UNIVERSITY OF LEEDS

Remote Sensing Vehicle Emissions - SHEFFIELD

INSTITUTE FOR TRANSPORT STUDIES

Project Report:

Vehicle Emission Measurement and Analysis - Sheffield City Council

Final version 1.1: 3rd December 2013

Dr James Tate

REMOTE SENSING VEHICLE EMISSIONS

a) Asline Road

b) Eyre Street

REMOTE SENSING VEHICLE EMISSIONS

c) Western Bank

d) Attercliffe Centre

REMOTE SENSING VEHICLE EMISSIONS

e) Prince of Wales Road

Principal Author(s)

Dr James Tate[a]

Author's Affiliations

[a] Institute for Transport Studies, Faculty of the Environment, University of Leeds, Leeds, LS2 9JT, UK. Email: j.e.tate@its.leeds.ac.uk, Tel: +44 (0) 113 343 6608.

TABLE OF CONTENTS

TABLE OF FIGURES

EXECUTIVE SUMMARY

- The UK has not met EU air quality limit values or UK objectives for NO_2 by the 2010 deadline (National Audit Office, 2009). It is well known that NO_2 levels in urban streets are dependent on: background levels, vehicle emissions of Nitric Oxide (NO) which quickly reacts with available Ozone (O_3) to form secondary NO_2 (sNO_2), and the primary NO_2 (pNO_2) emitted directly by vehicles. Recent UK studies (Carslaw et al, 2011) have demonstrated that NO_X emissions from passenger cars with petrol engines have been shown to fall in line with Euro standards. NO_X emissions from all categories of diesel vehicles (light- and heavy-duty) have been shown to have changed little in the last 15 years or so in urban driving conditions. This element of the Sheffield City Council Low Emission Zone (LEZ) project aims to review and assess the fleet composition and its environmental performance in the City of Sheffield. The measurements will also refresh and bolster the UK evidence and understanding of on-road vehicle emission characteristics.
- The on-road (or "real-world") emission performance of the Sheffield vehicle fleet was surveyed using a remote sensing instrument (http://www.esp-global.com/, RSD4600). This Vehicle Emission Measurement System (VEMS) senses the tailpipe emissions of vehicles as they drive-through a monitoring site by scanning through the exhaust plume trailing a vehicle. The Vehicle Registration Mark (VRM or number plate), speed and acceleration are also recorded. This surveillance system was deployed for two days (0800 – 1800hrs) at five sites across the City of Sheffield between Tuesday 23rd April and Thursday the 13th of June 2013 (totalling 10-days of measurements). The specification of each surveyed vehicle was sourced, by cross-referencing the VRMs with the www.carweb.co.uk UK detailed vehicle registration information database. By combining these information streams, the operational fleet composition and its emission performance, for each vehicle/ fuel type and Euro standard sub-category can be assessed. A total of 28 207 quality checked vehicle emission measurements with co-ordinated detailed vehicle information were collated.
- The vehicle population observed by the vehicle emission remote sensing device in Sheffield, averaged across the five sites comprised 70.8% Cars, 3.79% Taxis, 17.0% LGV, 2.45% OGVs (rigid and articulated), 5.86% Buses (Passenger Service Vehicles – PSVs) and 0.3% Coaches. The on-road passenger car fleet in Sheffield is dominated by Euro 3 classification or better vehicles. Whilst petrol cars still comprise 58.5% of the operational passenger car fleet in Sheffield, diesel cars are becoming more popular. For the current generation of Euro 5 cars (first registered in period September 2009 – August 2014) the share of diesel cars was greater than those with petrol engines. Eight diesel cars were observed that are registered to comply with the Euro 6 emissions standard. The presence of this vehicle suggests that select motor-manufacturers are now introducing this next generation of vehicle technology ahead of the legislated date (September 2014). There are also early signs that the hybrid car market is beginning to flourish, with proportions rising from 0.21% of the Euro 4 passenger cars observed to 1.8% of Euro 5's.
- By applying known NO_2/NO_X shares to the measurement dataset for the different vehicle Euro standard/ fuel type sub-categories, the worst contributors to the increasing primary component of NO_2 at roadsides in Sheffield, modern diesel cars and vans have been highlighted. These findings are in-line with other work, that highlight an unwanted side-effect of current diesel engine emission abatement technologies, diesel oxidation catalysts (DOCs) and diesel particle filters (DPFs), is an increase in tail-pipe emissions of NO_2 (primary), particularly in urban driving conditions.
- Diesel vehicle NO_X emission controls, both light- and heavy-duty, have been shown to underperform in the urban driving conditions in Sheffield. Estimated NO_X emission factors ($grams.km^{-1}$) based on the remote sensing results are broadly in agreement with similar, recent studies in Cities across the UK (e.g. Tate, 2010; Carslaw et al 2011).

- European Commission and UK policies are encouraging the purchase of new diesel cars over their petrol-driven counter-parts, due to their lower like-for-like carbon dioxide (CO_2) emission ratings for the legislated test conditions. Whilst this shift in purchasing behaviour is helping motor manufacturers meet their initial average car CO_2 rating targets (gCO_2/km) in-place from 2012 onwards, the trade-off has been the halt in urban air quality improvements of NO_2 and NO_X since 2000-2004.
- The introduction and development of diesel particle filter technologies through Euro standards 3 to 5 has seen progressive reductions in the amount of PM emitted at the tail-pipe by light- and heavy-duty diesel vehicles. The remote sensing opacity measure indicates PM emission levels from heavy-duty vehicles are very high relative to light-duty vehicles.
- Vehicle emission remote sensing research (Carslaw et al, 2012) and recent findings from EU vehicle emission laboratories (e.g. Hausberger et al, 2010) are highlighting limitations with the EU type approval drive cycle the New European Drive Cycle (NEDC). The NEDC only covers a limited engine speed and power range, so engines "optimised" for low emissions over the NEDC, may produce higher emissions when in normal on-road operation.
- Motor manufacturers are complying with the emissions legislation by developing exhaust after-treatment technologies and configuring their operation for these test conditions. The accelerations in the artificial EU type approval drive cycle the New European Drive Cycle (NEDC) developed in the 1970's are however slight in comparison with those of "normal" driving. Real-world driving with prompter accelerations demands more power from the engine. At higher power demands it is suggested more emphasis is given to vehicle performance than the emissions of local air quality pollutants. As the complexity and sophistication of engine management and exhaust after-treatment systems has increased, so has the potential for motor manufacturers to optimize their operation for the legislated test conditions to a greater degree, at the disregard of "normal" on-road operations. There are also concerns about how the performance of the complex, multi-component diesel emission control systems will degrade with time and usage. Frustratingly although the technology and capability exists, emissions of NO_X and NO_2 have not fallen as they should.
- An extension from prior vehicle emission remote sensing studies, was to identify and assess the emission performance of the 'Hackney' and 'Private Hire Vehicle' (PHV) taxis in Sheffield. The 'Hackney carriages' and 'Private Hire Vehicle (PHVs)' taxi fleets comprised 3.79% of the fleet observed at the Sheffield remote sensing sites. As taxis are typically intensively operated light-duty vehicles, with high annual mileages, it is suggested the degradation of their engine and exhaust after-treatment systems is greater than those of a comparable (make, model, year of registration) private passenger car. The stop-start driving conditions in urban areas, with dense traffic signal control and high traffic demand is not well suited to the efficient and clean operation of standard diesel taxis/ cars. Without regular periods of sustained, higher engine power operation (i.e. motorway driving/ speeds) the conditions needed for Diesel Particle Filters (DPFs) to regenerate are absent. DPF faults are therefore common on taxis and expensive to rectify as they are often not under warranty. The remote sensing results demonstrated that the emission performance of taxis is far worse than its private passenger car and LGV counter-parts. This is important, not only in understanding the emission contribution from taxis in Sheffield, but provides an in-sight into the future emission performance of all passenger cars, as their engines and exhaust (emission) after-treatment systems degrade further with use.
- The next Euro 6 emission standard regulations (EC 715/2007) will be extended to consider "normal conditions of use" (real driving conditions). The regulations are not yet finalised, but a combined approach of randomised real driving test cycles supplemented with on-road testing using Portable Emission Measurement Systems (PEMS) in vehicles

is likely. For light-duty vehicles, implementation during the Euro 6 period is expected in a 3-step approach (Phase 1, 2 and 3). Preliminary laboratory testing of Euro 6 light- and heavy-duty diesel vehicles (Hausberger et al, 2012) indicates significantly improved NO_X control, but the number of test vehicles is still low, and are only available from a small number of premium manufacturers. It is important the next generation of Euro 6 vehicles do emit less NO_X and NO_2 emissions per kilometre when driven in urban conditions if the European air quality limits are to be met in the next 5-10 years.

- There are early signs that the use of hybrid cars and Buses in Sheffield is beginning to flourish. Hybrid vehicle technology, with its regenerative breaking is well matched to the frequent stop-start operation of urban driving. Hybrid cars, with petrol-electric powertrains, were observed to emit NO_X, NO_2 and PM_{10} at a nominal level. The Alexander Dennis diesel-electric double-decker Buses operating in Sheffield were also observed to emit less NO_X and PM_{10} than comparable (standard) diesel vehicles.
- Hybrid vehicles and powertrains are well suited to urban driving conditions. Petrol-electric hybrid cars have been the norm, as smaller, lighter petrol engines can be used. Petrol also burns much more cleanly than diesel, with three-way catalytic converter technology able to reliably reduce emissions of local air quality pollutants such as CO and NO_X to a low-level. The hybrid drive offers the opportunity to re-use kinetic energy, making vehicles more fuel and CO_2 efficient. Diesel-electric powertrains may offer further (slight) reductions in CO_2 emissions, however effectively controlling emissions of local air quality pollutants such as NO_X is significantly more challenging. Diesel-electric powertrains may be a low carbon technology, but they are likely not to be a low emission vehicle as their emissions of NO_X will be significantly higher than a comparable petrol-electric vehicle. It is therefore surprising that manufacturers have developed and are selling diesel-electric cars. Two diesel-electric hybrid cars were observed in Sheffield, a Mercedes E300 BLUETEC and a Peugeot 3008 hybrid. The NO_X emission measurements for these new vehicles were both high.

Policy Recommendations

- The UK is considering whether Low Emission Zones, that restrict or deter older (e.g. Euro 3 and older) LGVs, OGVs, Buses and Coaches that are considered to be larger, more polluting from accessing environmentally sensitive areas. The vehicle emission remote sensing results indicate that LEZs whilst likely to significantly reduce tail-pipe emissions of PM_{10} that are well known to be harmful to health, they are expected to have limited success in reducing NO_X and primary NO_2 emissions.
- There is obviously a compelling need to develop a sustainable, low carbon public transport system that delivers substantial reductions in emissions that are harmful to both the global (carbon) and local environments (quality of life). The City Bus fleet is therefore suggested to be a priority vehicle sector. Sheffield City Council also has a greater influence on these than other light- and heavy-duty vehicle types, through Bus Quality partnerships, Local Transport Plans and Bus operator engagements etc. Their observed fleet share is greater than Coaches and OGVs combined. Estimated on-road NO_X and PM emission factors for City Buses are comparatively high. As Buses make repeated scheduled journeys each day there is also a greater opportunity to reduce emissions in a sensitive area by renewing a small number of vehicles with cleaner technology than with any other category of vehicle. Potential cleaner Bus technologies to become available in the medium-term include:
  - The next generation of Euro 6 Buses are expected to emit significantly less NO_X emissions than its predecessors. If for example the City of Sheffield is considering refreshing the Bus fleets servicing high frequency routes in the short- to medium-term, serious consideration is given to procuring a fleet of Euro 6 vehicles; and/ or

- Compressed Natural Gas and (CNG) and Compressed Bio-Gas (CBG) fuelled Buses also promise significant environmental benefits, reported to emit ≈10 times less NO_X and PM than comparable standard Euro 5 diesel vehicles. CNG or CBG engines do not need to rely on overly complex exhaust after treatment systems to control tailpipe emissions and achieve EEV status (Enhanced Environmentally friendly Vehicle). Although CNG is an established low carbon and low emission vehicle engine technology across the globe, the real operational environmental impact is uncertain as Gas fuel leakage during refuelling and storage on the vehicle is largely unknown. The financial case for CNG/ CBG only becomes attractive as larger volumes of fuel are supplied. The future of CNG/ CBG is uncertain in the UK as the fuel supply infrastructure and pricing structure is not widely available inhibiting up-take. Investment in CNG and CBG refuelling infrastructure, with quality controlled operations that reduce leakage to a low-level, could act as the driver to un-lock the potential of a cheaper and cleaner fuel for Bus and Commercial Vehicle operations;
- Hybrid power-trains. The current generation of diesel-electric hybrid buses for example promise 30% reductions in fuel and CO_2 emissions, but also cut the emissions of the local air quality pollutants NO_X and PM_{10} by 50% or more. It is suggested if the future development of Bus diesel-electric drive technology considered the operation and optimisation of emission control systems (DOCs, DPFs, SCR – Selective Catalytic Reduction) to a greater degree, emissions of local pollutants could be reduced to a nominal level; and/ or
- Plug-in Hybrid drive systems. Chargeable plug-in hybrid Buses, such as the Volvo concept (2012) adapted from its proven hybrid 7700 series can operate in full electric mode on urban roads for up to 10kms. Critically the batteries can withstand being fast recharged in ≈ 10 minutes. Therefore with 10 minute layover periods between service repetitions at the start/ end of lines, plug-in hybrid Buses could conceivably fully recharge and always operate in full electric mode in the Sheffield AQMAs (Air Quality Management Areas), so would not contribute to local air quality (except re-suspended particles, brake and tyre wear).

There is a price premium for all these cleaner Bus technologies. Financial support to invest in emerging cleaner Bus technologies, accelerating their up-take and development may be applied for from the Department for Transport for example: Green Bus Fund.

As ‘Hackney’ and PHV’ taxis in Sheffield have been observed to emit significantly more NO_X, NO_2 and PM_{10} than comparable passenger cars, it is recommended that policies and incentives should be targeted at accelerating the renewal of the Sheffield taxi fleet with less polluting vehicles. The feasibility of phasing in ‘green (hybrid only) taxi ranks’ at priority locations such as the train station, or offering a discount on license fees for petrol-hybrid vehicles, could be a low capital cost but effective air quality management policies.

As part of a ‘green taxi’ feasibility study, it is recommended a ‘Business Case for Hybrid Taxis’ is developed for taxi drivers and companies that documents and contrasts the fuel consumption and operating costs of standard diesel and comparable hybrid cars in real urban driving conditions. As the rated fuel consumption and CO_2 performance is for the standard test cycle (NEDC), that contains fewer stop-start motions than are typical in real urban driving conditions for example, the reported figures are suggested to under-sell the benefits (fuel and cost savings) of hybrid cars. Maintenance costs may also be lower as the electric drive also takes the load away from the engine and brakes (regenerative braking). A ‘green taxi’ fleet could be a rare “win-win” where profitability is increased for operators, whilst also reducing emissions of local air quality pollutants (NO_X, NO_2, PM) to a nominal level.

1. Introduction

The University of Leeds, Leeds, LS2 9JT ("the University") acting through The Institute for Transport Studies (ITS) was commissioned by Sheffield City Council to deliver a 10-day Vehicle Emission remote sensing Measurement campaign, supplying the instrument and ancillaries/ support vehicle, Project Management, operators and analysis/ interpretation of the results.

The surveys were undertaken on ten weekdays in school term-time between Tuesday 23rd April and Thursday the 13th of June 2013. The instrument was operated at five sites:

- Asline Road;
- Eyre Street;
- Western Bank (A57);
- Attercliffe Centre (A6178);
- Prince of Wales Road (A6102).

The University of Leeds tasks/ objectives:

- Identify and agree five suitable Vehicle Emission Measurement System (VEMS) sites in / adjacent to the Sheffield AQMAs;
- Deliver 10 days of data collection between 0800-1800hrs (weather permitting). This includes instrumentation/ support vehicle hire, operators and time for number plate entry/ data checks;
- Source annoymised detailed Motor Vehicle registration information from www.CarwebUK.co.uk;
- Characterise/ specify the observed on-road, operational vehicle fleet proportions, and compare with the vehicle type proportions determined from the Automatic Number Plate Recognition (ANPR) cameras in routine operation across the City;
- Characterise the distribution of on-road vehicle fleet emissions (NO_X, CO, HC, PM_{10}), including estimates of primary NO_2 emissions, classified by vehicle type (Car, Taxi, LGV, OGVs, Bus), age, fuel type and emission standard (e.g. Euro 0 - 6);
- Identify the abundance and significance of high-emitting vehicles;
- Quantify the discrepancies between: the on-road emission measurements, available emission factors/ inventories and Euro emission standards; and
- Instrumented car survey to map the speed/ acceleration/ engine power demands across the Sheffield network; and
- Data analysis, reporting, project management and press liaison time.

The majority of plots in this report were produced using the open-source software 'R' (R. Team, 2013).

This report includes sections:

2. Background and purpose.

3. Materials and method. This includes a description of the Remote Sensing Device (RSD), the Study Sites and data collected, and the instrumented car/ vehicle tracking survey;
4. Results.
    - Vehicle Emission Measurements Results and Interpretation; and
    - Vehicle tracking surveys.
5. Recommendations for Future work.

2. Background and purpose

The 60th anniversary of the Great Smog of London in 1952 has passed, which resulted in 4,000 deaths across the capital. The same number of people still die each year in London from air pollution. The total number of UK deaths in 2008 due to poor air quality has been put at 30,000. Although the health impacts and costs, estimated to be £8-20 billion per annum are almost twice those of physical inactivity, it fails to receive the same level of attention. Under closer scrutiny the health evidence is strengthening, with the World Health Organization classifying diesel engine exhaust as carcinogenic to humans in June 2012 (WHO, 2012).

Road transport is the main source of the pollution in UK urban areas. The ever more stringent EU vehicle emission standards were perceived to deliver cleaner air, but levels of a key pollutant in our busy streets haven't been falling. As concentrations of the pollutant in question, Nitrogen Dioxide (NO_2), are often above EC air quality standards (limit values) in European urban areas, nations are exposed to potential infraction fines for non-compliance with EU law. So why hasn't air quality been improving, when traffic levels have been relatively stable in the central areas of UK Cities since the 1990's?

Modern diesel vehicle emission controls underperform in urban driving conditions when exhaust gases from the engine are relatively cool, inhibiting the operation of catalysts and filters. Such stop-start traffic motions are common place in the streets of our towns and cities, but aren't adequately represented in the legislated vehicle emission standard test conditions. Recent UK research that surveyed the emission performance of large numbers of vehicles on the road has highlighted the deficiencies in diesel vehicle emission controls in urban driving conditions (Carslaw et al, 2011). The oxides of nitrogen emission performance of diesel cars and vans in urban driving conditions have been shown to have changed little in the past 15 years. So a brand new diesel car and one that has been driven for over 10 years, in urban driving conditions, emit similar amounts of a critical pollutant. Worryingly from a local air quality perspective diesel cars are more popular than ever. In 2010 sales of diesel cars overtook those with petrol engines for the first time (SMMT, 2011).

European Commission and UK policies are encouraging the purchase of new diesel cars over their petrol-driven counter-parts, due to their lower like-for-like carbon dioxide (CO_2) emission ratings. Whilst this shift in purchasing behaviour is helping motor manufacturers meet their initial average car CO_2 rating targets (gCO_2/km) in-place from 2012 onwards, the trade-off has been the halt in urban air quality improvements since 2000-2004. Motor manufacturers face a similar trade-off between CO_2 and emissions of local air quality pollutants, but at a vehicle level as they optimize the operation of the engine and emission controls. Motor manufacturers are complying with the emissions legislation by developing exhaust after-treatment technologies and configuring their operation for the test conditions. The accelerations in the artificial 1970's test cycle still in use are however slight in comparison with those of "normal" driving. Real-world driving with prompter accelerations demands more power from the engine. At higher power demands more emphasis is given to vehicle performance than the emissions of local air quality pollutants. As the complexity and sophistication of engine management and exhaust after-treatment systems has increased, so has the potential for motor manufacturers to optimize their operation for the legislated test conditions to a greater degree, at the disregard of "normal" on-road operations. There are also concerns about how the performance of the complex, multi-component diesel emission control systems will degrade with time and usage.

Frustratingly although the technology and capability exists, the combination of weak outdated European regulations and an industry intent on working to legislation, but not in the spirit of the laws, has resulted in air quality not improving as it should. The substantial health and environmental implications, along with the threat of potentially unlimited fines from the European Commission for not achieving air quality targets, has raised the importance of air pollution once again. The problem is not the UK's not alone; most Member States in the EU are not complying with the air quality standards. The motor industry is going to have to do much more to produce cleaner more efficient vehicles as the easy, low-cost options of encouraging a shift to diesel and reducing vehicle weight by losing the spare tyre have been taken.

There is clearly a need to better understand the emission characteristics of vehicles on the road with "real-world" driving conditions and behaviour. Vehicle emission Remote Sensing Device instruments measure the tailpipe emissions of vehicles as they drive-through a monitoring site. The technology works by scanning the exhaust plume trailing the vehicle. This approach is commonly used in the U.S. and Canada in large-scale pre-screening testing for vehicle inspection and maintenance emission programs. Manufactured by ESP (http://www.esp-global.com/) the RSD-4600 instrument used in this study is able to characterise emissions from thousands of vehicles per day. The measurements, when combined with detailed Vehicle Registration Information allow the on-road vehicle fleet emissions to be characterised, broken down by vehicle type (Car, Taxi, LGV, OGV, Bus and Coach), age, fuel type, emission standard (e.g. Euro 0 - 6). This combination of RSD emission measurements and vehicle registration information provides a rare opportunity to:

- Study the composition of the vehicle fleet being driven on the road in detail. This is important as for example, modern diesel passenger cars are known to typically complete more miles per year than comparable petrol cars, or indeed older diesel cars. As it is newer passenger diesel cars that are now understood to be one of the main contributors towards the increase in primary NO_2 emissions, and hence worsening of roadside NO_2 concentrations at heavily trafficked locations, it is important to develop an accurate and up-to-date knowledge of their proportions on the road;
- Study the emission characteristics of each vehicle fuel type and Euro standard on the road. Whilst the RSD is not able to measure NO_2 directly, with knowledge of a vehicle's fuel type, Euro standard, nitrogen oxide (NO) emissions and recommended primary NO_2 fraction (Grice et al, 2009, Carslaw et al, 2013), it is possible to predict the NO_2 contribution.

With an improved evidence base and understanding of the proportion of vehicle miles driven by different vehicle type sub-categories (fuel type and Euro standard) and characterisation of on-road vehicle emissions in Air Quality Management Areas, Authorities will be able to:

- Design targeted and more effective management strategies;
- Better specify vehicle fleet proportions in emission models; and
- Calibrate and validate emission models.

3. Materials and Method

3.1 ESP Remote Sensing Detector (RSD-4600) operation

The vehicle emission remote sensing measurements were carried out using a AccuScanTM RSD-4600 instrument supplied by Environmental Systems Products (ESP, Arizona, US) as a dedicated across-road vehicle emissions monitoring system. Individual exhaust plumes trailing vehicles are measured by casting a focused beam of Non-Dispersive Infrared (NDIR) and Ultraviolet (UV) light across the plume. A corner cube mirror reflects the IR/UV beam back to the remote sensing detector (spectrophotometer and opacity) module. Open-path NDIR spectroscopic techniques were first used to measure CO vehicle emissions by Bishop et al (1989). Enhancements to measure a portion of HC emissions (Cadle & Stephens, 1994), the addition of a high-speed UV spectrometer capable of measuring NO (Popp et al, 1997, Zhang et al, 1996) and a UV opacity meter (wavelength 230nm) to provide a PM_{10} proxy (index) measure (Stedman et al, 1997) followed. The RSD-4600 measurements include the concentration ratios of NO, CO, HC and the PM_{10} proxy (opacity measure) to the concentration of CO_2. The measurement ratios therefore reflect the pollutant emissions per unit of fuel used. The use of CO_2 as a reference gas facilitates quantitative measurements of exhaust species without knowledge of the plume location or extent of dilution. The emission measurements are supported by: a speed/ acceleration module, temperature and barometric pressure sensors, a camera system to capture a clear digital image of the vehicles number plate for post-processing, and a control/ data logging PC. This approach is commonly used in the US and Canada in large-scale pre-screening testing for vehicle inspection and maintenance emission programs (e.g. Stedman et al, 1997). The basic deployment configuration is similar to the Source/Detector and Mirror Box arrangement shown below in Figure 1.

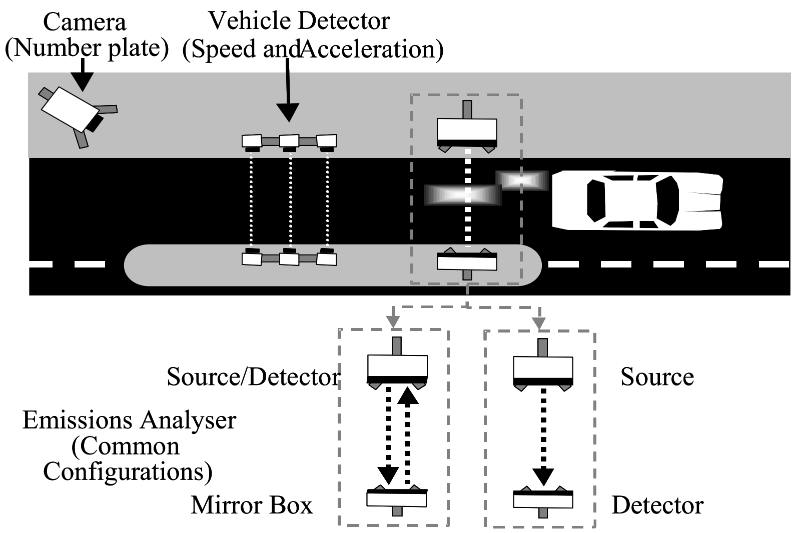


Figure 1: Vehicle Emissions Measurement System (RSD-4600) Schematic

In accordance with the manufacturer operating procedures, the remote sensing beam is located in a position where it will intersect a significant proportion of exhaust gas, with the beam aligned between 250 - 300 mm from the road surface. It is important the source/ detector module (SDM) is well aligned with the corner cube mirror. An alignment laser beam and digital level are initially used to coarsely align the IR/UV beam before a real-time beam intensity measure is used to fine-tune the setup. The system was powered on for a minimum of 45 minutes prior to an initial on-site calibration to gain thermal stability in the circuitry, source and detector elements. On-site quality assurance procedures include calibration of the SDM to the known concentration of gas in a reference cell that is placed (automated) in the beam path. The calibration is verified (an audit) by a blended calibration gas (1000ppm propane, 2% CO, 13.6% CO_2, 1000ppm NO) released into the sensing beam. These calibrations and audits were conducted hourly during normal operation. All routine calibrations were within normal performance tolerances.

A measurement is defined as a beam block (by a vehicle body) followed by a half second of data collection. If the data collection is interrupted by another beam block, i.e. a following vehicle with a headway less than 0.5 seconds, the measurement attempt is aborted. A measurement is declared 'valid' when: the size of the observed CO_2 emission plume is sufficient to allow emission ratios to be calculated (i.e. the maximum CO_2 concentration in the measurement open-path is > 10% and the mean of 5 consecutive 50Hz CO_2 measurements is > 5%); a speed/ acceleration measure is present with the speed is in the range 5 to 60kmh^{-1}; and a clear 'static' digital image of the number plate is captured. The 5 consecutive 50Hz measurements prior to a beam block are considered as the background concentration for that pass-by. The collection of a high proportion of 'valid' measurements requires:

- Selected monitoring sites are restricted to single lane operation;
- The optical beam path distance is limited to less than 10 m;
- The majority of vehicle engines are under load as they drive through the measurement site. This is to ensure significant emission plumes are available for measurement. Sites are therefore recommended to have an uphill grade;
- Weather and environmental conditions are favourable as high wind speeds rapidly disperse exhaust plumes. The equipment is also not weather-proof, so cannot be operated in rain or snow.

The RSD-4600 was deployment was led by Dr James Tate (ITS), supported by Christopher Rushton (ITS PhD student) in accordance with guidelines in the operator's manual, risk assessments, operator/ pedestrian/ driver safety issues and public rights of ways. At the start of each RSD-4600 sampling session, ambient conditions and road gradients were logged.

The 'static' digital image of each 'valid' drive-through measurement was viewed off-line and the number plate (Vehicle Registration Mark – VRM) alphanumeric character string added to the measurement dataset. This record was cross-referenced with the www.carweb.co.uk UK detailed vehicle registration database, so the vehicle fleet composition could be characterised, broken down by vehicle type (Car, Taxi, LGV, OGV, Bus), age, fuel type and emission standard (e.g. Euro 0 - 6).

3.2 Study Sites

The five survey locations in the Sheffield are illustrated in Figure 2, with the road gradient and coordinates of the sites documented in table 1.

Table 1. Survey sites

Location	Coordinates	Altitude (m)	Road slope
Asline Road	53°21'56.62"N 1°28'19.16"W	74m	1.1°
Eyre Street	53°22'29.59"N 1°28'21.30"W	70m	0°
Western Bank	53°22'51.18"N 1°29'22.52"W	131m	2.3°
Attercliffe Centre	53°23'41.11"N 1°25'51.55"W	51m	1.7°
Prince of Wales Road	53°22'55.46"N 1°24'39.45"W	74m	1.8°

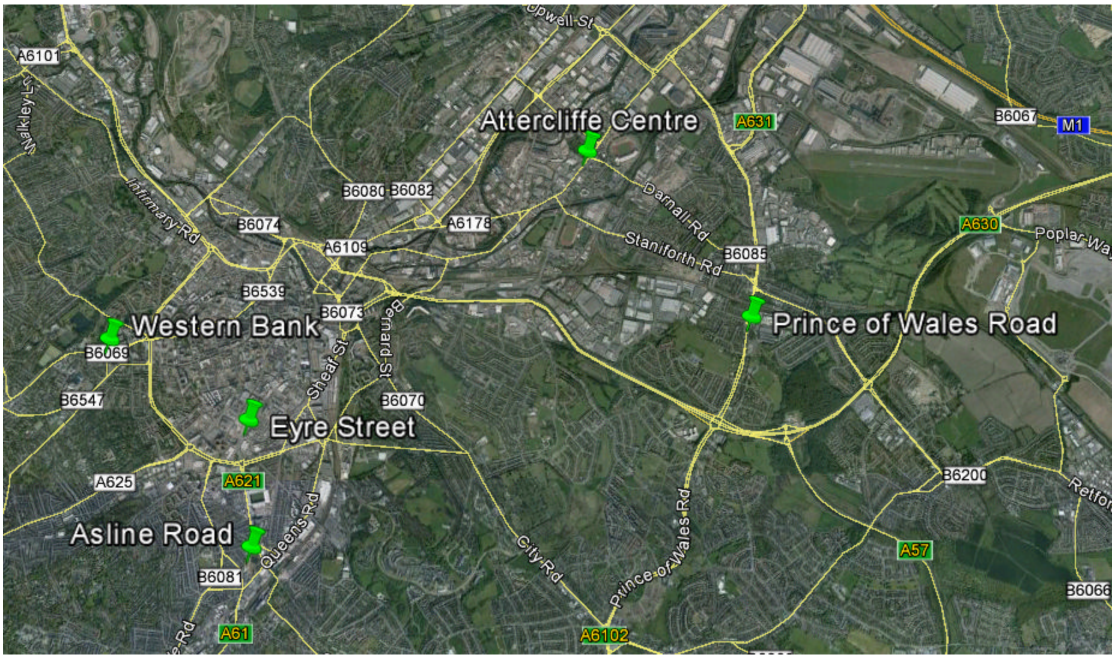


Figure 2: Sheffield Measurement Sites.

3.3 Data collection

The surveys took place on weekdays in school term time between the 23rd of April and the 13th of June 2013. CarwebUK Ltd (www.carweb.co.uk) matched the number plate records (VRMs) with the UK Motor Vehicle Registration Information database. The information fields made available include details of the vehicle make/ model, engine specification and performance. A summary of the Motor Vehicle Registration Information available for each vehicle record are listed in table 2.

Table 2: Overview of the information fields in the Motor Vehicle Registration Information database.

Vehicle details	Engine details	Performance/ transmission	Environmental details
VRM	Fuel type	Acceleration to $100kmh^{-1}$	Fuel Cons. - Combined
Manufacturer/ model	Engine capacity	Number forward gears	Fuel Cons. - ExtraUrban
Date 1st registration	No. cylinders	Drive axle(s)	Fuel Cons. - UrbanCold
Body style	Euro status	Maximum power	Grams per km NOx,CO,PM
Country Of Origin		Maximum torque	SoundLevel - EngineSpeed
Size: Height, Length, Width			SoundLevel - DriveBy
Gross weight			SoundLevel - Stationary

The number of 'valid' records (emission measurement and detailed vehicle information sourced from the number plate/ VRM) for each survey date and site are presented in Table 3.

Table 3: Data Collection Overview.

Site	Date (dd/mm/yyyy)	Time (BST, hh:mm)	N° Valid Records
Asline Road	23/04/2013	10:26 – 18:00	1156
	24/04/2013	08:18 – 18:00	1675
Eyre Street	30/04/2013	08:14 – 18:01	2500
	01/05/2013	08:01 – 18:00	2460
Western Bank	13/05/2013	08:30 – 18:00	3121
	14/05/2013	08:24 – 16:27*	3084
Attercliffe Centre	04/06/2013	08:02 – 18:00	4180
	05/06/2013	08:12 – 18:00	4594
Prince of Wales Road	12/06/2013	08:20 – 16:37*	4064
	13/06/2013	08:25 – 13:27*	1373
		TOTAL	**28 207**

Note: * Surveys ended earlier than the scheduled 18:00hrs because of heavy rain.

3.4 Vehicle tracking surveys

A Ford Mondeo (Euro 4, 2.0l petrol, VRM CF55 OKP) hatchback car (un-laden) was equipped with a VBox II Lite (www.velocitybox.co.uk) survey grade, fast up-date (10Hz) GPS and CAN interface (CAN002 module) instrument/ data-logger. Connected to the car's CAN Bus (information network), the vehicle's position, GPS and road (wheel revolutions) speed, and engine speed were recorded at 10Hz. The vehicle tracking survey took place on Monday the 16th of September 2013. The times and routes covered are illustrated in Figure 3 and Table 4.

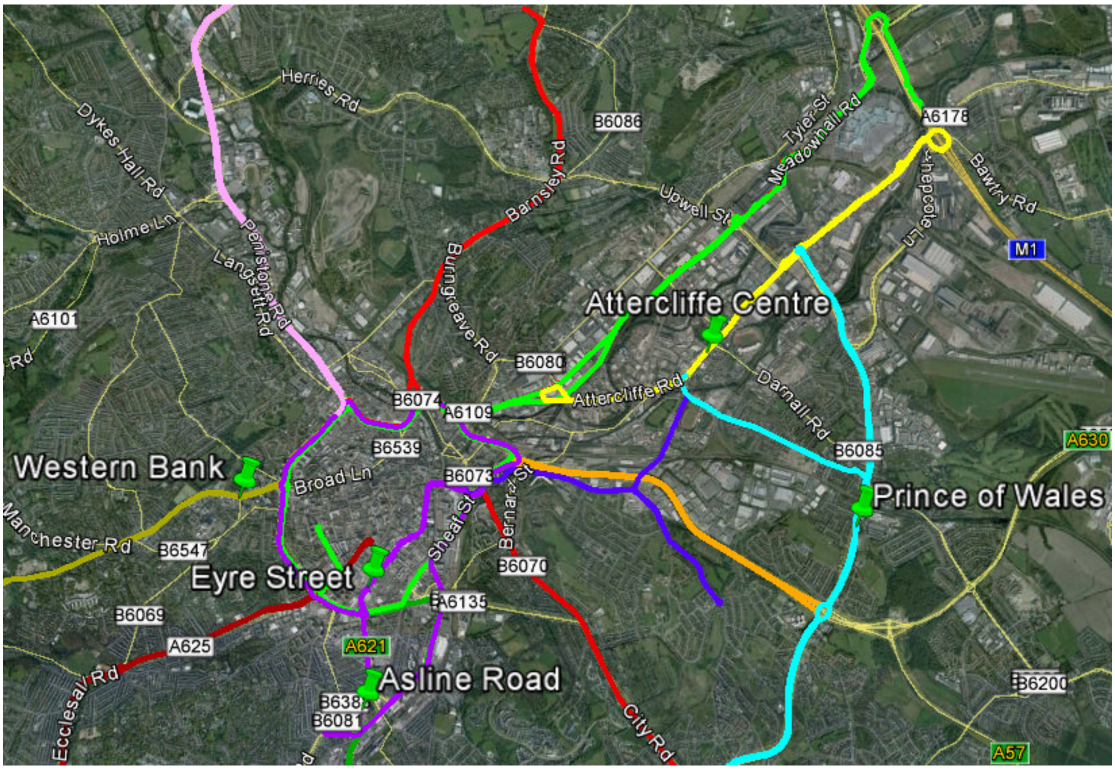


Figure 3: Vehicle tracking routes across Sheffield.

Table 4: Vehicle tracking data collection.

START time [BST] (hh:mm)	**END time [BST] (hh:mm)**	**ROUTE description**	**LINE colour** (Figure 3)	**DISTANCE (km)**
08:34	09:25	A6109 Meadow Hall Road / Brightside Lane Inner Ring Road (anti-clockwise)	green	19.7
09:26	09:46	A6178 Attercliffe Road	yellow	10.4
10:59	11:35	B6200 Staniforth Road A6102 Prince of Wales Road	cyan	21.1
11:36	11:49	Chippingham Street Shirland Lane	blue-violet	6.7
11:54	12:03	A57 Sheffield Parkway	orange	7.4
12:04	12:18	A6135 City Road	red	6.9
12:19	12:52	A61 Chesterfield Road	purple	14.4
13:43	14:18	Inner Ring Road (clockwise)	dark green	12.9
14:18	14:42	A625 Ecclesall Road	dark red	11.4
15:53	16:30	A57 WesternBank	amber	7.2
16:30	17:12	A61 Penistone Road	pink	24.9
17:12	17:46	A6135 Barnsley Road	red	14.5
		GRAND TOTAL		**157.5 km**

The primary aim of the vehicle tracking surveys, was to assess the typical distribution of speed, acceleration and engine power demands (accounting for road grade) across the Sheffield road network (main routes), and compare this with the measurements at the five RSD survey locations. As GPS altitude data is not reliable, particularly in urban areas with slower vehicle speeds and restricted view of the sky, the GPS position was fitted to a Digital Terrain Model (DTM) that maps the earth's terrain excluding building and vegetation with a 5m resolution. The DTM was created by Bluesky International Limited, made available for education and research via the Mimas, Landmap Service (http://landmap.mimas.ac.uk/). If the vehicle is travelling above $12ms^{-1}$ then the gradient calculation is simply the distance travelled in the measured second by the change in height in that measured second. At slower speeds an average grade over the preceding and proceeding 5m sections is calculated helps to smooth out errors caused by inaccurate GPS longitude/ latitude measurements, and therefore inaccurate height derivation from the DTM.

4. Results

4.1 Fleet Characteristics

The detailed vehicle registration information allows the on-road vehicle fleet proportions to be studied in detail, including: vehicle type, age, Euro emission standard and fuel type. Vehicle emission standards are defined in a series of European Union Directives (98/69/EC and 1999/96/EC) staging the progressive introduction of increasingly stringent standards. Currently, emissions of NO_X, HC, carbon monoxide (CO), and particulate matter are regulated for most vehicle types. For each vehicle type different standards apply. Compliance is determined by running the vehicle on a standardised drive cycle (speed profile). Noncompliant vehicles cannot be sold in the EU. No use of specific technologies is mandated to meet the standards, though available technology is considered when setting the standards. The stages are typically referred to as Euro 1, Euro 2, Euro 3, Euro 4, Euro 5 and Euro 6. The emission standards come into force on a set date for new type approvals. For example Euro 4 emission limits for cars came into force on 1st January 2005. Cars first registered after this date should therefore comply with the Euro 4 emission standard. Several Member States, including the UK have used tax incentives to encourage motor manufacturers to accelerate the introduction of cleaner vehicles. Table 5 presents the dates Euro emission standards came into effect for passenger cars.

Table 5: Emission standard dates for Car and Light-Commercial Vehicle Categories (e.g. Latest EU directive for Euro 5 and 6 - 2007/715/EC)

Vehicle type	Fuel type	Euro class.	Dates	Emission standards (g/km)				
				CO	NOx	HC	HC+NOx	PM
Car	Diesel	1	1992-1995	2.72	-	-	0.97	0.14
		2	1996-1999	1.0	-	-	0.7	0.08
		3	2000-2004	0.64	0.5	-	0.56	0.05
		4	2005-Aug2009	0.5	0.25	-	0.3	0.025
		5	Sep2009 – Aug2014	0.5	0.18	-	0.23	0.005
		6	Sep2014 –	0.5	0.08	-	0.17	0.005
	Petrol	1	1992-1995	2.72	-	-	0.97	-
		2	1996-1999	2.2	-	-	0.5	-
		3	2000-2004	2.3	0.15	0.2	-	-
		4	2005-Aug2009	1.0	0.08	0.1	-	-
		5	Sep2009 – Aug2014	1.0	0.06	0.1	-	0.005
		6	Sep2014 –	1.0	0.06	0.1	-	0.005
LGV (1760-3500kg)	Diesel	1	1994-1997	6.9	-	-	1.7	0.25
		2	1998-2000	1.5	-	-	1.2	0.17
		3	2001-2005	0.95	0.78	-	0.86	0.10
		4	2006-Aug2010	0.74	0.39	-	0.46	0.06
		5	Sep2010 – Aug2015	0.74	0.28	-	0.35	0.005
		6	Sep2015 –	0.74	0.125	-	0.215	0.005

Table 6 presents the vehicle number samples for each vehicle type surveyed by the Remote Sensing instrument, split by year of first registration. This database of 'valid' records comprised 70.8% Cars, 3.79% Taxis, 17.0% LGV, 2.45% OGVs (rigid and articulated), 5.86% Buses (Passenger Service Vehicles – PSVs) and 0.3% Coaches.

Table 6: Vehicle number samples by vehicle type and year of first registration.

YEAR	Car	Taxi	LGV	OGV	Bus	Coach
Pre-1970	3	0	1	1	0	0
1970	0	0	0	0	0	0
1971	0	0	0	0	0	0
1972	0	0	0	0	0	0
1973	1	0	0	0	0	0
1974	0	0	0	0	0	0
1975	0	0	0	0	0	0
1976	0	0	0	0	0	0
1977	0	0	0	0	0	0
1978	0	0	0	0	0	0
1979	1	0	0	0	0	0
1980	1	0	0	0	0	0
1981	0	0	0	0	0	0
1982	0	0	0	0	0	0
1983	0	0	0	0	0	0
1984	1	0	1	0	0	0
1985	3	0	1	0	0	0
1986	3	0	1	0	0	0
1987	5	0	0	0	0	0
1988	4	0	0	0	0	0
1989	6	0	1	0	0	0
1990	5	0	1	0	0	0
1991	8	0	1	0	1	0
1992	8	0	5	0	0	0
1993	17	0	1	0	0	0
1994	16	0	2	0	0	0
1995	36	0	1	2	0	0
1996	86	0	9	9	0	0
1997	153	0	21	5	3	0
1998	259	0	25	11	128	0
1999	419	28	45	16	295	0
2000	687	40	59	11	49	0
2001	962	26	149	26	18	0
2002	1370	28	187	27	192	0
2003	1456	40	225	17	32	0
2004	1557	85	293	46	49	0
2005	1597	104	328	65	16	0
2006	1529	116	399	50	106	0
2007	1736	248	494	61	113	1
2008	1419	218	487	68	258	6
2009	1309	91	326	47	5	0
2010	1376	20	442	52	94	1
2011	1553	16	552	58	135	0
2012	1636	8	550	84	58	0
2013	756	0	201	35	102	0
TOTAL	**19978**	**1068**	**4808**	**691**	**1654**	**8**

Table 7: Observed vehicle fleet proportions (%): vehicle/ fuel type and Euro standard.

	CAR				Taxi				LGV		OGV	Bus		COACH
EURO Standard	*Petrol*	*Diesel*	*Hybrid*	*Hybrid Diesel*	*Petrol*	*Diesel*	*Hybrid*	*Hybrid Diesel*	*Petrol*	*Diesel*	*Diesel*	*Diesel*	*Hybrid Diesel*	*Diesel*
Euro 0	0.20	0.025	0	0	0.00	0.28	0	0	0.028	0.021	0.007	0.007	0	0
Euro 1	0.34	0.11	0	0	0.00	0.032	0	0	0	0.14	0.09	0.011	0	0
Euro 2	4.17	0.65	0	0	0.00	0.021	0	0	0.032	0.48	0.22	1.76	0	0
Euro 3	15.41	6.24	0.01	0	0.014	0.99	0.00	0	0.11	4.17	0.79	1.39	0	0
Euro 4	14.74	11.69	0.057	0	0.082	2.18	0.00	0	0.04	6.93	0.65	1.32	0	0.028
Euro 5	6.58	10.26	0.31	0.007	0.00	0.18	0.0035	0	0.02	5.07	0.69	1.02	0.36	0
Euro 6	0.01	0.03	0	0	0.00	0.00	0.00	0	0.00	0.00	0.01	0	0	0
Total (%)	**41.45**	**28.99**	**0.37**	**0.01**	**0.10**	**3.68**	**0.0035**	**0**	**0.23**	**16.81**		**5.50**	**0.36**	
GRAND TOTAL (%)	**70.83**				**3.79**				**17.05**		**2.45**	**5.86**		**0.028**

Table 7 specifies the observed vehicle fleet proportions, broken down by vehicle/ fuel type, and their Euro category. Figure 4 illustrates the observed passenger car fleet proportions, broken down by Euro standard and fuel type. The 'on-road' passenger car fleet is dominated by Euro3 classification or better vehicles. Cars registered in 2000 onwards (Euro3 classification or better) comprise more than 92% of the 'on-road' passenger car fleet. Whilst petrol engine cars (petrol and petrol-electric hybrids) currently comprise 59% of the passenger car fleet in Sheffield, diesel cars are becoming more popular. In 2010 sales of diesel cars overtook those with petrol engines in the UK for the first time (SMMT, 2011).

It is interesting to note that the dataset contains pass-by measurements of a small sample of Euro 6 vehicles introduced ahead of the legislation (September 2014):

- 8 Euro 6 diesel car pass-by measurements (3 Mercedes AMG Bluetec, 5 Mazda CX-5 D);
- 4 Euro 6 petrol cars.

The presence of these vehicles suggests that select motor-manufacturers are now able to introduce this next generation of vehicle technology ahead of the legislated date.

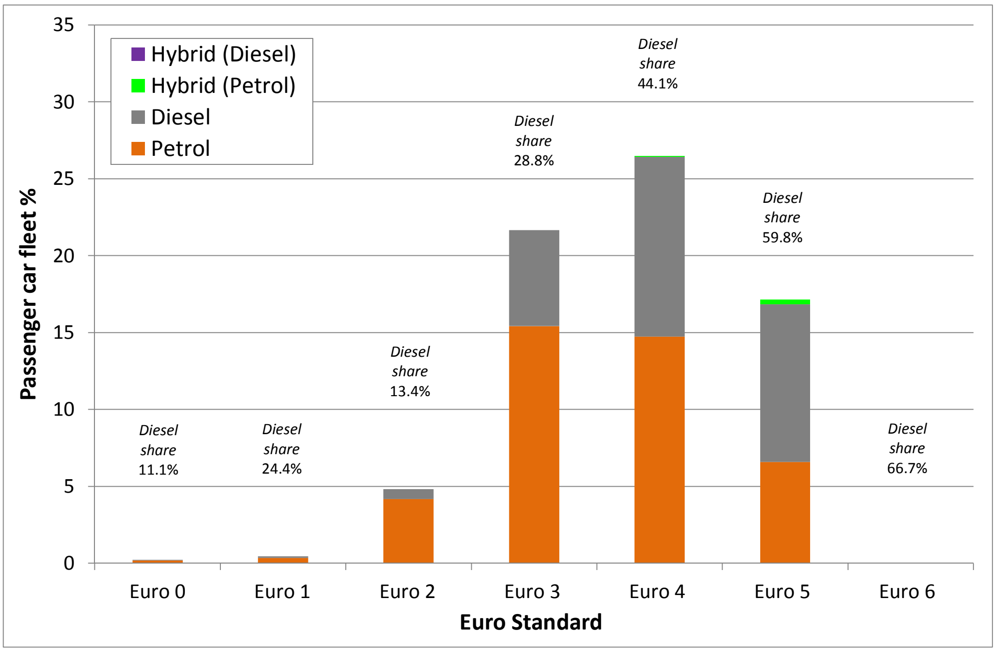


Figure 4: Observed passenger car fleet proportions, broken down by Euro standard and fuel type.

Figure 5 presents the age distribution (histogram) of the observed petrol, diesel, petrol-electric hybrids and diesel-electric hybrids. The number of registered dual petrol and gas (CNG or LPG) fuelled passenger cars is low. The popularity of CNG/ LPG that promised to be a low carbon and emission technology appears to have waned. Only 15 cars were registered as CNG/ LPG and it is expected many of these may not be running on gas, so have not been explicitly analysed. There are early signs that the hybrid (petrol-electric and more recently diesel-electric powertrains) car market is beginning to flourish.

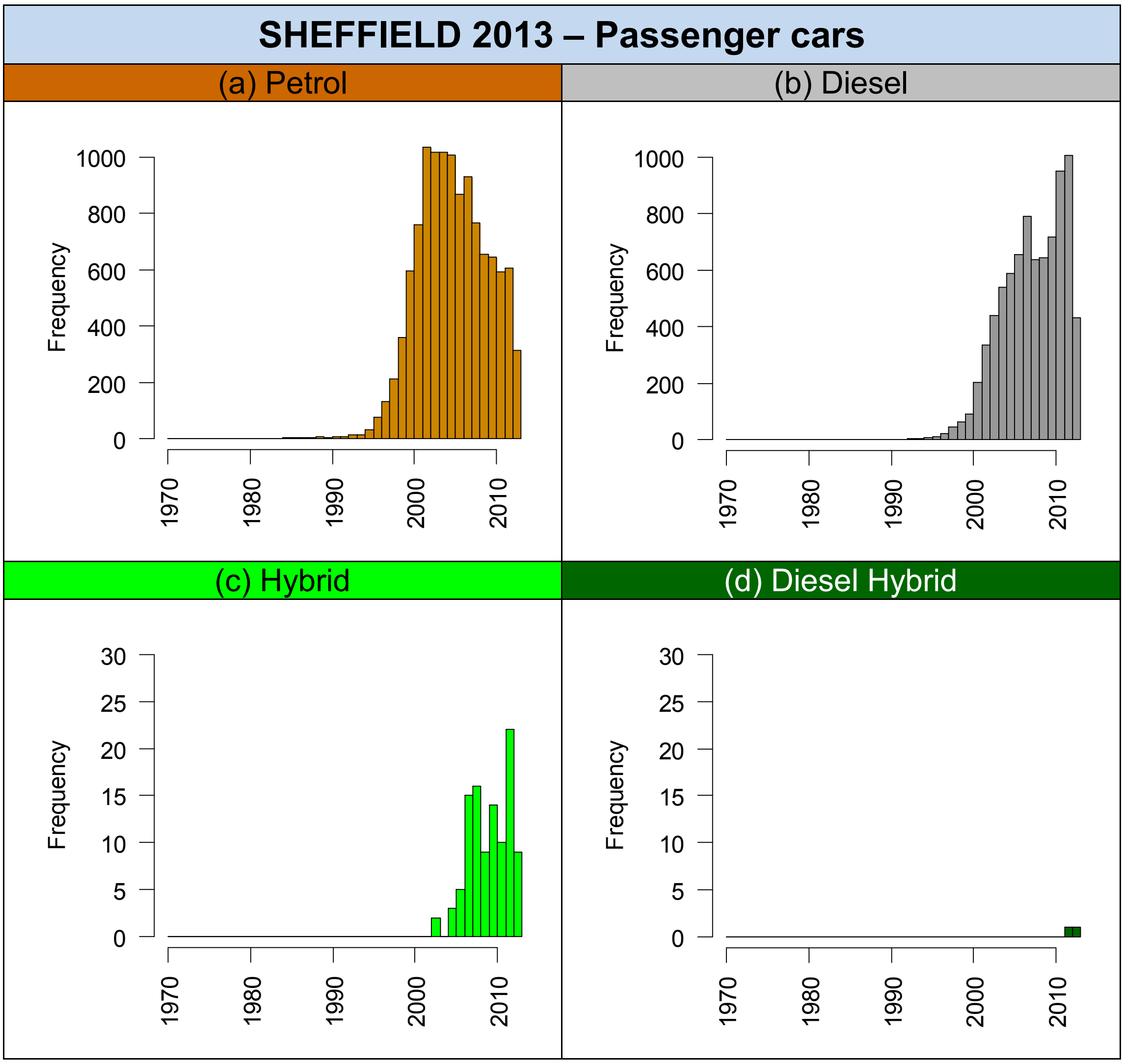


Figure 5: Vehicle age distributions of the observed passenger cars: (a) petrol, (b) diesel, (c) hybrid and (d) diesel hybrid cars.

Figure 6 presents the age distribution (histograms) of the observed taxis: Hackney and Private Hire Vehicles (PHVs). License restrictions mean all the Hackney carriages are less than 15 years old, and Private Hire Vehicles are less than ten years old. The taxi fleet is comprised of passenger cars and Light Commercial Vehicles (13.5%). Diesel engine vehicles dominate (85.7%), with a small proportion of petrol (12.9%) and hybrid (petrol-hybrid, 1.4%) vehicles.

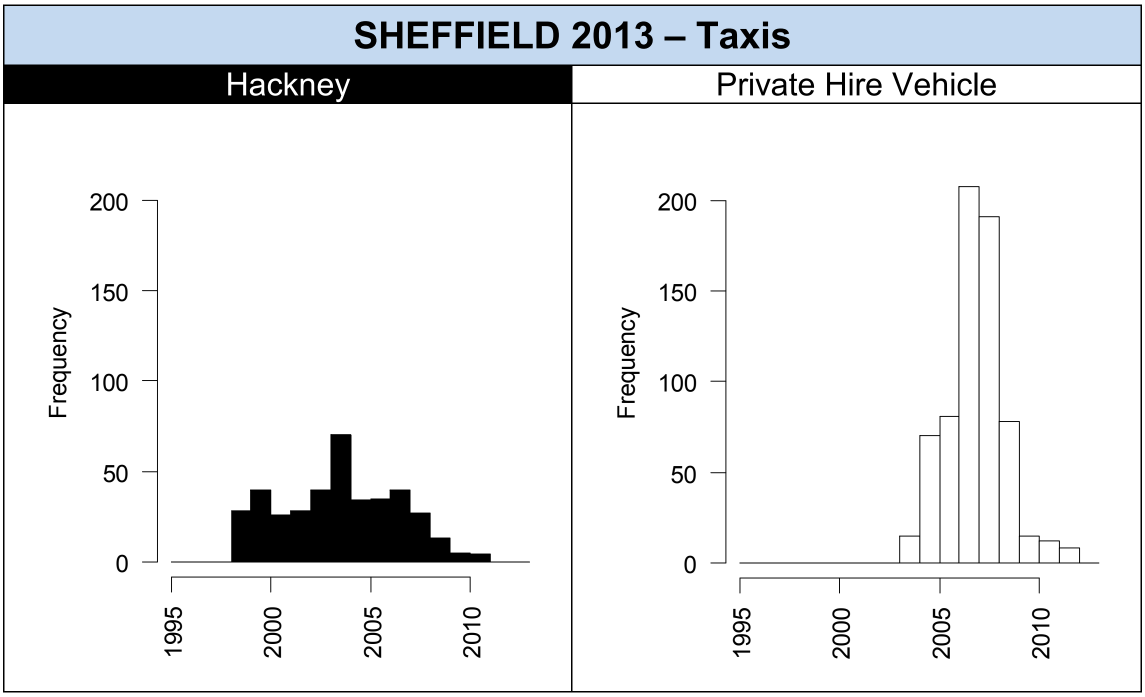


Figure 6: Vehicle age distributions of the observed taxi fleet: (a) Hackney, (b) Private Hire Vehicle (PHV).

Figure 7 presents the age distribution (histogram) of the observed petrol and diesel fuelled van fleet. Vans are pre-dominantly diesel vehicles. Only a small number of older, petrol vans are still in circulation in Sheffield.

Figure 8 presents the age distribution (histogram) of the Single-decker, Double-decker and Hybrid Double-decker Buses observed at the five measurement sites. The observed Sheffield Bus fleet (Passenger Service Vehicles) are predominantly single-decker vehicles (≈60%). The remainder are double-decker Buses powered by standard diesel engines (≈34%) or hybrid (diesel-electric) powertrains (≈6%).

Other Goods Vehicles (OGVs or Heavy-Goods Vehicles, HGVs) all are run on diesel fuel, with the majority (≈94%) of vehicles registered after 2000. Greater than half (≈55%) of the observed OGVs meet the Euro 4 or Euro 5 emission standards. Two pass-bys by Euro 6 articulated OGVs (Mercedes ACTROS 2545LS) were recorded.

It should be noted that a limitation of the standard remote sensing measurement configuration is that vehicles with elevated exhaust tail-pipes cannot be surveyed as no (or minimal) exhaust plume is observed by the sensing beam close to ground-level. A proportion of and OGVs are configured with elevated tail-pipes. The database is therefore somewhat biased, as these vehicles are not represented.

As the digital (static image) camera is triggered when a sufficiently large (>10%) CO_2 plume is observed, vehicles with tail-pipes located at a mid-way point on the chassis and a high ride height (or break in the body panels) can lead to the premature activation of the camera. In this situation a static image is taken of the side of the vehicle, without the number plate in field of view. Although the emission measurement is 'valid', the number plate and therefore age/ emission category are 'unknown'. This mainly affects OGVs with tail-pipes positioned close to ground-level behind the driver cab unit, which also have a break in trailer/ fixed bed body-panels.

These are not considered to be significant limitations because there tend to be few of these vehicles in urban areas, but the reported proportion of OGVs in the fleet and their emission contribution is expected to be under-reported. If an accurate specification of the local, operational fleet is needed, it is recommended number plate records (VRMs) collected from fixed ANPR systems should be cross-referenced with the UK vehicle registration database.

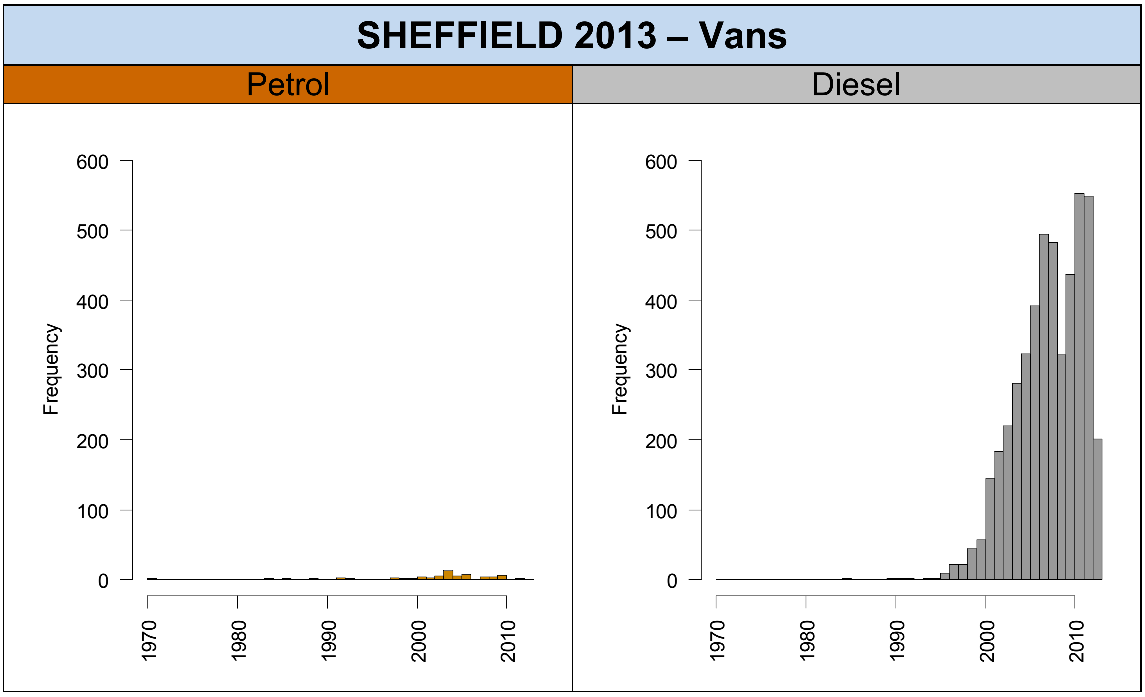


Figure 7: Vehicle age distributions of the observed petrol, diesel and LPG/ CNG vans

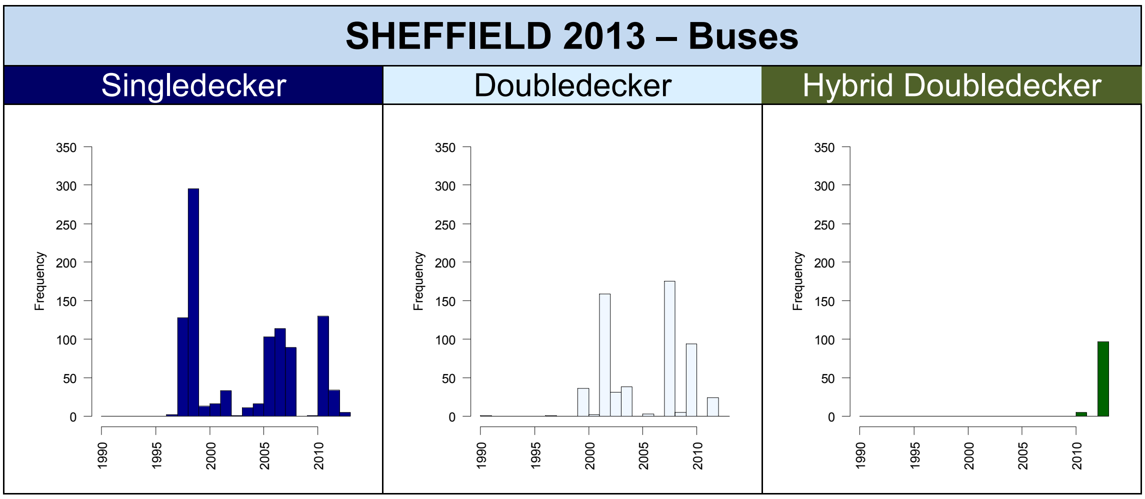


Figure 8: Vehicle age distributions of the observed Bus fleet.

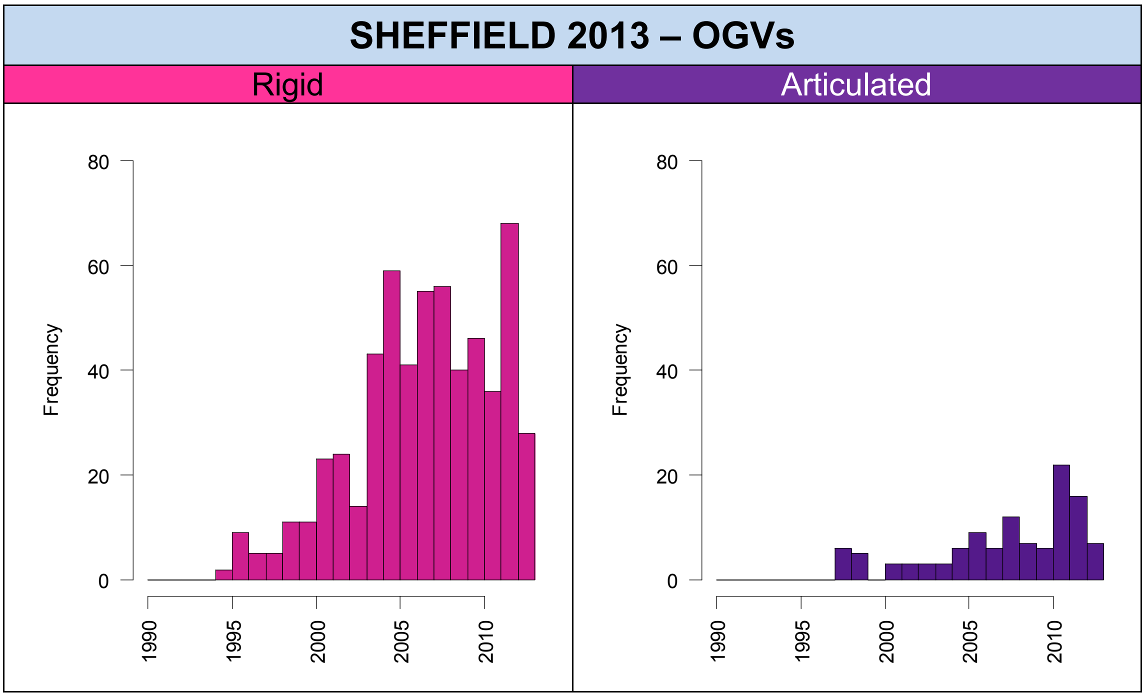


Figure 9: Vehicle age distributions of the heavy-duty fleet: Bus, Coach and HGVs.

The observed vehicle fleets at each of the five survey locations are documented in Table 8. The fleet proportions were similar at the Attercliffe Centre and Prince of Wales sites, with high proportions of Commercial vehicles: Vans (LGVs) ≈22% and OGVs ≈4%. Eyre Street carries a very high proportion of Buses (≈30%), an order of magnitude greater than at any of the other sites, including the Western Bank arterial that runs Bus services for the University of Sheffield, Children's hospital and further afield.

Table 8: Observed vehicle types and fuel type proportions (%) at the survey locations.

Vehicle type	SITE									
	Asline Road		Eyre Street		Western Bank		Attercliffe Centre		Prince of Wales	
	N	(%)	N	(%)	N	(%)	N	(%)	N	(%)
Car	2260	(79.8)	2746	(55.4)	4921	(79.3)	6144	(70.0)	3907	(71.9)
Taxi	94	(3.3)	344	(6.9)	240	(3.9)	270	(3.1)	120	(2.2)
Van	448	(15.8)	389	(7.8)	825	(13.3)	1957	(22.3)	1189	(21.9)
Bus	7	(0.2)	1433	(28.9)	173	(2.8)	44	(0.5)	5	(0.1)
OGV	22	(0.8)	48	(0.9)	46	(0.7)	359	(4.1)	216	(3.9)
TOTAL	**2831**		**4960**		**6205**		**8774**		**5437**	

The detailed Vehicle Registration Information (VRI) also includes the reported vehicle specific fuel consumption for the New European Drive Cycle (NEDC). The NEDC consists of two parts: the urban ECE (duration: 780s, maximum speed $50kmh^{-1}$) and the extra-urban EUDC (duration: 400s, maximum speed $120kmh^{-1}$). The urban ECE starts with a cold engine. The VRI includes fuel consumption figures for the combined (urban ECE and EUDC), extra-urban and urban (cold) drive cycles. The VRI fuel consumption figures (units - litres per 100km) have been converted into carbon dioxide (CO_2) emissions per unit distance (grams per km). The distribution of carbon dioxide emission per unit distance for each fuel type and Euro standard combination, for the NEDC combined drive cycles is presented in the Figure 10 boxplot. The bold horizontal line shows the **median** value. The bottom and top of the box show the 25th and 75th **percentiles** respectively. The vertical dashed lines, termed ‘whiskers’, present the 1.5 times the **interquartile** range of the data. Outliers are not plotted to truncate the y-axis scale. The notches drawn as a ‘waist’ on either side of the median give an indication of the 95% confidence interval of the median.

Petrol and diesel passenger cars are progressively becoming more fuel and CO_2 efficient with each successive Euro standard. It is perhaps surprising that there’s little difference between the median CO_2 per km for the observed petrol and diesel cars. The observed diesel passenger cars are however typically larger, with a higher kerb weight, larger frontal area and engine capacity (illustrated in Figures 11, 12 and 13 respectively).

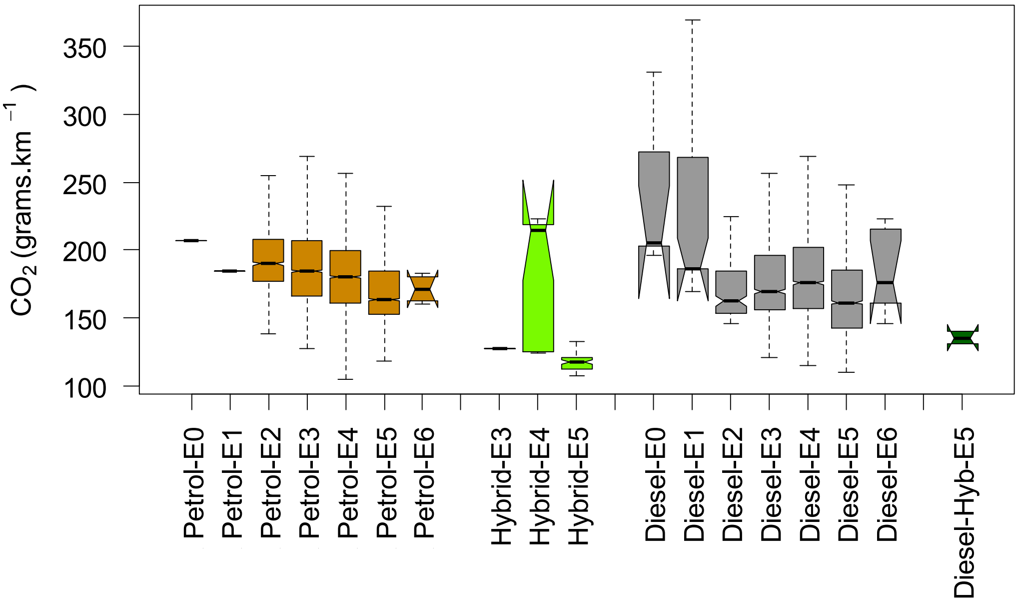


Figure 10: The distribution of the predicted CO_2 per km for the observed passenger cars, categorised by fuel type and Euro standard.

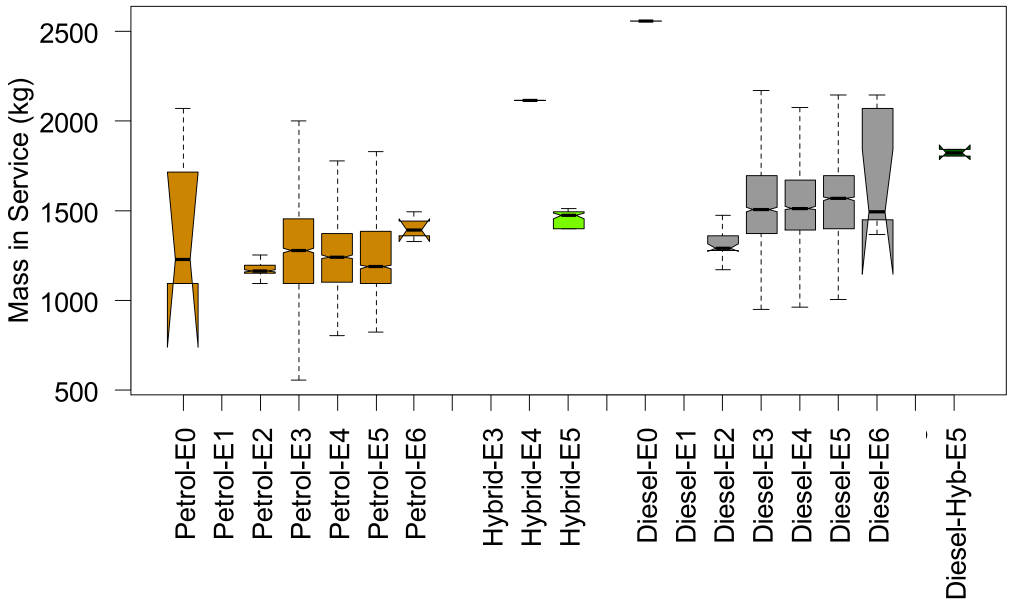


Figure 11: The distribution of reported vehicle kerb weights (mass in service) for the observed passenger cars categorised by fuel type and Euro standard.

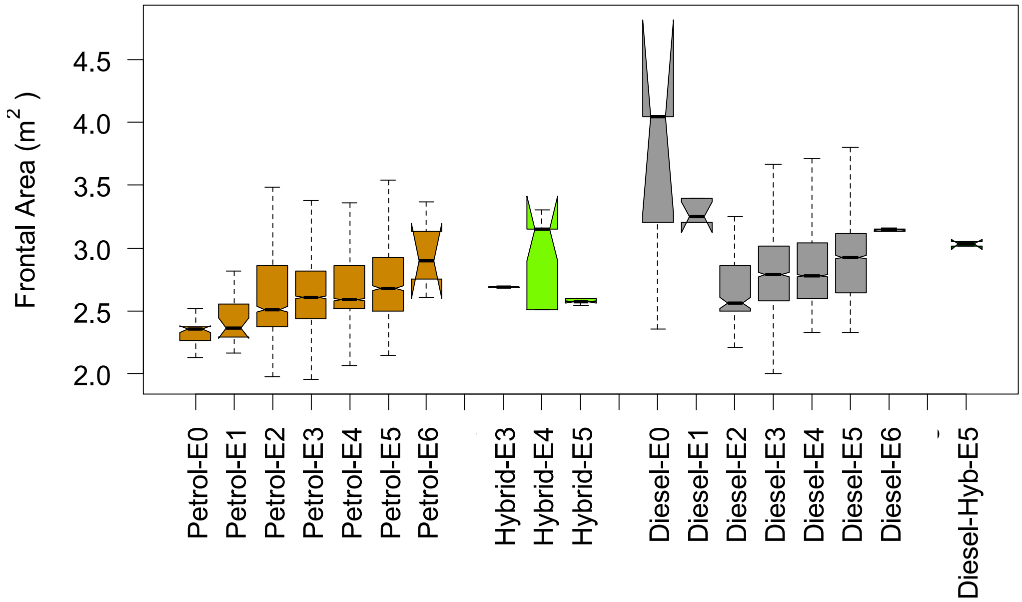


Figure 12: The distribution of frontal areas of observed passenger cars categorised by fuel type and Euro standard.

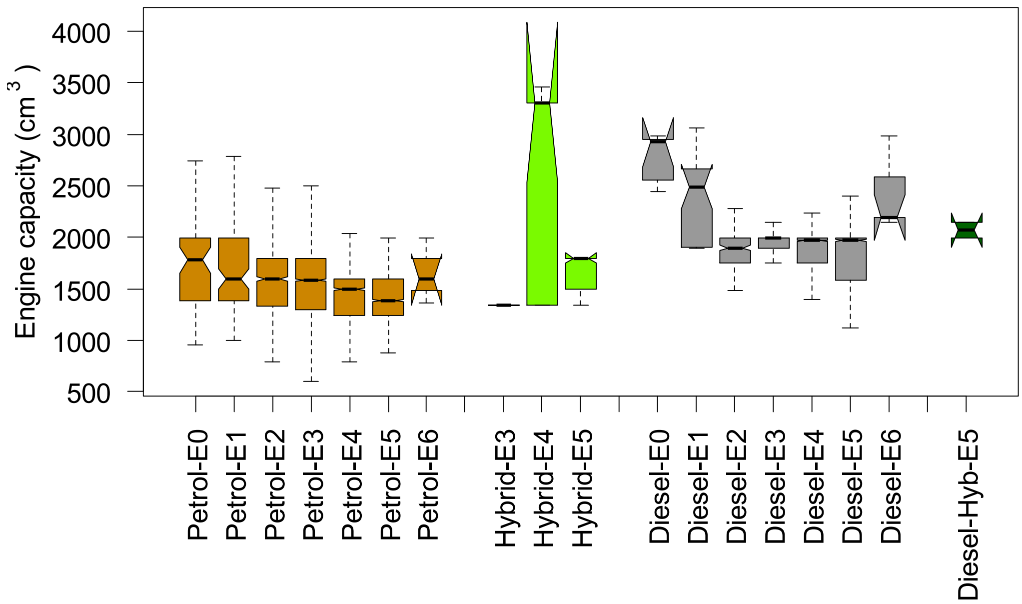


Figure 13: The engine capacity distributions of the observed passenger cars categorised by fuel type and Euro standard.

The median engine capacity for Euro2 onwards petrol or diesel engine passenger cars is relatively constant at 1.4litres and 2.0litres respectively. The kerb (un-laden) weight of both the observed petrol and diesel engine passenger cars is however steadily increasing with each successive Euro standard. These increases in weight are driven by many factors such as improved safety requirements and equipment (air-bags, crumple zones), higher specification vehicles and a growing demand for larger vehicles such as sports utility vehicles. Paradoxically increases in vehicle weight have also been caused by the use of pollution control equipment such as catalysts and diesel particle filters.

Euro 4 standard Hybrid cars are dominated by two contrasting model series, the:

- Honda Civic Hybrid (5 vehicles with an engine capacity of1.4l, ≈1400kg); and
- Lexus RX400H (8 vehicles with an engine capacity of 3.3l, ≈2115kg).

Euro 5 standard Hybrid cars (total 40) are dominated by Toyota vehicles:

- Prius (21 vehicles with an engine capacity of1.5l, ≈1490kg);
- Auris (5 vehicles with an engine capacity of1.8l, ≈1470kg).

The other Euro 5 hybrids observed include:

- Six Honda cars with an average engine capacity of 1.4l and kerb weight of 1560kg;
- Four Lexus CT 200H cars with an engine capacity of 1.8l, ≈1515kg;
- Two Lexus RX450H cars with an engine capacity of 3.5l, ≈2220kg; and a
- Porsche Cayenne (3l, 2315kg).

Current hybrid cars into two broad categories: those of moderate size/ performance, and larger higher powered vehicles.

4.2 Emission Measurements and estimation of Emission Factors

The Sheffield 2013 database of 'valid' RSD measurements (speed, acceleration and emission measurement, number plate record), successfully matched with SMMT Vehicle Registration information, was 28 207 records. The RSD-4600 instrument measures the NO (nitric oxide)/CO_2 ratio in the exhaust plume. Although it doesn't measure NO_X and NO_2 directly, with knowledge of a vehicles' fuel type, Euro standard, nitrogen oxide (NO) emissions and recommended primary NO_2 fractions (Hausberger et al, 2011; Grice et al, 2009 and Jerksjö et al, 2008), it is possible to predict the NO_X and NO_2 emission factors and contributions. The addition of Diesel Oxidisation Catalysts (DOCs) on light-duty diesel vehicles from Euro 3 onwards has led to a dramatic increase in emissions of NO_2 directly from vehicles (Carslaw, 2005). The latest Hausberger et al. (2011) results have been used in this study/ analysis, which suggest NO_2 fractions of Euro 5 light-duty diesel vehicles are lower than Euro 4. This is because Euro 5 DOCs have a higher palladium content that are known to have better f-NO_2 characteristics (Hausberger, 2011). The NO_2 fractions applied are in-line with the averages reported by Carslaw et al (2013) who carried out vehicle emission remote sensing measurements using the University of Denver instrument that can speciate NO, NO_2 and ammonia (NH_3). This study did observe considerable variation within vehicle categories and between vehicles, so NO_2 and NO_X assessments of individual vehicles from this study are not considered robust. The averages for vehicle categories i.e. Euro 4 diesel passenger cars, are considered to be reliable. For current petrol car technologies the f-NO_2 is low. This however may not always be the case. The emergence of ultra-lean burn engine technology may in future lead to an increase in NO_X and NO_2 emissions from petrol engines. Heavy diesel average f-NO_2 values are significantly lower than those reported for light-duty diesels.

Table 9: Recommended vehicle NO_2 fractions.

Vehicle class	Euro class	PHEM – Hausberger et al (2011) % NO_2 (by volume)	Grice et al. (2009) % NO_2 (by volume)	Jerksjö et al. (2008) % NO_2 (by volume)
Petrol cars	All	5	3	≈ 1
Diesel cars	Euro I and earlier Euro II Euro III Euro IV Euro V	8 11 35 42.6 36.3	11 11 30 55 55	14 – 20 14 – 20 30 – 47 55 – 60
Vans	Euro I and earlier Euro II Euro III Euro IV Euro V	8 11 35 45 35	11 11 30 55 55	14 – 20 14 – 20 30 – 47 55 – 60
HGVs	Euro I and earlier Euro II Euro III Euro IV Euro V	1.7 2.7 6.8 11.0 7.4	11 11 14 10 10	7 7 9 13 13
Buses	Euro I and earlier Euro II Euro III Euro IV Euro V	2.8 3.2 6.6 8.5 7	11 11 14 35 10	10 10 30 25 - 52 48

4.3 Emission Measurement Results – Passenger cars

The distribution of the NO, predicted NO_2, predicted NO_X, CO, HC and PM (index) fuel based (ratio to CO_2) passenger car emission measurements, categorised by Euro standard and fuel/ technology type are presented in the Figure 14 and 15 'boxplots'. The NO emissions per unit of fuel used are higher for the older Euro standard categories for all fuel/ technology types Figure 14(a). As documented in table 9, the primary NO_2 is high for Euro 3 and newer light-duty diesel vehicles. Figure 14(b) illustrates the distribution of the predicted NO_2 emissions per unit of fuel used, which is typically low, except for the Euro 3 – 5 diesel sub-categories. The distribution of observed/ predicted NO_X emissions per unit of fuel used in Figure 14(c), illustrates:

- The NO_X performance per unit of fuel consumed of the Euro 3 – 5 petrol cars that dominate the fleet is relatively low; and
- The NO_X performance of diesel cars per unit of fuel consumed is high and relatively stable through all Euro standards.

The CO emissions per unit of fuel used are higher for the older petrol Euro standard categories, as illustrated in Figure 15(a). The measured CO emissions from all other passenger vehicle sub-types with a reasonable sample size are low in comparison. The distribution of HC emissions per unit of fuel consumed are similar to the CO species, only being elevated for older petrol cars. The PM_{10} (index) proxy measurement (opacity method) indicate Euro 0 – 2 diesel cars emit relatively high amounts of PM_{10}. The introduction and development of diesel particle filter technologies through Euro standards 3 to 5 has seen progressive reductions in the amount of PM emitted. The PM_{10} (index) emissions from Euro 5 diesel vehicles are only slightly above those of the petrol counter-parts (Euro 5). The PM_{10} (index) measure for newer petrol cars is higher than one might expect. The instrument is scanning the exhaust plume trailing the vehicle, which therefore may contain primary tail-pipe emissions but also particles from brake/ tyre wear and those re-suspended from the road surface. This analysis is extended in Figures 16 and 17, by weighting each vehicle's emission measurement by its registered (www.carweb.co.uk, NEDC drive-cycle) CO_2 performance, so the known fuel efficiency of each individual passenger car can be considered. This allows emission factors (grams per kilometre) to be estimated for each pollutant, assuming:

- driving conditions at the measurement are representative of the general area;
- registered CO_2 performance measure is reliable.

The mean observed passenger car pass-by speed of 20.4km.h^{-1} (standard deviation 5.6) is considered broadly representative of a City network (day-time average). The mean registered CO_2 performance for petrol and diesel passenger cars has been cross-checked with the prediction from the respected HandBook Emission Factors for Road Transport (HBEFA version 3.1 – www.hbefa.net) emission model. The HBEFA 'traffic flow condition' was assumed to be the 'Urban – City Trunk Road – Saturated flow conditions - 50km.h^{-1} (speed limit)'. The average speed for this 'traffic flow condition' is 36 km.h^{-1} (and 29 km.h^{-1} for HGVs). The rated (DVLA) and modelled (HBEFA -URB/Trunk-City/50/Saturated) CO_2 performance are broadly in agreement, except for the older Euro categories which have a lower number of observed vehicles. Rated CO_2 performance information is not available for all vehicle records from the detailed Vehicle Registration Information (VRI - database), particularly for the pre-Euro (0) passenger car sub-categories. To avoid omitting these important measurements, the HBEFA average CO_2 performance was assumed to be representative if the vehicle specific information was not available.

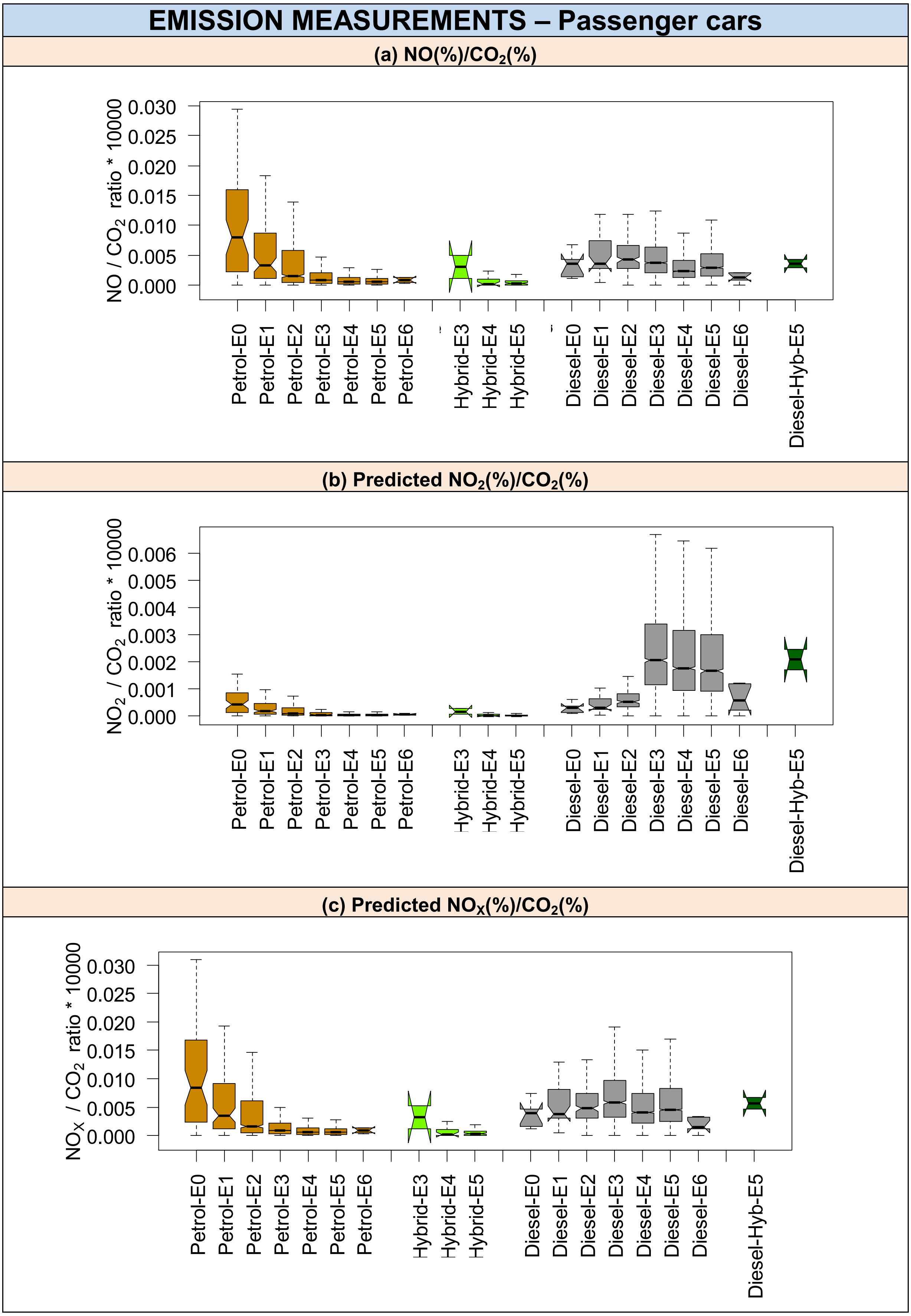
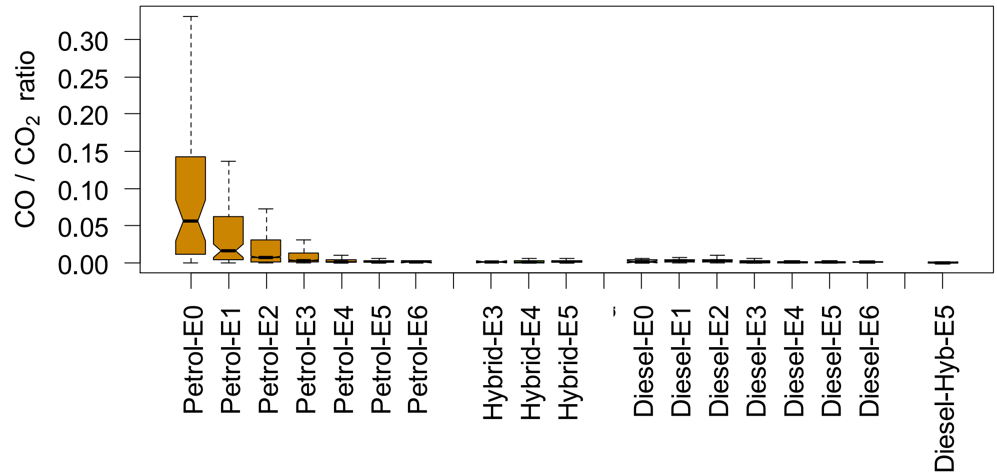


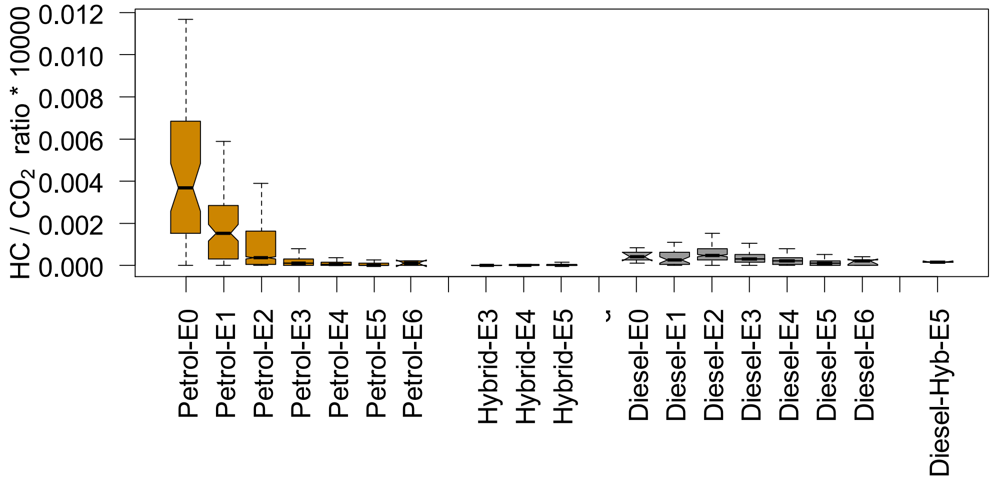
Figure 14: The distribution of the fuel based passenger car emission measurements categorised by fuel type and Euro standard (a) NO, (b) NO_2, (c) NO_X

EMISSION MEASUREMENTS – Passenger cars

(a) $CO(\%)/CO_2(\%)$



(b) $HC(\%)/CO_2(\%)$



(c) Particle Mass (PM_{10}) index / $CO_2(\%)$

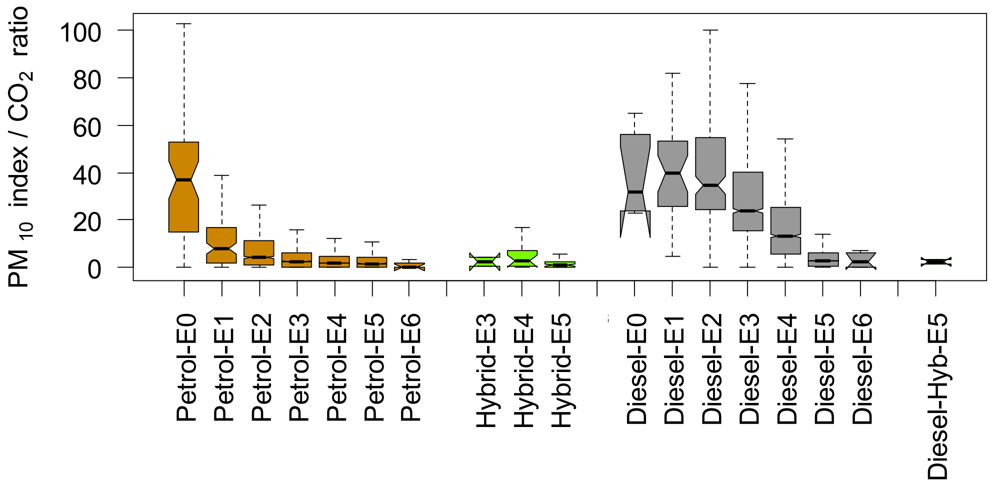
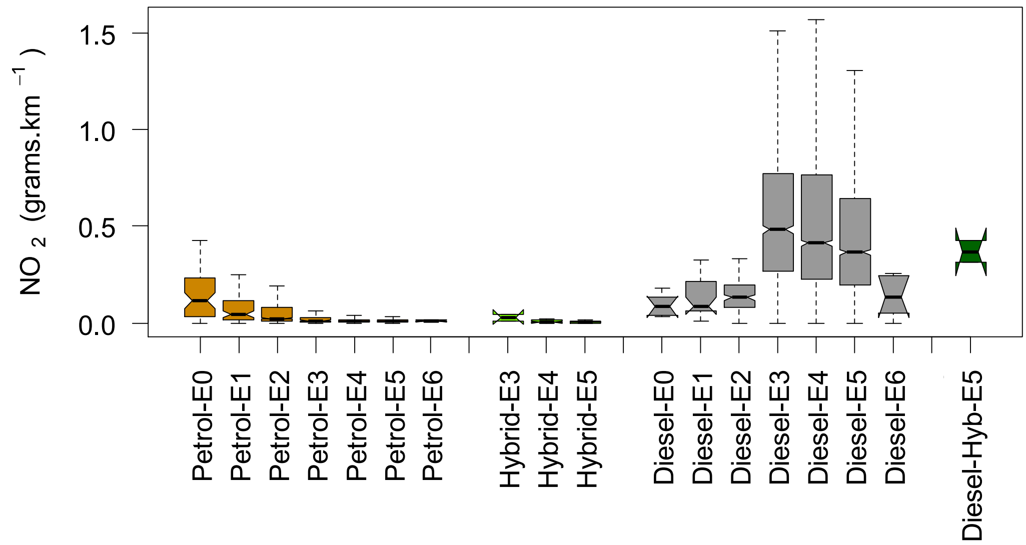


Figure 15: The distribution of the fuel based passenger car emission measurements categorised by fuel type and Euro standard (a) CO, (b) HC, (c) PM (index)

EMISSION FACTORS – Passenger cars

(a) Predicted NO_2 (grams.km^{-1})



(b) Predicted NO_X (grams.km^{-1})

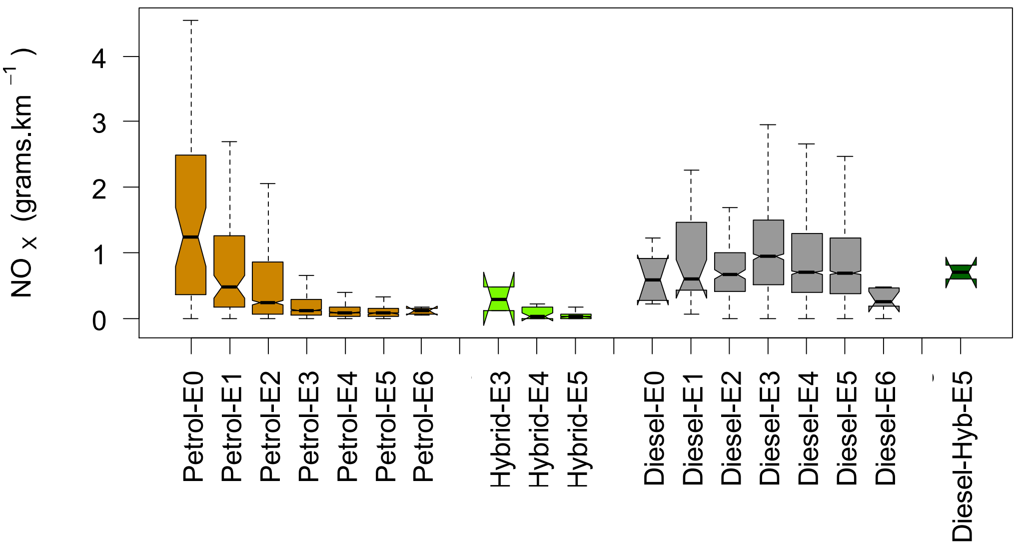


Figure 16: The distribution of the predicted passenger car emission factors (grams per kilometre) categorised by fuel type and Euro standard (a) NO_2, (b) NO_X.

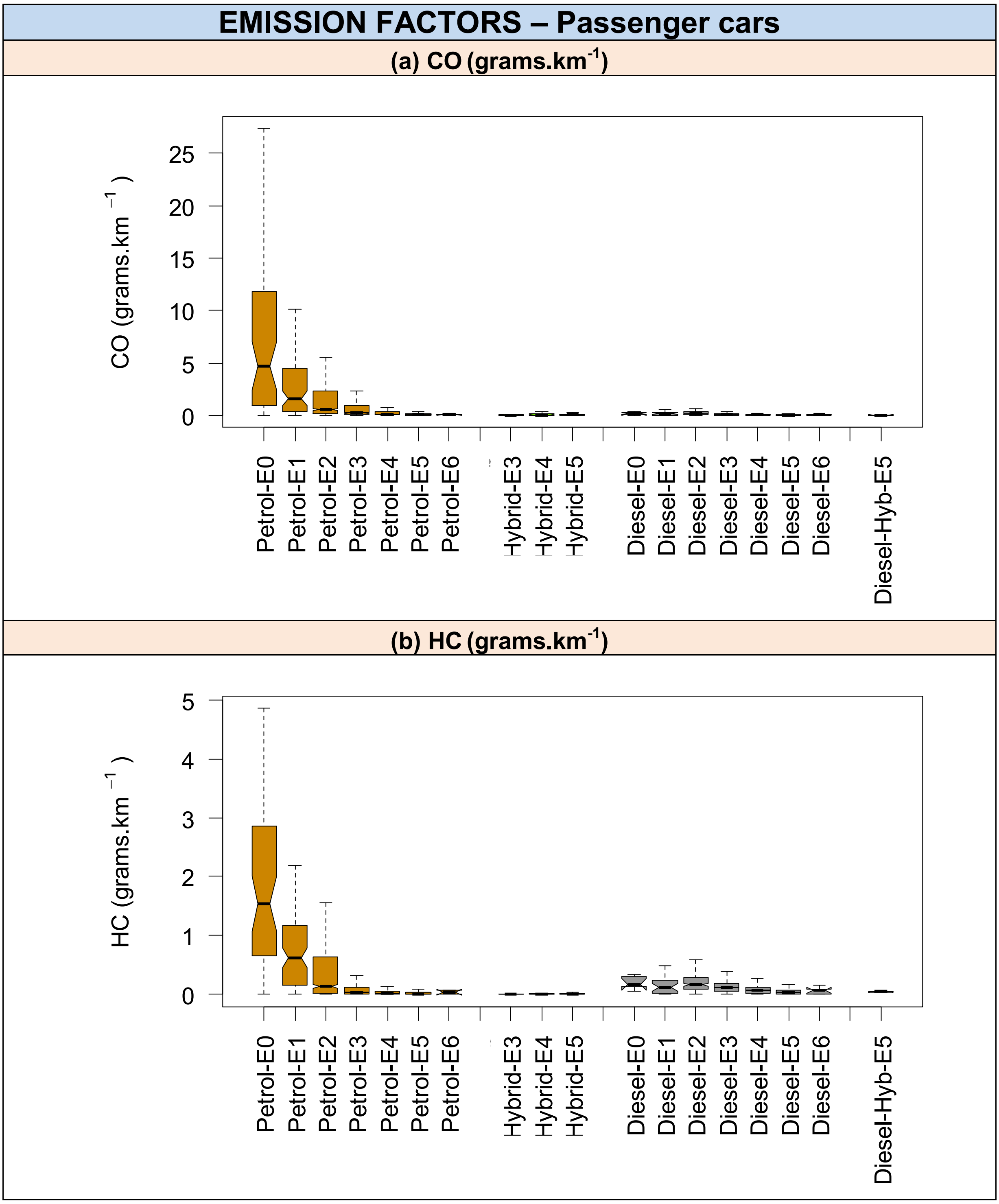


Figure 17: The distribution of the predicted passenger car emission factors (grams per kilometre) categorised by fuel type and Euro standard (a) CO, (b) HC.

The variation in NO_2 and NO_X emission factors estimates for petrol and diesel passenger cars by year of registration are also presented in Figure 18, which clearly illustrates that whilst the engine and emissions controls on modern petrol cars are now emitting NO_X at a low level, there has been little improvement in the NO_X performance of diesel passenger cars in urban areas in the last twenty years.

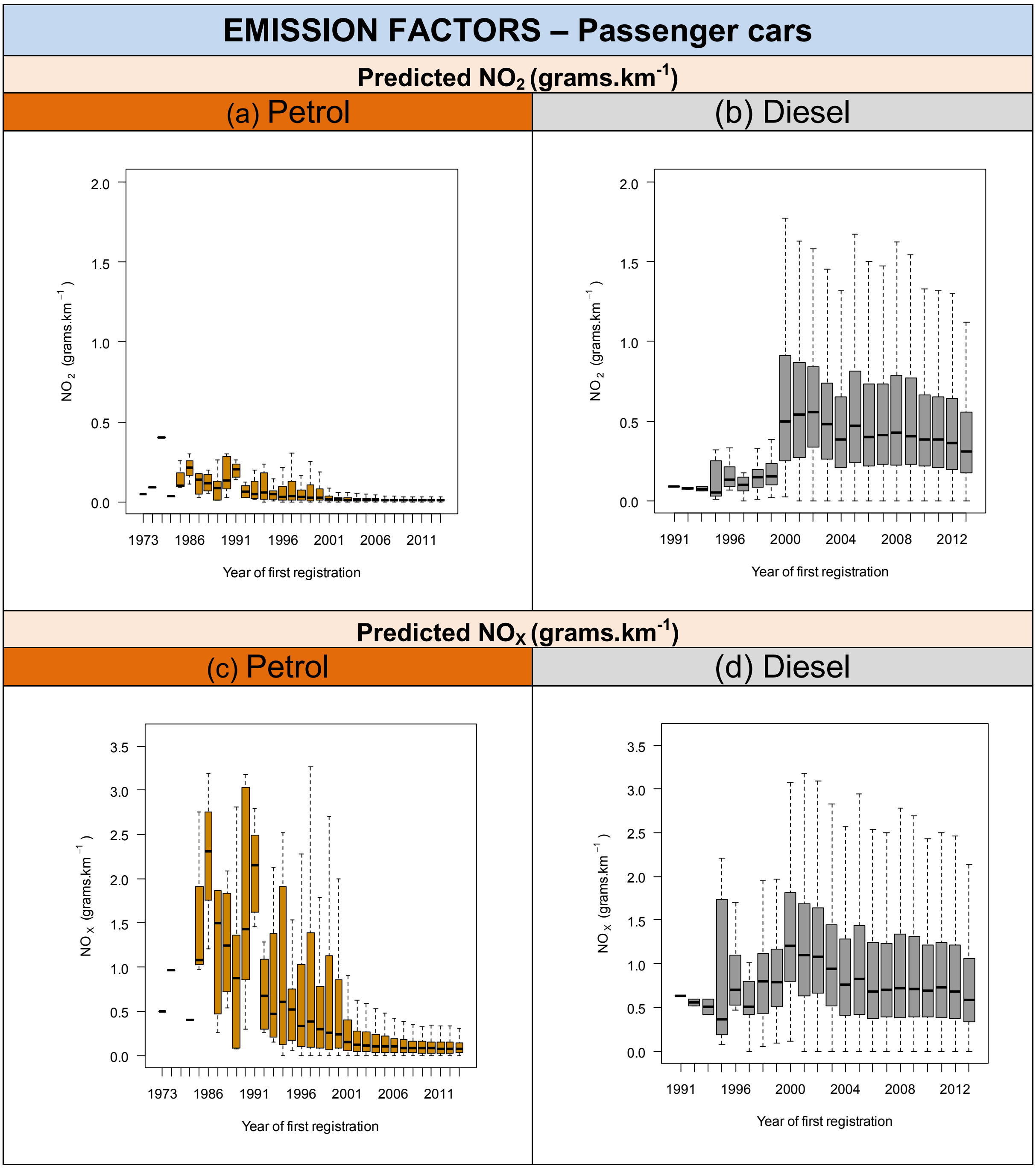


Figure 18: The distribution of the predicted passenger car emission factors (grams per kilometre) categorised by Fuel type and Year of registration (a) Petrol NO_2, (b) Diesel NO_2, (c) Petrol NO_X, (b) Diesel NO_X

The predicted NO_X emission factor trends are broadly in-line with earlier studies/ findings (Carslaw et al, 2011) for petrol and diesel passenger cars. The predicted emission factors for passenger cars, alongside the other vehicle categories are documented in the appendix Table A1. The absolute values are however slightly lower. This is partly due to the lower assumed f-NO_2 fractions, but may also be due to differences in the local observed traffic situations.

The power demands on an engine greatly influence fuel consumption and emission rates. Engine power is needed to overcome rolling resistance, internal friction (engine and powertrain), aerodynamic drag, road gradient and changes in kinetic and potential energy (acceleration). The engine power demands of each vehicle pass-by can be estimated as Vehicle Specific Power (*VSP*). *VSP* is now commonly used in vehicle emission models and supports the analysis of transient (low time resolution, ≈ 1Hz) emissions measurements. The empirical relationship derived by Jimenez-Palacios (1998) is used in this study:

$$VSP \approx 0.22.v.a + 4.39.\sin(slope).v + 0.0954.v + 0.0000272.v^3$$

VSP (kW/tonne) where: *v* is the vehicle speed (in mph), *a* is the vehicle acceleration (in mph/sec), *slope* is expressed in degrees. Figure 16 illustrates the influence of VSP on the average NO_X emission factors for Diesel (left panel) and Petrol (right panel) passenger cars. The average emission factors for each fuel type and Euro standard have been calculated for VSP bins (bin size 5 $kW.t^{-1}$). The influence of *VSP* on the emission characteristics of Euro 0 – 5 diesel passenger cars is broadly consistent, with the average NO_X emission factors increasing with *VSP*. Average NO_X emission factors of petrol cars also increase with *VSP,* but unlike diesels, their engine and NO_X emission controls improve through the Euro standards. The results suggest the emission controls of Euro 4 and 5 petrol cars operate well throughout the observed range of power demands.

Emissions along roads with higher engine power demands, such as up-hill sections or approaches to traffic junctions/ signals where vehicles are often accelerating, can therefore be expected to be higher.

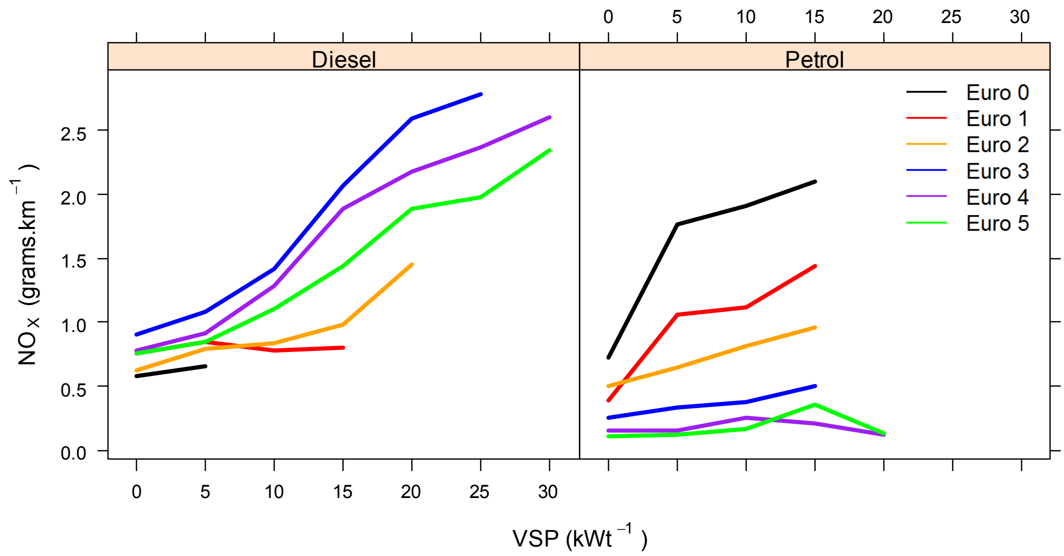


Figure 19: The influence of VSP on the average NO_X performance of (a) Diesel cars (left-panel), (b) Petrol cars (right-panel).

As the speed/ acceleration distributions and road grade are different at the five sites, the *VSP* characteristics will also vary. Differences in the emission factor estimates may therefore be expected. The estimated emission factors for each survey location, categorised by Euro standard, are presented in the Figure 20 boxplots for both Diesel (top-panel) and Petrol (bottom-panel) passenger cars. The median and distribution of emission factors is remarkably consistent between locations for both Diesel and Petrol passenger cars, through the Euro standards 0 to 5.

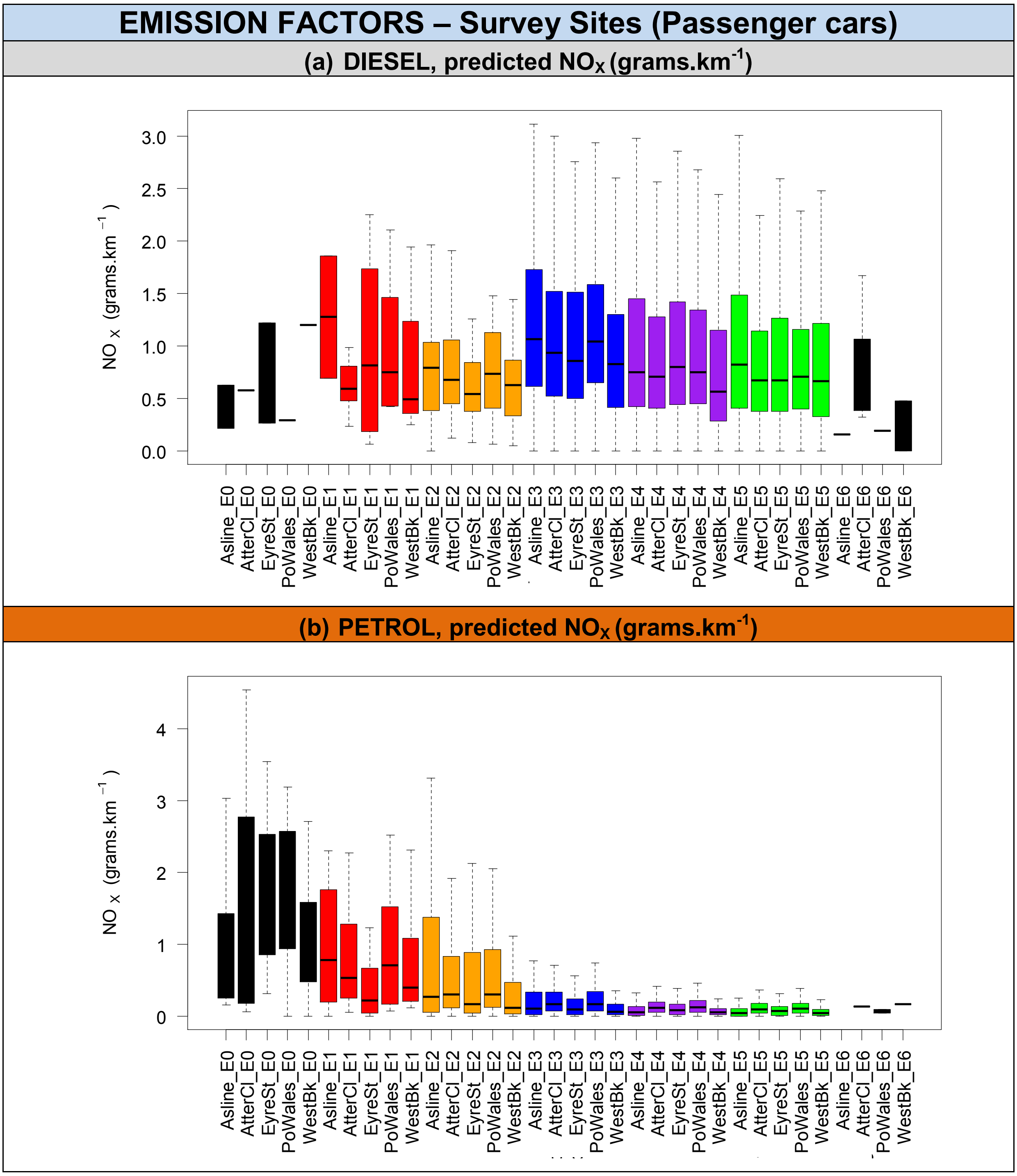


Figure 20: The passenger car emission contributions categorised by Survey Site (abbreviation annotated – see table 1) and Euro standard (annotated E0 – E6), and fuel type (a) Diesel, (b) Petrol.

[Note the boxplots are colour coded for each Euro category:
Euro 0 – **black**, Euro 1 – **red**, Euro 2 – **orange**, Euro 3 – **blue**, Euro 4 – **purple**,
Euro 5 – **green,** Euro 6 – **dark green**]

The estimated emission contribution from each passenger car fuel type and Euro standard combination is presented in the Figure 21 bar charts. The contribution accounts for the passenger car fleet proportions (annotated in [%]) and emission characteristics. Whilst the pre-Euro (Euro 0) petrol cars have poor on-road CO and HC performance, attributed to an absence or degraded exhaust after-treatment system, as they only comprise less than 0.3% of the sample population their contribution is predicted to be small. Similarly although the tail-pipe PM_{10} performance of pre-Euro and Euro 1 diesel cars is poor, as these vehicles are scarce their emission contribution is low.

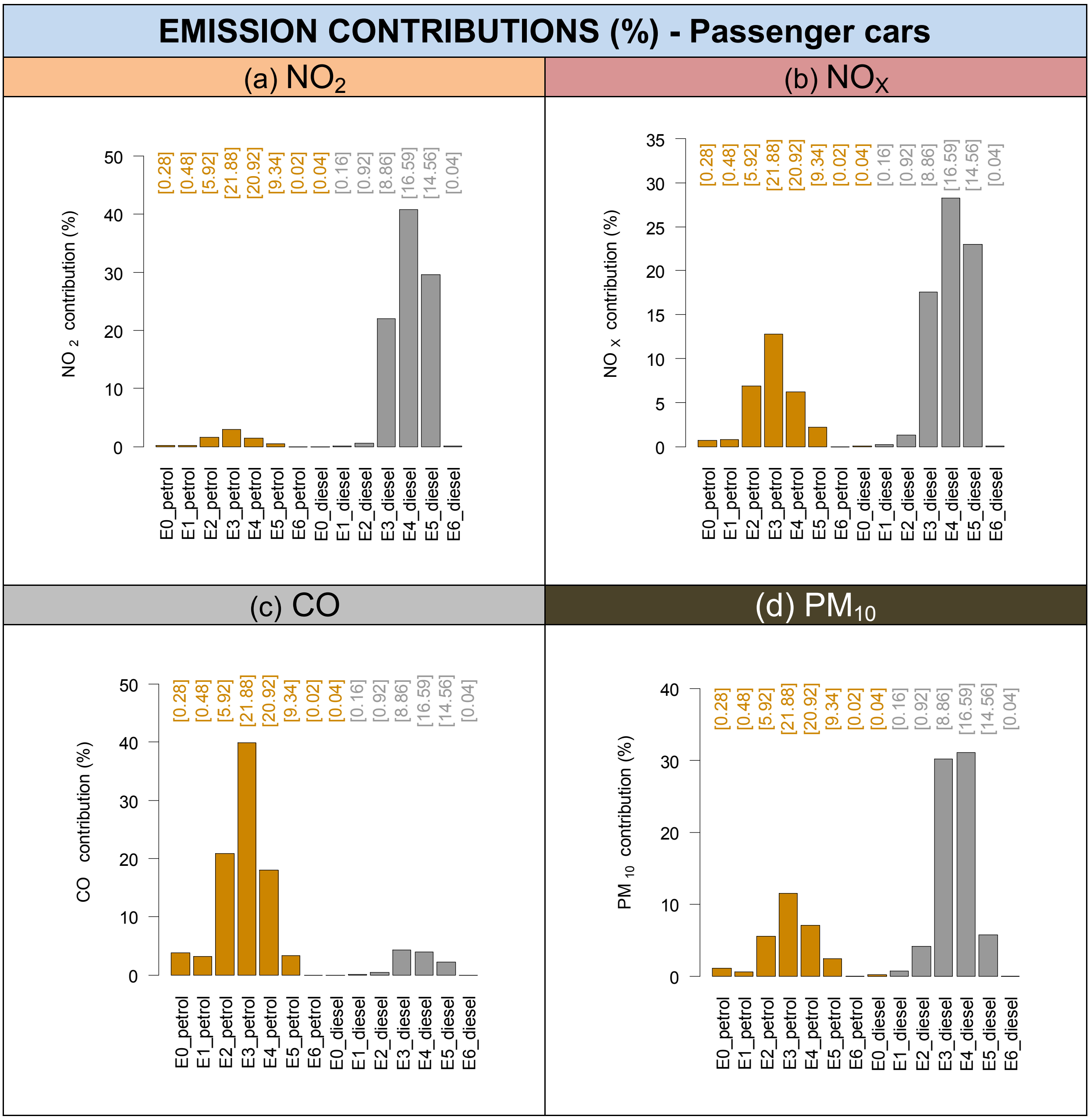


Figure 21: The passenger car emission contributions categorised by Fuel type and Euro standard (a) NO_2, (b) NO_X, (c) CO, (d) PM_{10}.

The remote sensing measurements indicate there has been little change in the NO_X performance of diesel cars through each Euro standard, or the last 15 years or so. Diesel NO_X reduction technologies are shown to be less effective in limiting NO_X emissions in "real-world" (or on-road) conditions. Developing exhaust after-treatment systems such as Diesel Particulate Filters (DPFs) and Diesel Oxidation Catalysts (DOCs), whilst effectively controlling PM_{10} emissions in real-world (on-road) conditions, they are suggested to be ineffective in relation to NO_X in urban driving conditions. As both DPFs (during filter regeneration) and DOCs oxidise exhaust gases, these after-treatment systems lead to higher emissions of NO_2 at the tail-pipe (termed primary NO_2). The measurements and analysis presented in Figure 21(a) clearly illustrate newer passenger diesel cars are a major contributor towards the increase in primary NO_2 emissions.

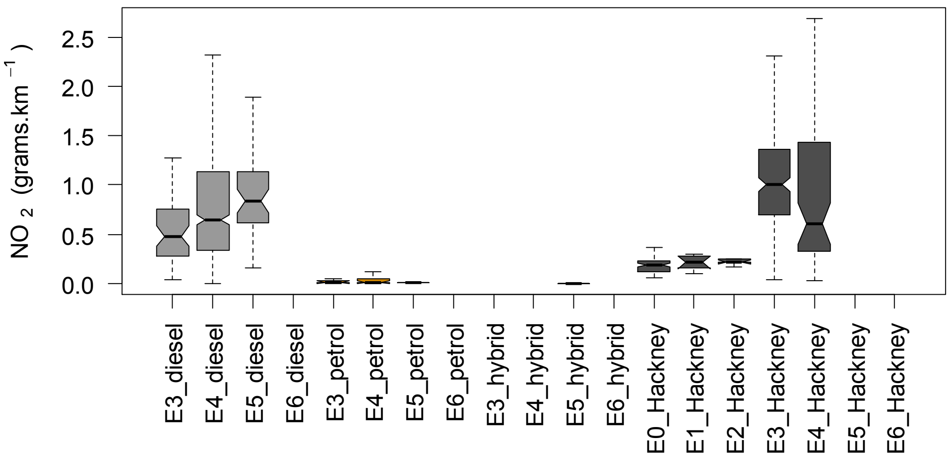
4.3 Emission Measurement Results – Taxis (car based)

The estimated NO_2, NO_X and PM (index) emission factors for the observed taxi fleet are presented in the Figure 22 boxplots. The emission factors for Diesel, Petrol and Hybrid powertrains are presented. Hackney carriages are all diesel based and illustrated as a separate taxi category. The results are broadly in-line with those of passenger cars, albeit with higher absolute values as taxis are typically larger, intensively operated light-duty vehicles, with high annual mileages, it is suggested the degradation of their engine and exhaust after-treatment systems is greater than those of a comparable (make, model, year of registration) private passenger cars. The stop-start driving conditions in urban areas, with dense traffic signal control and high traffic demand is also not well suited to the efficient and clean operation of standard diesel taxis/ cars. Without regular periods of sustained, higher engine power operation (i.e. motorway driving/ speeds) the conditions needed for Diesel Particle Filters (DPFs) to regenerate are absent. DPF faults are therefore common on taxis and expensive to rectify as they are often not under warranty. The remote sensing results demonstrated that the emission performance of taxis is far worse than its private passenger car counter-parts. This is important, not only in understanding the emission contribution from taxis in Sheffield, but also provides an in-sight into the future emission performance of all passenger cars, as their engines and exhaust (emission) after-treatment systems degrade further with use.

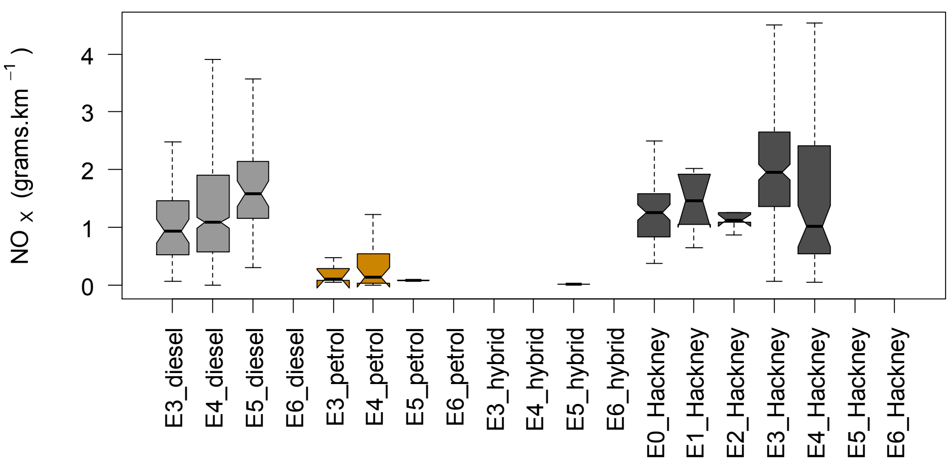
Of all the types of taxis operating in Sheffield the Hackney carriages (diesel) have the worst emission performance, notably their PM_{10} emissions. Hackney carriages are permitted to wait at designated locations in the City centre for passengers. Engines are often kept on. Idling engines not only generate emissions, but as idling exhaust gases are relatively cool, they actively lower DOC and DPF temperatures reducing their effectiveness. A policy to curb un-necessary engine idling at taxi ranks is expected to directly reduce idling emissions but also have wider benefits. Instead of exhaust after-treatment systems being actively cooled by idling emissions, residual heat is kept in the catalysts and they are therefore more effective when the vehicle resumes operation. The diesel Hackney carriage fleet also has a high proportion of vehicles from a single manufacturer: the LTI 'London Hail Taxi' models 'TXI', 'TXII' and 'TX4'. Thirty per cent of the Diesel Hackney carriages are of the iconic 'London Hail Taxi' design.

EMISSION FACTORS – Taxis (car based)

(a) Predicted NO_2 (grams.km^{-1})



(b) Predicted NO_X (grams.km^{-1})



(c) Predicted PM (index)

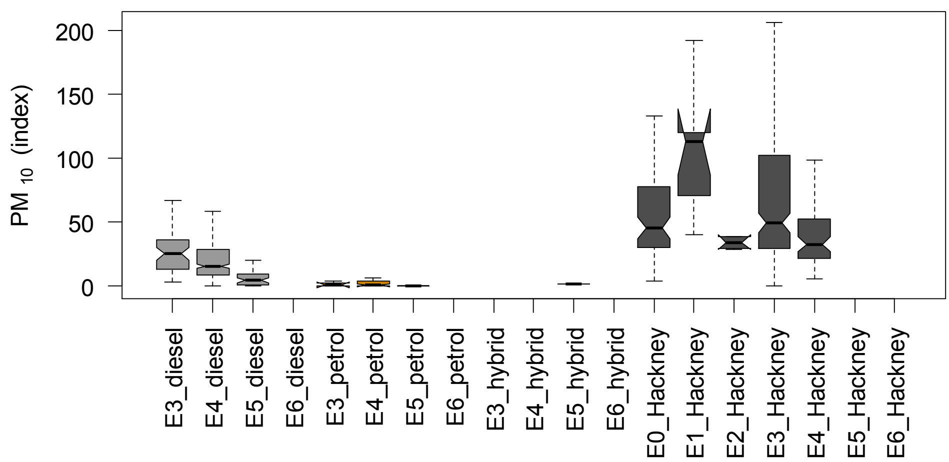


Figure 22: The distribution of the predicted Van emission factors (grams per kilometre) categorised by fuel type and Euro standard (a) NO_2, (b) NO_X, (c) PM (index)

The petrol and hybrid taxis consistently emit less air quality pollutants than their diesel counter-parts. Hybrid vehicle technology, with its regenerative braking systems is particularly well suited to the frequent stop-start driving conditions City taxis typically operate in. Their enhanced electrical systems would also allow drivers to operate heating, ventilation and communication systems whilst waiting at taxi ranks, without keeping the engine running (idling). The current generation of petrol-hybrid vehicles emit low-levels of NO_X and NO_2 in urban driving conditions, in contrast to light-duty diesels. They also offer fuel savings as kinetic energy that would have otherwise been lost under braking, is captured and re-used.

Table 10: Observed taxi fleet proportions (%): registered taxi fleet, vehicle/ fuel type and Euro standard.

	Hackney	PHV		
EURO Standard	*Diesel*	*Petrol*	*Hybrid*	*Diesel*
Euro 0	79	0	0	0
Euro 1	9	0	0	0
Euro 2	6	0	0	0
Euro 3	224	4	0	55
Euro 4	72	23	0	544
Euro 5	0	1	1	50
Euro 6	0	0	0	0
TOTAL (%)	**36.55**	**2.25**	**0.09**	**60.82**

4.4 Emission Measurement Results – Vans

The estimated NO_2, NO_X and PM (index) emission factors for the observed van fleet are presented in the Figure 23 boxplots. The results are broadly in-line with those of passenger cars, albeit with higher absolute values as vans are larger, typically more powerful and heavily loaded vehicles. This is expected as there is a high degree of commonality between the engine and emission control technologies (powertrain) of passenger cars and vans.

The peak NO_2 and NO_X emission for vans are the latest Euro 5 vehicles. It is suggested this is because the average van weight is increasing with time. Newer vehicles may well also be driven more aggressively (higher average *VSP*) and operated with larger loads.

Diesel van particle emission controls are shown to improve with each successive Euro standard.

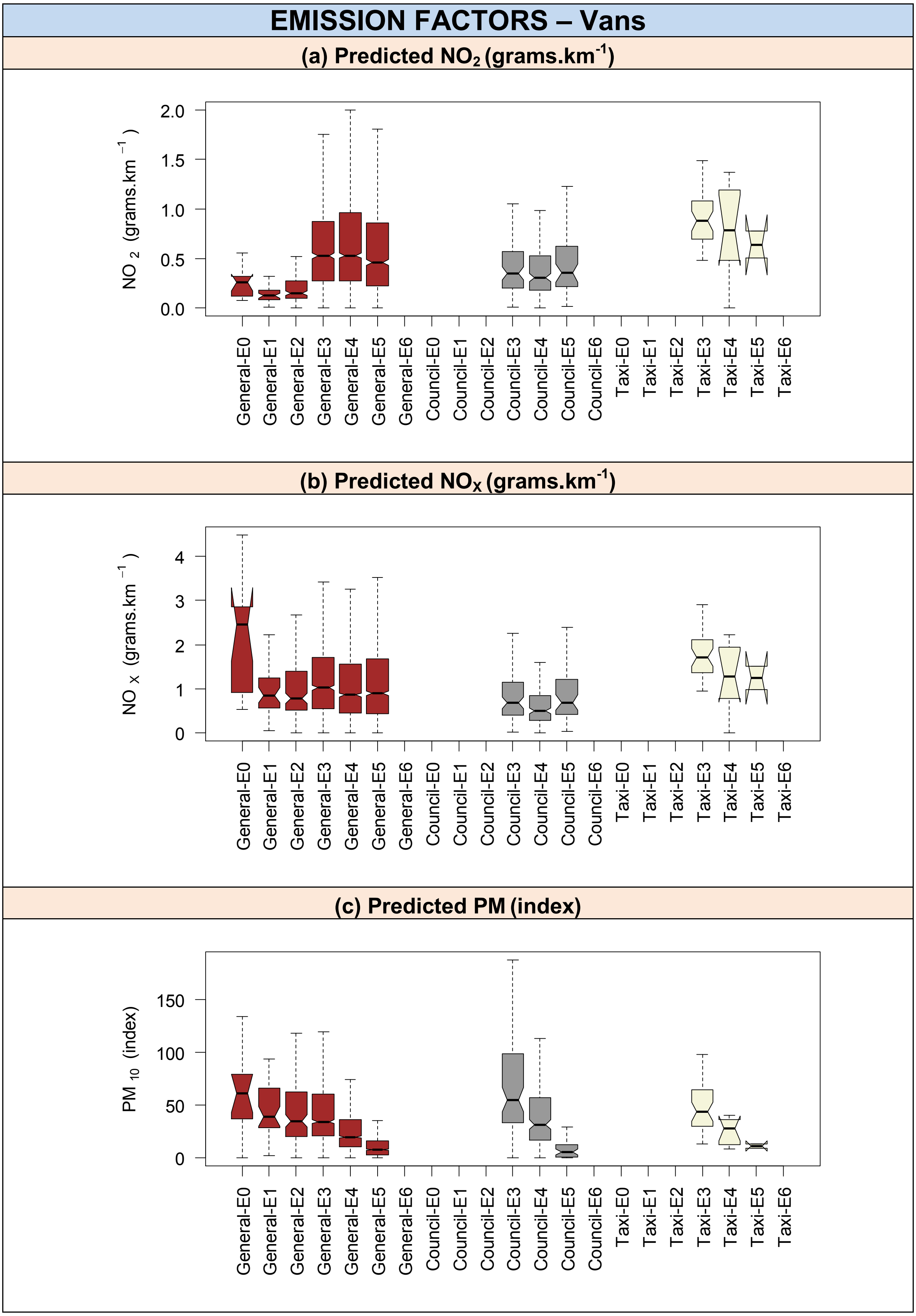


Figure 23: The distribution of the predicted Van emission factors (grams per kilometre) categorised by fuel type and Euro standard (a) NO_2, (b) NO_X, (c) PM (index)

4.4 Emission Measurement Results – OGVs

The estimated NO_2, NO_X and PM (index) emission factors for the operational Ordinary Goods Vehicles (OGVs) are presented in the Figure 24 boxplots. As rated CO_2 performance information for each observed vehicle was not available in the Vehicle Registration Information database (www.carweb.co.uk), average values from the HBEFA for each vehicle sub-category (e.g. OGV rigid Euro 4) were used. The number of OGVs recorded is low in comparison with the other vehicle categories. When the observations are dis-aggregated by Euro classification and whether it is a Rigid or Articulated vehicle, the sample size for the different sub-categories are low. The confidence in the predicted mean Emission Factors are therefore low, indicated by the broad ‘notches’ in the boxplots. OGV particle emission controls are however shown to improve with each successive Euro standard, but their NO_X performance (Emission Factors) in the urban driving conditions are broadly similar through the Euro standards 0 – 5.

4.5 Emission Measurement Results – Buses

The estimated NO_2, NO_X and PM (index) emission factors for the observed Buses are presented in the Figure 25 boxplots. As rated CO_2 performance information for each observed vehicle was not available in the Vehicle Registration Information database (www.carweb.co.uk), average values from the HBEFA for each vehicle sub-category (e.g. Single-decker Euro 4 Bus) were used.

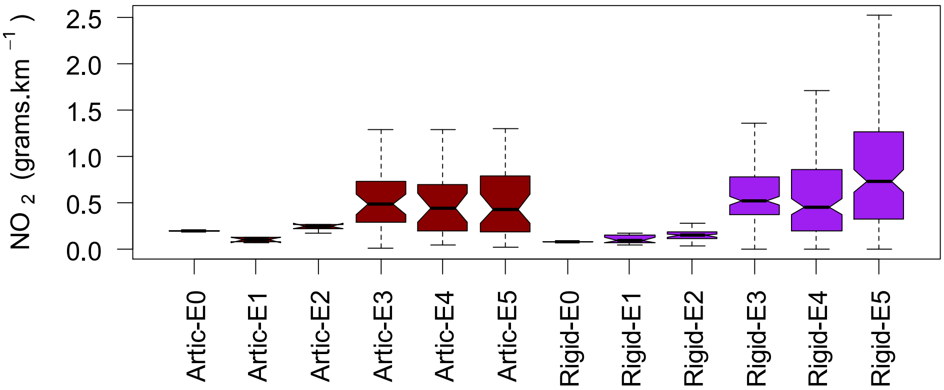
The scheduled Bus service NO_X emission factors were the highest observed/ predicted. Scheduled Buses are also intensively operated, heavy-duty vehicles. Many vehicles operates 18+hours per day, 7 days per week throughout the year, over fixed urban driving routes with frequent stops and starts. These are extremely challenging operating conditions for exhaust after-treatment systems, particularly NO_X emission controls.

The scheduled Bus service NO_X emission factors, given uncertainties in the mean, are broadly similar for the Euro 1 – 5 generations of vehicles. The results suggest an average Euro 1 – 4 scheduled Bus emits ≈10 times more NO_X than a typical diesel car (Euro 0 -5). The on-road measurements indicate the NO_X emission performance of the newer Euro 5 Double-decker Buses is similar to its predecessors. The Euro 5 single-decker Buses generate more NO_X than their predecessors. A policy of renewing the Bus fleet with Euro 5 specification vehicles is therefore not expected to lower emissions of NO_X.

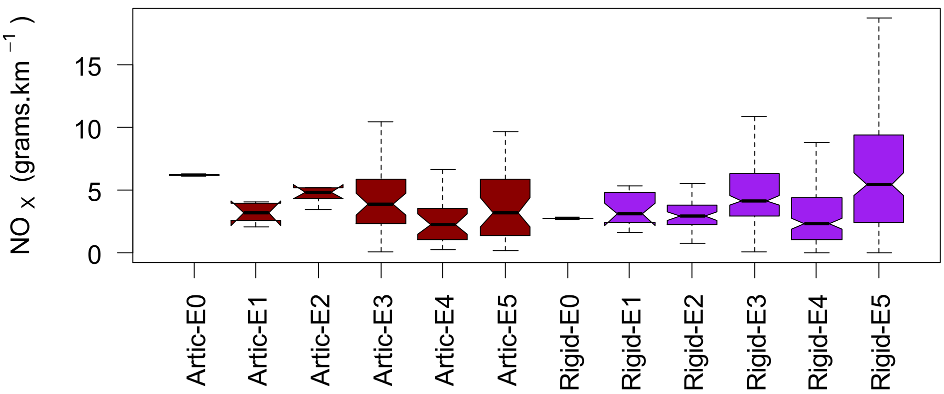
The schedule Bus fleet is assumed to be of interest to Sheffield City Council as the authority has more influence these vehicles than other heavy-duty, and indeed light-duty, vehicle types through Bus Quality partnerships, Local Transport Plans and Bus operator engagements etc. Their observed fleet share is also greater than OGVs. As scheduled Buses repeat services/ journeys/ routes many times a day, multiple pass-bys/ measurements of many vehicles were available. Figures 26 and 27 present the estimated emission factors for individual Single-decker and Double-decker Buses respectively, where five or more pass-by measurements were available.

EMISSION FACTORS – OGVs

(a) Predicted NO_2 (grams.km^{-1})



(b) Predicted NO_X (grams.km^{-1})



(c) Predicted PM (index)

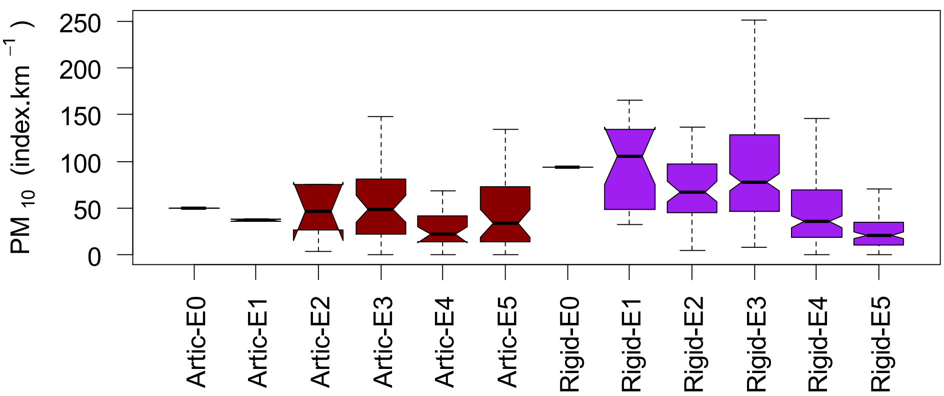
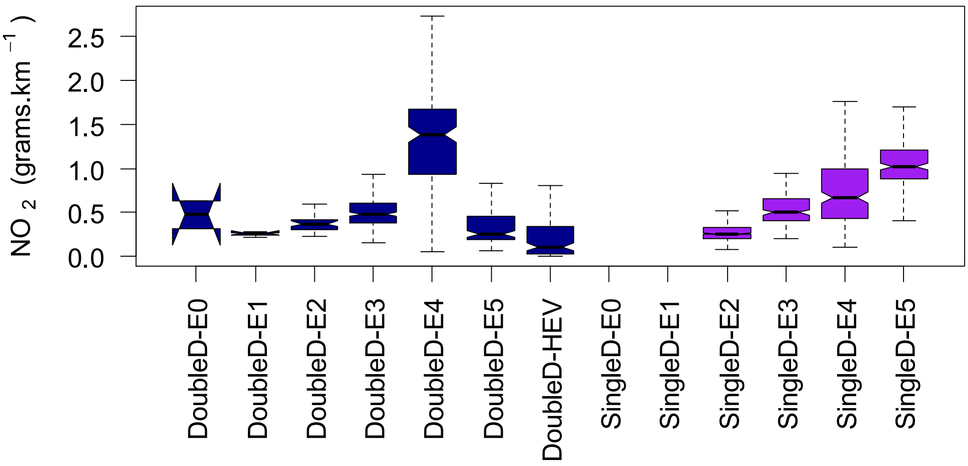


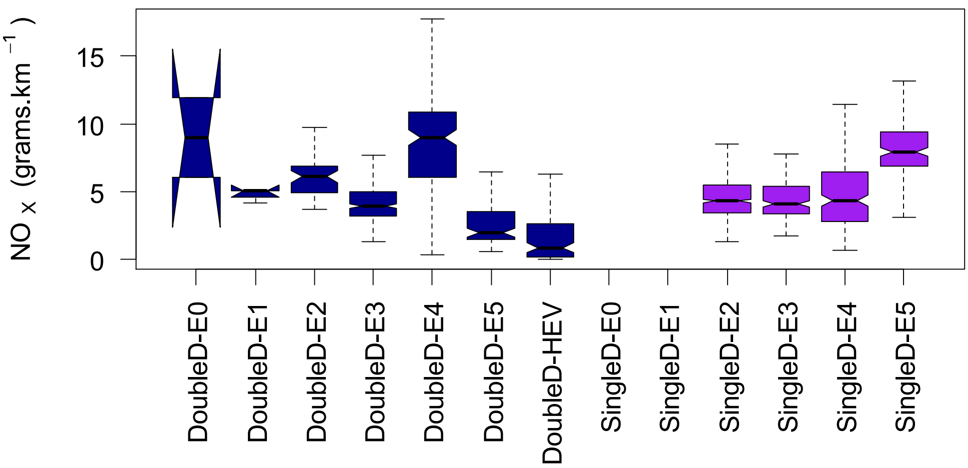
Figure 24: The distribution of the Rigid and Articulated OGV emission factors (grams per kilometre) categorised by fuel type and Euro standard (a) NO_2, (b) NO_X, (c) PM (index)

EMISSION FACTORS – Buses

(a) Predicted NO_2 (grams.km^{-1})



(b) Predicted NO_X (grams.km^{-1})



(c) Predicted PM (index)

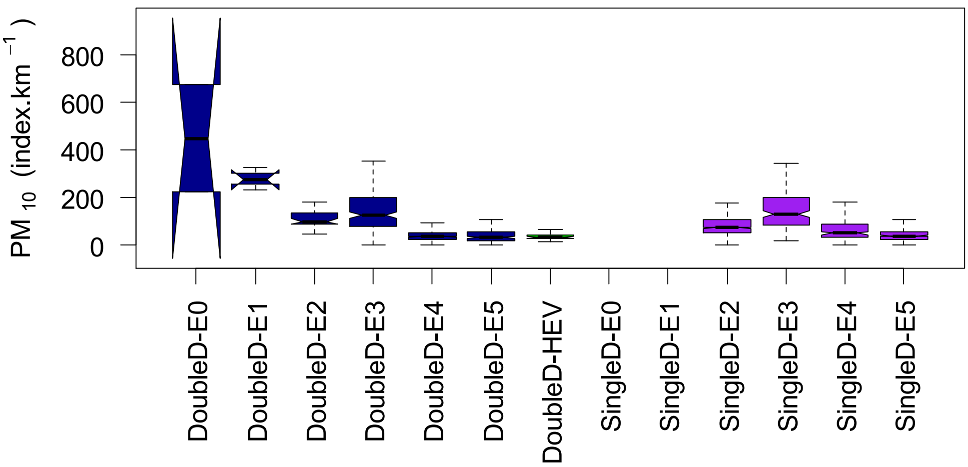


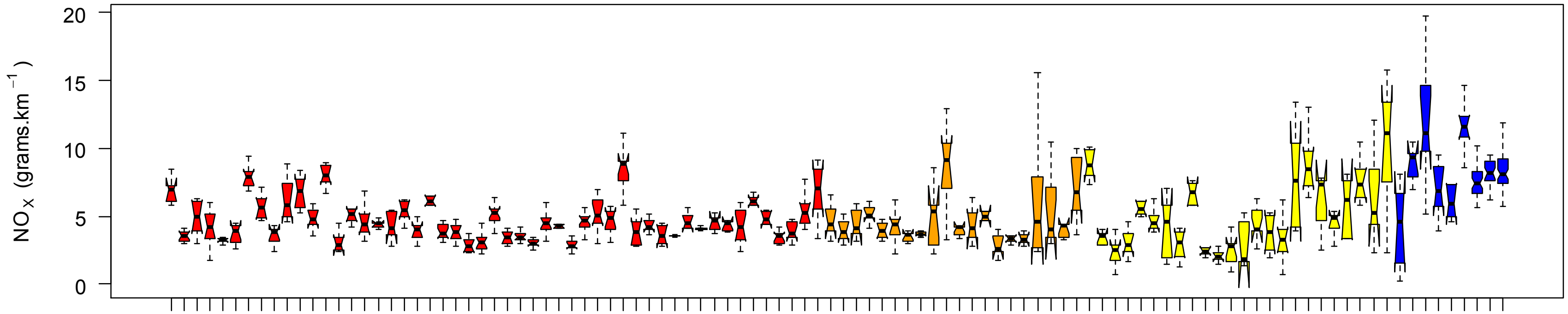
Figure 25: The distribution of the Bus emission factors (grams per kilometre) categorised by fuel type and Euro standard (a) NO_2, (b) NO_X, (c) PM (index)

Although there is some variation in the estimated emission factors for an individual vehicle, there is greater variation between vehicles of the same Euro classification or otherwise. Older Buses were found to be the worst emitters of PM_{10}. This trend is clearer for the larger, heavier Double-decker Buses e.g. Figure 27(b). Although more recent Euro 4 and Euro 5 heavy-duty vehicles have better PM_{10} emission characteristics (estimated emission factors), levels are still very high (e.g. Euro Single-decker 5 Bus, mean value ≈40) relative to Euro 5 passenger cars (mean value ≈4). There is a marked difference in the NO_X emission performance trends of Single-decker and Double-decker Buses. Single-decker Buses are predicted to emit similar amounts of NO_X through the Euro standards 2-4. Eight of the nine Euro 5 Single-decker Buses, for which there are multiple observations/ pass-bys, were observed to be consistently emitting large amounts of NO_X. All these vehicles were from a single manufacturer - Alexander Dennis. The NO_X controls (exhaust after-treatment systems) on these vehicles are not effective for their operating conditions in Sheffield. The last three vehicles in the Figure 26 (a) (far-right hand-side) are all Alexander ALX200 "midi-buses". These are lighter single-decker vehicles at ≈8900kg un-laden. There are 127 measurements from just these three vehicles as they made multiple pass-bys at the Eyre Street survey location, so confidence in the assessment and predicted Emission Factor is high.

EMISSION FACTORS – Individual SINGLE-DECKER Buses

Multiple pass-by measurements

(a) Predicted NO_X (grams.km^{-1})



(b) Predicted PM (index)

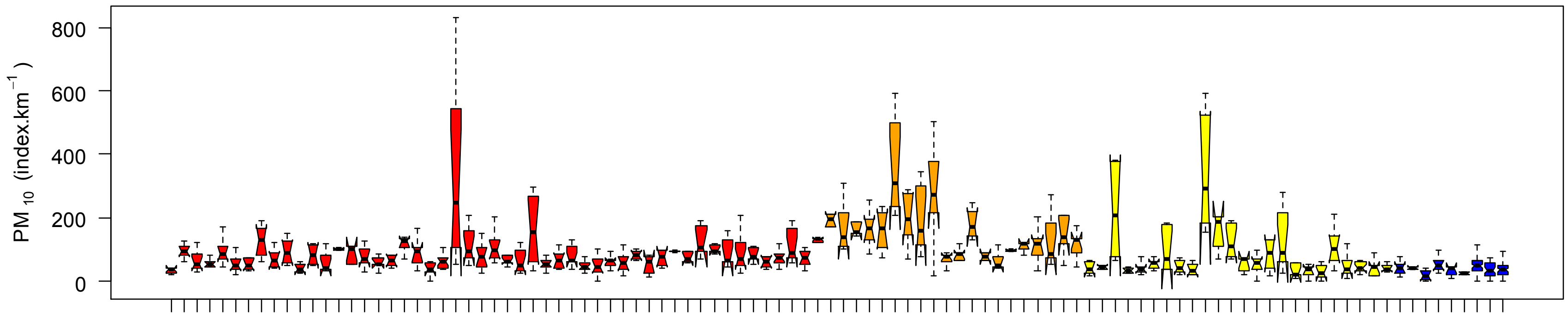


Figure 26: The estimated emission factors for individual Single-decker Buses ordered by age of first registration (a) NO_X, (b) PM_{10} (index)

[Note the boxplots are colour coded according to the vehicles respective Euro standard: Euro 2 – **red**, Euro 3 – **orange**, Euro 4 – **yellow**, Euro 5 – **blue**]

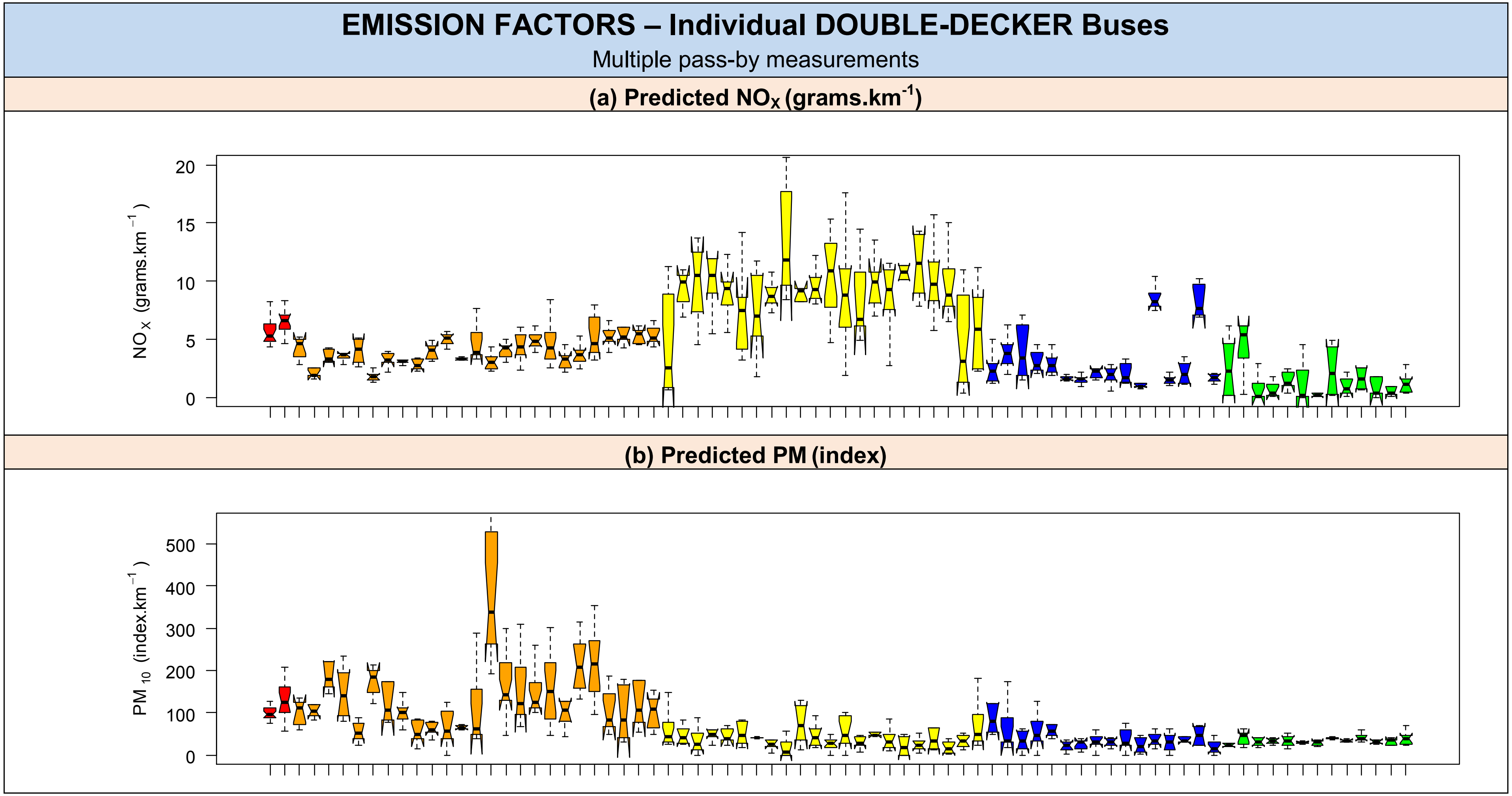


Figure 27: The estimated emission factors for individual Double-decker Buses ordered by age of first registration (a) NO_X, (b) PM_{10} (index)

[Note the boxplots are colour coded according to the vehicles respective Euro standard: Euro 2 – **red**, Euro 3 – **orange**, Euro 4 – **yellow**, Euro 5 – **blue,** Euro 5 HEV – **green**]

4.6 Passenger Car Emission Distributions

An application of vehicle emission RSD technology is to identify the abundance and significance of high-emitting vehicles on the road. The density plots in Figure 28 present the changes in the estimated NO_X emission factor (continuous) distributions for the passenger car fleet, categorised by the Euro standard and fuel type (Petrol, left-panels; Diesel, right-panels). The *y* axis scales are set in the top-panel so the maximum densities can be viewed, whereas the scales in the bottom-panels are truncated so the right-hand tail of the distributions containing the vehicles with poorer emission performance are illustrated.

Petrol cars with elevated NO_X emissions in the right-hand tail of the distributions are commonly older vehicles in the Euro categories 0 – 2. The proportion of vehicles with very low emissions also tends to increase with each successive more stringent Emission standard. The skewed nature (gamma distribution) of the vehicle emission ratios indicates that a small number of more polluting vehicles can contribute a significant proportion to the total emissions. The distributions of diesel cars Euro 0 to 5 are broadly similar (range and distribution).

The density plots for the PM_{10} (index) measure are illustrated in Figure 29. The petrol car distributions/ results are similar to the NO_X species, except in Figure 23(c) a separation between the skewed gamma distribution and *outliers*, that could be termed high emitting vehicles, is apparent. The proportion of the diesel cars with elevated PM_{10} (index) emissions falls through the Euro 0 -5 emission categories. The majority of Euro 4 and 5 diesel cars emit comparatively little PM_{10}.

The density distributions for the CO species (Figure 30) are quite different those of NO_X and PM_{10}. The separation of *outlier* measurements from the sample populations, suggests a small number of vehicles have considerably poorer emission performance than the average fleet and may well have an engine and/ or emission control fault, or may not be in ‘hot-running’ operation (e.g. a recent ‘cold-start’).

In order to quantify the abundance and emission contribution of high-emitting vehicles, it is necessary to develop and apply classification criteria. In this study a two-step approach has been used:

1. Identify passenger cars with *elevated* emissions. The threshold for passenger cars with *elevated* emissions is when an emission factor estimate is greater than the fleet mean plus 3 standard deviations for any pollutant (NO_X, PM_{10} and CO); and
2. Identify *high-emitters*. A *high-emitter* is a car that is classified as having *elevated* emissions for more than one pollutant species.

Table 11 documents the *elevated* emission threshold and the number, percentage and contribution to the estimated total emissions. The small proportion of vehicles classified as having *elevated* emissions, are responsible for a significant proportion of the total NO_X (12%), PM_{10} (21%) and CO (35%) estimated to be emitted.

The contribution to the total emissions of the critical species NO_X and PM_{10} from the small (0.14% of the passenger car fleet) subset of *high-emitter* cars is less pronounced (0.6% and 2% respectively). These *high-emitter* cars did however contribute a more significant proportion of the total CO (3%) estimated to be emitted. This investigation suggests a policy of identifying and removing *high-emitters* would have a minimal impact on the total emissions of NO_X and PM_{10}.

Table 11: Summary of passenger cars identified as having 'elevated' emissions.

Pollutant	***Mean*** *(grams.km^{-1})*	***Elevated*** Emission Threshold (Mean + 3stdev)	**% Vehicles**	**% Contribution** (Emission total)
NO_X	0.552	2.704	1.94	12.00
PM_{10} Index	11.339	91.194	1.39	21.26
CO	0.680	9.951	1.09	34.60

Table 12: The emission contribution from passenger cars identified as being 'high-emitters'

Number vehicles	***% Vehicles***	**%NO_X emissions**	**%PM_{10} emissions**	**%CO emissions**
49	0.14	0.63	1.96	3.30

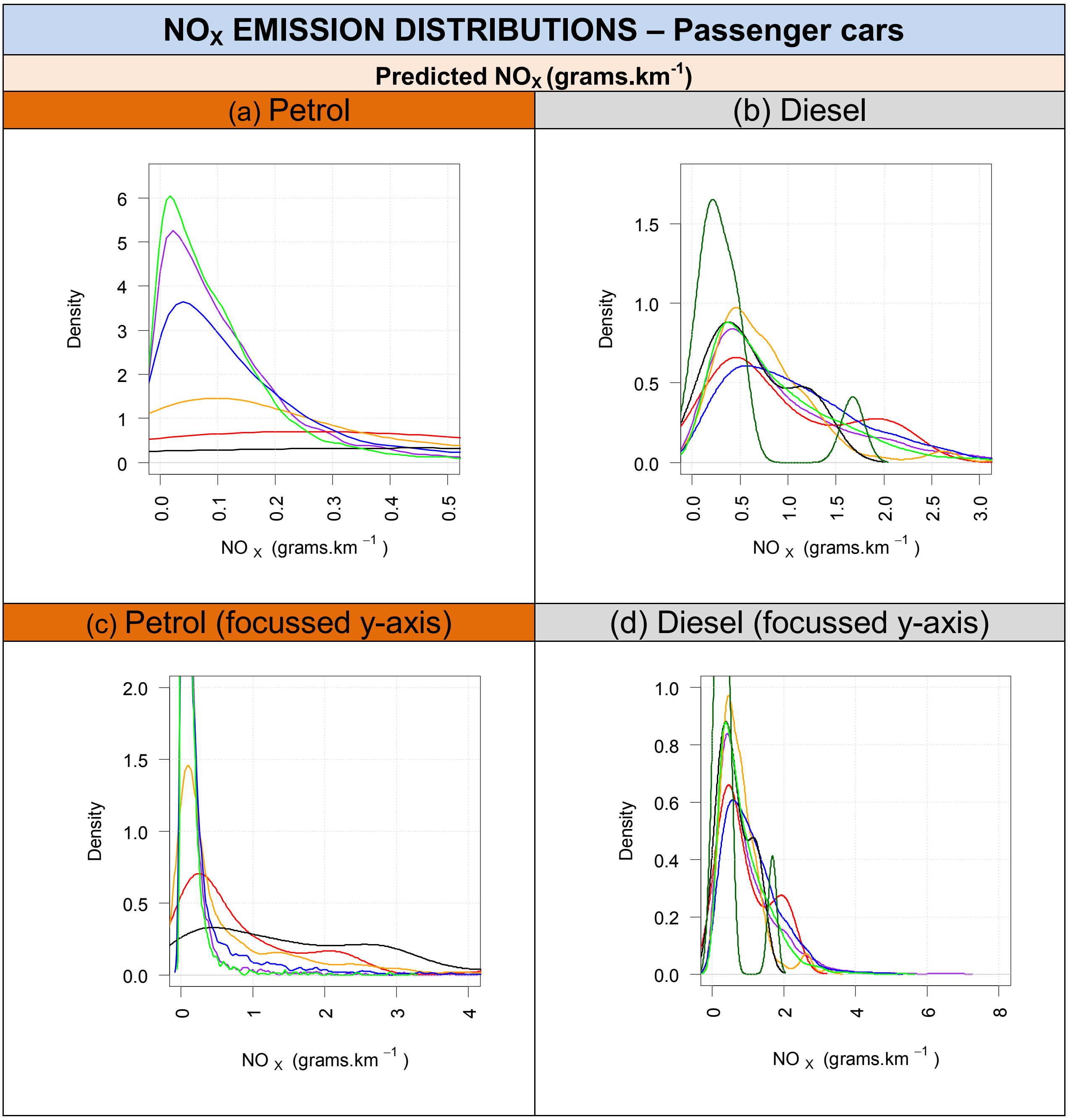


Figure 28: Density Distribution Plots of the estimated NO_X emission factors of passenger cars categorised by fuel type and Euro category: (a) and (c) petrol, (b) and (d) diesel.

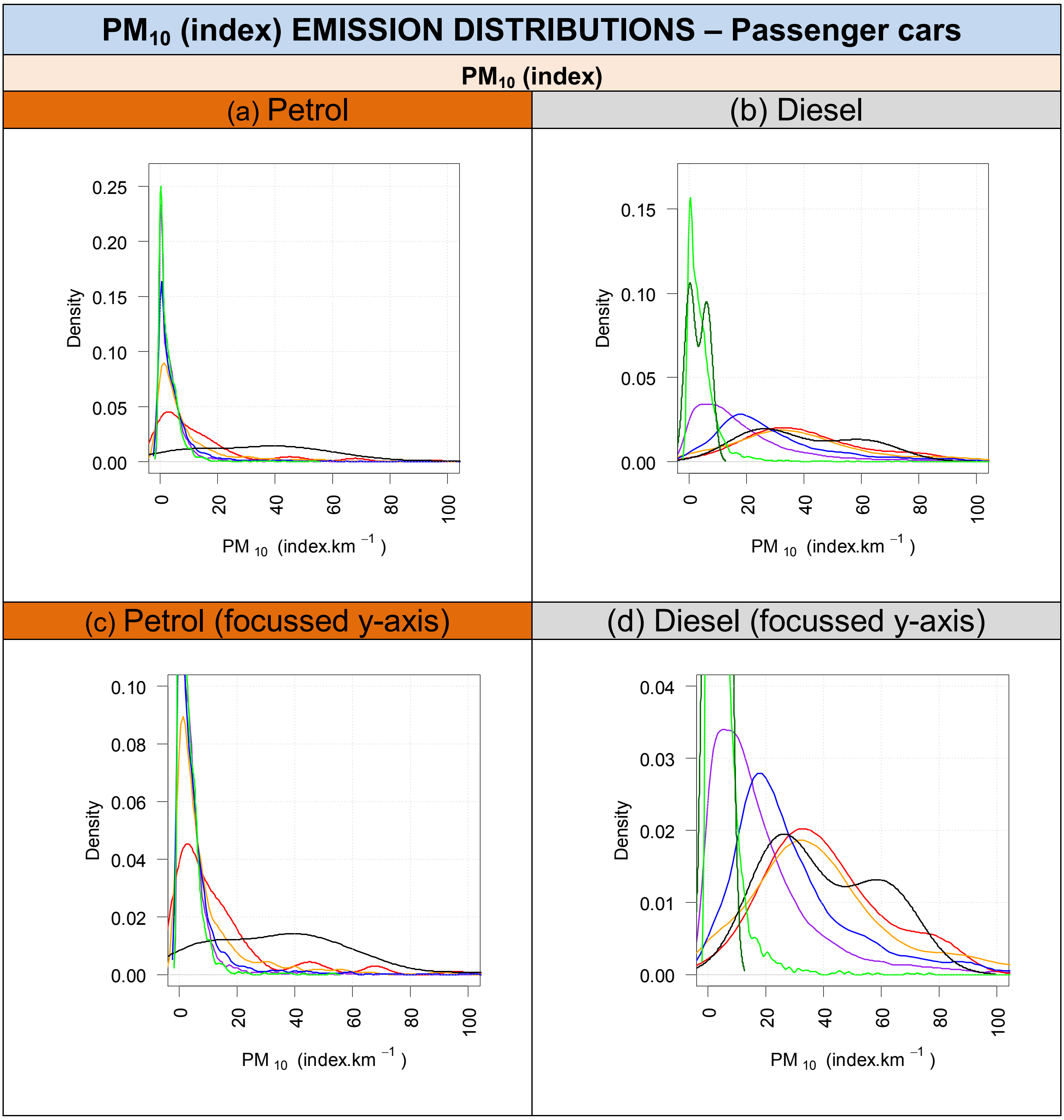


Figure 29: Density Distribution Plots of the estimated PM_{10} emission factors of passenger cars categorised by fuel type and Euro category: (a) and (c) petrol, (b) and (d) diesel.

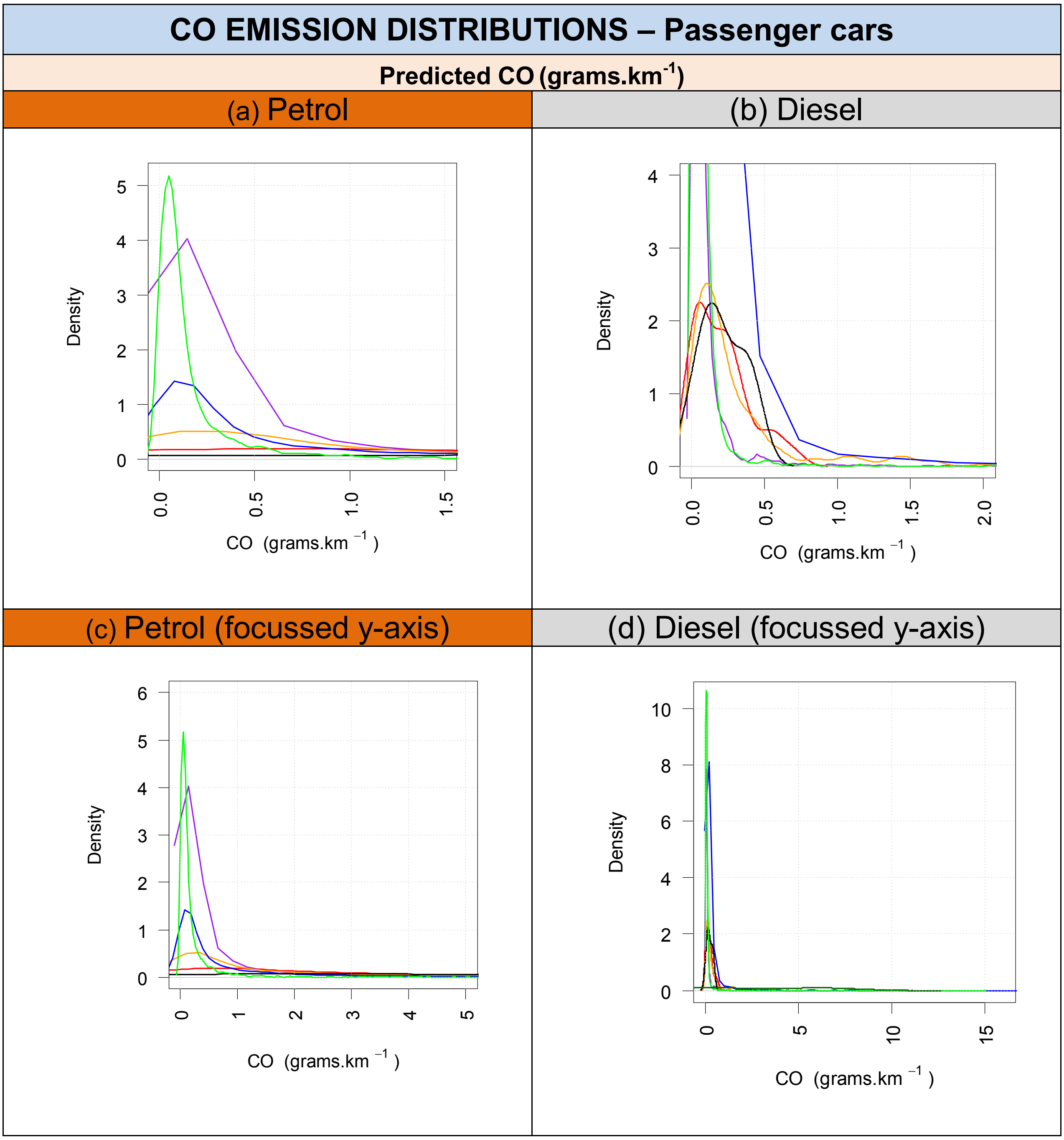


Figure 30: Density Distribution Plots of the estimated CO emission factors of passenger cars categorised by fuel type and Euro category: (a) and (c) petrol, (b) and (d) diesel.

4.7 Speed, Acceleration and Engine Power demands across Sheffield and at the five Vehicle Emission Measurement sites

A criticism of remote sensing studies is that they only survey a limited range of vehicles operation conditions at the fixed sites. The presence of traffic management (signing and cones) is also considered to temper driver's behaviour.

Vehicle tracking surveys were carried out across the wider Sheffield road network, recording the speed and position of a Super-mini (market segment) as it was driven on the main routes in the City during peak and off-peak periods. The position of the vehicle trajectories were fitted to a Digital Terrain Model, so the road gradient and power demands on the engine (*VSP* parameter described in section 4.2) could be reliably calculated.

The distribution of second-by-second (1Hz) speed and acceleration, speed and *VSP*, for the vehicle tracking and vehicle emission measurement (remote sensing) system (passenger cars only) are compared in Figure 31. The frequency of speed/ acceleration and speed/ *VSP* occurrences in hexagonal bins are illustrated on a grey-scale. Darker hexagon bins therefore indicate a higher frequency of data points in that range than lighter shaded areas.

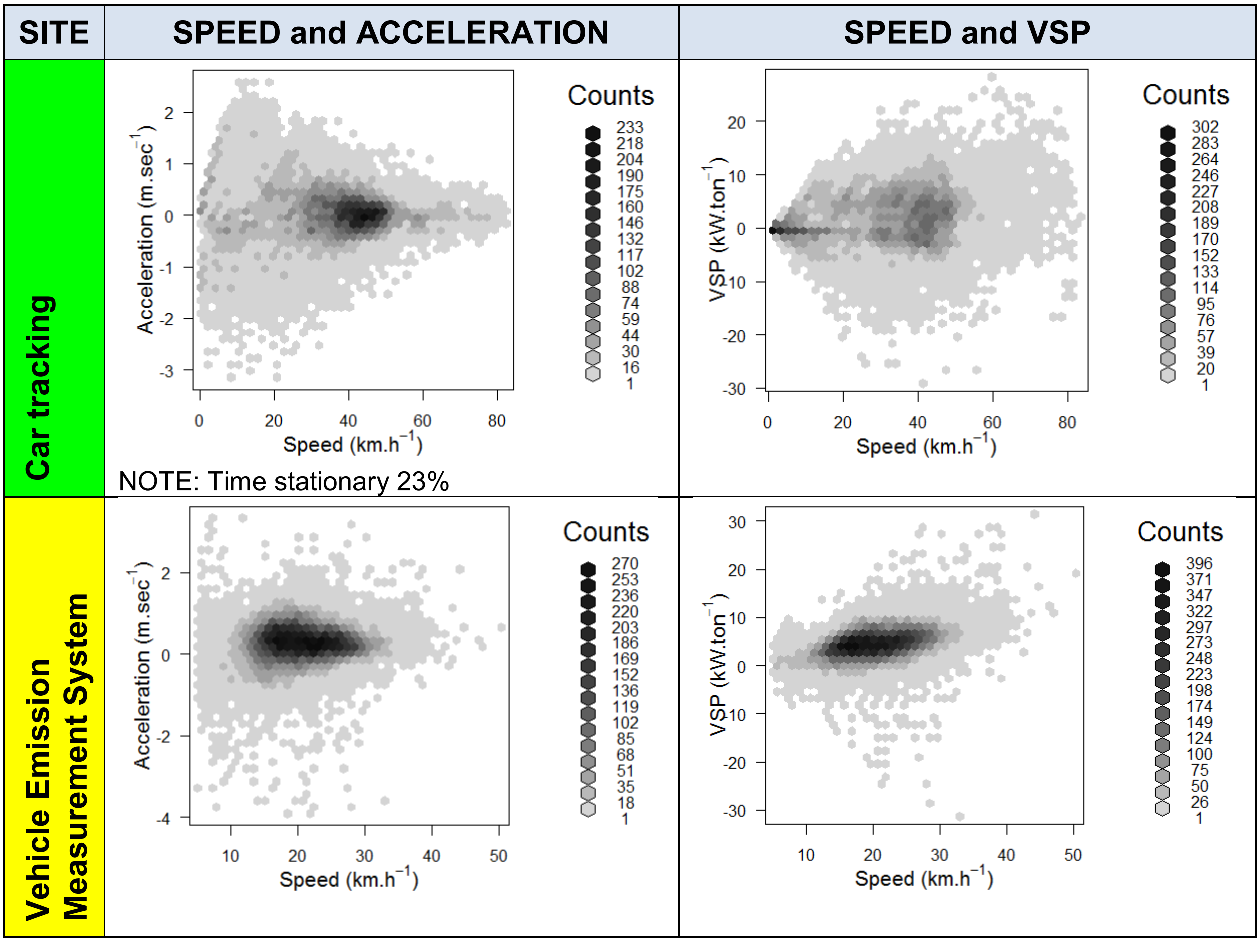


Figure 31: Frequency diagrams of the observed Speed and Accelerations & Speed and VSP distributions from the Vehicle tracking surveys (All) and those recorded by the Vehicle Emission Measurement System (VEMS).

The range of the vehicle accelerations and estimated VSP observed by the mobile and fixed systems are broadly similar. The vehicle tracking surveys cover a wider speed range as the vehicle was driven in 30 m.p.h., 40 m.p.h. and 60 m.p.h. zones. The tracked car also spent more time at lower speeds, as it responded to traffic signals, surrounding vehicles and minor incidents on the network. The remote sensing sites are therefore considered to be broadly representative of the central roads in Sheffield. The average results and emission factors do not appear to be sensitive to the local driving conditions and site location, as illustrated in Figure 20 (Figure 20: The passenger car emission contributions categorised by Survey Site). The distribution of speeds, accelerations and *VSP* at each of the survey sites are presented in the Appendices, Figure A1.

5. Recommendations for Future Work

- The RSD/ VRM look-up approach can rapidly detect and provide an early indication of the performance of emerging vehicle technologies. Historically there has been a greater than one-year time lag between the introduction of a new Euro standard, and the release of an assessment of their emission performance from laboratories. The success or otherwise of the Euro 6 emission standard legislation is of critical importance to the levels of nitrogen dioxide in the medium-term, and whether exceedances of the NO_2 annual mean limit value will be curbed at heavily trafficked locations. A continuing programme of vehicle emission remote sensing campaigns in the UK should be conducted in 2014 so an early assessment of the environmental performance of the Euro 6 generation of vehicles, from different manufacturing clusters, can be established.

- The method to estimate Emission Factors (EFs) relies on estimates of average fuel consumption rates. Confidence in the fuel consumption estimates for passenger cars is higher than for the other vehicle categories, as vehicle and manufacturer/ model specific data is available, rather than being based on average modelled results (HBEFA version 3.2). The informing fuel consumption and CO_2 emission rates for all vehicle categories is considered to be optimistic for the stop-start, urban driving conditions in Sheffield. In future studies, efforts to collate recorded fuel consumption rates (litres / 100km) would enhance the robustness of the emission assessments and estimated emission factors. It is important that these efforts target all vehicle categories to be consistent, seeking support of Public Transport operators and the Road Haulage Association (http://www.rha.uk.net/) for example.

- By fusing knowledge and information from:
  - Vehicle tracking surveys across City networks (all vehicle types); and
  - PEMS (Portable Emission Measurement Systems e.g. http://www.sensors-inc.com/) results;

  an alternative vehicle emission modelling framework maybe developed, that better represents the “real-world” or “on-road” emission performance of the local vehicle fleet.

- Methods to use the remote sensing emission measurements as a real-time ‘*high-emitting*’ vehicle screening tool could be explored. With support from the VOSA (http://www.dft.gov.uk/vosa/) Agency, vehicles classified in real-time as ‘*high-emitters*’ could be pulled in for subsequent testing at a near-by Authorised Testing Facility in an attempt to reduce emissions from the worst offending vehicles.

- Integrate a RSD ‘body-sensor’ to detect when a vehicle is passing the test area. This information can be used to trigger the static camera instead of when a sufficiently large (>10%) CO_2 plume is observed. This would prevent the premature activation of the camera for vehicles with: tail-pipes located at a mid-way point on the chassis, and a high ride height or break in the body panels. This would improve the capture rate of number plate records for the commercial vehicle types.

- Emerging research instruments (Burgard et al, 2006) in the US have recently extended the RSD capability to sense nitrogen dioxide (NO_2) and ammonia (NH_3). A study with this research instrument has been carried out in Greater London in the summer of 2012 and 2013. Results from this study, particularly the average and variation in observed primary NO_2 fractions for the different vehicle segments are awaited and will be combined in future studies/ analysis.

- Collate the Sheffield vehicle emission remote sensing evidence with other UK studies, i.e. the Leeds City region surveys 2012 (Bradford, Kirklees, Leeds and York), Cambridge 2013, and the Greater London study, so enhanced analysis techniques can be applied and confidence in assessments of vehicle sub-categories with low sample sizes can be improved.
- Develop a detailed traffic and vehicle emission modelling capability to help design and provide improved, reliable assessments of the Sheffield Air Quality Action Plans. It is now practical to couple traffic microsimulations, which model the movement of individual vehicles through the well specified road network, with instantaneous vehicle emission models that provides second-by-second fuel consumption and tail-pipe emission predictions. As the modelling approach is a step towards a second-by-second "virtual" representation of the "real" traffic network, it naturally encapsulates many events and processes that effect vehicle emissions. Urban Buses for example have to make additional stops-and-starts to pick up passengers on their scheduled routes. As Buses are large, heavy-duty diesel vehicles these stop-start motions have a significant fuel and emission penalty. The proposed detailed modelling approach can simulate and consider this behaviour, more aggregate approaches do not.

  Advances in desktop computing mean it is also now feasible to micro-simulate traffic movements at a detailed level as they negotiate traffic junctions, signals and interact with each other for complete City networks e.g. Tate, 2012. Microscopic traffic simulation models are frequently used by transport engineers and planners to analyse traffic operations and evaluate management strategies. It is therefore likely that traffic microsimulation networks developed for transport planning purposes may be available to support improved environmental assessments.

6. References

Bishop, G., Starkey, J., Ihlenfeldt, A. 1989. IR long-path photometry: a remote sensing tool for automobile emissions. Analytical Chemistry, 61: 671A.

Burgard, D.A.; Dalton, T.R.; Bishop, G.A.; Starkey, J.R.; Stedman, D.H. 2006. A Nitrogen Dioxide, Sulfur Dioxide, and Ammonia Detector for Remote Sensing of Vehicle Emissions. Rev. Sci. Instrum., 2006, 77, 014101/1-014101/5 [DOI: 10.1063/1.2162432].

Cadle, S., Stephens, R. 1994. Remote sensing of vehicle exhaust emissions. Environmental Science & Technology, 28: 258A-.

Carslaw, D. 2005. Evidence of an increasing NO_2/NO_X emissions ratio from road traffic emissions. Atmospheric Env. 39, pp. 4793 – 4802.

Carslaw, D. and Beevers, S. 2005. Estimations of road vehicle primary NO_2 exhaust emission fractions using monitoring data in London. Atmospheric Env. 39, pp 167-177

Carslaw, D., Beevers, S. Westmoreland, E. Williams, M. Tate, J. Murrells, T. Stedman, J. Li, Y., Grice, S., Kent, A. and I. Tsagatakis. 2011. Trends in NO_X and NO_2 emissions and ambient. [Accessed 9th March 2011] http://uk-air.defra.gov.uk/reports/cat05/1103041401_110303_Draft_NOx_NO2_trends_report.pdf

Carslaw, D., Williams, M., Tate, J., Beevers, S. 2012. The importance of high vehicle power for passenger car emissions. Atmospheric Environment, In press, 10.1016/j.atmosenv.2012.11.033

Carslaw, D., Rhys-Tyler, G. 2013. Remote sensing of NO2 exhaust emissions from road vehicles, A report to Defra. King's College London and Newcastle University, Draft 11th April 2013

Grice, S., Stedman, J., Kent, A., Hobson, M., Norris, J., Abbott, J., Cooke, S. 2009. Recent trends and projections of primary NO_2 emissions in Europe. Atmospheric Env. 43, pp. 2154 – 2167.

Hausberger, S. 2010. Fuel Consumption and Emissions of Modern Passenger Cars. Report Nr. I-25/10 Haus-Em 07/10/676 from 29.11.2010. Technical University of Graz, AT.

Hausberger, S., Rexeis, M., Zallinger, M., Luz, R. 2011. User Guide to the PHEM Emission Model. Version 10. Technical University of Graz, Austria, January 2011.

HEBFA. 2010. Handbook emission factors for road transport (HBEFA). Version 3.1, Jan. 2010. [Accessed 18th September 2012] http://www.hbefa.net/

Jerksjö, M., Sjödin, A., Bishop, G.A., Stedman, D.H., 2008. On-road emission performance of a European vehicle fleet over the period 1991-2007 as measured by remote sensing. 18th CRC On-Road Vehicle Emissions Workshop San Diego, March 31-April 2, 2008.

Jiminez-Palacios, J. 1999. Understanding and Quantifying Motor Vehicle Emissions with Vehicle Specific Power and TILDAS Remote Sensing. PhD Thesis, Department of Mechanical Engineering, Massachusetts Institute of Technology.

National Audit Office. 2009. Briefing for the House of Commons Environmental Audit Committee. December 2009. [Accessed 12th January 2010] http://www.nao.org.uk/publications/0910/eac_briefing_-_air_quality.aspx

Popp, P., Bishop, G., Stedman, D. 1997. Development of a High-Speed Ultraviolet Spectrophotometer Capable of Real-Time NO and Aromatic Hydrocarbon Detection in Vehicle Exhaust. 7th CRC On-Road Vehicle Emissions Workshop, San Diego, CA.

R Development Core Team. 2006. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. ISBN 3-900051-07-0, URL http://www.R-project.org.

SMMT. 2011. New car market betters forecast but was down 4.4% in 2011 to 1.94 million. The Society of Motor Manufacturers and Traders (SMMT), 6th of January 2012. [Accessed 6th January 2012] http://www.smmt.co.uk/2012/01/new-car-market-bettersforecast-but-was-down-4-4-in-2011-to-1-94-million/

Stedman, D., Bishop, G., Aldrete, P. 1997. On-road evaluation of an automobile emission test program. Environmental Science & Technology, 31: 927-31.

Tate, J. 2010. The on-road emission characteristics of UK passenger cars: The application of a remote sensing vehicle emission measurement system. Transport and Air Pollution Conference, Zurich, 2010.

Tate, J. 2012. Assessing Low Emission Zone and Demand Management policies using detailed traffic and vehicle emission measurements and coupled models. 19th International Transport and Air Pollution Conference, Thessaloniki, Greece, 26-27 November, 2012

Tate, J. 2012. Modelling Low Emission Zone and Demand Management measures in the City of York using Detailed Traffic-emission Tools. Investigation of Air Pollution Standing Conference, June 2012, London. [Accessed 24th July 2012] http://www.iapsc.org.uk/document/0612_J_Tate_for_web.pdf

Volvo Buses. 2011. The only commercially viable hybrid. [Accessed 6th January 2012] http://www.volvobuses.com/bus/global/engb/products/City%20buses/Volvo%207700%20Hybrid/Pages/Introduction_new.aspx

Wright Bus. 2011. Hybrid-electric vehicles a clean way forward. [Accessed 6th January 2012]

WHO. 2012. Diesel Engine Exhaust Carcinogenic. International Agency for Research on Cancer, World Health Organisation. [Accessed 12th July 2012] http://press.iarc.fr/pr213_E.pdf

Zhang, Y., Stedman, D., Bishop, G., Beaton, S., Guenther, P., McVey, I. 1996. Enhancement of Remote Sensing for Mobile Source Nitric Oxide. J. Air Waste Manage. Assoc, 46: 25-29.

7. Appendices

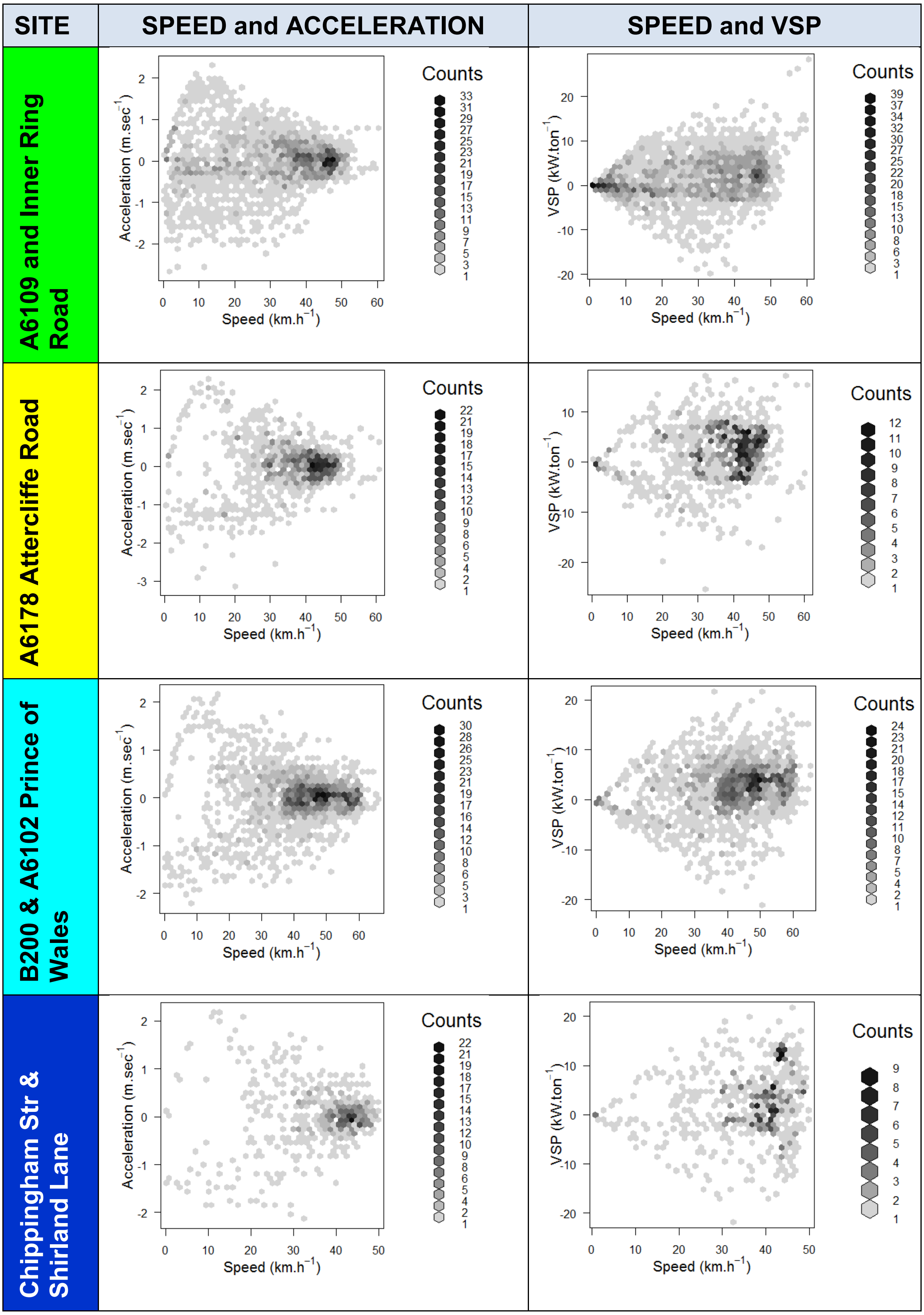
Table A1: Summary CO_2, NO_X, NO_2 and PM_{10} (index) emission factors – Passenger cars & Taxis.

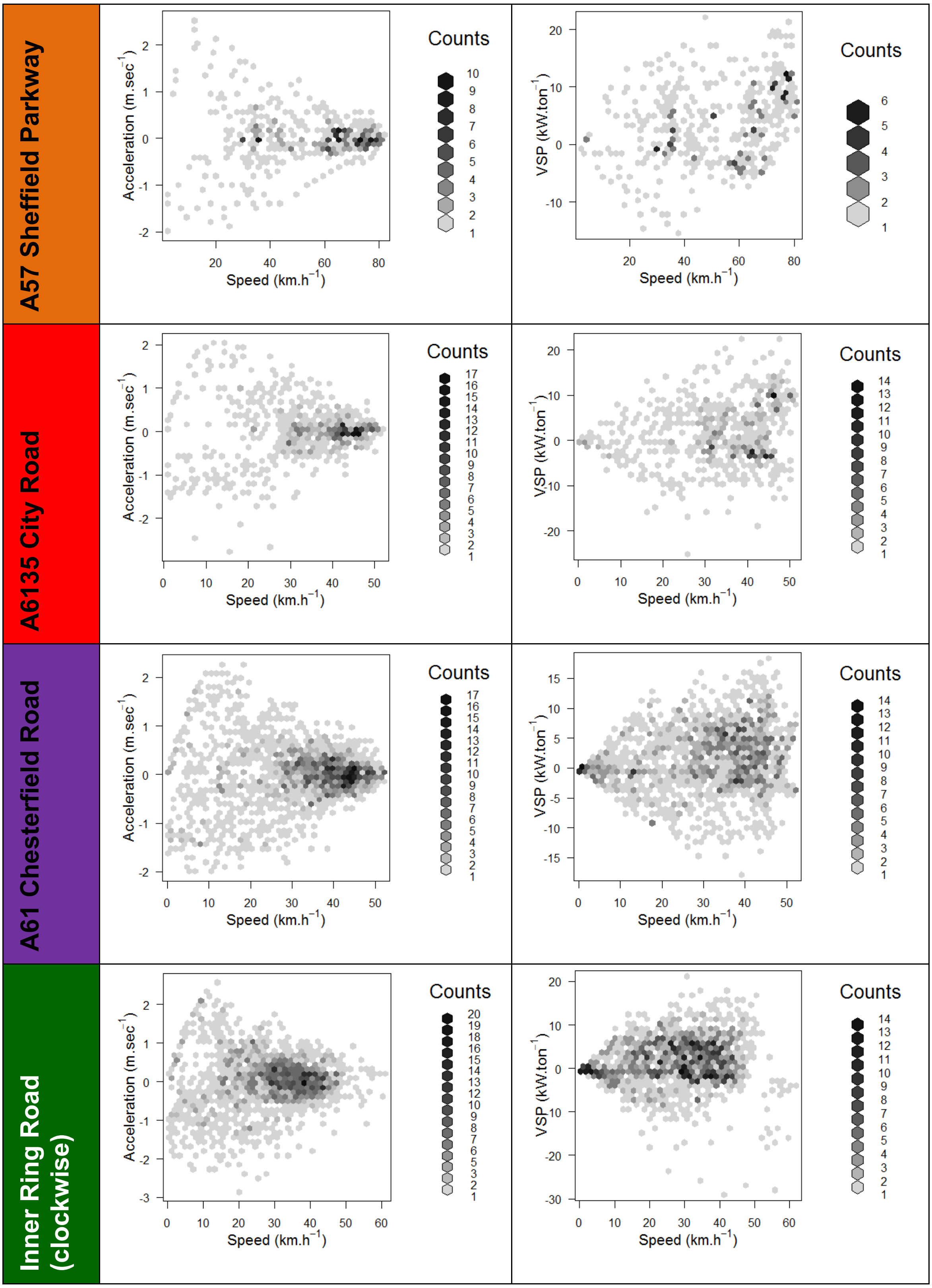
VEHICLE type	FUEL type	EURO Standard	Number of vehicles	CO_2 (grams.km^{-1})	NO_X (grams.km^{-1})	NO_2 (grams.km^{-1})	PM_{10} (index) (grams.km^{-1})
Car	Petrol	Euro 0	56	208.4	1.477	0.138	41.840
		Euro 1	96	207.6	0.929	0.087	14.494
		Euro 2	1176	197.6	0.645	0.060	10.646
		Euro 3	4347	192.8	0.324	0.030	5.960
		Euro 4	4158	184.7	0.165	0.015	3.852
		Euro 5	1855	171.4	0.130	0.012	2.877
		Euro 6	4	171.4	0.113	0.011	0.947
	Diesel	Euro 0	7	240.6	0.630	0.091	39.873
		Euro 1	31	226.4	0.921	0.134	50.482
		Euro 2	182	182.4	0.770	0.150	50.649
		Euro 3	1761	181.5	1.100	0.564	38.768
		Euro 4	3293	186.7	0.944	0.559	21.347
		Euro 5	2889	170.0	0.877	0.462	4.496
		Euro 6	8	184.3	0.434	0.218	3.083
	Hybrid	Euro 4	2	127.6	0.296	0.028	2.469
		Euro 5	16	186.4	0.102	0.010	7.298
		Euro 6	87	123.2	0.049	0.005	1.657
	Hybrid-Diesel	Euro 5	1	135.5	0.702	0.370	2.538
Taxi - PHV	Petrol	Euro 0	0	N/a	N/a	N/a	N/a
		Euro 1	0	N/a	N/a	N/a	N/a
		Euro 2	0	N/a	N/a	N/a	N/a
		Euro 3	4	210.5	0.191	0.018	1.449
		Euro 4	23	196.4	0.376	0.035	4.617
		Euro 5	1	205.8	0.086	0.008	0.000
		Euro 6	0	N/a	N/a	N/a	N/a
	Diesel	Euro 0	0	N/a	N/a	N/a	N/a
		Euro 1	0	N/a	N/a	N/a	N/a
		Euro 2	0	N/a	N/a	N/a	N/a
		Euro 3	55	179.0	1.165	0.598	44.147
		Euro 4	544	174.5	1.323	0.783	28.117
		Euro 5	50	174.7	1.724	0.908	7.191
		Euro 6	0	N/a	N/a	N/a	N/a
	Hybrid	Euro 4	0	N/a	N/a	N/a	N/a
		Euro 5	1	118.6	0.029	0.003	1.755
		Euro 6	0	N/a	N/a	N/a	N/a
Taxi	Hackney Diesel	Euro 0	79	217.9	1.288	0.187	66.601
		Euro 1	9	264.1	1.414	0.205	119.717
		Euro 2	6	302.9	1.268	0.247	39.124
		Euro 3	224	239.5	2.154	1.105	87.740
		Euro 4	72	234.9	1.546	0.915	42.070
		Euro 5	0	N/a	N/a	N/a	N/a
		Euro 6	0	N/a	N/a	N/a	N/a

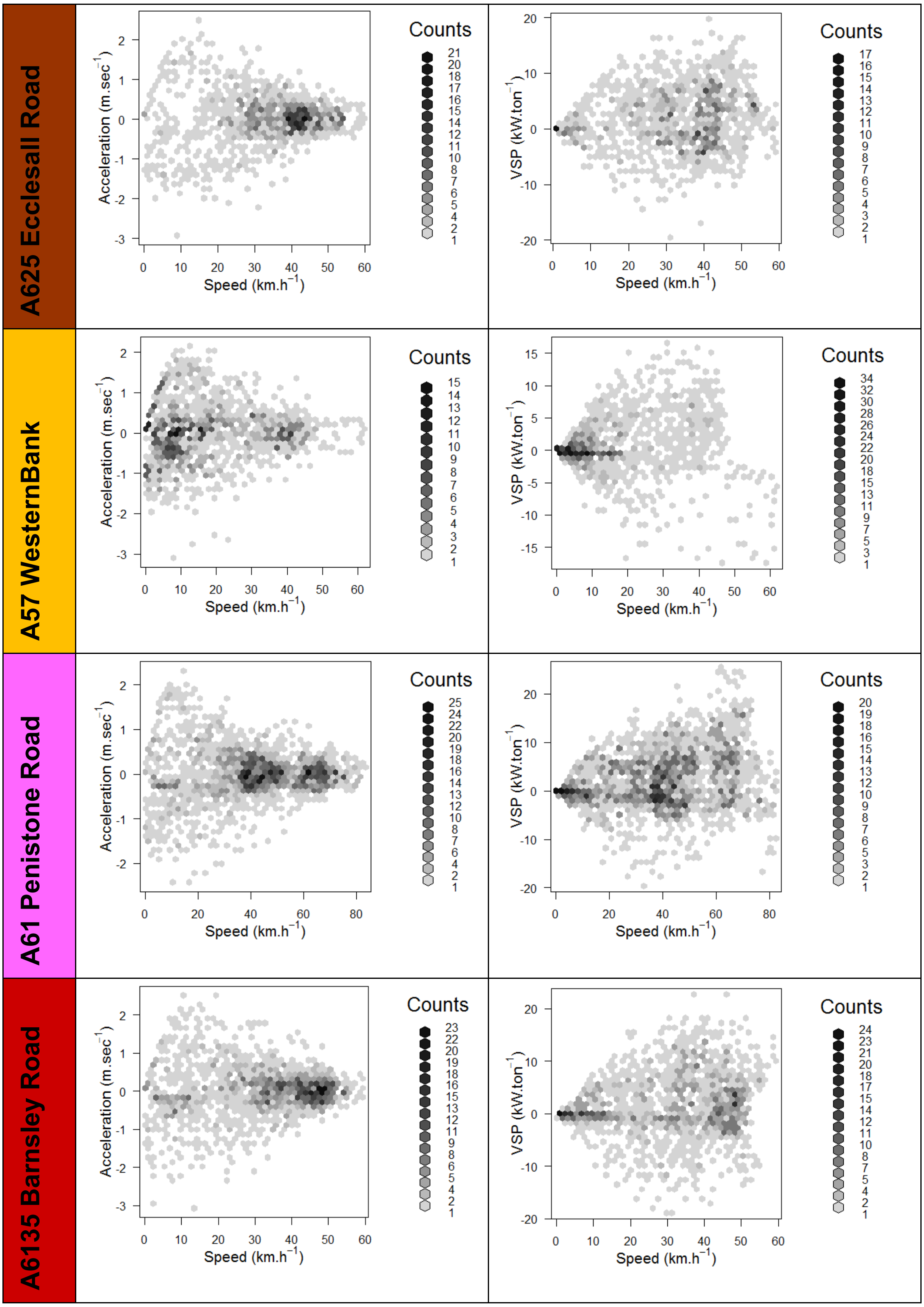
Table A2: Summary CO_2, NO_X, NO_2 and PM_{10} (index) emission factors – Heavy-duty.

VEHICLE type	FUEL type	EURO Standard	Number of vehicles	CO_2 (grams.km^{-1})	NO_X (grams.km^{-1})	NO_2 (grams.km^{-1})	PM_{10} (index) (grams.km^{-1})
LGV	Petrol	Euro 0	8	241.9	3.545	0.331	53.274
		Euro 1	0	N/a	N/a	N/a	N/a
		Euro 2	9	192.5	0.614	0.057	16.883
		Euro 3	30	199.2	0.462	0.043	11.901
		Euro 4	12	184.3	0.193	0.018	3.528
		Euro 5	7	176.2	0.182	0.017	2.084
		Euro 6	0	N/a	N/a	N/a	N/a
	Diesel	Euro 0	6	241.9	1.291	0.188	79.184
		Euro 1	39	218.7	0.955	0.139	60.396
		Euro 2	134	202.0	1.027	0.200	49.593
		Euro 3	1177	189.0	1.273	0.653	55.649
		Euro 4	1956	195.0	1.114	0.685	32.863
		Euro 5	1430	220.2	1.207	0.619	12.810
		Euro 6	0	N/a	N/a	N/a	N/a
Single-Decker Bus (PSV)	Diesel	Euro 0	1	N/a	N/a	N/a	N/a
		Euro 1	1	N/a	N/a	N/a	N/a
		Euro 2	454	737.0	4.634	0.281	91.396
		Euro 3	164	819.0	4.823	0.585	155.217
		Euro 4	204	806.0	5.068	0.779	89.476
		Euro 5	169	843.0	8.394	1.077	41.798
		Euro 6	0	N/a	N/a	N/a	N/a
Double-Decker Bus (PSV)	Diesel	Euro 0	2	922.0	8.962	0.478	447.723
		Euro 1	3	730.0	4.800	0.256	278.495
		Euro 2	42	737.0	6.457	0.392	118.996
		Euro 3	229	819.0	4.196	0.509	165.765
		Euro 4	175	806.0	8.683	1.334	42.868
		Euro 5	118	843.0	3.023	0.388	45.569
		Euro 6	0	N/a	N/a	N/a	N/a
	Hybrid-Diesel	Euro 5	102	591.0	1.860	0.239	36.323
OGV Rigid	Diesel	Euro 0	1	539.0	2.758	0.090	94.109
		Euro 1	19	470.0	3.679	0.120	95.697
		Euro 2	55	494.0	3.329	0.171	80.829
		Euro 3	185	630.5	4.813	0.601	102.034
		Euro 4	159	514.8	2.980	0.580	72.689
		Euro 5	157	753.0	6.174	0.834	26.921
		Euro 6	0	N/a	N/a	N/a	N/a
OGV Artic	Diesel	Euro 0	5	470.0	3.199	0.105	37.224
		Euro 1	6	494.0	5.430	0.279	63.9483
		Euro 2	39	648.6	4.462	0.557	101.0664
		Euro 3	25	521.0	2.934	0.571	48.386312
		Euro 4	37	753.0	4.152	0.561	161.0992622
		Euro 5	2	753.0	5.930	0.801	32.9814
		Euro 6	1	539.0	2.758	0.090	94.109

Figure A1: Speed, Acceleration and VSP frequency diagrams for the twelve vehicle tracking routes (see Figure 3 and Figure 4).




A57 Sheffield Parkway
A6135 City Road
A61 Chesterfield Road
Inner Ring Road (clockwise)
Acceleration (m.sec^{-1})
VSP (kW.ton^{-1})
Speed (km.h^{-1})
Counts



A625 Ecclesall Road
A57 WesternBank
A61 Penistone Road
A6135 Barnsley Road
Acceleration (m.sec^{-1})
VSP (kW.ton^{-1})
Speed (km.h^{-1})
Counts