	0.23	263	3%	32%	35%	3%	1%	14%	43%	10%	4%	28%	31%	40%	1%
Eur2 LCV (Toyota Hilux DCab) A	1.69	0.20	0.30	258	4%	34%	40%	4%	2%	12%	50%	14%	3%	19%	27%	52%	2%
Eur2 LCV (Toyota Hilux DCab) B	1.83	0.15	0.35	247	5%	34%	35%	5%	4%	14%	47%	12%	4%	20%	27%	40%	12%
Eur2 LCV (Toyota Hilux DCab) C	1.59	0.19	0.23	276	4%	34%	37%	4%	3%	18%	43%	12%	3%	21%	37%	39%	3%
Eur2 LCV (Toyota Hilux SCab)	1.69	0.12	0.27	283	4%	31%	33%	4%	3%	15%	38%	13%	3%	28%	26%	45%	1%
Eur4 LPV (Audi A5)	0.94	0.30	0.04	226	4%	31%	33%	5%	2%	11%	45%	13%	3%	27%	26%	37%	10%
Eur4 LPV (Toyota Prado) A	1.68	0.35	0.05	305	3%	35%	38%	4%	1%	14%	51%	12%	2%	20%	47%	27%	7%

Vehicle	**Trip total emission factor**				**Trip percentage (by time)**												
	(g/km)				***a* * *v* (W/kg)**				**Gradient (%)**					**Velocity (km/h)**			
	NOx	NO_2	$PM_{2.5}$	CO_2	<-9.2	≥-9.2 to <0	≥0 to <9.2	≥9.2	<-4%	≥-4 to <-1	≥-1 to <1	≥1 to <4	≥4	<10	≥10 to <50	≥50 to <90	≥90
Light duty diesel																	
Eur4 LPV (Toyota Prado) B	1.66	0.66	0.04	296	5%	34%	38%	5%	1%	16%	47%	14%	3%	18%	35%	45%	2%
Eur4 LPV (Toyota Prado) C	1.48	0.25	0.05	285	4%	34%	36%	4%	2%	10%	50%	12%	4%	22%	26%	48%	3%
Eur4 LCV (Ford Transit Van) A	1.45	0.31	0.05	299	5%	35%	35%	5%	3%	18%	43%	12%	5%	20%	38%	38%	4%
Eur4 LCV (Ford Transit Van) B	1.40	0.39	0.03	314	3%	33%	41%	2%	1%	16%	47%	12%	3%	21%	41%	35%	3%
Eur4 LCV (Hyundai iLoad Van)	1.39	0.23	0.03	209	2%	36%	37%	2%	2%	15%	45%	12%	3%	24%	49%	26%	1%
Eur4 LCV (Nissan Urvan)	1.28	0.22	0.09	294	4%	26%	48%	3%	3%	13%	47%	15%	4%	18%	36%	30%	15%
Eur5 LCV (Ford Transit Van)	0.86	0.32	0.00	289	5%	34%	32%	6%	1%	13%	44%	16%	3%	22%	29%	36%	13%
Eur5 LCV (Merc Sprinter Van) #1			0.01	287	3%	33%	36%	3%	2%	14%	44%	13%	3%	24%	30%	43%	4%
Eur5 LCV (Merc Sprinter Van) #2	1.13	0.07			4%	29%	34%	5%	3%	13%	40%	13%	3%	28%	30%	33%	9%
Heavy duty diesel																	
J97 (Isuzu Elf 4.5t)	4.16	0.72	1.73	516	3%	31%	35%	3%	1%	13%	44%	11%	3%	28%	40%	27%	5%
EurIII (Mitsubishi Canter 4.5t)A	9.90	1.06	0.40	296	4%	28%	34%	4%	1%	11%	44%	12%	3%	28%	28%	33%	10%
EurIII (Mitsubishi Canter 4.5t)B	6.89	0.72	0.43	204	2%	33%	44%	1%	3%	16%	42%	14%	5%	20%	39%	37%	4%
EurIII (Mitsubishi Canter 4.5t)C	2.82	0.20	0.54	320	2%	33%	36%	3%	2%	14%	44%	12%	3%	26%	47%	26%	2%
EurV (Mitsubishi Canter 6t) A	4.09	0.65	0.02	281	3%	27%	33%	3%	3%	14%	35%	11%	3%	34%	30%	29%	7%
EurV (Mitsubishi Canter 6t) B	4.23	0.62	0.02	252	4%	30%	38%	3%	4%	10%	48%	10%	4%	25%	29%	37%	10%

Table D.2 NO$_X$ emission factors for gradient and *av* binning criteria**

Vehicle	Binning criteria								
	Acceleration * velocity (W/kg)				Gradient (%)				
	< -9.2	≥-9.2 to <0	≥0 to <9.2	≥9.2	< -4%	≥-4 to < -1	≥-1 to <1	≥1to< 4	≥4
	NOx emission factor (g/km)								
Light duty petrol									
JLA LPV (Honda Stream)	0.20	0.20	0.15	0.15	0.23	0.18	0.14	0.17	0.29
JCBA LPV (Subaru Forester)	0.16	0.15	0.15	0.15	0.11	0.13	0.14	0.16	0.22
JCBA LPV (Toyota Avensis)	0.12	0.12	0.12	0.09	0.09	0.07	0.11	0.15	0.20
Eur3 LPV (Mazda 3)	0.31	0.26	0.22	0.18	0.11	0.26	0.23	0.23	0.36
Eur3 LPV (Toyota RAV4)	0.17	0.14	0.15	0.14	0.13	0.14	0.15	0.15	0.17
Eur4 LCV (Great Wall Ute)	0.28	0.25	0.22	0.31	0.27	0.18	0.22	0.28	0.40
Light duty diesel									
JKC LPV (Toyota L/cruiser)	3.34	4.58	4.53	8.31	2.47	4.35	4.16	5.07	9.12
JKD LPV (Toyota Prado)	4.11	3.26	4.03	6.52	3.56	4.19	4.00	3.66	3.58
JKD LCV (Toyota Hilux) A	2.06	2.45	3.87	6.78	2.64	2.97	3.28	3.45	5.51
JKD LCV (Toyota Hilux) B	3.45	3.48	3.45	3.35	2.70	2.89	3.42	3.47	5.71
JKD LCV (Toyota Hilux) C	3.39	3.77	3.69	3.80	2.71	3.32	3.44	3.90	6.44
Eur2 LCV (Ford Transit Van)	1.53	1.47	1.53	1.97	1.38	1.36	1.43	1.52	2.52
Eur2 LCV (Toyota Hilux DCab) A	1.93	1.63	1.82	3.20	1.56	1.52	1.64	1.98	3.15
Eur2 LCV (Toyota Hilux DCab) B	1.96	2.00	1.73	1.40	1.52	1.74	1.65	1.95	2.96
Eur2 LCV (Toyota Hilux DCab) C	1.72	1.31	1.36	1.85	1.10	1.34	1.16	1.41	2.72
Eur2 LCV (Toyota Hilux SCab)	2.33	1.98	2.02	2.38	2.73	1.88	1.72	2.88	2.90
Eur4 LPV (Audi A5)	1.07	0.97	0.81	0.70	0.54	0.84	0.61	0.91	2.64
Eur4 LPV (Toyota Prado) A	1.30	1.27	1.76	2.91	1.38	1.19	1.48	1.66	3.23
Eur4 LPV (Toyota Prado) B	2.12	1.67	1.62	1.23	1.44	1.42	1.44	2.04	2.25
Eur4 LPV (Toyota Prado) C	0.77	1.19	1.45	2.76	0.83	0.97	1.02	1.69	3.49
Eur4 LCV (Ford Transit Van) A	1.44	1.55	1.57	1.13	1.06	1.26	1.48	1.56	2.70
Eur4 LCV (Ford Transit Van) B	1.44	1.43	1.32	1.81	1.06	1.08	1.23	1.56	2.69
Eur4 LCV (Hyundai iLoad Van)	0.85	1.04	1.60	2.22	1.15	0.96	1.17	1.54	2.79
Eur4 LCV (Nissan Urvan)	1.08	1.14	1.11	1.21	1.20	1.06	1.20	1.02	1.14
Eur5 LCV (Ford Transit Van)	0.94	0.82	0.79	0.96	0.60	0.77	0.81	0.84	1.29
Eur5 LCV (Merc Sprinter Van) #2	1.11	1.07	1.03	1.68	0.86	0.89	1.09	1.25	1.45
Heavy duty diesel									
J97 (Isuzu Elf 4.5t)	4.07	4.13	4.09	3.69	3.74	3.73	3.94	4.40	5.13
EurIII (Mitsubishi Canter 4.5t) A	10.40	12.07	10.63	8.63	14.30	13.54	9.45	10.34	12.02
EurIII (Mitsubishi Canter 4.5t)B	3.30	5.45	5.61	3.98	5.00	5.47	5.42	4.97	6.88
EurIII (Mitsubishi Canter 4.5t)C	2.46	2.93	2.53	1.91	2.18	2.55	2.87	2.54	2.83
EurV (Mitsubishi Canter 6t) A	3.11	3.84	5.00	5.19	2.87	3.94	4.25	4.76	6.51
EurV (Mitsubishi Canter 6t) B	6.23	4.92	3.76	3.25	3.05	3.27	4.01	5.36	7.12

Table D.3 Cold start emission factors (first 3km of trip)

Vehicle	Trip total EF (g/km)			Cold start EF (g/km)			Ratio of cold/total EF		
	NO_X	$PM_{2.5}$	CO_2	NO_X	$PM_{2.5}$	CO_2	NO_X	$PM_{2.5}$	CO_2
Light duty petrol									
JLA LPV (Honda Stream)	0.18	0.003	207	0.46	0.01	390	2.6	2.9	1.9
JCBA LPV (Subaru Forester)	0.15	0.007	255	0.31	0.00	538	2.1	0.1	2.1
JCBA LPV (Toyota Avensis)	0.17	0.006	233	0.77	0.00	358	4.5	0.6	1.5
Eur3 LPV (Mazda 3)	0.30	0.002	200	1.20	0.01	604	4.0	4.7	3.0
Eur3 LPV (Toyota RAV4)	0.32	0.002	281	3.00	0.00	618	9.2	0.7	2.2
Eur4 LCV (Great Wall Ute)	0.32	0.002	273	1.70	0.00	404	5.4	2.3	1.5
Light duty diesel									
JKC LPV (Toyota L/cruiser)	4.78	0.150	290	8.29	0.13	494	1.7	0.8	1.7
JKD LPV (Toyota Prado)	4.61	0.154	310	2.60	0.17	237	0.6	1.1	0.8
JKD LCV (Toyota Hilux) A	3.74	0.180	348	13.06	0.29	1129	3.5	1.6	3.2
JKD LCV (Toyota Hilux) B	3.81	0.163	310	6.48	0.24	545	1.7	1.5	1.8
JKD LCV (Toyota Hilux) C	3.98	0.187	286	4.86	0.17	653	1.2	0.9	2.3
Eur2 LCV (Ford Transit Van)	1.69	0.274	283	4.52	0.60	689	2.7	2.2	2.4
Eur2 LCV (Toyota Hilux DCab) A	1.69	0.300	258	2.89	1.44	367	1.7	4.8	1.4
Eur2 LCV (Toyota Hilux DCab) B	1.83	0.346	247	2.02	0.34	270	1.1	1.0	1.1
Eur2 LCV (Toyota Hilux DCab) C	1.59	0.230	276	6.38	0.15	517	4.0	0.7	1.9
Eur2 LCV (Toyota Hilux SCab)	1.66	0.226	263	4.35	0.16	633	2.6	0.7	2.4
Eur4 LPV (Audi A5)	0.94	0.038	226	3.41	0.01	477	3.6	0.3	2.1
Eur4 LPV (Toyota Prado) A	1.68	0.053	305	1.41	0.06	506	0.8	1.2	1.7
Eur4 LPV (Toyota Prado) B	1.66	0.040	296	2.93	0.07	512	1.8	1.7	1.7
Eur4 LPV (Toyota Prado) C	1.48	0.047	285	3.73	0.08	471	2.5	1.7	1.7
Eur4 LCV (Ford Transit Van) A	1.45	0.050	299	1.06	0.02	122	0.7	0.5	0.4
Eur4 LCV (Ford Transit Van) B	1.40	0.033	314	2.11	0.03	383	1.5	1.1	1.2
Eur4 LCV (Hyundai iLoad Van)	1.39	0.025	209	1.51	0.04	370	1.1	1.7	1.8
Eur4 LCV (Nissan Urvan)	1.28	0.095	294	0.63	0.08	255	0.5	0.8	0.9
Eur5 LCV (Ford Transit Van)	0.86	0.002	294	1.50	0.00	468	1.7	1.8	1.6
Eur5 LCV (Merc Sprinter Van)	1.13	0.005	288	2.62	0.01	298	2.3	1.4	1.0
Heavy duty diesel									
J97 (Isuzu Elf 4.5t)	4.16	1.732	516	2.74	1.79	357	0.7	1.0	0.7
EurIII (Mitsubishi Canter 4.5t) A	9.90	0.400	297	6.20	0.40	221	0.6	1.0	0.7
EurIII (Mitsubishi Canter 4.5t) B	6.89	0.428	204	41.75	1.07	1187	6.1	2.5	5.8
EurIII (Mitsubishi Canter 4.5t) C	2.83	0.538	321	3.60	2.79	478	1.3	5.2	1.5
EurV (Mitsubishi Canter 6t) A	4.09	0.021	281	1.50	0.01	420	0.4	0.7	1.5
EurV (Mitsubishi Canter 6t) B	4.23	0.021	252	4.77	0.02	176	1.1	0.8	0.7

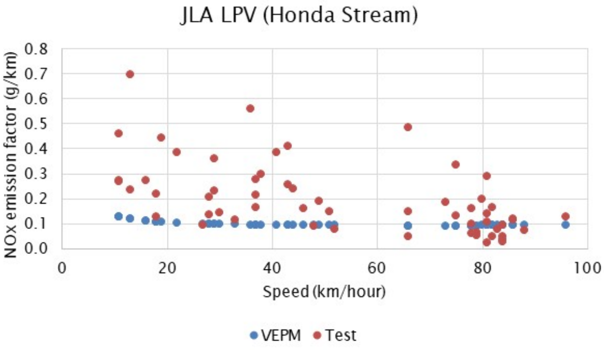
Appendix E: PEMS comparisons with VEPM

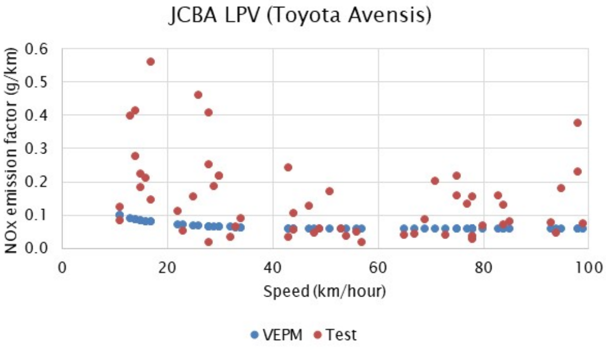
This appendix shows all PEMS results graphed at one-minute resolution compared against VEPM predictions for NOx, NO_2, $PM_{2.5}$ and CO_2. Due to the variability in emission rates, plots are not displayed with the same y-axis range.

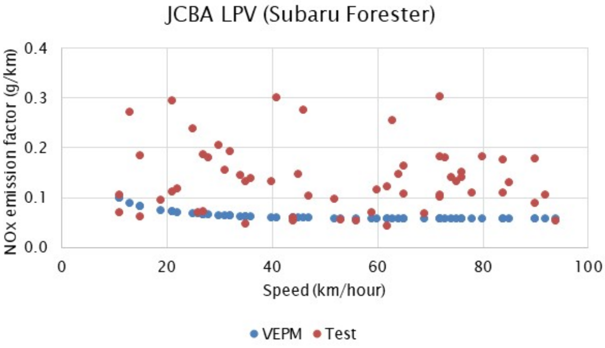
Note: A 0% gradient was assumed for all VEPM emissions factor estimates.

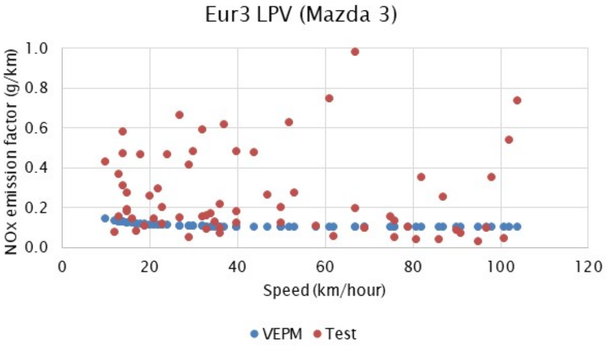
Note: All heavy vehicles were unladen (ie load=0%).

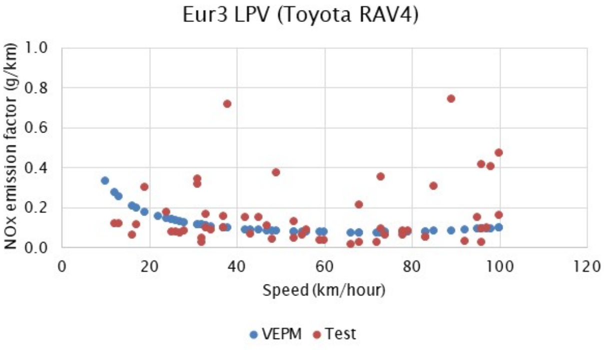
E.1 NO$_X$

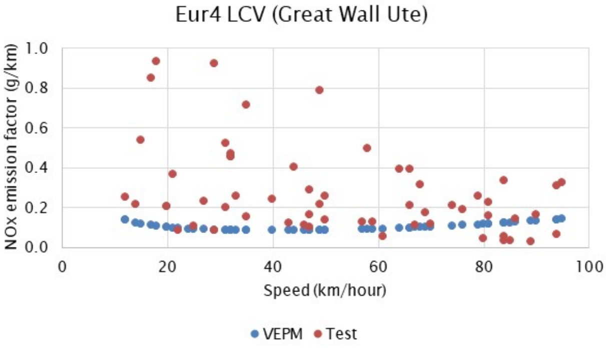


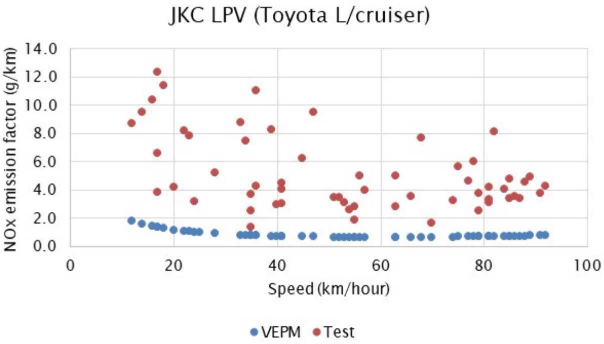


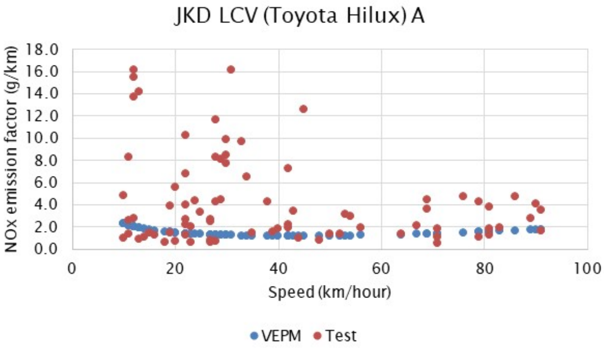


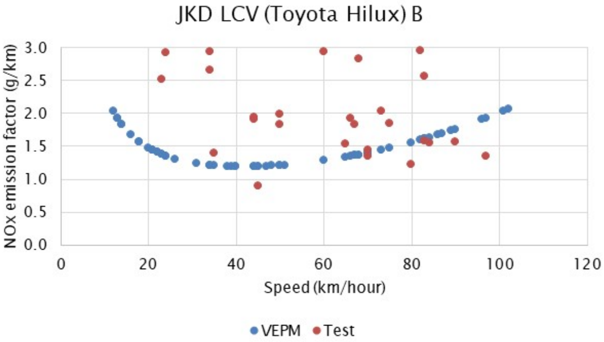


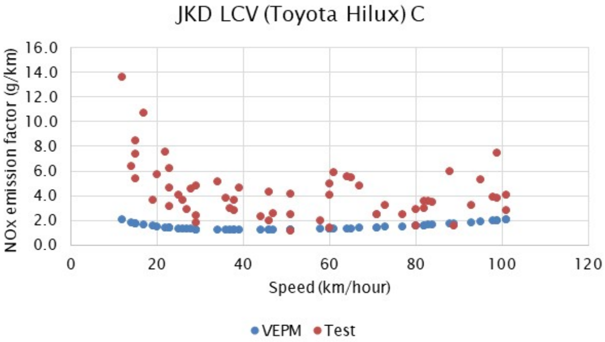


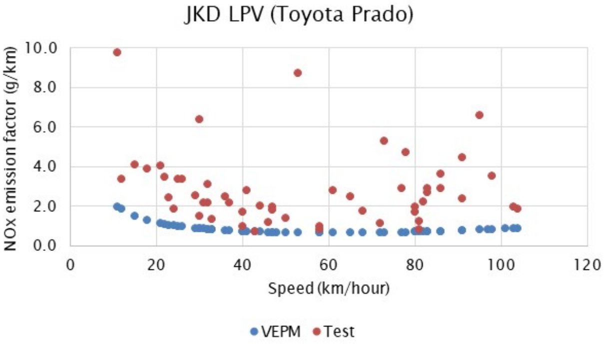


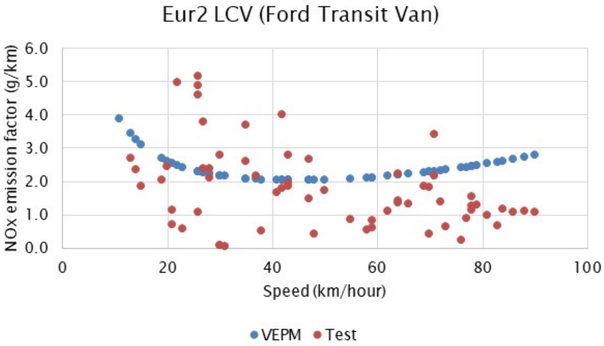

JKC LPV (Toyota L/cruiser)
NOx emission factor (g/km)
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
0
20
40
60
80
100
Speed (km/hour)
VEPM
Test

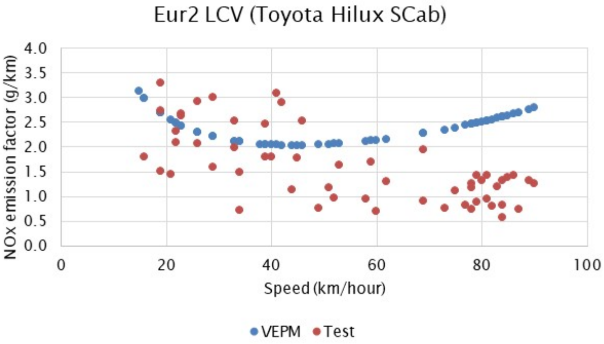

JKD LCV (Toyota Hilux) A
NOx emission factor (g/km)
18.0
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
0
20
40
60
80
100
Speed (km/hour)
VEPM
Test

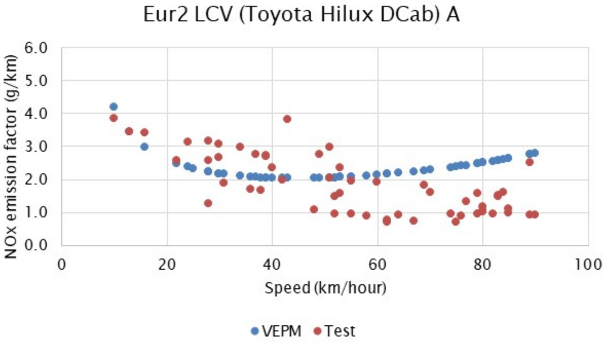

JKD LCV (Toyota Hilux) B
NOx emission factor (g/km)
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0
20
40
60
80
100
120
Speed (km/hour)
VEPM
Test


JKD LCV (Toyota Hilux) C
NOx emission factor (g/km)
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
0
20
40
60
80
100
120
Speed (km/hour)
VEPM
Test

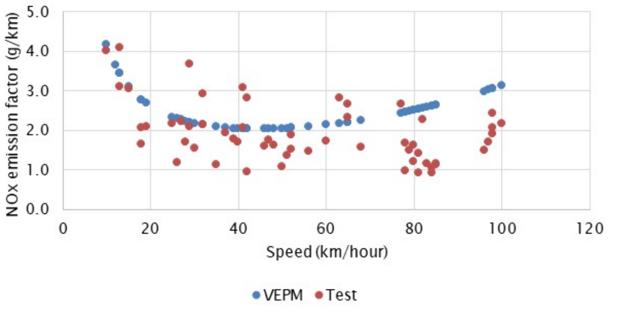

JKD LPV (Toyota Prado)
NOx emission factor (g/km)
10.0
8.0
6.0
4.0
2.0
0.0
0
20
40
60
80
100
120
Speed (km/hour)
VEPM
Test


Eur2 LCV (Ford Transit Van)
NOx emission factor (g/km)
6.0
5.0
4.0
3.0
2.0
1.0
0.0
0
20
40
60
80
100
Speed (km/hour)
VEPM
Test

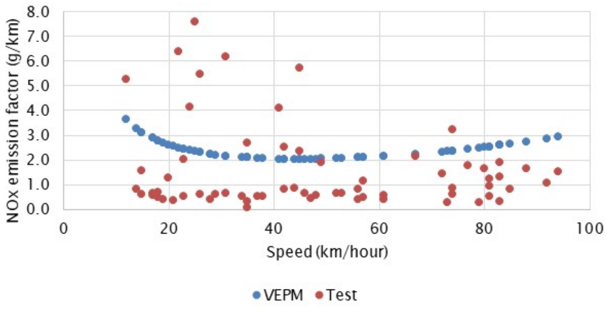

Eur2 LCV (Toyota Hilux SCab)
NOx emission factor (g/km)
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0
20
40
60
80
100
Speed (km/hour)
VEPM
Test


Eur2 LCV (Toyota Hilux DCab) A
NOx emission factor (g/km)
6.0
5.0
4.0
3.0
2.0
1.0
0.0
0
20
40
60
80
100
Speed (km/hour)
VEPM
Test

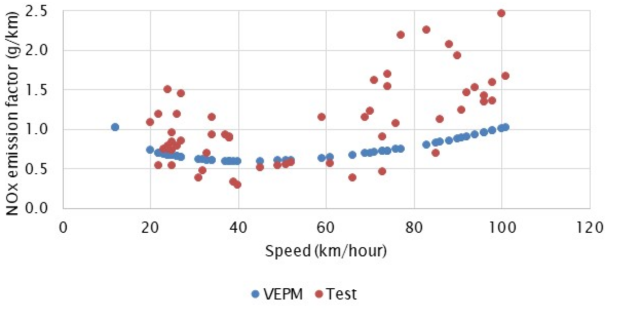
Eur2 LCV (Toyota Hilux DCab) B



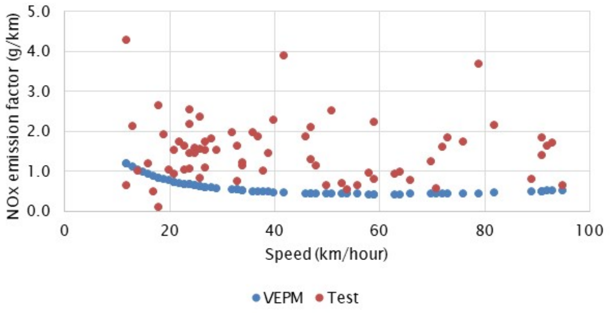
Eur2 LCV (Toyota Hilux DCab) C



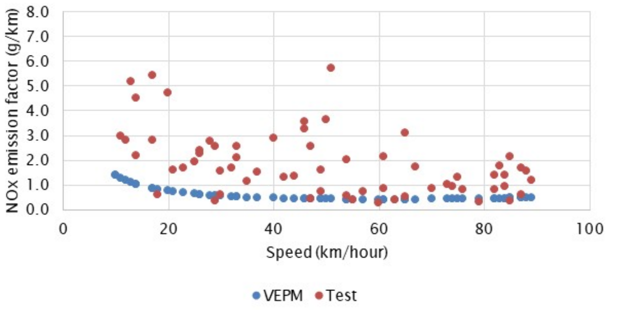
Eur4 LCV (Nissan Urvan)



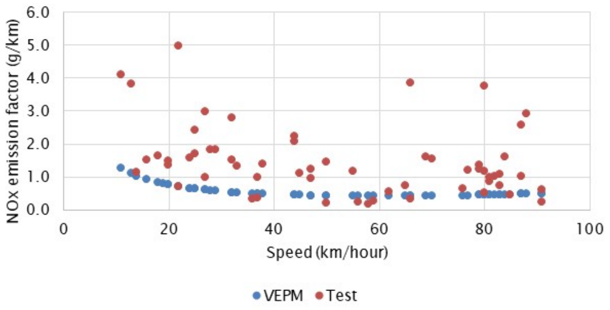
Eur4 LPV (Toyota Prado) A



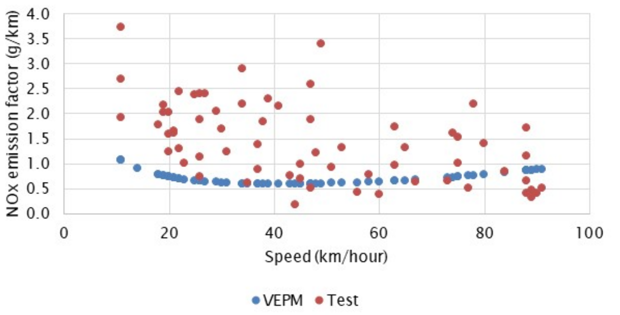
Eur4 LPV (Toyota Prado) B



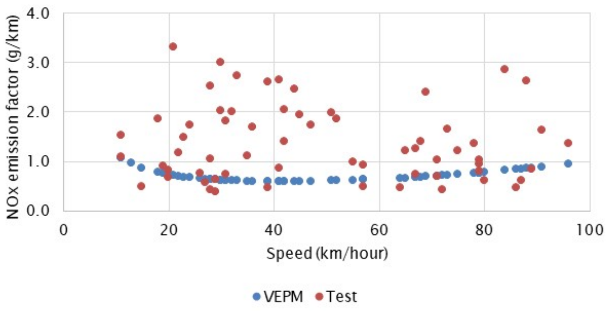
Eur4 LPV (Toyota Prado) C

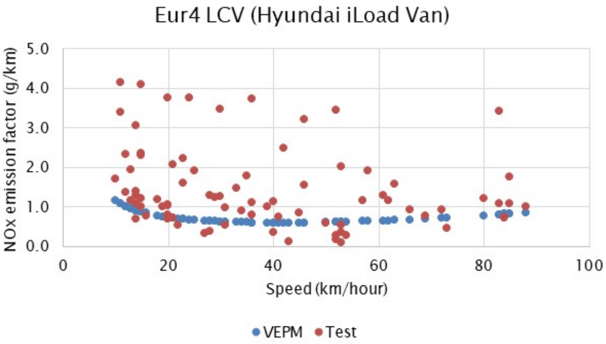


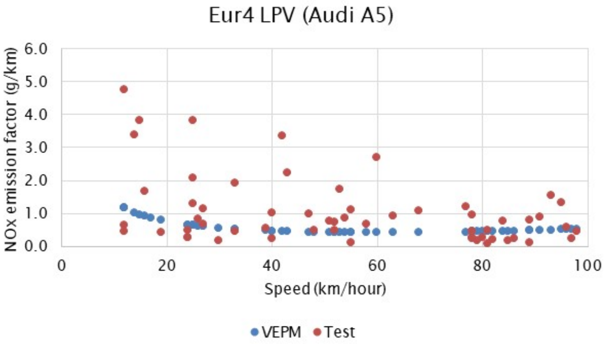
Eur4 LCV (Ford Transit Van) A

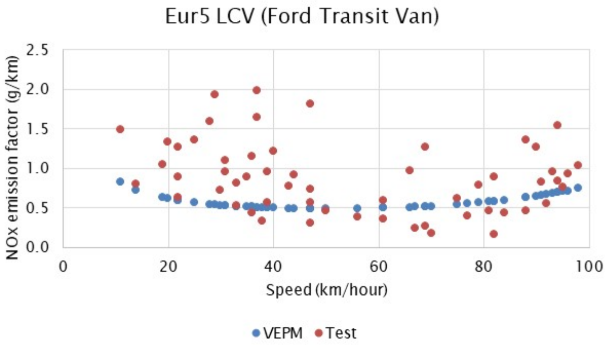


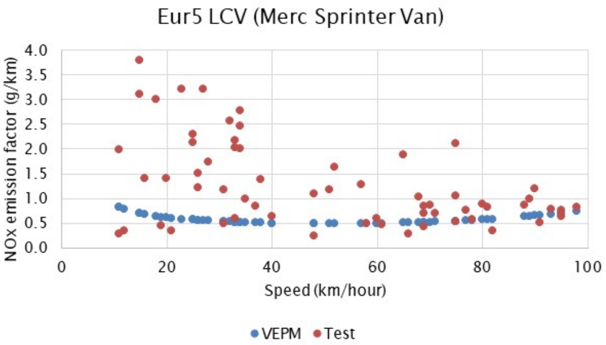
Eur4 LCV (Ford Transit Van) B

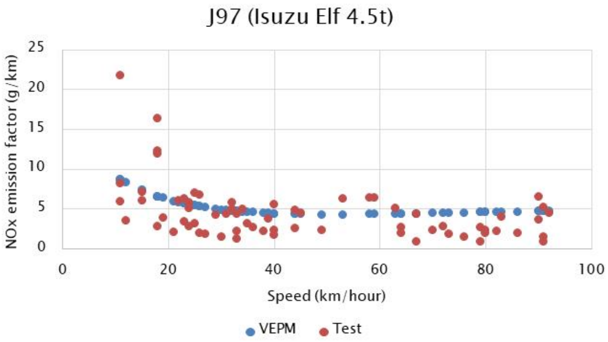


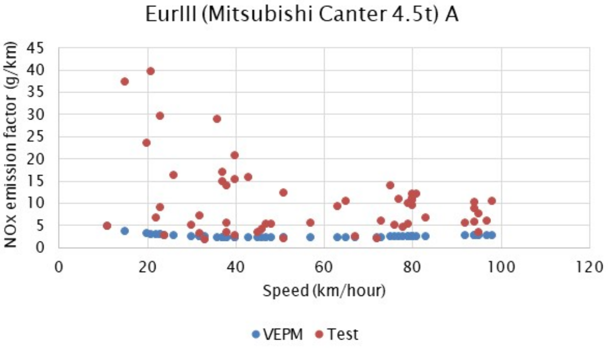

Eur4 LCV (Hyundai iLoad Van)
NOx emission factor (g/km)
0.0
1.0
2.0
3.0
4.0
5.0
0
20
40
60
80
100
Speed (km/hour)
● VEPM ● Test

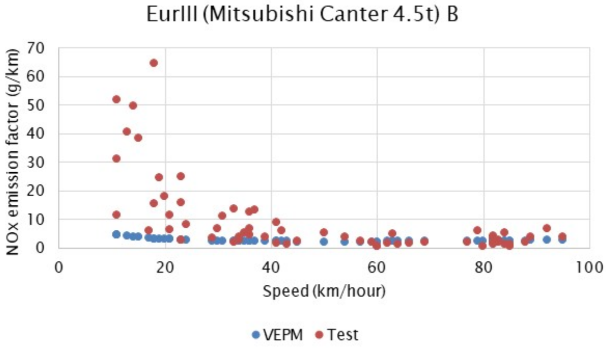

Eur4 LPV (Audi A5)
NOx emission factor (g/km)
0.0
1.0
2.0
3.0
4.0
5.0
6.0
0
20
40
60
80
100
Speed (km/hour)
● VEPM ● Test

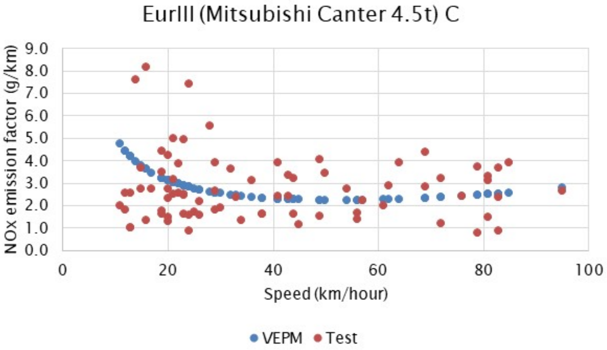

Eur5 LCV (Ford Transit Van)
NOx emission factor (g/km)
0.0
0.5
1.0
1.5
2.0
2.5
0
20
40
60
80
100
Speed (km/hour)
● VEPM ● Test

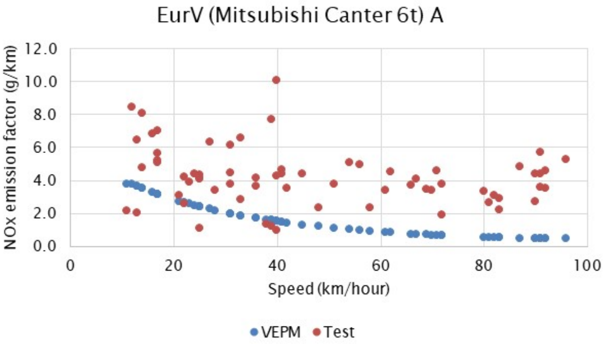

Eur5 LCV (Merc Sprinter Van)
NOx emission factor (g/km)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
0
20
40
60
80
100
Speed (km/hour)
● VEPM ● Test

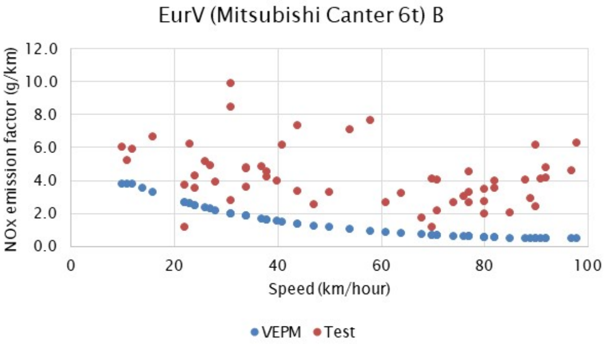

J97 (Isuzu Elf 4.5t)
NOx emission factor (g/km)
0
5
10
15
20
25
0
20
40
60
80
100
Speed (km/hour)
● VEPM ● Test


EurIII (Mitsubishi Canter 4.5t) A
NOx emission factor (g/km)
0
5
10
15
20
25
30
35
40
45
0
20
40
60
80
100
120
Speed (km/hour)
● VEPM ● Test

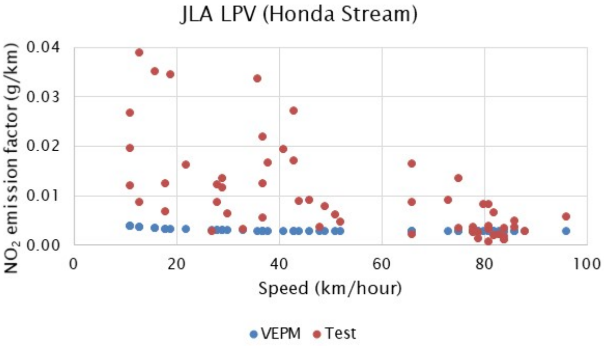

EurIII (Mitsubishi Canter 4.5t) B
NOx emission factor (g/km)
0
10
20
30
40
50
60
70
0
20
40
60
80
100
Speed (km/hour)
● VEPM ● Test

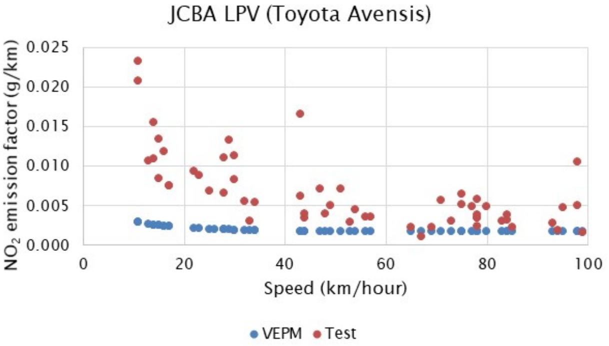

EurIII (Mitsubishi Canter 4.5t) C
NOx emission factor (g/km)
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
0
20
40
60
80
100
Speed (km/hour)
● VEPM ● Test

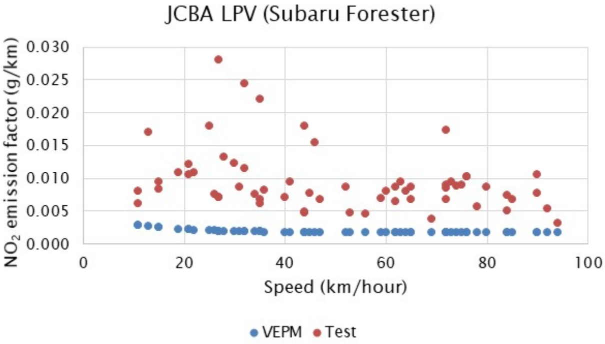

EurV (Mitsubishi Canter 6t) A
NOx emission factor (g/km)
12.0
10.0
8.0
6.0
4.0
2.0
0.0
0
20
40
60
80
100
Speed (km/hour)
VEPM
Test

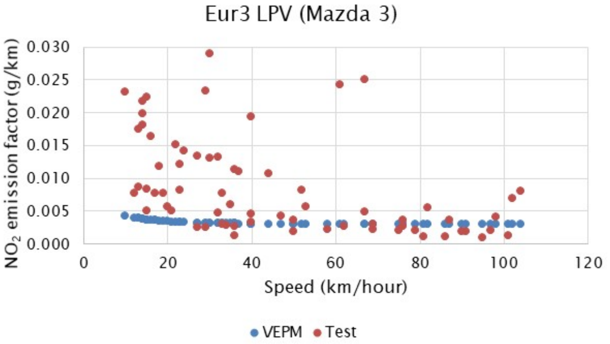

EurV (Mitsubishi Canter 6t) B
NOx emission factor (g/km)
12.0
10.0
8.0
6.0
4.0
2.0
0.0
0
20
40
60
80
100
Speed (km/hour)
VEPM
Test

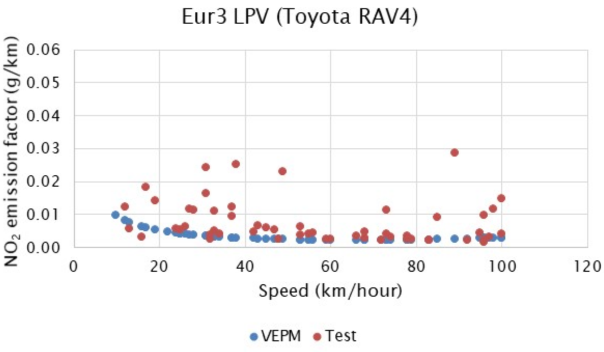
E.2 NO$_2$

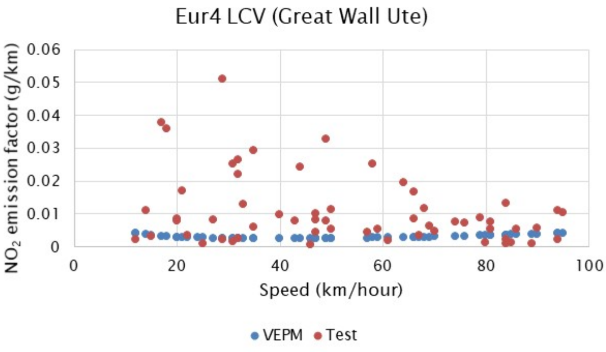

JLA LPV (Honda Stream)
NO2 emission factor (g/km)
0.04
0.03
0.02
0.01
0.00
0
20
40
60
80
100
Speed (km/hour)
VEPM
Test

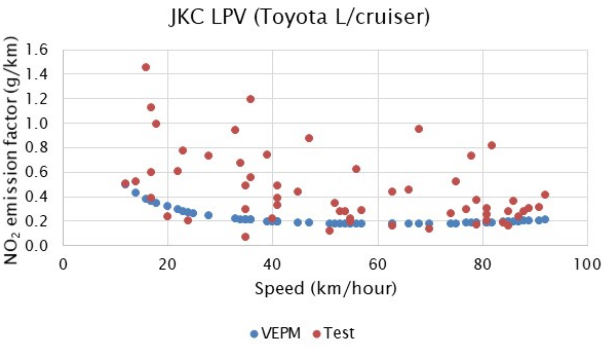

JCBA LPV (Toyota Avensis)
NO2 emission factor (g/km)
0.025
0.020
0.015
0.010
0.005
0.000
0
20
40
60
80
100
Speed (km/hour)
VEPM
Test

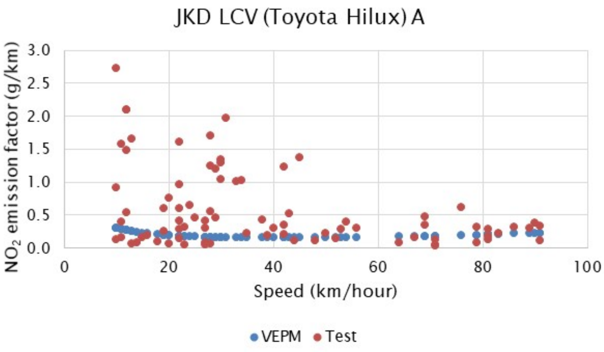

JCBA LPV (Subaru Forester)
NO2 emission factor (g/km)
0.030
0.025
0.020
0.015
0.010
0.005
0.000
0
20
40
60
80
100
Speed (km/hour)
VEPM
Test

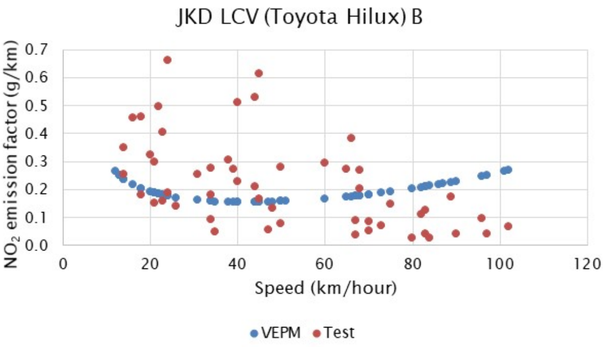

Eur3 LPV (Mazda 3)
NO2 emission factor (g/km)
0.030
0.025
0.020
0.015
0.010
0.005
0.000
0
20
40
60
80
100
120
Speed (km/hour)
VEPM
Test

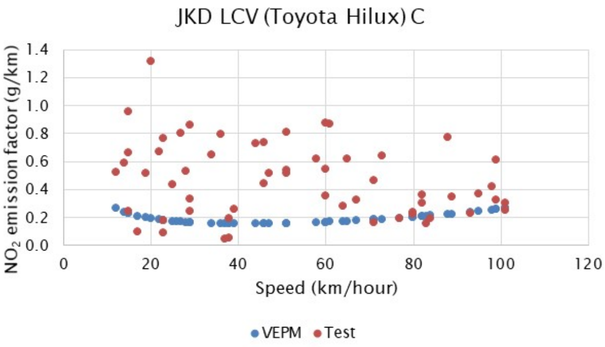

Eur3 LPV (Toyota RAV4)

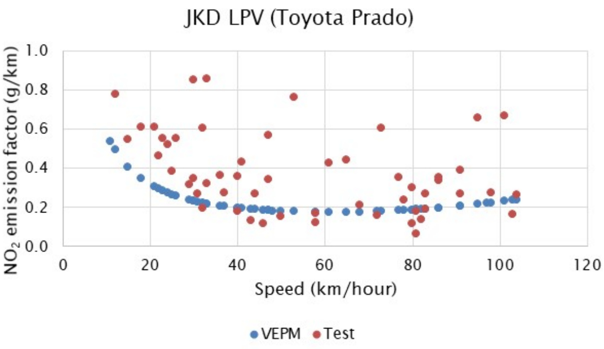

Eur4 LCV (Great Wall Ute)

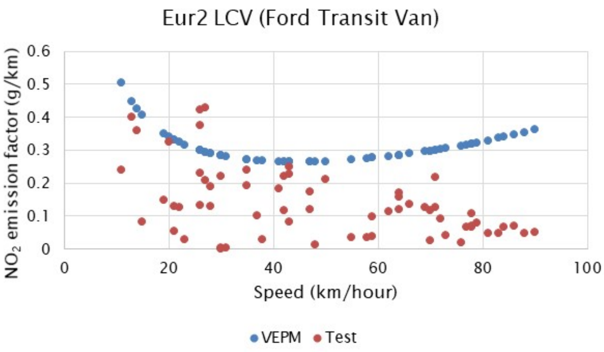

JKC LPV (Toyota L/cruiser)

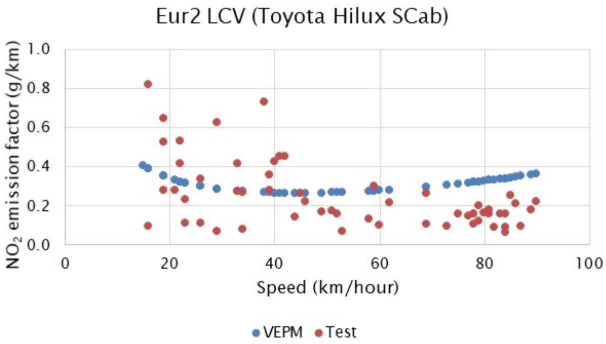

JKD LCV (Toyota Hilux) A

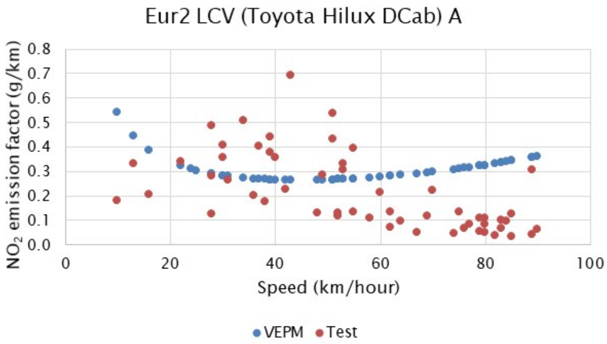

JKD LCV (Toyota Hilux) B

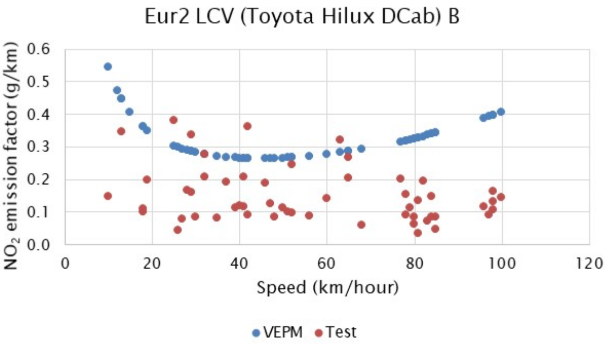

JKD LCV (Toyota Hilux) C

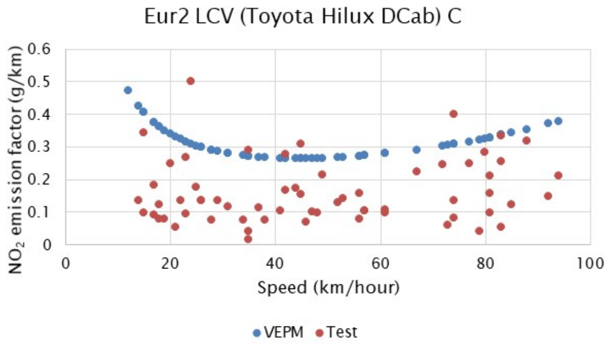

JKD LPV (Toyota Prado)

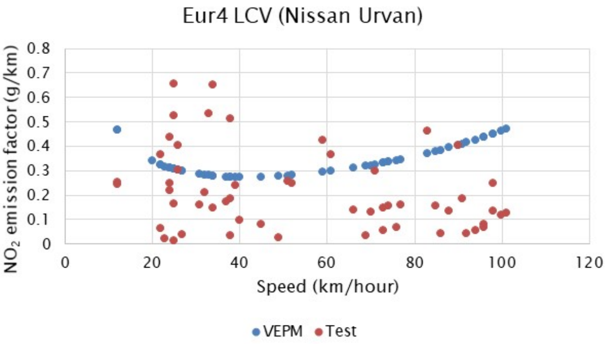

Eur2 LCV (Ford Transit Van)

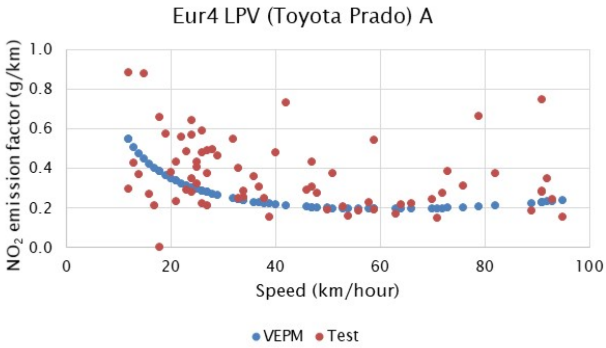

Eur2 LCV (Toyota Hilux SCab)
NO2 emission factor (g/km)
1.0
0.8
0.6
0.4
0.2
0.0
0
20
40
60
80
100
Speed (km/hour)
VEPM
Test

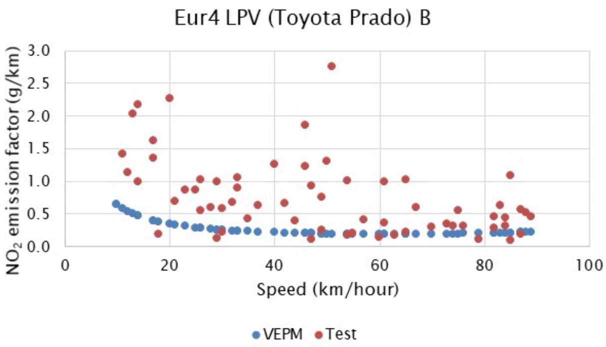

Eur2 LCV (Toyota Hilux DCab) A
NO2 emission factor (g/km)
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
20
40
60
80
100
Speed (km/hour)
VEPM
Test

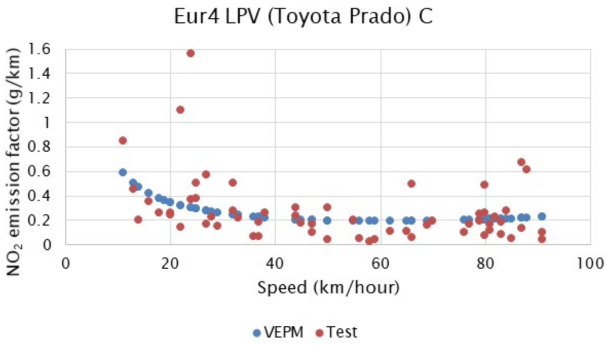

Eur2 LCV (Toyota Hilux DCab) B
NO2 emission factor (g/km)
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
20
40
60
80
100
120
Speed (km/hour)
VEPM
Test

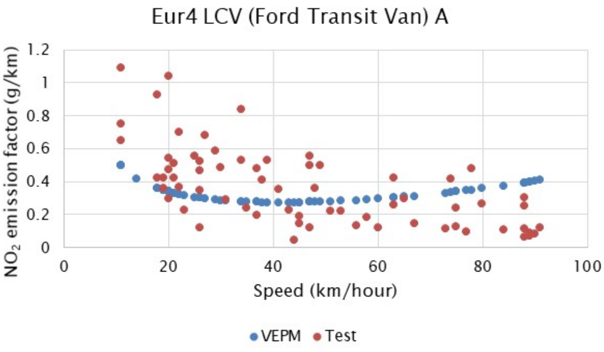

Eur2 LCV (Toyota Hilux DCab) C
NO2 emission factor (g/km)
0.6
0.5
0.4
0.3
0.2
0.1
0
0
20
40
60
80
100
Speed (km/hour)
VEPM
Test

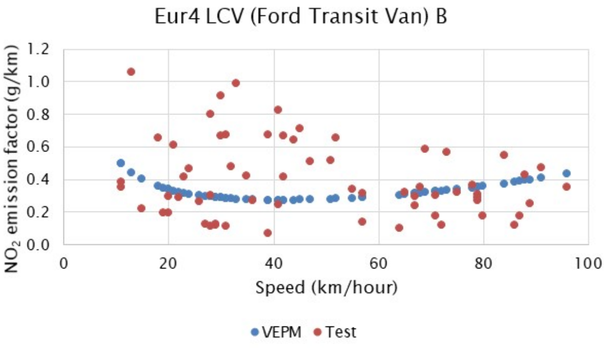

Eur4 LCV (Nissan Urvan)
NO2 emission factor (g/km)
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
20
40
60
80
100
120
Speed (km/hour)
VEPM
Test

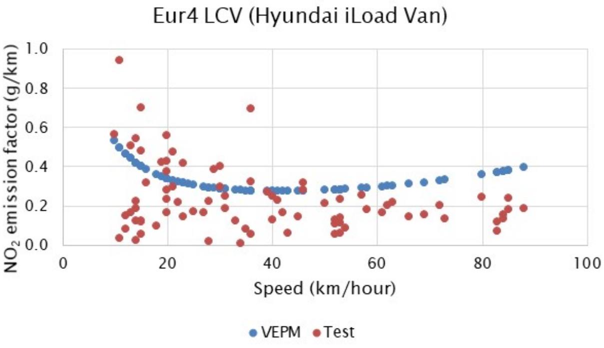

Eur4 LPV (Toyota Prado) A
NO2 emission factor (g/km)
1.0
0.8
0.6
0.4
0.2
0.0
0
20
40
60
80
100
Speed (km/hour)
VEPM
Test

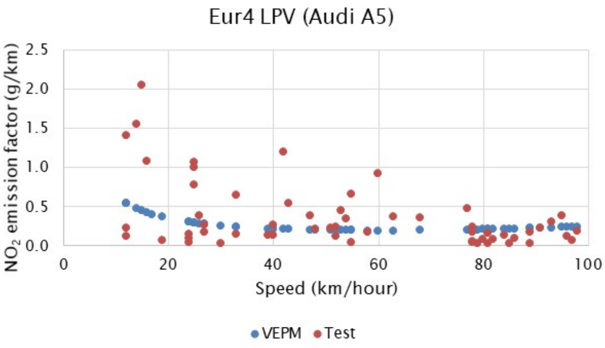

Eur4 LPV (Toyota Prado) B
NO2 emission factor (g/km)
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0
20
40
60
80
100
Speed (km/hour)
VEPM
Test

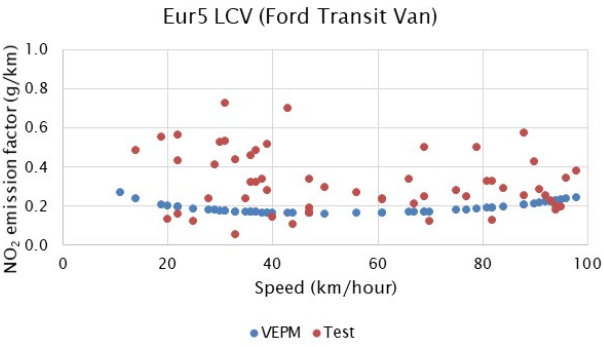

Eur4 LPV (Toyota Prado) C
NO2 emission factor (g/km)
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
20
40
60
80
100
Speed (km/hour)
VEPM
Test

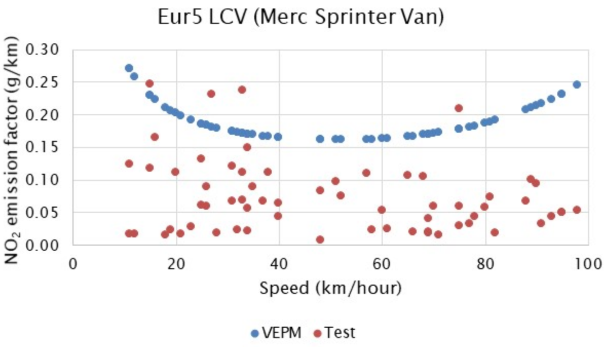

Eur4 LCV (Ford Transit Van) A
NO_2 emission factor (g/km)
0
0.2
0.4
0.6
0.8
1
1.2
0
20
40
60
80
100
Speed (km/hour)
● VEPM ● Test

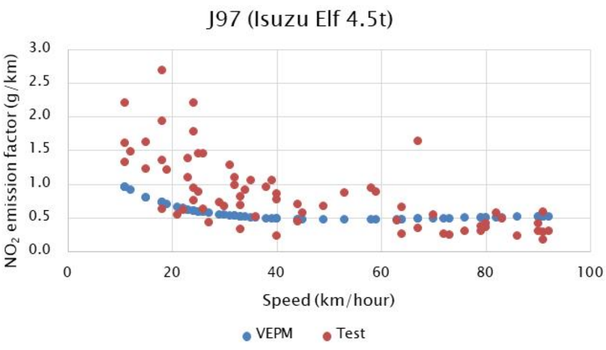

Eur4 LCV (Ford Transit Van) B
NO_2 emission factor (g/km)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
0
20
40
60
80
100
Speed (km/hour)
● VEPM ● Test

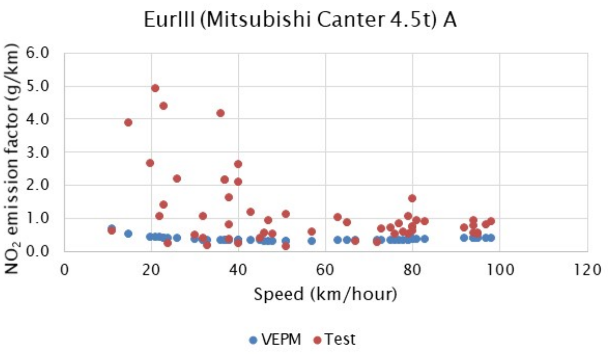

Eur4 LCV (Hyundai iLoad Van)
NO_2 emission factor (g/km)
0.0
0.2
0.4
0.6
0.8
1.0
0
20
40
60
80
100
Speed (km/hour)
● VEPM ● Test

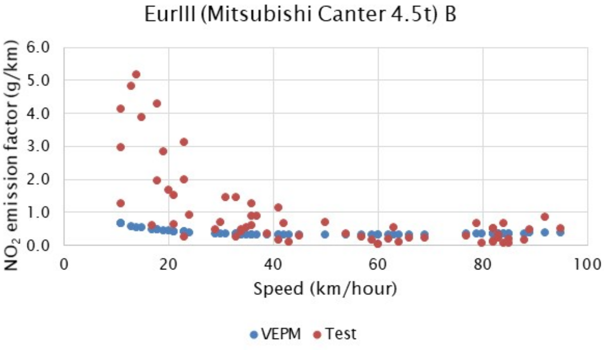

Eur4 LPV (Audi A5)
NO_2 emission factor (g/km)
0.0
0.5
1.0
1.5
2.0
2.5
0
20
40
60
80
100
Speed (km/hour)
● VEPM ● Test

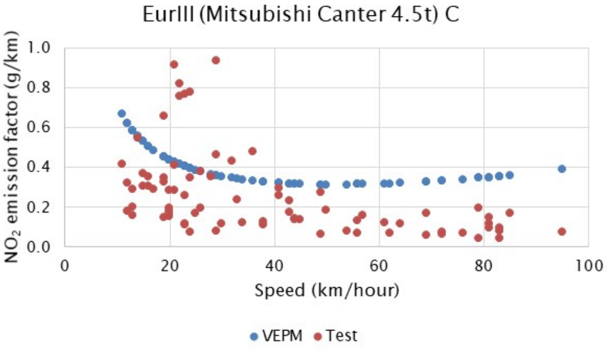

Eur5 LCV (Ford Transit Van)
NO_2 emission factor (g/km)
0.0
0.2
0.4
0.6
0.8
1.0
0
20
40
60
80
100
Speed (km/hour)
● VEPM ● Test

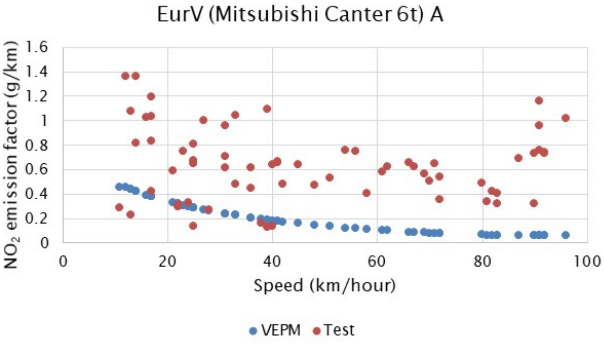

Eur5 LCV (Merc Sprinter Van)
NO_2 emission factor (g/km)
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0
20
40
60
80
100
Speed (km/hour)
● VEPM ● Test

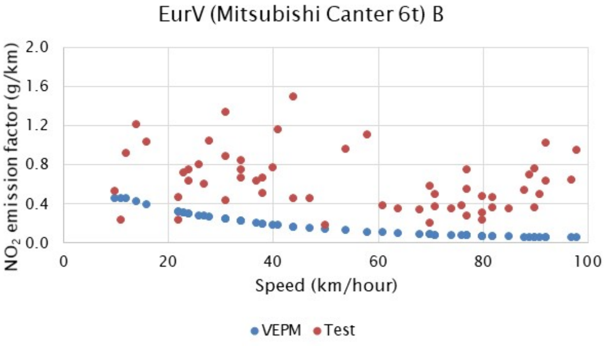

J97 (Isuzu Elf 4.5t)
NO_2 emission factor (g/km)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
0
20
40
60
80
100
Speed (km/hour)
● VEPM ● Test


EurIII (Mitsubishi Canter 4.5t) A
NO_2 emission factor (g/km)
0.0
1.0
2.0
3.0
4.0
5.0
6.0
0
20
40
60
80
100
120
Speed (km/hour)
● VEPM ● Test

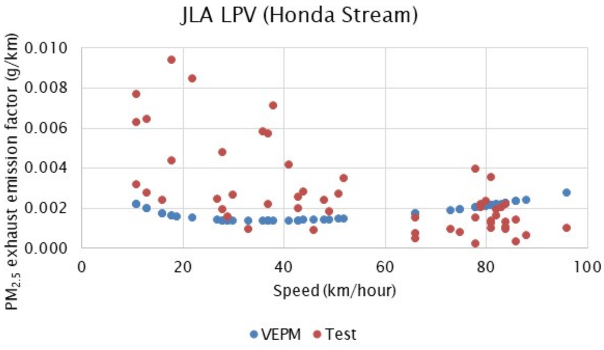

EurIII (Mitsubishi Canter 4.5t) B
NO2 emission factor (g/km)
6.0
5.0
4.0
3.0
2.0
1.0
0.0
0
20
40
60
80
100
Speed (km/hour)
● VEPM ● Test

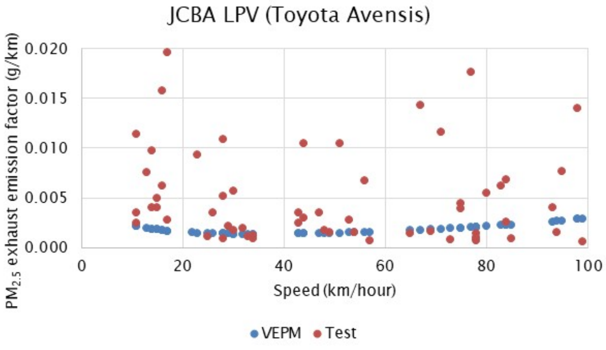

EurIII (Mitsubishi Canter 4.5t) C
NO2 emission factor (g/km)
1.0
0.8
0.6
0.4
0.2
0.0
0
20
40
60
80
100
Speed (km/hour)
● VEPM ● Test

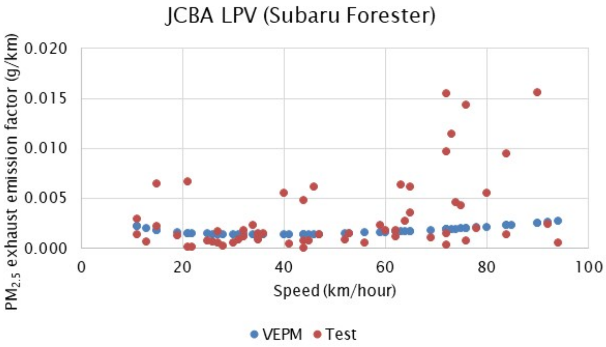

EurV (Mitsubishi Canter 6t) A
NO2 emission factor (g/km)
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
20
40
60
80
100
Speed (km/hour)
● VEPM ● Test

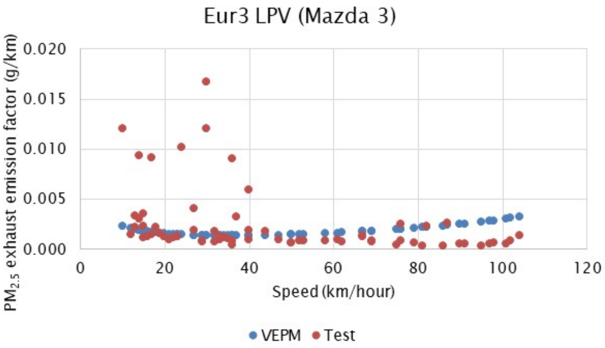

EurV (Mitsubishi Canter 6t) B
NO2 emission factor (g/km)
2.0
1.6
1.2
0.8
0.4
0.0
0
20
40
60
80
100
Speed (km/hour)
● VEPM ● Test

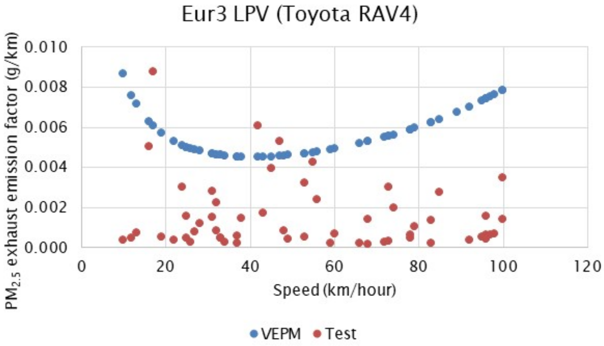
E.3 $PM_{2.5}$

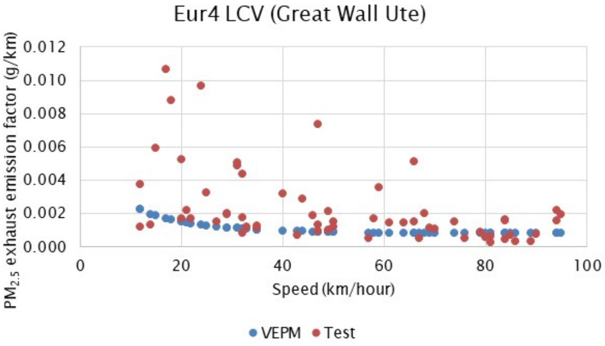

JLA LPV (Honda Stream)
PM2.5 exhaust emission factor (g/km)
0.010
0.008
0.006
0.004
0.002
0.000
0
20
40
60
80
100
Speed (km/hour)
● VEPM ● Test

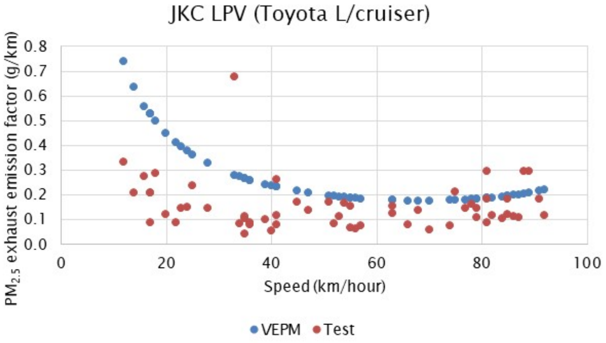

JCBA LPV (Toyota Avensis)
PM2.5 exhaust emission factor (g/km)
0.020
0.015
0.010
0.005
0.000
0
20
40
60
80
100
Speed (km/hour)
● VEPM ● Test

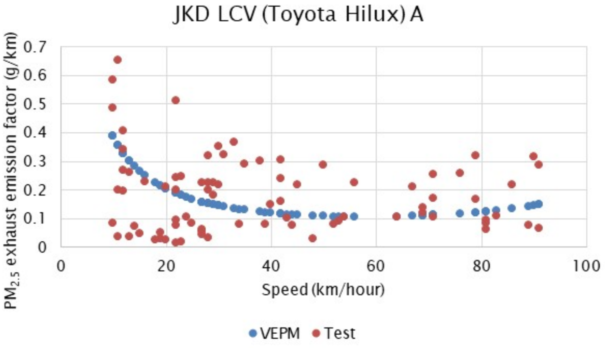

JCBA LPV (Subaru Forester)

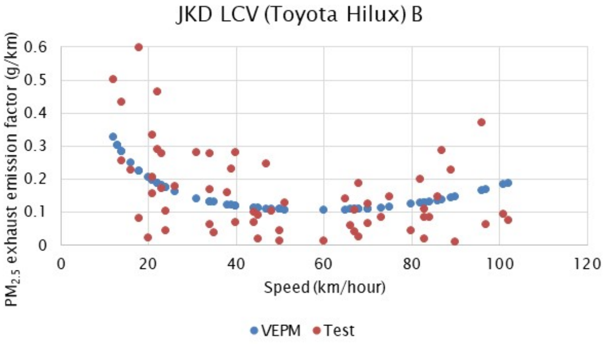

Eur3 LPV (Mazda 3)

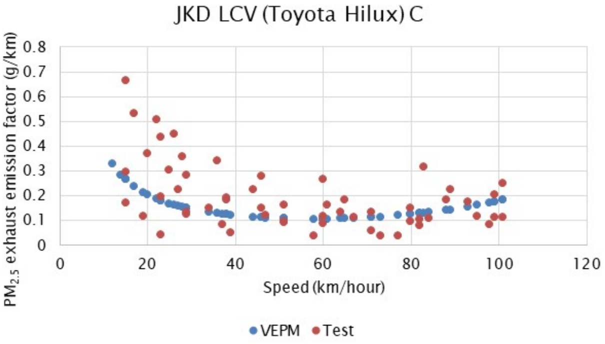

Eur3 LPV (Toyota RAV4)

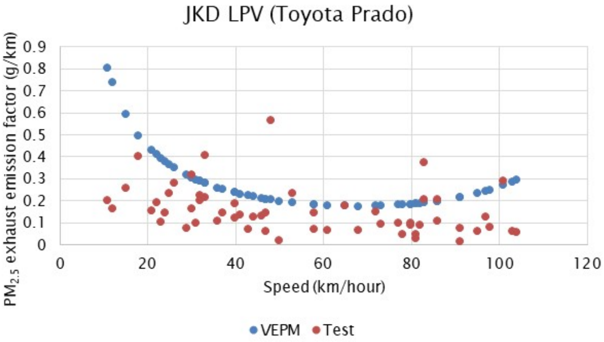

Eur4 LCV (Great Wall Ute)

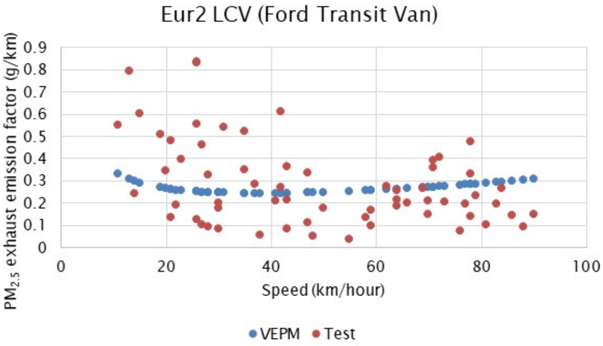

JKC LPV (Toyota L/cruiser)

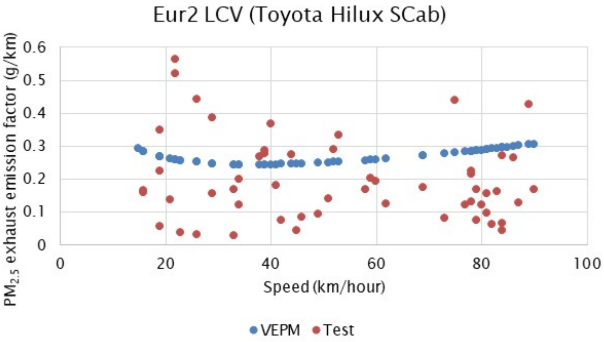

JKD LCV (Toyota Hilux) A

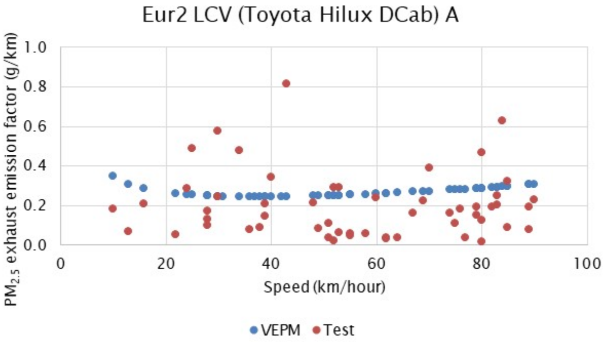

JKD LCV (Toyota Hilux) B

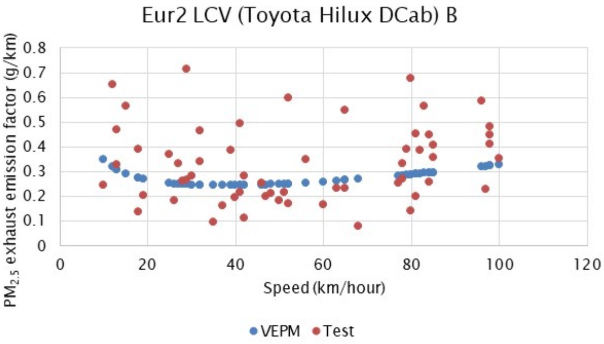

JKD LCV (Toyota Hilux) C

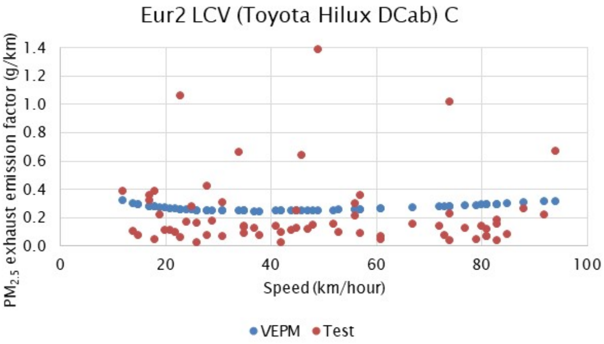

JKD LPV (Toyota Prado)
PM$_{2.5}$ exhaust emission factor (g/km)
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9
0 20 40 60 80 100 120
Speed (km/hour)
● VEPM ● Test

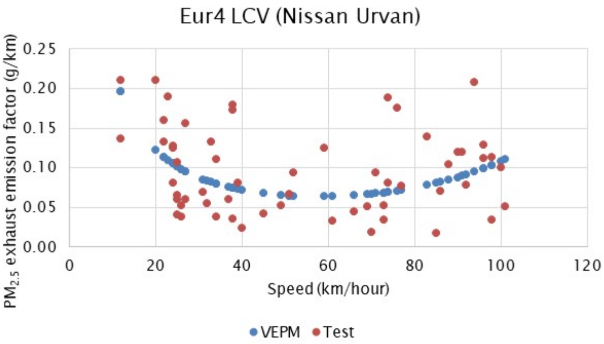

Eur2 LCV (Ford Transit Van)
PM$_{2.5}$ exhaust emission factor (g/km)
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9
0 20 40 60 80 100
Speed (km/hour)
● VEPM ● Test

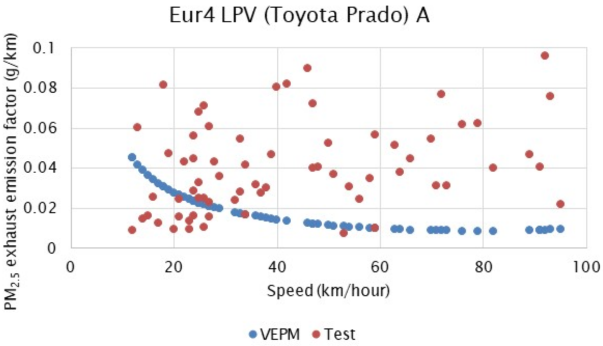

Eur2 LCV (Toyota Hilux SCab)
PM$_{2.5}$ exhaust emission factor (g/km)
0 0.1 0.2 0.3 0.4 0.5 0.6
0 20 40 60 80 100
Speed (km/hour)
● VEPM ● Test

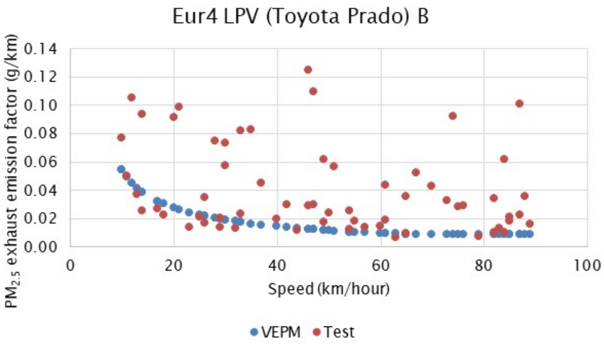

Eur2 LCV (Toyota Hilux DCab) A
PM$_{2.5}$ exhaust emission factor (g/km)
0.0 0.2 0.4 0.6 0.8 1.0
0 20 40 60 80 100
Speed (km/hour)
● VEPM ● Test

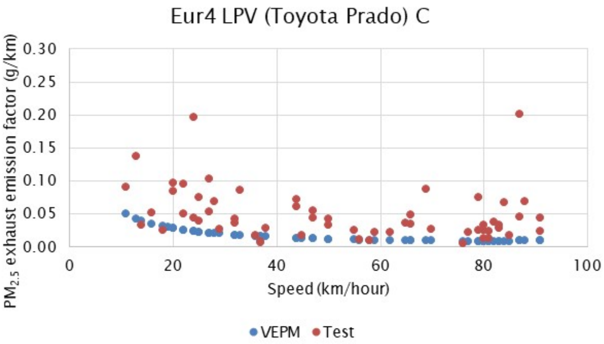

Eur2 LCV (Toyota Hilux DCab) B
PM$_{2.5}$ exhaust emission factor (g/km)
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8
0 20 40 60 80 100 120
Speed (km/hour)
● VEPM ● Test

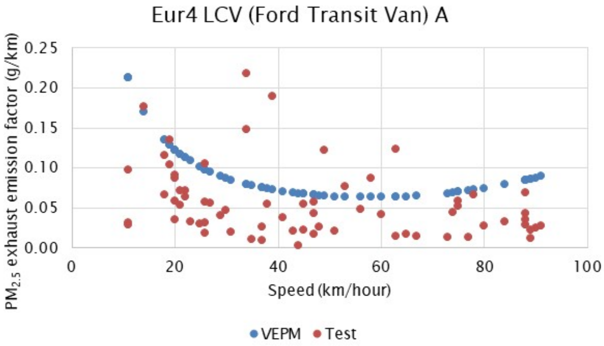

Eur2 LCV (Toyota Hilux DCab) C
PM$_{2.5}$ exhaust emission factor (g/km)
0.0 0.2 0.4 0.6 0.8 1.0 1.2 1.4
0 20 40 60 80 100
Speed (km/hour)
● VEPM ● Test

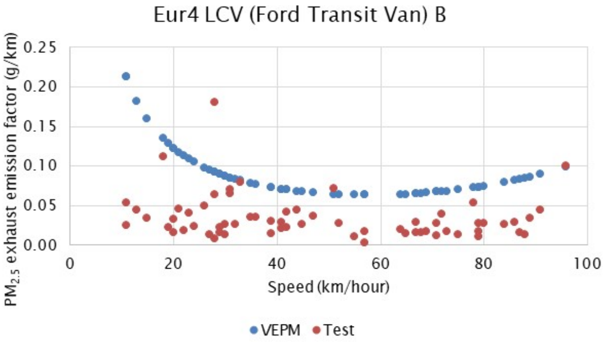

Eur4 LCV (Nissan Urvan)
PM$_{2.5}$ exhaust emission factor (g/km)
0.00 0.05 0.10 0.15 0.20 0.25
0 20 40 60 80 100 120
Speed (km/hour)
● VEPM ● Test

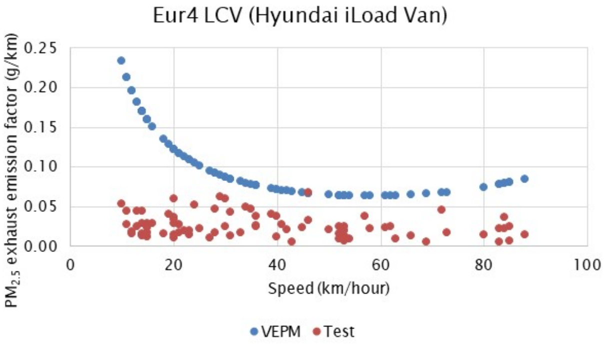

Eur4 LPV (Toyota Prado) A
PM$_{2.5}$ exhaust emission factor (g/km)
0 0.02 0.04 0.06 0.08 0.1
0 20 40 60 80 100
Speed (km/hour)
● VEPM ● Test

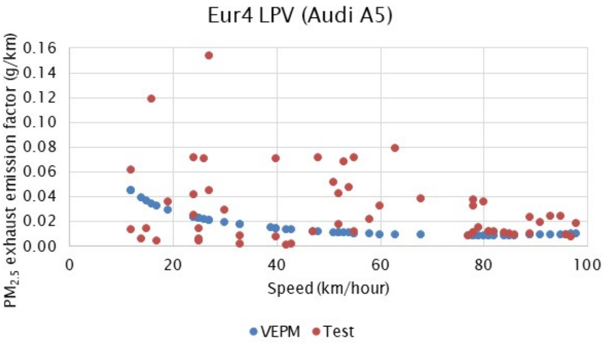

Eur4 LPV (Toyota Prado) B
$PM_{2.5}$ exhaust emission factor (g/km)
0.00
0.02
0.04
0.06
0.08
0.10
0.12
0.14
0
20
40
60
80
100
Speed (km/hour)
● VEPM ● Test

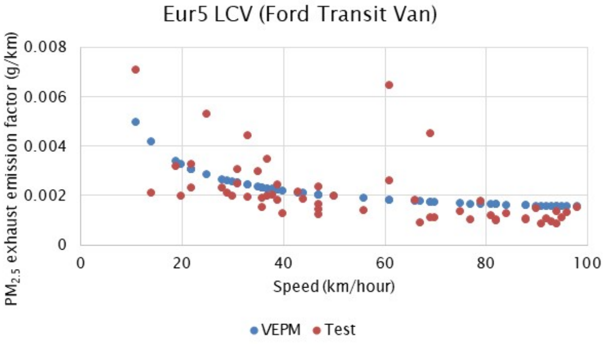

Eur4 LPV (Toyota Prado) C
$PM_{2.5}$ exhaust emission factor (g/km)
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0
20
40
60
80
100
Speed (km/hour)
● VEPM ● Test

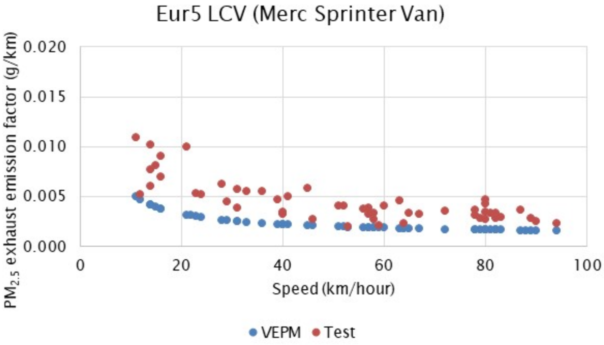

Eur4 LCV (Ford Transit Van) A
$PM_{2.5}$ exhaust emission factor (g/km)
0.00
0.05
0.10
0.15
0.20
0.25
0
20
40
60
80
100
Speed (km/hour)
● VEPM ● Test

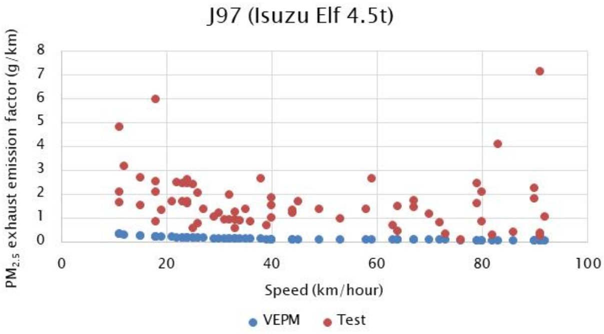

Eur4 LCV (Ford Transit Van) B
$PM_{2.5}$ exhaust emission factor (g/km)
0.00
0.05
0.10
0.15
0.20
0.25
0
20
40
60
80
100
Speed (km/hour)
● VEPM ● Test

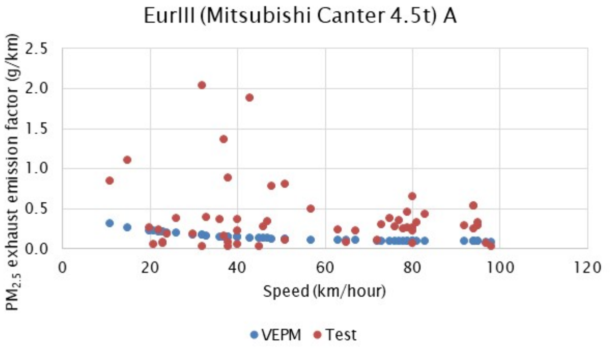

Eur4 LCV (Hyundai iLoad Van)
$PM_{2.5}$ exhaust emission factor (g/km)
0.00
0.05
0.10
0.15
0.20
0.25
0
20
40
60
80
100
Speed (km/hour)
● VEPM ● Test

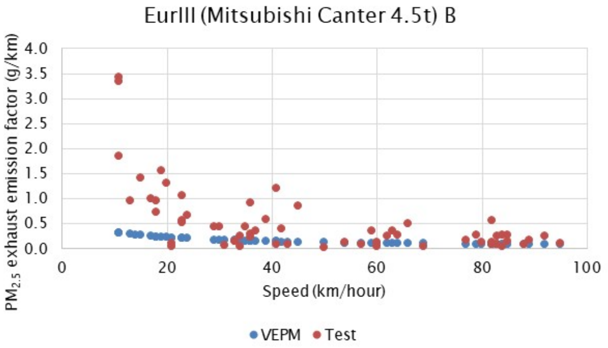

Eur4 LPV (Audi A5)
$PM_{2.5}$ exhaust emission factor (g/km)
0.00
0.02
0.04
0.06
0.08
0.10
0.12
0.14
0.16
0
20
40
60
80
100
Speed (km/hour)
● VEPM ● Test

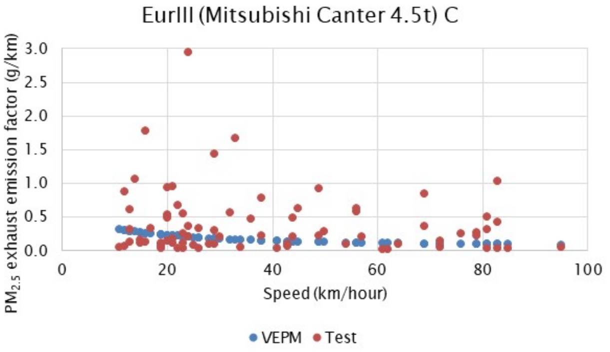

Eur5 LCV (Ford Transit Van)
$PM_{2.5}$ exhaust emission factor (g/km)
0
0.002
0.004
0.006
0.008
0
20
40
60
80
100
Speed (km/hour)
● VEPM ● Test

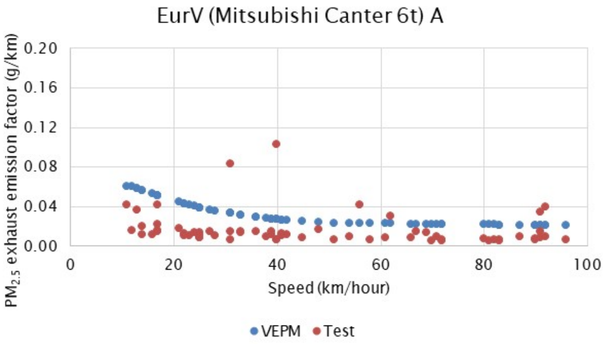

Eur5 LCV (Merc Sprinter Van)
$PM_{2.5}$ exhaust emission factor (g/km)
0.000
0.005
0.010
0.015
0.020
0
20
40
60
80
100
Speed (km/hour)
● VEPM ● Test

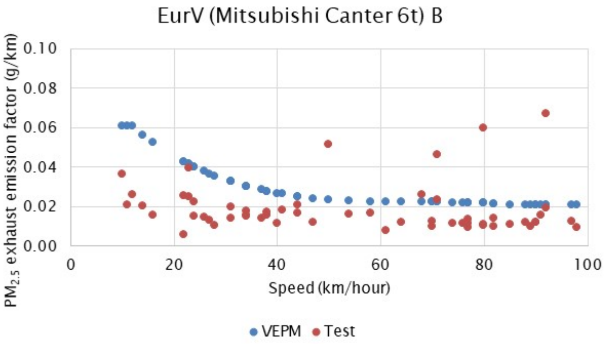

J97 (Isuzu Elf 4.5t)


EurIII (Mitsubishi Canter 4.5t) A

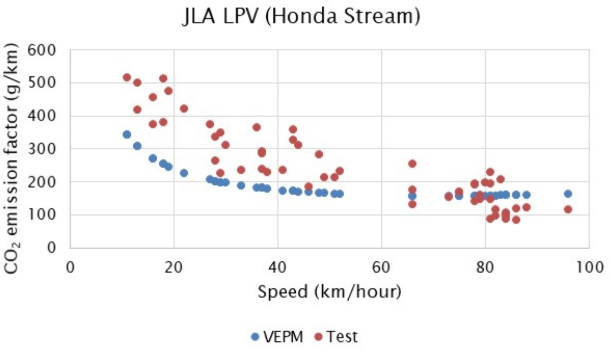

EurIII (Mitsubishi Canter 4.5t) B

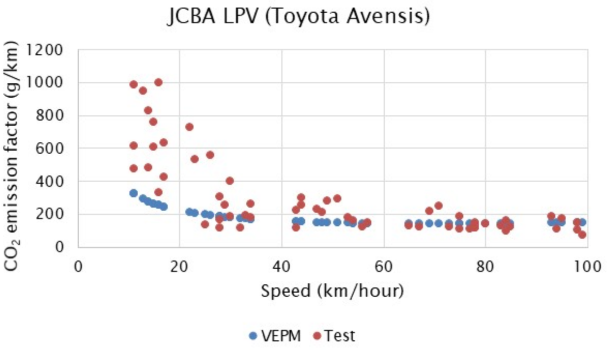

EurIII (Mitsubishi Canter 4.5t) C

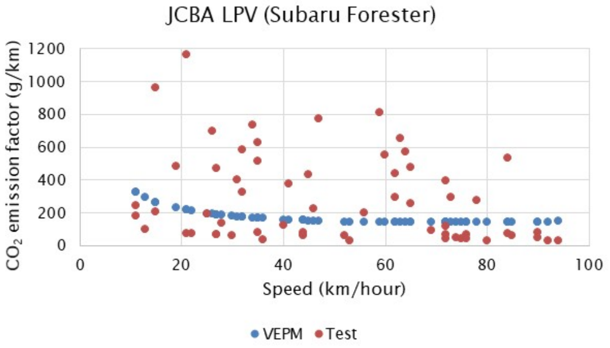

EurV (Mitsubishi Canter 6t) A

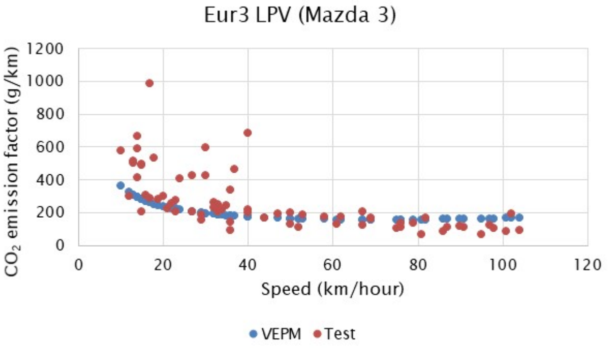

EurV (Mitsubishi Canter 6t) B

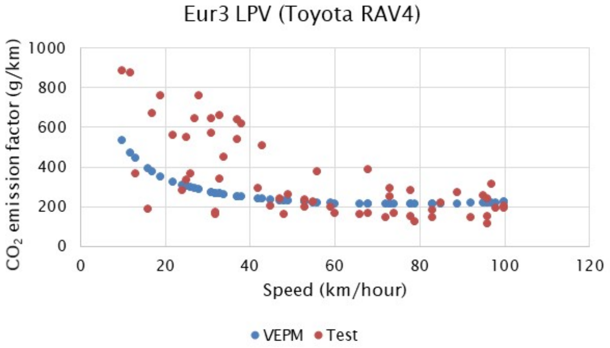
E.4 CO_2

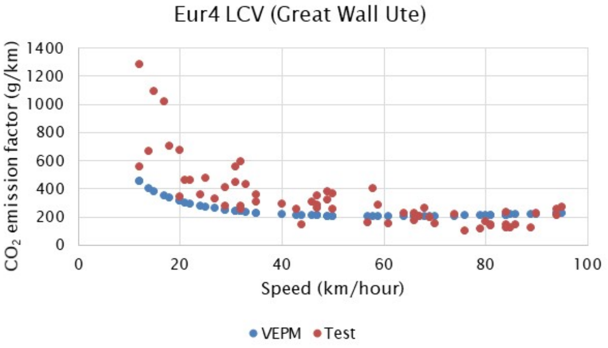

JLA LPV (Honda Stream)
CO_2 emission factor (g/km)
0
100
200
300
400
500
600
Speed (km/hour)
0
20
40
60
80
100
● VEPM ● Test

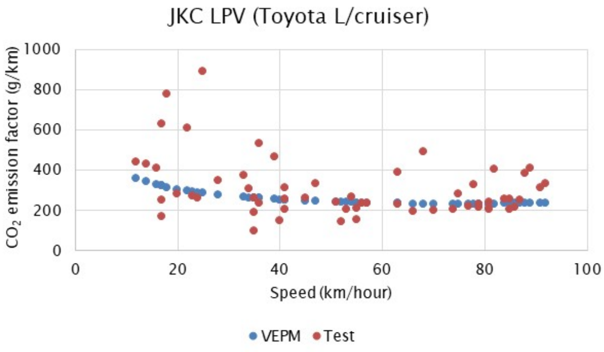

JCBA LPV (Toyota Avensis)
CO_2 emission factor (g/km)
0
200
400
600
800
1000
1200
Speed (km/hour)
0
20
40
60
80
100
● VEPM ● Test

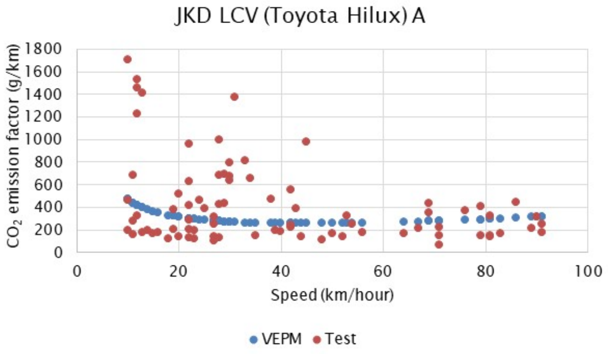

JCBA LPV (Subaru Forester)
CO_2 emission factor (g/km)
0
200
400
600
800
1000
1200
Speed (km/hour)
0
20
40
60
80
100
● VEPM ● Test

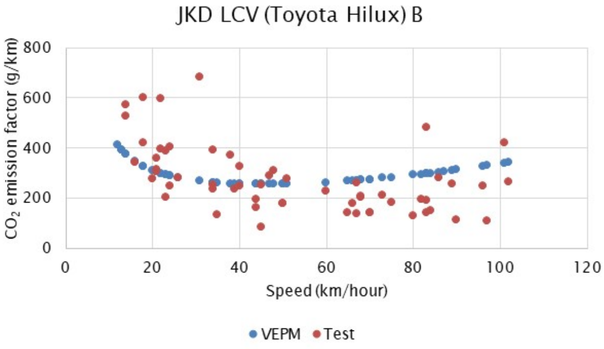

Eur3 LPV (Mazda 3)
CO_2 emission factor (g/km)
0
200
400
600
800
1000
1200
Speed (km/hour)
0
20
40
60
80
100
120
● VEPM ● Test

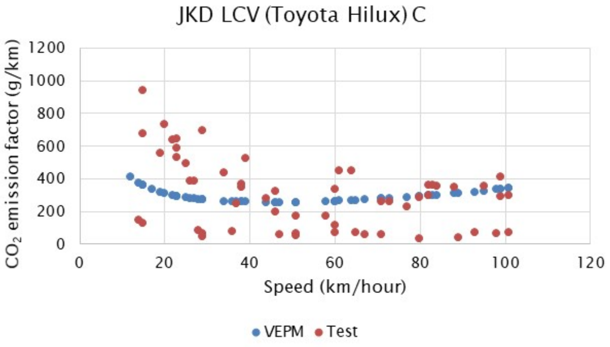

Eur3 LPV (Toyota RAV4)
CO_2 emission factor (g/km)
0
200
400
600
800
1000
Speed (km/hour)
0
20
40
60
80
100
120
● VEPM ● Test

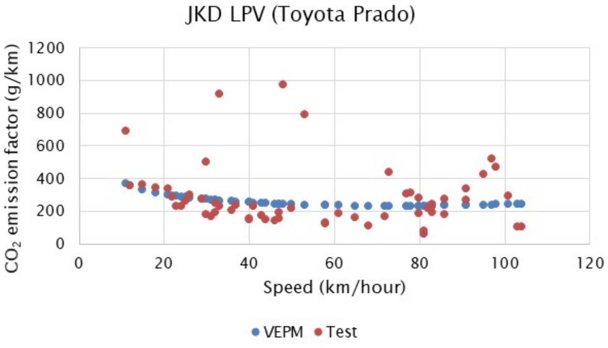

Eur4 LCV (Great Wall Ute)
CO_2 emission factor (g/km)
0
200
400
600
800
1000
1200
1400
Speed (km/hour)
0
20
40
60
80
100
● VEPM ● Test

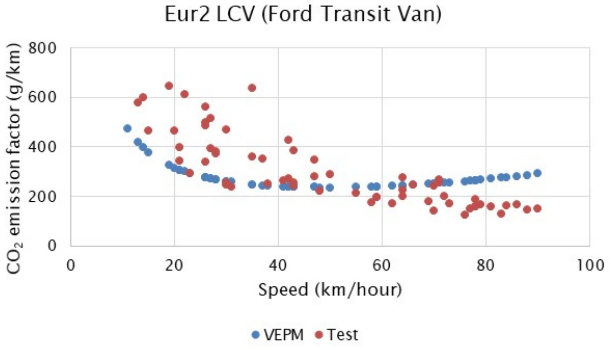

JKC LPV (Toyota L/cruiser)
CO₂ emission factor (g/km)
0
200
400
600
800
1000
0
20
40
60
80
100
Speed (km/hour)
VEPM
Test

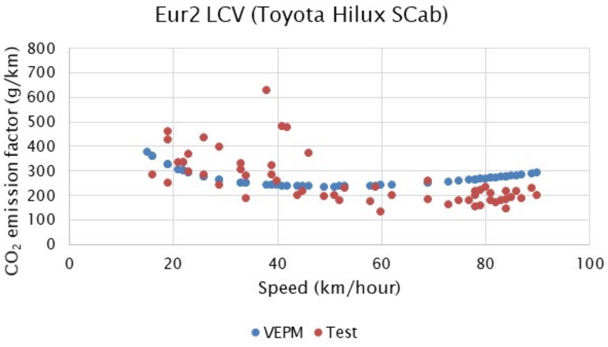

JKD LCV (Toyota Hilux) A
CO₂ emission factor (g/km)
0
200
400
600
800
1000
1200
1400
1600
1800
0
20
40
60
80
100
Speed (km/hour)
VEPM
Test

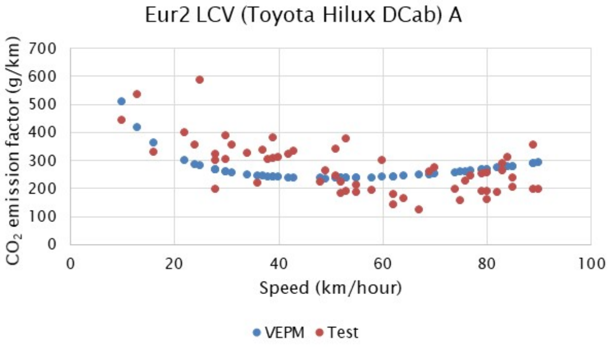

JKD LCV (Toyota Hilux) B
CO₂ emission factor (g/km)
0
200
400
600
800
0
20
40
60
80
100
120
Speed (km/hour)
VEPM
Test

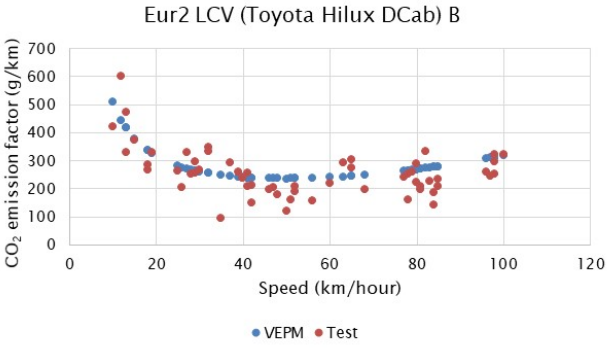

JKD LCV (Toyota Hilux) C
CO₂ emission factor (g/km)
0
200
400
600
800
1000
1200
0
20
40
60
80
100
120
Speed (km/hour)
VEPM
Test

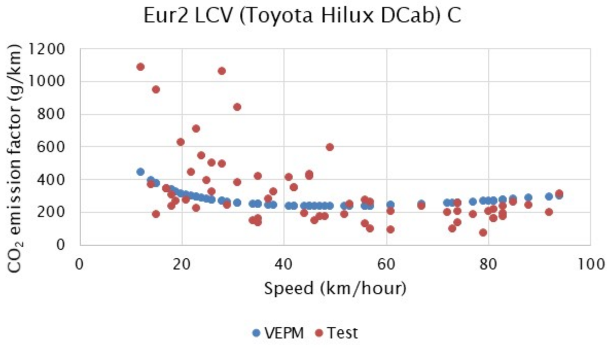

JKD LPV (Toyota Prado)
CO₂ emission factor (g/km)
0
200
400
600
800
1000
1200
0
20
40
60
80
100
120
Speed (km/hour)
VEPM
Test

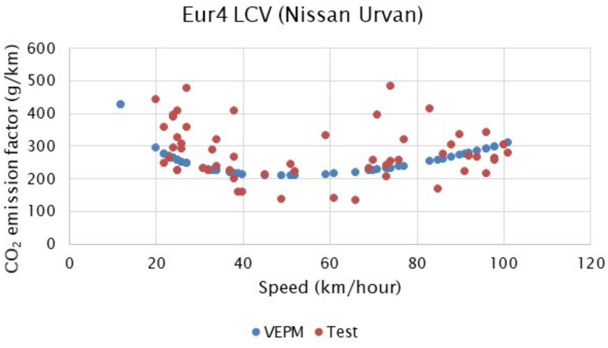

Eur2 LCV (Ford Transit Van)
CO₂ emission factor (g/km)
0
200
400
600
800
0
20
40
60
80
100
Speed (km/hour)
VEPM
Test

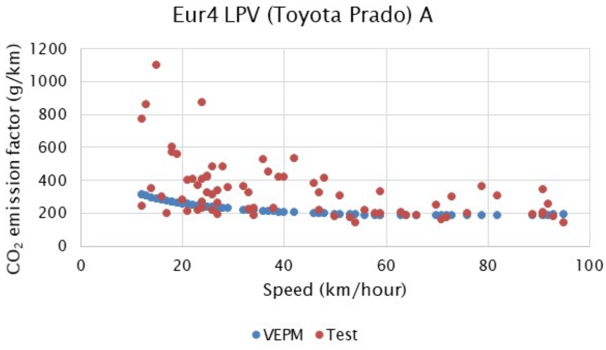

Eur2 LCV (Toyota Hilux SCab)
CO₂ emission factor (g/km)
0
100
200
300
400
500
600
700
800
0
20
40
60
80
100
Speed (km/hour)
VEPM
Test

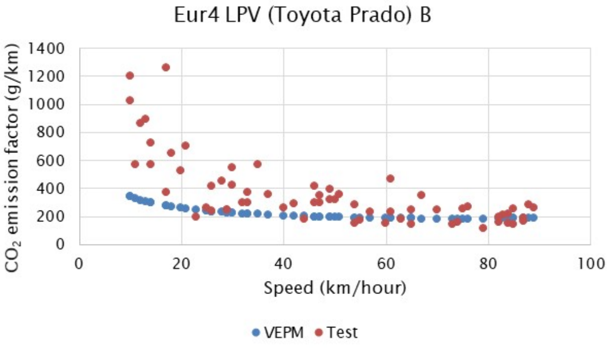

Eur2 LCV (Toyota Hilux DCab) A
CO₂ emission factor (g/km)
0
100
200
300
400
500
600
700
0
20
40
60
80
100
Speed (km/hour)
VEPM
Test

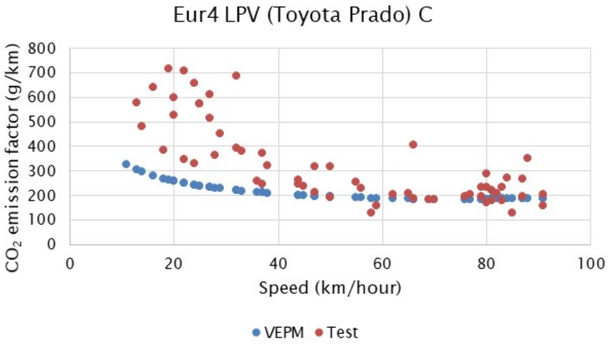

Eur2 LCV (Toyota Hilux DCab) B

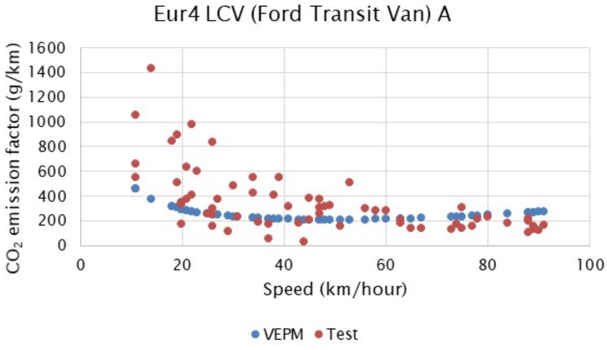

Eur2 LCV (Toyota Hilux DCab) C

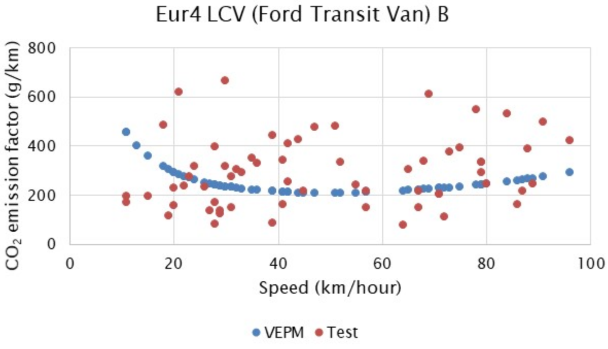

Eur4 LCV (Nissan Urvan)

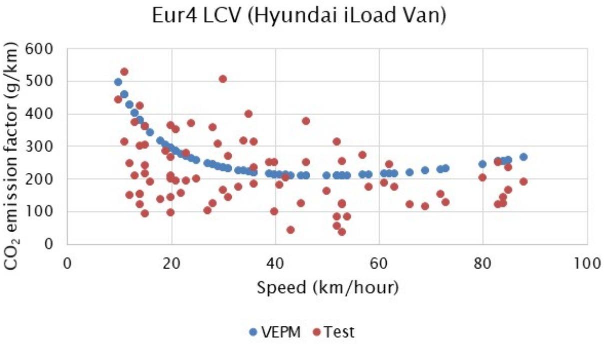

Eur4 LPV (Toyota Prado) A

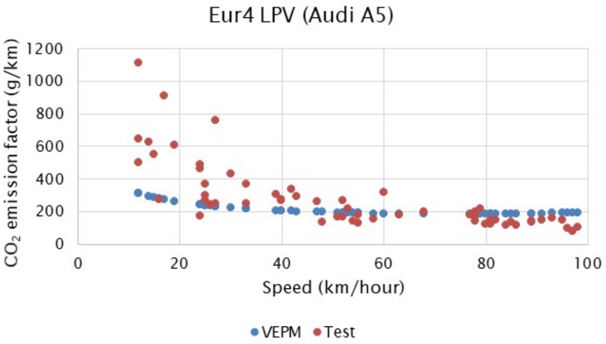

Eur4 LPV (Toyota Prado) B

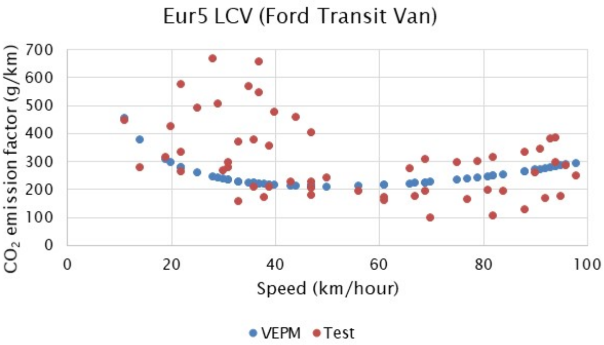

Eur4 LPV (Toyota Prado) C

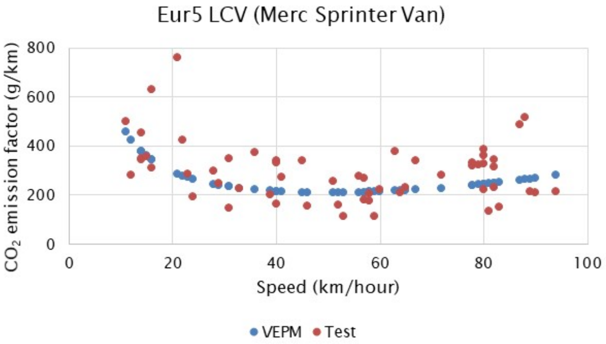

Eur4 LCV (Ford Transit Van) A

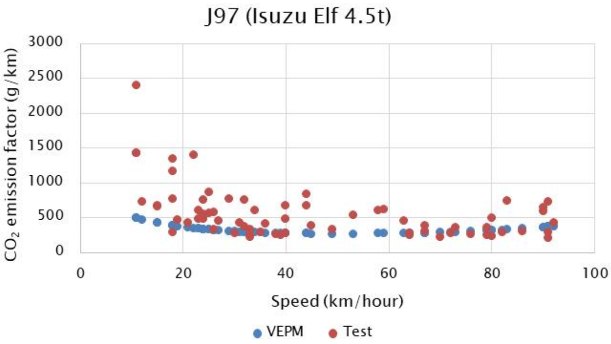

Eur4 LCV (Ford Transit Van) B

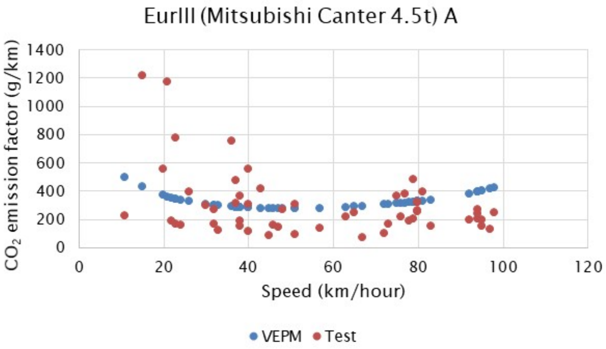

Eur4 LCV (Hyundai iLoad Van)
CO$_2$ emission factor (g/km)
600
500
400
300
200
100
0
0
20
40
60
80
100
Speed (km/hour)
● VEPM ● Test

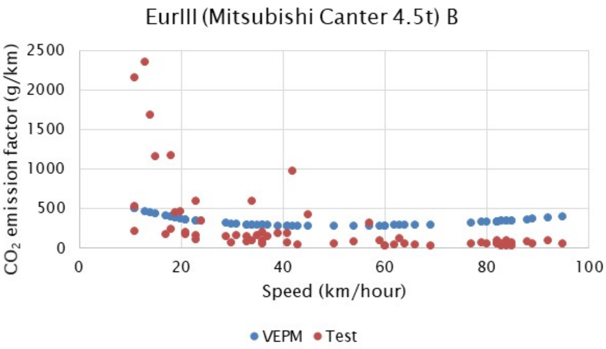

Eur4 LPV (Audi A5)
CO$_2$ emission factor (g/km)
1200
1000
800
600
400
200
0
0
20
40
60
80
100
Speed (km/hour)
● VEPM ● Test

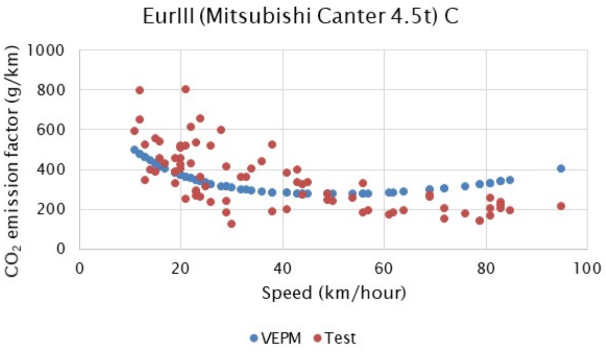

Eur5 LCV (Ford Transit Van)
CO$_2$ emission factor (g/km)
700
600
500
400
300
200
100
0
0
20
40
60
80
100
Speed (km/hour)
● VEPM ● Test

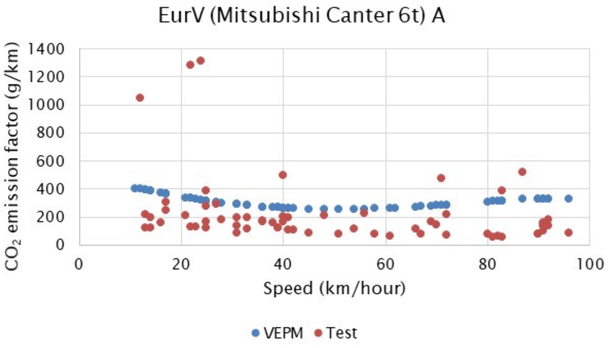

Eur5 LCV (Merc Sprinter Van)
CO$_2$ emission factor (g/km)
800
600
400
200
0
0
20
40
60
80
100
Speed (km/hour)
● VEPM ● Test

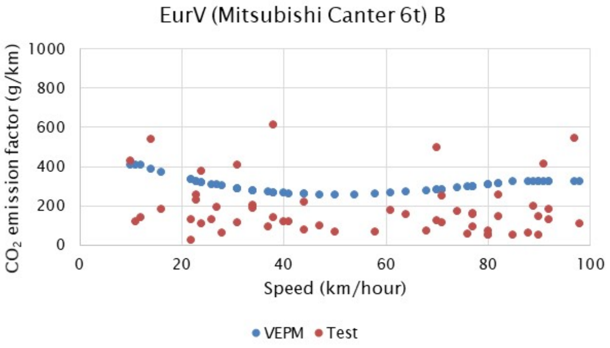

J97 (Isuzu Elf 4.5t)
CO$_2$ emission factor (g/km)
3000
2500
2000
1500
1000
500
0
0
20
40
60
80
100
Speed (km/hour)
● VEPM ● Test


EurIII (Mitsubishi Canter 4.5t) A
CO$_2$ emission factor (g/km)
1400
1200
1000
800
600
400
200
0
0
20
40
60
80
100
120
Speed (km/hour)
● VEPM ● Test


EurIII (Mitsubishi Canter 4.5t) B
CO$_2$ emission factor (g/km)
2500
2000
1500
1000
500
0
0
20
40
60
80
100
Speed (km/hour)
● VEPM ● Test


EurIII (Mitsubishi Canter 4.5t) C
CO$_2$ emission factor (g/km)
1000
800
600
400
200
0
0
20
40
60
80
100
Speed (km/hour)
● VEPM ● Test


EurV (Mitsubishi Canter 6t) A
CO2 emission factor (g/km)
1400
1200
1000
800
600
400
200
0
0
20
40
60
80
100
Speed (km/hour)
● VEPM
● Test


EurV (Mitsubishi Canter 6t) B
CO2 emission factor (g/km)
1000
800
600
400
200
0
0
20
40
60
80
100
Speed (km/hour)
● VEPM
● Test

Appendix F: Glossary of terms, abbreviations and acronyms

a	acceleration, in m/s^2
Ah	amp-hour, a unit of electric charge or battery capacity
°C	degrees Celsius, a measure of temperature
cc	cubic centimetre, a measure of volume and engine size
CO	carbon monoxide
CO_2	carbon dioxide
COPERT	COPERT (Computer Programme to calculate Emissions from Road Transport) is a software tool used to calculate air pollution and greenhouse gases from road transport
D	diesel automotive fuel
EEA	European Environment Agency
f-NO_2	fraction of NO_2 in NO_x emissions
GFA	(borosilicate) glass fibre filter, type A
GPS	global positioning system
GVM	gross vehicle mass
h	hour, a measure of time
harmful emissions	emissions which primarily are of concern due to their impact on human health
HC	hydrocarbons
HCV	heavy duty (GVM > 3.5 tonnes) commercial vehicle
Hz	hertz, a measure of frequency equal to 1 cycle per second
ICCT	International Council on Clean Transportation
IR	infrared, light with a wavelength from 700nm to 1mm, longer than that of visible light
km	kilometre, a measure of distance
l	litre, a measure of volume
lambda (λ)	the ratio between the amount of oxygen present in a combustion chamber versus the amount needed to obtain complete combustion
LCV	light duty (GVM < 3.5 tonnes) commercial vehicle
LPM	litres per minute
LPV	light duty (GVM < 3.5 tonnes) passenger vehicle
m	metre, a measure of distance
mm	millimetre, or 10^{-3}m
MFC	mass flow controller
MoT	Ministry of Transport
MVR	Motor Vehicle Register
NDIR	non dispersive infrared
NEDC	New European driving cycle is the previous drive cycle used for type approval of light duty vehicle fuel consumption and emissions in Europe. Since September 2017, the NEDC has gradually been replaced by the new Worldwide Harmonised Light Vehicles Test Procedure (WLTP).

nm	nanometre, or 10^{-9}m
NO$_2$	nitrogen dioxide
NO$_x$	nitrogen oxides, mainly made up of NO and NO$_2$
NO	nitric oxide, a precursor to the formation of NO$_2$
OBD	on-board diagnostics
ODO	odometer reading, typically in km
Pa	pascal, a measure of pressure
PEMS	portable emissions measurement system, a setup used to measure real-world emissions
PM	particulate matter
PM$_{2.5}$	particulate matter less than 2.5µm (microns) in diameter
PM$_{10}$	particulate matter less than 10µm (microns) in diameter
ppb	parts per billion, 1 in 10^9
ppm	parts per million, 1 in 10^6
PTFE	polytetrafluoroethylene polymer (ie Teflon)
RDE	real driving emissions are the emissions of a vehicle under its normal conditions of use
real-world	representing real vehicles driving under real conditions, as opposed to test conditions
RSD	remote sensing device
s	second, a measure of time
SCCM	standard cubic centimetre per minute, a measure of flowrate
SH	state highway
SLPM	standard litre per minute
SUV	sports utility vehicle
Transport Agency	NZ Transport Agency
type-approval testing	testing to confirm a light duty vehicle model or heavy duty engine complies with its regulated emissions standard
µg	microgram, or 10^{-6}g
µm	micrometre, or 10^{-6}m, also known as a micron
ute	a passenger vehicle with a cargo tray in the rear. This term is also used in Australia and New Zealand to describe vehicles that would be called ‘light trucks’ or “pickups’ in other countries.
UV	ultraviolet, light with a wavelength from 10nm to 400nm, shorter than that of visible light
uvSmoke	a measure of the opacity but in the ultraviolet light (UV) spectrum, used as a proxy for particulate emissions in remote sensing
v	average speed, in m/s or km/h
V	volt, a unit of electrical potential
VEPM	Vehicle Emission Prediction Model, developed by the NZ Transport Agency to predict harmful emissions and fuel consumption for the New Zealand fleet
W	watt, a unit of electrical power
WLTP	Worldwide Harmonised Light Vehicle Test Procedure is the current laboratory test used for type approval of light duty vehicle fuel consumption and emissions in Europe. Note at time of writing, this test procedure is not required for type approval of new vehicles entering New Zealand.

91P	unleaded petrol automotive fuel with a 91 octane rating
95P	unleaded petrol automotive fuel with a 95 octane rating