# The significance of vehicle technology and driver behaviour in determining road vehicle exhaust emission rates

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Abstract:

This research utilises data from instrumented vehicles and road side remote sensing in an urban environment to explore the relationships between exhaust tail pipe emissions, vehicle technology, and driver behaviour. An investigation is carried out into the nature of variability that exists in the driving behaviour of a sample of drivers, and the influence of such variability on fuel consumption and the emission rates of exhaust pollutants. Analysis of data from remote sensing reveals that emissions from petrol cars (CO, HC, NO, PM) are all observed to display a statistically significant reduction with the introduction of each successive Euro emissions standard from Euro 1 onwards. However, Euro 2 diesel cars are observed to emit statistically higher rates of NO than either Euro 1 or Euro 3 standard diesel cars. When the New European Driving Cycle is synthesised from remote sensing data and compared with type approval data published by the UK Vehicle Certification Agency, mean CO emissions from petrol cars $\leq 3$ years old measured using remote sensing are found to be 1.3 times higher than published original type approval test values; this factor increases to 2.2 for cars 4 – 8 years old, and 6.4 for cars 9 – 12 years old. The corresponding factors for diesel cars are 1.1, 1.4, and 1.2 respectively. This thesis has made an original contribution to the field in two main areas; firstly by quantifying the ‘real-world’ emission rates for a sample of the UK vehicle fleet in an urban area, and demonstrating the statistically significant differences in emission rates between groups of vehicles; and secondly, by proposing a feasible method to move towards reconciling essentially instantaneous road side measurements of exhaust emissions obtained from remote sensing, with laboratory based measurements taken over a legislated driving cycle as part of the new vehicle type approval process.

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The work reported in Chapter 3 is based on a research project funded by a major international vehicle manufacturer. The project was implemented in partnership with colleagues at the University of Southampton, but all of the quantitative analysis reported in Chapter 3 is my own work.

I am grateful to colleagues at the London Borough of Southwark (Mr Bill Legassick) and the London Borough of Ealing (Dr John Freeman) for the supply of remote sensing data used in Chapters 4, 5 and 6, and acknowledge with thanks the role of Transport for London in the original data collection project. All processing and analysis of the remote sensing data reported in Chapters 4, 5, and 6 is my own work.

## Publications relating to this work

### *Peer reviewed journal papers*

**Rhys-Tyler GA**, Bell MC. Toward reconciling instantaneous roadside measurements of light duty vehicle exhaust emissions with type approval driving cycles. Environmental Science & Technology 2012, 46(19), 10532-10538. DOI: 10.1021/es3006817

**Rhys-Tyler GA**, Legassick W, Bell MC. The significance of vehicle emissions standards for levels of exhaust pollution from light vehicles in an urban area. Atmospheric Environment 2011, 45(19). DOI: 10.1016/j.atmosenv.2011.03.035

### *Other peer reviewed publications*

**Rhys-Tyler GA**. Network Management for Environmental Benefit. Chartered Institution of Highways and Transportation, 2012. CIHT Network Management Notes.

### *Conference proceedings*

**Rhys-Tyler GA**, Bell MC. Informing air quality management strategies using vehicle exhaust emissions data from remote sensing: A case study of London. In: Proceedings of the 43rd Universities Transport Studies Group Conference. 2011, Open University, Milton Keynes, UK.

**Rhys-Tyler GA**, Bell MC. Derivation of predictive models of vehicle exhaust emissions from instrumented vehicle measurements: Analytical and statistical challenges. In: Proceedings of the 42nd Universities Transport Studies Group Conference. 2010, University of Plymouth, UK.

**Rhys-Tyler GA**, Bell MC. Influencing driver behaviour for environmental benefit: The role of ITS technologies. In: Proceedings of the 16th ITS World Congress. 2009, Stockholm, Sweden.

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# Chapter 1. Road Transport and the Environment

## 1.1 Introduction to Policy and Practice

Historically, highway network management has focused mainly on the objectives of delay minimisation, capacity maximisation, and safety. Network management for environmental benefit has to date tended to be limited to interventions such as queue management and relocation, route information via variable message signing and other communications methods, and public transport priority. Relatively little attention has been paid to date to the potential for active management of highway infrastructure, vehicles, and driver behaviour to achieve environmental benefits, for example in the field of local air quality. Progress in this area is hampered to a degree by a lack of objective evidence to inform policy development. The primary objective of this thesis is to contribute to the development of such an evidence base to inform future local air quality management.

In recent years, there has been an increasing awareness of the importance of environmental issues in transportation network management and operations, particularly in the context of public health and climate change policy. However, there is always the risk that such issues will be seen in isolation, with traffic engineers dealing with traffic issues, and environmental scientists addressing issues such as local air quality and noise. Emerging technologies, combined with innovative communications and data processing applications, present an opportunity to develop far more sophisticated network management tools for policy makers and network managers. The next generation of network management systems will have the potential sophistication and flexibility to internalise these multi-disciplinary factors. Whilst the technological issues can be addressed in due course, the availability of such systems will bring into focus the requirement to address policy and appraisal conflicts between potentially competing objectives.

## 1.2 The Cost of Environmental Damage – Why is it Important?

### *1.2.1 Traffic congestion*

UK legislation such as the Traffic Management Act 2004 and related secondary legislation have placed significant emphasis, through the Network Management Duty, on securing and facilitating the expeditious movement of traffic, and reducing traffic congestion. Estimates of the cost of traffic congestion to the UK economy have ranged widely from £7bn to £20bn per annum depending on methodology and price base (Goodwin 2004). More recently, the Eddington Report estimated the cost to the economy of lost travel time due to congestion to increase by £23 - £24bn in future years to 2025 unless mitigating action is taken (Eddington 2006).

### *1.2.2 Poor air quality and reduced life expectancy*

At the same time, the Department for Environment, Food and Rural Affairs has estimated that poor air quality (in particular caused by manmade particulate matter) reduces average life expectancy in the UK by six months, with equivalent health costs estimated to be £15bn per annum, within the range £8 - £17bn (DEFRA 2010).

### *1.2.3 Climate change and $CO_2$*

It is estimated that the level of $CO_2$e ($CO_2$ equivalent) emissions attributable to the domestic UK road transport sector was 113.6 million tonnes in 2009 (DfT 2011a). Applying a central estimate non-traded price of carbon (DECC 2011) of £54 per tonne (low estimate £27, high estimate £81) in 2009 gives a total $CO_2$e cost from road transport in the UK of approximately £6.1bn per annum.

### *1.2.4 Impact of road noise on health, amenity, and productivity*

The Inter-departmental Group on Costs and Benefits (Noise) have produced estimates combining WebTag values (per decibel values for the loss of amenity due to road noise) with data on population exposure to road noise in major agglomerations. This work found a total annoyance disutility of current road noise in England of £3 – £5 billion per annum. In addition, the cumulative UK impact of noise pollution on health[1] has been estimated at around £2 – 3bn per annum, and the productivity cost of noise pollution at around £2bn per annum (DEFRA 2008).

## 1.3 Government Spending Priorities

So it can be seen that, in terms of public policy, the costs of traffic congestion, poor air quality, noise pollution, and climate change to the UK economy are, whilst different in scale, estimated to be of similar orders of magnitude.

The UK Government states that “Whilst ..... the wider costs associated with transport are of similar order, this does not necessarily mean that *(Government)* spending should be split evenly between the various objectives. Efficient spending decisions will depend on the effectiveness and cost of individual measures and should be considered on a case by case basis through robust cost-benefit analysis. However in terms of option generation, there may be a strong business case for interventions which address these impacts simultaneously” (Cabinet Office 2009).

There is obviously some uncertainty regarding the absolute levels of environmental costs imposed on society by these factors, and some problems are easier (or more cost effective) to solve than others. There is also a political dimension to budget allocations in terms of evolving public attitudes. Nevertheless, as the Government has stated, there are benefits to be gained in

[1] *For example, research indicates a higher risk of high blood pressure and heart disease with exposure to prolonged high noise levels.*

adopting an holistic, multi-criteria approach to network management, informed by local context and local challenges, within a national framework. This is particularly true where there are correlations or relationships between environmental factors.

### 1.4 The Transport Policy Context

Clearly, transport policy is subject to change with each successive government of varying political complexions. The Department for Transport white paper "Creating Growth, Cutting Carbon: Making Sustainable Local Transport Happen" (DfT 2011b) currently provides the primary policy framework for local transport in the United Kingdom.

**Creating Growth, Cutting Carbon**

"Our vision is for a transport system that is an engine for economic growth, but one that is also greener and safer and improves quality of life in our communities".

"We will need to build on current progress in reducing transport emissions to meet the United Kingdom's commitments, and current projections suggest that road transport will need to be largely decarbonised by 2050".

"As cars are likely to remain the dominant transport mode, the Government wants to improve their environmental performance and is committed to supporting the market in electric, and other ultra-low emission vehicles."

"The Government is convinced that progressive electrification of the passenger car fleet will play an important role in decarbonising transport, supported by policies to increase generation capacity and decarbonise the grid."

"The Government believes that it is at the local level that most can be done to enable people to make more sustainable transport choices and to offer a wider range of genuinely sustainable transport modes – environmentally sustainable as well as fiscally, economically and socially sustainable."

Clearly, the "Creating Growth, Cutting Carbon" white paper has direct relevance to the debate surrounding transport policy and wider environmental and health issues, in particular reducing carbon dioxide emissions and other greenhouse gases, but also health and life expectancy, and nurturing a sustainable environment.

Consistent with the view from the Cabinet Office, the Department for Transport expects that there will be strong synergies between different goals. For example, they suggest that measures to encourage modal shift to sustainable modes will help to tackle congestion, reduce greenhouse gases, and improve air quality and public health.

However, the biggest challenge identified in the white paper is tackling climate change and economic growth together. With the UK's historical reliance on fossil fuels, the achievement of the Government's targets for reductions in greenhouse gas emissions whilst also achieving the desired levels of economic growth will require significant changes in both travel behaviour, transport technology, energy generation, and over the longer term, land use planning.

## 1.5 Climate Change and $CO_2$

The Stern Review (HM Treasury 2006) emphasised the need to reduce global emissions of carbon dioxide and other greenhouse gases if we were to avoid dangerous climate change. Consequently, the Climate Change Act 2008 (HM Government 2008) committed the UK Government to achieving at least an 80% reduction in greenhouse gases, relative to 1990 levels, by 2050. The Government's Carbon Plan (HM Government 2011) reiterates the UK's commitment to the reduction in emissions of greenhouse gases, and sets out how the transport sector will contribute to this reduction. This includes supporting new low emission vehicle technologies, high speed rail and electrification, sustainable aviation and shipping, promoting the use of sustainable biofuels, and changing travel behaviour.

UK domestic transport is responsible for around 22% of all UK domestic $CO_2$ emissions. The majority (circa 92%) of $CO_2$ emissions from domestic transport comes from road transport. $CO_2$ emissions from UK domestic road transport increased by around 10.4% between 1990 and 2007, but in 2009 had reduced to approximately 2.2% above 1990 levels (DfT 2011a).

## 1.6 Local Air Pollution and Air Quality Management Areas

Technological improvements have reduced emissions of air pollutants over the last thirty years, although for some pollutants this trend has slowed. Today, sources of UK air pollution are dominated by power generation and transport.

The UK Government and the devolved administrations published the latest Air Quality Strategy for England, Scotland, Wales and Northern Ireland (Command paper No. 7169) in 2007 (DEFRA 2007). The strategy sets out the air quality standards and objectives to be achieved, introduces a policy framework for addressing the problem of fine particulates, and identifies potential new national policy measures which modelling indicates could give further health benefits and move closer towards meeting the Strategy's objectives. Under the legislation, local authorities are required regularly to review and assess air quality in their area and take action when the objectives in regulation cannot be met by specified target dates. When a regulated pollutant exceeds the objective value, the authority must declare an 'Air Quality Management Area' (AQMA) and develop an Action Plan to tackle problems in the affected areas.

**Air Quality Management Areas (AQMAs)**

To date, 258 Local Authorities – approximately 64% of those in the UK - have established one or more Air Quality Management Areas (AQMAs). Most of these are in urban areas and result from traffic emissions of nitrogen dioxide ($NO_2$) or particulates ($PM_{10}$). As at September 2011, 203 Action Plans have been submitted to DEFRA, and a further 55 are in preparation.

Such a plan may include a variety of mitigation measures such as traffic management measures, the introduction of low emissions zones targeting certain vehicle types, demand management measures, and land use planning in the longer term. Road traffic emissions are the main source of air pollution in around 91% of the AQMAs declared; only a few have been designated as a result of industrial sources, domestic or shipping emissions (DEFRA 2011a).

**The dieselisation of the UK car fleet**

Less than 10% of new cars registered in 1997 in the UK were diesel powered; by 2010, this figure had risen to 46% (DfT 2011c). In 2010, 28.9% of cars operating on UK roads were diesel powered (DfT 2011d). Diesel cars, although more fuel efficient, tend to produce higher levels of polluting particulate matter and oxides of nitrogen in their exhaust gases compared to equivalent petrol powered cars. In particular, there is an increasing body of evidence that modern diesel engines are producing a higher proportion of primary nitrogen dioxide ($NO_2$) in their exhaust gases, as a result of the adoption of technologies to control particulate matter. This is a problem for local air quality and human health, and the subject of active research by motor manufacturers and the academic community.

## 1.7 Local Air Pollution and Human Health Impacts

DEFRA has stated that there is now clear evidence that there is no ‘safe’ level for exposure to fine particles ($PM_{10}$ and $PM_{2.5}$, where $PM_{10}$ are particles <= 10 µm in diameter, and $PM_{2.5}$ are particles <= 2.5µm in diameter), i.e. no exposure threshold below which no health disbenefits are expected to occur. The UK Air Quality Strategy therefore concludes that, for this pollutant, a policy based on achieving limit values alone will not generate the maximum benefit in public health for the investment made. This is because such an approach focuses only on the areas where concentrations are highest, while in reality adverse effects on health are likely to be much more widespread. (DEFRA 2007). Whilst at the present time, only $PM_{10}$ is a regulated particulate pollutant, targets for $PM_{2.5}$ are included in the Strategy, which include a relative 15% cut in urban background exposure in $PM_{2.5}$ (annual mean) between 2010 and 2020, in addition to an absolute target of 25µg $m^{-1}$ (annual mean). Vehicle brake and tyre wear constitutes over a quarter of air borne particulates, and these sources are now receiving more attention by vehicle manufacturers and researchers.

There have been particular challenges in achieving the nitrogen dioxide ($NO_2$) targets because of the growth in the use of diesel powered passenger cars in recent years, and the growth in the number of diesel powered light duty commercial vehicles or ‘white vans’. Current European vehicle type approval regulations applying to new vehicles regulate levels of $NO_x$ emissions, but not explicitly $NO_2$ emissions, and there is some evidence to suggest that the proportion of $NO_2$ in $NO_x$ is increasing as a result of changes in engine technology and exhaust after-treatment systems (DEFRA 2011b).

**Health Impacts of Air Pollution**

**Oxides of nitrogen ($NO_x$), comprising nitrogen dioxide ($NO_2$) and nitric oxide (NO) -** Can cause inflammation of the airways, affect lung function and cause breathing difficulties.

**Particulates -** Airborne particulate matter (PM) is made up of a complex mixture of solid and liquid particles, including carbon, complex organic chemicals, dust, and other compounds, suspended in the air. Short and long term exposure can worsen respiratory and cardiovascular illness, including lung cancer, and increase mortality.

### 1.8 Noise from Road Transport

Noise has the potential to cause annoyance, loss of amenity, and negative impacts on human health including high blood pressure and heart disease. Ambient or environmental noise is unwanted or harmful outdoor sound created by human activities. The European Noise Directive 2002/49/EC or ‘END’ (European Commission 2002) relating to the assessment and management of environmental noise has the aim of providing a common basis for tackling the noise problem across the EU. This includes:

- Monitoring the environmental problem; by requiring authorities in Member States to draw up "strategic noise maps" for major roads, railways, airports and agglomerations. These maps will be used to assess the number of people annoyed and sleep-disturbed respectively throughout Europe.
- Informing and consulting the public about noise exposure, its effects, and the measures considered to address noise.
- Addressing local noise issues by requiring competent authorities to draw up action plans to reduce noise where necessary and maintain environmental noise quality where it is good. The directive does not set

any limit value, nor does it prescribe the measures to be used in the action plans, which remain at the discretion of the competent authorities.

| Type of noise exposure | Impact | Proportion affected, per annum | Potential years of healthy life lost in Europe through noise-related death or disability | Monetised UK Impact (£ million per annum) |
|---|---|---|---|---|
| Daytime traffic | Heart disease | 3% of all heart disease cases across EU | 211,000 | £1,183 |
| 24-hour background noise | Severe annoyance | 15% of all Europeans | 278,000 | £1,571 |
| Traffic / leisure noise | Tinnitus (ringing in the ears) | 3% of all tinnitus cases | 9,300 | £52 |
| Day time and night time noise | Slower learning by children | 0.01% of all Europeans | 45,000 | £252 |

**Table 1: Health effects of noise pollution from road transport**

*Adapted from DEFRA 2008.*

## 1.9 Monitoring the Environmental Performance of Networks

Network managers have a range of potential interventions in their toolkit, depending on the nature of the problem and local context. A prerequisite for effective management of environmental factors at the local level is adequate and timely information at an appropriate level of spatial resolution. This usually implies some form of environmental monitoring system generating data which is converted into management information through appropriate processing. In urban areas, this is increasingly carried out within the scope of an urban traffic management and control (UTMC) system.

Current research is addressing the need for comprehensive information on the environmental performance of highway networks, and making this information available to network management systems. One example of this was the MESSAGE (Mobile Environmental Sensing System Across GRID Environments) project (2006-2009), implemented by an academic consortium comprising Imperial College, Newcastle University, Cambridge University, Leeds University, and Southampton University. The project was funded by EPSRC and the Department for Transport.

The project addressed the issue of a current lack of vehicle emissions and air quality data at an adequate temporal and spatial resolution, suitable to use in real-time UTMC systems. As part of the project, a low-cost sensor module or ‘mote’ was developed which could be deployed in large numbers across an urban area. The system featured a wireless communication system, where environmental sensor data could be transferred in real-time from mote to mote in a ‘daisy-chain’ configuration, with intelligent data routing, via a gateway node to a UTMC compliant database. The system was deployed in pilot trials in both Gateshead and Leicester in 2009. Such a pervasive sensor and communications network has the potential to facilitate the development of the next generation of network management systems, allowing planning and operational decisions to be made on the basis of network data which is both real time, and at a high level of spatial resolution, to meet environmental, health, and operational objectives.

## 1.10 Policy Interventions

### *1.10.1 Network management for $CO_2$ reduction*

Highway network management with the objective of $CO_2$ reduction encompasses a wide range of potential interventions to facilitate the movement of people and freight whilst reducing or minimising the amount of fossil fuel consumed (essentially, there is a linear relationship between fuel consumption and $CO_2$ production). Significant technological progress has been made in recent years by vehicle manufacturers to improve the fuel efficiency of road vehicle engines (grams of $CO_2$ produced per kilometre travelled). These technological improvements are in turn supported by incentives in the vehicle taxation system. At the local level network managers can adopt measures to manage demand by encouraging modal shift to more fuel efficient modes, by making these modes relatively more attractive than the private car. This might include interventions such as public transport priority, and parking supply management and pricing. The tuning of urban traffic control systems to maximise system efficiency can reduce fuel consumed by managing stop-start traffic conditions and vehicle speeds.

### *1.10.2 Network management for improved local air quality*

Increasingly stringent European emission standards applied to new vehicle type approval over the last twenty years have resulted in modern road vehicles which are generally cleaner than their predecessors, particularly petrol fuelled vehicles with the adoption of three-way catalytic converters. Nevertheless, traffic conditions and variability in driver behaviour can influence the amount of pollutant generated by a vehicle. Stop-start conditions, with frequent braking, acceleration, and gear changing, tend to make pollutant emissions worse, since peaks in pollutant emissions from vehicles are often produced by transient events in the vehicle operation. In modern engines, these transient events can dominate the total pollutant emissions produced. It therefore follows that if the highway network can be managed and operated to minimise stop-start conditions, and produce ‘smoother’ flow conditions, the production of harmful exhaust pollutants can be reduced. However, the evidence base for such network management interventions, particularly as it relates to tailpipe exhaust emissions from vehicles ‘in-use’ on the highway network, is currently weak.

### *1.10.3 UTMC and environmental management*

Historically, the focus in urban traffic control (UTC) and urban traffic management and control (UTMC) has been on delay minimisation and/or capacity maximisation. Simply improving traffic flow in this manner by optimising the performance of the transport system in whole or in part, often has an environmental benefit in terms of reduced stop / start operation, for example through the coordination of traffic signals.

More novel existing techniques in systems such as SCOOT (Split Cycle Offset Optimisation Technique) include both public transport priority and gating / queue relocation, where a conscious decision is taken by the network manager to reduce queues in an environmentally sensitive areas (e.g. near pedestrian areas, street canyons, and schools where there are potentially higher densities of population to pollute), and queue vehicles in less sensitive areas or where the local topography can facilitate dispersion of pollutants in the atmosphere.

SCOOT version 4.5 incorporated the option of including vehicle exhaust emissions estimates in the SCOOT objective function. The SCOOT program was modified so that the user could choose the objective function used in the offset optimiser. It can be changed from the standard objective function of a weighted sum of delays and stops, to the weighted sum of estimated emissions. The program estimates carbon monoxide (CO), carbon dioxide ($CO_2$), oxides of nitrogen ($NO_x$), particulates and Volatile Organic Compounds (VOCs) emitted by vehicles on a link, node or region basis, based on traffic flow and average speed. Average speed is not a particularly reliable predictor of some pollutants, but the principle of internalising emissions estimates within the objective function for traffic control is an active area of current academic research.

### *1.10.4 Encouraging walking and cycling*

Encouraging modal shift from motorised modes (in particular the private car) to non-motorised modes such as walking and cycling will clearly achieve benefits in terms of reducing emissions from combustion of fossil fuels, and reductions in noise. However, care should be taken to ensure that appropriate facilities are available for cyclists and pedestrians to mitigate any potential increase in injury accident risk. Almost a quarter of the adult population in England are currently classified by the NHS as obese (NHS 2010). Two thirds of the adult population do not meet recommended activity levels. There are clearly potential synergistic benefits to be gained in terms of both environmental quality, and public health.

### *1.10.5 Encouraging low / zero emission vehicles*

The UK Office for Low Emission Vehicles (OLEV) has been tasked by the Government with promoting the take up of ultra low carbon vehicles. The Government has confirmed financial support to consumers in the form of a grant of up to £5,000 towards purchase of an ultra-low carbon car for the life of the current Parliament. The consumer grant reduces the up-front cost of eligible vehicles by 25 per cent, and is open to both private and business fleet buyers. At the same time, the required infrastructure to support electric vehicles and plug-in hybrids needs to be considered. The 'Plugged in places' initiative is providing pump priming funding for publicly accessible charging points to help drivers of electric and plug-in hybrid cars recharge when they are away from home. http://www.dft.gov.uk/topics/sustainable/olev/

### *1.10.6 Intelligent Speed Adaptation*

Intelligent speed adaptation (ISA) is a system that provides the driver with information on the speed limit for the road currently being travelled on. This information can be used to display the current speed limit inside the vehicle and warn the driver when he or she is speeding. It can also be linked to the vehicles engine and brakes to limit the speed of the vehicle directly, on either a voluntary or mandatory basis. The system was developed primarily to enhance safety, because of the known relationship between speed and injury severity in an accident. However, it has been suggested that limiting vehicle speed in this way can also have environmental benefits. Recent research suggests that reductions in $CO_2$ emissions can be achieved on motorway-type roads when mandatory speed control is used to limit vehicle speeds to 70mph (Carslaw et al 2010). However, for most other types of road, constraining vehicles to speed limits was estimated to have less effect on $CO_2$ emissions. The greater benefit for fuel consumption / $CO_2$ emissions at higher speeds is logical when one considers that vehicle aerodynamic drag is approximately proportional to the square of speed, whilst the power required to overcome such drag is proportional to the cube of speed. At lower speeds, gear changing behaviour will tend to complicate the analysis, and possibly erode benefits. This suggests that, if $CO_2$ reduction on motorways is an objective, simple speed limiter devices on passenger cars (as commonly used on commercial vehicles), set to the legal speed limit, might be effective. An alternative method of achieving the same objective would be wider use of average speed camera enforcement on motorways. However, the political acceptability and cost-benefit of such interventions would need to be assessed.

#### *1.10.7 Low emissions zones*

The London LEZ started operation in 2008 and is currently one of only two such zones in operation in the UK, the other being in Norwich. The aim of the London scheme is to improve air quality in the city by deterring the most polluting vehicles from driving in the area. The vehicles currently affected by the LEZ are older diesel engine trucks, buses, coaches, large vans, minibuses and other heavy vehicles. Cars and motorcycles are not currently affected by the scheme. As a result, the scheme tends to target heavy diesel-powered vehicles, prioritising particulate (PM) reduction. The London LEZ commenced on 4 February 2008 for lorries over 12 tonnes, buses and coaches. The LEZ emission standards describe the minimum Euro standard which vehicles must meet to be exempt from a charge. Meeting these emission standards can be done by using a vehicle whose engine was type approved to this standard (or better), or by retrofitting exhaust after-treatment technology to raise the emission standard.

From 3 January 2012, larger vans and minibuses are required to meet the Euro 3 emissions standard for particulate matter (previously exempt), and lorries, buses and coaches are required to meet the Euro 4 emissions standard for particulate matter (previously Euro 3). Daily penalty charges are imposed for contraventions of the low emission zone.

In 2011, DEFRA announced grant funding to support low emission zone feasibility studies in 16 local authorities across England, as part of its Air Quality Grant Programme 2011-12.

## 1.11 Identification of the Research Gap

This thesis focuses primarily on the issue of ‘in-use’ exhaust emissions from road transport in the United Kingdom. Given the significance of road transport exhaust emissions as a contributor to local air pollution, in particular particulate matter and oxides of nitrogen, there is very little information in the published literature regarding the ‘in-use’ exhaust emissions characteristics of the current UK road vehicle fleet. A compounding factor is that the UK road vehicle fleet is in a constant state of change, with vehicle and emission control technologies evolving, and fuel types changing in response to market and economic conditions.

Some small scale studies were carried out in London in the 1990’s measuring carbon monoxide (CO) and hydrocarbons (HC) (Sadler et al., 1996; Muncaster et al., 1996; Revitt et al., 1999), using roadside remote sensing, but both instrumentation and fleet characteristics have evolved over the intervening period. A European Joint Commission Services Study into ‘In-use vehicle emission controls’, carried out in 1994-1998, included roadside remote sensing measurements at a number of locations, including two locations in the UK. The study assessed the effectiveness of remote sensing as a method of screening the vehicle fleet for high emitters (Barlow, 1998). The EU FP5 REVEAL project developed a low cost roadside remote sensing device (RSD) to collect data on overall car fleet emissions characteristics and gross emitters, which included a field trial in London in 2003 (REVEAL, 2004). The REVEAL RSD was later used in Winchester, UK in 2006 to research driver motivation for voluntary vehicle emissions related maintenance (Felstead, 2007). However, none of these studies has succeeded in developing a comprehensive and statistically robust characterisation of the exhaust emission rates of the UK road vehicle fleet. This thesis makes a significant contribution to scientific knowledge in this area by deriving exhaust emission rates for a range of road vehicle classes in an urban area, and by demonstrating statistically significant differences in the emission rates by vehicle age and Euro emissions class. It then goes on to present an original methodology for reconciling these derived emission rates with official published data from laboratory based type approval drive cycle tests.

A secondary focus of this thesis is on the significance of variability in driver behaviour for exhaust emission rates and fuel consumption, and the scope for influencing driver behaviour. A number of previous studies have researched variability in driver behaviour, and in particular its impact on fuel consumption (for example, Holmen & Niemeier, 1998; Ericsson 2001; Felstead et al 2008; Beusen et al 2009; Carslaw et al 2010). However, the constant evolution of vehicle technology, and the potential for changes in driver attitudes, requires that these issues be kept under review. This thesis demonstrates the existence and extent of variability in driver behaviour within a very limited experimental context, and its impact on fuel consumption and emissions. It also highlights some significant aspects of experimental design, including temporal resolution, which will inform future studies. A more original dimension of this thesis is the statistical investigation of the efficacy of a smart phone based application for influencing driver behaviour, and encouraging eco-driving.

## 1.12 Research Objectives

This research focuses on a particular aspect of environmental management, the relationships between vehicle technology, driver behaviour, and tailpipe exhaust emissions from light duty vehicles. In summary, the research objectives are to:

a) Characterise and quantify variability in driver behaviour from available datasets as it influences vehicle operation;
b) Quantify the impact such variability in driver behaviour has on road vehicle tailpipe exhaust emissions;
c) Quantify, using appropriate statistical techniques, the efficacy of a novel smart phone based application for encouraging eco-driving;

d) Quantify the variability in observed road vehicle tailpipe exhaust emissions due to heterogeneity in vehicle technology, fuel type, and vehicle age;
e) Assess the statistical significance of such variability in exhaust emissions with respect to vehicle technology, fuel type, and vehicle age;
f) Reconcile observed ‘on-road’ vehicle exhaust emission rates with those observed in laboratory conditions at vehicle type approval;
g) Assess the implications of the research outcomes for local and national transport and air quality policy.
h) Produce recommendations for the way forward in terms of future research initiatives.

## 1.13 The Methodological Approach

The thesis commences in Chapter 2 by utilising a pre-existing dataset to investigate the nature of variability in driver behaviour, and the relationship between such variability and exhaust emissions and fuel consumption. The dataset contains data from a sample of forty individuals driving an instrumented vehicle over the same suburban route, chosen to eliminate as far as possible external traffic influences. In so doing, analytical issues such as temporal sampling rate and temporal synchronisation of dependent and independent variables are addressed. Characteristics of environmentally ‘efficient’ and ‘inefficient’ drivers are identified, and a cluster analysis technique is applied to group drivers according to relevant metrics and attributes.

Chapter 3 expands on the theme of variability in driver behaviour to explore the potential for influencing driver behaviour using a novel smart phone application to provide feedback to drivers in the form of eco-driving ‘scores’. The chapter reports the results of a small scale experiment involving seven participants. Data were collected over the journey to work route using the GPS functionality of the smart phones, and experimental algorithms applied to calculate eco-scores based on speed and acceleration rates. The experiment is limited by both the number of trial participants, and the time duration of the trial.

Nevertheless, some interesting insights were gained into the potential efficacy of such a system, and the impact variability in driver behaviour on outcomes.

Chapter 4 introduces the concept of remote sensing of road vehicle emissions to characterise fleet emissions. The chapter describes the general approach, the data collection methodology, data processing, and characterisation of technical aspects of the observed fleet. Ropkins et al. (2009) provide a comprehensive critical review of the techniques utilised to monitor real-world vehicle exhaust emissions. Real-world measurements (measurements of exhaust emissions from vehicles in operation on the highway network) differ from laboratory based measurements (typically using test cycles) because they have a more realistic potential to capture the range of variability typically encountered in real-world driving, including variability in driver behaviour, interactions with other road users, and interactions with highway infrastructure, all of which have the potential to influence exhaust emissions. Real-world measurements using techniques such as remote sensing also have the potential to monitor a representative cross section of vehicle ages and levels of maintenance (including faulty vehicles), sampling many thousands of vehicles, which would not be practical or cost effective to attempt in laboratory conditions. The disadvantages of remote sensing in this context relate to the variability in ambient atmospheric conditions, variation in size and location of exhaust plume, and limitations on the levels of absolute accuracy achievable in practice using such methods. Remote sensing can be seen as a useful complement to more detailed measurements using laboratory based chassis dynamometers or engine test beds, or on-road instrumented vehicles. Other researchers have identified its potential to provide statistically robust fleet emission characteristics through repeat measurements over a sustained period of time (McCrae et al., 2005).

Chapter 5 presents the results obtained from the analysis of emission rates carried out in Chapter 4. Importantly, Chapter 5 presents a rigorous statistical analysis of the emissions data, demonstrating clearly the statistically significant differences in emissions performance between vehicles of differing emission

(Euro) classes. A key finding is that emissions do not necessarily decline monotonically with the introduction of successive emissions control legislation. Data is presented for all of the main vehicle classes by fuel type, including passenger cars, taxis, buses, light commercial vehicles, medium and heavy commercial vehicles, to the extent that the data sample size permits. Observations are made on the contribution of ‘gross emitters’ to total emission rates, and comparisons are made with previous studies in the UK and Europe.

Finally in Chapter 6, an original method is proposed to reconcile emissions measurements obtained from roadside remote sensing, and emissions data obtained from statutory European type approval emissions tests carried out over a defined drive cycle. This is a key step in bridging the gap between two differing measurement techniques, which are historically applied for different purposes. The methodology requires future refinement, but is seen as a step change in integrating results from these two data sources. In particular, the application of the methodology highlights (a) the differences in emission rates from a type approval drive cycle, and ‘in-use’ emission rates observed ‘on-street’; and (b), the increase in ‘on-street’ emission rates observed with respect to vehicle age / mileage, relative to the original published type approval emission rates.

Chapter 7 presents conclusions and recommendations for future research and policy.

## 1.14 Summary

This research has been part funded by the EPSRC FUTURES project (grant reference GR/S90881/01) and Newcastle University. The FUTURES (Future Urban Technologies: Undertaking Research to Enhance Sustainability) programme (2004-2009) was concerned with research into *“the role of new technologies in progressing towards more sustainable urban mobility”.* The research programme focused on people, systems and vehicles as key elements which, in combination, result in the levels and patterns of urban mobility and the associated economic, social and environmental impacts.

The original research presented in this thesis focuses primarily on the variability of light vehicle emissions with changes in prevailing emission standards. However, the research also presents evidence of the significance of variability in driver behaviour on emissions and fuel consumption. Evidence is presented quantifying the differences between ‘real-world’ emission rates, and those measured at vehicle type approval, and how these relationships change over time with vehicle age. In addition, a case study is utilised to assess the potential of information technology to influence driver behaviour for environmental benefit.

In the final analysis, “*progress towards more sustainable urban mobility”* will require innovation in all three areas; vehicle technology, driver behaviour, and systems design. This thesis serves to identify and quantify some of the benefits which can be achieved in two of these three fields.

# Chapter 2. Variability in Driver Behaviour and Emissions

## 2.1 Introduction

In recent years, significant progress has been made in reducing and mitigating the environmental impact of road transport through regulation of vehicle emissions and technological advancement. The regulatory driving cycles used for vehicle type approval have evolved over time, but their representativeness of 'real world' driving is still subject to discussion and debate (Samuel et al, 2002; Andre, 2004; Pelkmans and Debal, 2006). The study of 'real-world' vehicle tail pipe emissions provides additional insights into the relationships between driver behaviour, vehicle technology, highway infrastructure, and traffic flow. Variability in driver behaviour, resulting from endogenous driver characteristics, external environmental influences, or a combination of both, has been identified by researchers as a source of variation in vehicle tail pipe emissions and fuel consumption. Some studies have sought to observe the significance of the natural variation in driver behaviour (Holmen and Niemeier, 1998; Ericsson, 2001), whereas others have sought to define or impose different types of behaviour, or preselect particular driver types, to measure the consequent effects on emissions and fuel consumption (De Vlieger et al, 2000; Rafael et al, 2006; Felstead et al, 2008).

When investigating the nature of variability in driver behaviour, and its influence on vehicle emissions and fuel consumption, it is desirable to remove as many confounding factors as possible (such as variations in vehicle type, highway network, traffic conditions, weather conditions etc.) such that any remaining variability can be ascribed to the driver alone. For example, Holmen and Niemeier (1998) carried out measurements in California using a single instrumented car with an automatic transmission over a predefined 3.2 mile route in light traffic conditions, driven by 24 randomly selected individuals. The study found evidence for significant differences in driving style and associated emissions, and that the intensity of operation within different operating modes (e.g. acceleration, deceleration) was more significant in predicting emissions than the frequency of different driving modes.

However, in a European context, the majority of passenger car transmissions are of the manual type, with the driver controlling gear selection for a given vehicle speed through appropriate use of the clutch and throttle. This adds an additional set of ‘choices’ for the driver, and consequently an additional source of potential variability between drivers.

This chapter reports the results of an independent analysis of data from a study where an instrumented passenger car with manual transmission was driven over a predefined route by a group of 40 drivers. Variation in driving behaviour is quantified using three parameters; throttle position, engine speed, and vehicle acceleration. Cluster analysis techniques are utilised to group types of driver behaviour, and the relationships between driver behaviour, fuel consumption, and exhaust emissions are explored.

## 2.2 Current European Instantaneous Emissions Modelling Practice

Current traffic micro-simulation models (such as AIMSUN, VISSIM, Dracula, Paramics etc) have the capability, in varying degrees, to incorporate instantaneous tail pipe emissions and fuel consumption models. For example, instantaneous emissions models developed by Int Panis (Int Panis et al 2006) have been implemented in Aimsun. These are based on ‘real-world’, second-by-second measurements of $NO_x$, VOC (volatile organic compounds), $CO_2$, and particulates with instrumented vehicles in urban traffic conditions. The emissions relationships were developed based on an original sample of six buses, two trucks, and seventeen cars (twelve petrol & five diesel). Model functions are specified by fuel type, engine capacity, EURO emissions standard, vehicle type and applied by market share. However, a limitation of this particular model is that the vehicle sample used for calibration was relatively small, limited to Euro 1 to 3 emission standard vehicle types, and data was only collected in an urban environment (with corresponding urban speeds).

As part of the ARTEMIS (Assessment and Reliability of Transport Emission Models and Inventory Systems) EU 5th framework project (1999-2007), two new instantaneous passenger car emissions models were developed at the EMPA research institute in Switzerland, and at Graz University of Technology (TUG) respectively (ARTEMIS 2007). The EMPA emissions matrix model developed in ARTEMIS is a function of engine speed, brake mean effective pressure (a function of torque and engine displacement), and a derivative of manifold pressure. The model was based on data collected from thirteen petrol cars (three pre Euro 1 & 10 Euro 3 standard), and seven Euro 2 standard diesel cars. Sixteen different real-world driving cycles per car were investigated, and CO, $CO_2$, HC, $NO_x$ and other vehicle related metrics (vehicle speed, engine speed, vehicle torque, etc.) were logged at a frequency of 10 Hz.

The PHEM emissions model, developed at TUG is based on engine speed n (rpm) and effective engine power P (kW). Engine power P was simulated on a second-by-second basis, where P is the ∑(rolling resistance, air resistance, acceleration, road gradient, transmission losses, and auxiliaries). Engine speed is simulated by a drivers' gear shift model and the actual transmission ratios. The model was initially calibrated using measurements of eight diesel cars and six Euro 3 standard petrol cars using a range of driving cycles on a rolling test bed at 1Hz. The model calibration data was extended in 2008 to sixty one passenger cars. PHEM is currently applicable up to Euro 4 emission standards. For both the EMPA and PHEM emissions models, prediction quality using a static map was not considered satisfactory for three-way catalyst vehicles. Since hot emissions of modern catalyst cars are very low, short emission peaks occurring in mainly transient loads tended to dominate the overall emission factor. The EMPA model used the derivative of engine manifold pressure for transient corrections as a dynamic variable. The PHEM model uses empirical transient correction functions, such as derivatives of engine power and engine speed over different time periods before the emission event occurs. With such dynamic corrections, both models are found to be more reliable.

The PHEM emissions model has been implemented in the Aimsun traffic micro-simulation model. Vehicle trajectories (speed & acceleration) created in the Aimsun micro-simulation are passed to the PHEM model to generate emissions (Zallinger et al 2008). However, this approach requires 'post-traffic micro-simulation' rationalisation of gear changing behaviour, with implicit local adjustments of the vehicle trajectories. Ideally, gear changing, and its influence on localised vehicle trajectories, would be internalised within the traffic micro-simulation model (so that gear changing was an output from the traffic micro-simulation to the emissions model).

### 2.3 The RETEMM Project

RETEMM, Real-world Traffic Emissions Monitoring and Modelling, funded by the UK Engineering and Physical Sciences Research Council, and completed in 2008, investigated the impact of driver behaviour on emissions (Bell et al 2008). Simultaneous measurements of real-world traffic conditions, driver behaviour, and vehicle emissions were undertaken. The independent analysis presented here utilises some of the data generated in the RETEMM project to illustrate the significance of variability in driver behaviour (and other variables) on fuel consumption and emissions.

Data collection was carried out during the period September to November 2006. A short (0.6km) circular route was defined in a suburban residential area (West Park), illustrated in Figure 1, characterised by having priority junctions only i.e. no traffic signals. The route comprised of four reasonably straight sections (Legs 1-4) varying in length between 140 and 165 metres.

Forty drivers were recruited, comprising 20 male and 20 female. The sample of drivers spanned a wide range of driving experience, and ages from 21 to 63. Drivers drove ten laps of the circuit in an anti-clockwise direction, commencing on Leg 1 through Legs 2, 3, and 4, and repeating continuously until the ten laps were complete. The analysis presented here utilises data collected from a Euro 4 standard petrol SI passenger car (2004 model Ford Mondeo 1.8 litre with manual transmission) fitted with an HORIBA OBS-1300 emissions measurement system, combined with GPS vehicle positioning (Daham 2006). Data was collected at 1 Hz. Map matching algorithms developed as part of the RETEMM project were used to ‘fit’ GPS measurements of vehicle position to a vector representation of the highway network (Skelton 2007).


**Figure 1: Aerial view of the West Park test route**

### 2.4 Data Processing

During data processing, it was noted that data logging commenced up to 90 seconds before the commencement of a measurement run (whilst the vehicle was stationary), and continued up to 60 seconds after a run was complete. In addition, inconsistencies in the GPS data for one of the drivers during the first loop rendered this positional data unreliable. Any potential sources of variability across drivers caused by these data characteristics were avoided by discarding them from this analysis; Loop 1 of every driver, and any data logged after completion of leg 4 of loop 10 was discarded. One ‘engine stall’ event, with a duration of five seconds, was removed from the data set. The ‘clean’ data set in this analysis comprises nine complete laps of the test circuit, loops 2 to 10 inclusive, for 40 drivers. In all this amounted to 29,886 one second observations. In addition, it was found that engine speed (RPM) data for three of the forty drivers was unreliable due to instrumentation faults. Thus, any analysis utilising engine speed (RPM) data was limited to thirty seven of the forty drivers.

During the course of the RETEMM project, it was discovered that the $NO_2$ sensor technology (zirconium dioxide) utilised for some of the on-vehicle tail pipe measurements suffered from cross sensitivity with ammonia ($NH_3$) because of chemical reaction with oxygen. This shortcoming called the $NO_2$ results from the $ZrO_2$ sensor into question, and they have generally not been presented here.

A preliminary inspection of the data flagged up some potential temporal synchronisation issues across measured variables. This is a challenging issue in vehicle emissions measurement, encompassing as it does several potential causes, namely synchronisation of the measurement of driver inputs, vehicle operating metrics, and gas flow through the engine and exhaust system. These issues are discussed later in this thesis. Further information on such issues can be found in Weilenmann et al 2003, Ajtay et al 2004, and Ropkins et al 2009.

### 2.5 Overview of Aggregate Emissions and Fuel Consumption

The illustrative analysis is presented here in three steps. The first compares total tail pipe emissions of all 40 drivers to identify high and low emitters. The second step examines in more detail the aspects of variability across and within drivers, utilising box plots to investigate the distribution of data. The third step looks at some of the driving characteristics of a small sample of drivers manifesting high and low emission characteristics respectively.

| Driver No. | n | CO (g) | CO2 (g) | HC (g) | Fuel (g) | Driver No. | n | CO (g) | CO2 (g) | HC (g) | Fuel (g) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 762 | 2.54 | 1593 | 0.54 | 479 | 21 | 652 | 9.44 | 1891 | 0.47 | 541 |
| 2 | 689 | 7.72 | 1928 | 0.28 | 585 | 22 | 653 | 5.71 | 1908 | 0.18 | 561 |
| 3 | 714 | 7.49 | 2019 | *0.13 | 604 | 23 | 628 | 7.95 | 2018 | 0.48 | 599 |
| 4 | 773 | 4.43 | 2053 | 0.21 | 600 | 24 | 626 | 15.54 | 2033 | 0.46 | 627 |
| 5 | 907 | 2.85 | 1804 | 1.06 | 542 | 25 | 632 | 8.92 | 2066 | 0.54 | 633 |
| 6 | 839 | 2.45 | 1577 | 0.86 | 479 | 26 | 779 | 10.72 | 1994 | 0.71 | 604 |
| 7 | 854 | 5.22 | 2060 | 1.39 | 605 | 27 | 648 | 14.97 | 1884 | 1.23 | 612 |
| 8 | 697 | 5.19 | 1798 | 1.48 | 527 | 28 | 710 | 3.97 | 1723 | 1.01 | 556 |
| 9 | 872 | *1.12 | 1789 | 0.85 | 538 | 29 | 776 | 3.96 | 1670 | 0.99 | 515 |
| 10 | 692 | 20.41 | 1888 | 1.87 | 580 | 30 | 709 | 7.79 | 1710 | 1.34 | 528 |
| 11 | 705 | 7.34 | 1791 | 1.15 | 536 | 31 | 818 | 1.66 | *1569 | 0.84 | *472 |
| 12 | 819 | 2.45 | 1629 | 0.77 | 486 | 32 | 860 | 7.12 | 2027 | 0.79 | 593 |
| 13 | 875 | 1.98 | 1813 | 1.05 | 536 | 33 | 711 | 6.49 | 1964 | 0.72 | 600 |
| 14 | **946 | 19.13 | **2214 | 1.64 | **652 | 34 | 833 | 1.43 | 2031 | 0.79 | 594 |
| 15 | *572 | **73.21 | 2104 | **2.47 | 632 | 35 | 833 | 1.36 | 1760 | 0.61 | 528 |
| 16 | 759 | 9.97 | 1995 | 0.48 | 568 | 36 | 772 | 2.75 | 1865 | 0.59 | 561 |
| 17 | 662 | 3.95 | 2003 | *0.13 | 576 | 37 | 686 | 5.74 | 2007 | 0.72 | 599 |
| 18 | 697 | 6.26 | 1866 | 0.99 | 560 | 38 | 787 | 2.98 | 1665 | 0.61 | 498 |
| 19 | 710 | 9.25 | 1891 | 1.37 | 557 | 39 | 880 | 2.52 | 1675 | 0.77 | 505 |
| 20 | 607 | 7.89 | 1909 | 0.30 | 558 | 40 | 742 | 4.03 | 1791 | 1.09 | 529 |

| | n | CO (g) | CO2 (g) | HC (g) | Fuel (g) |
|---|---|---|---|---|---|
| Mean | 747 | 8.15 | 1874 | 0.85 | 561 |
| Median | 728 | 5.72 | 1890 | 0.78 | 560 |
| Range | 374 | 72.09 | 645 | 2.34 | 179 |
| Min.* | 572 | 1.12 | 1569 | 0.13 | 472 |
| Max.** | 946 | 73.21 | 2214 | 2.47 | 652 |
| Sum | 29886 | 325.89 | 74973 | 33.94 | 22456 |
| Count | 40 | 40 | 40 | 40 | 40 |

**Table 2: Summary of aggregate emissions / fuel consumption by driver.**

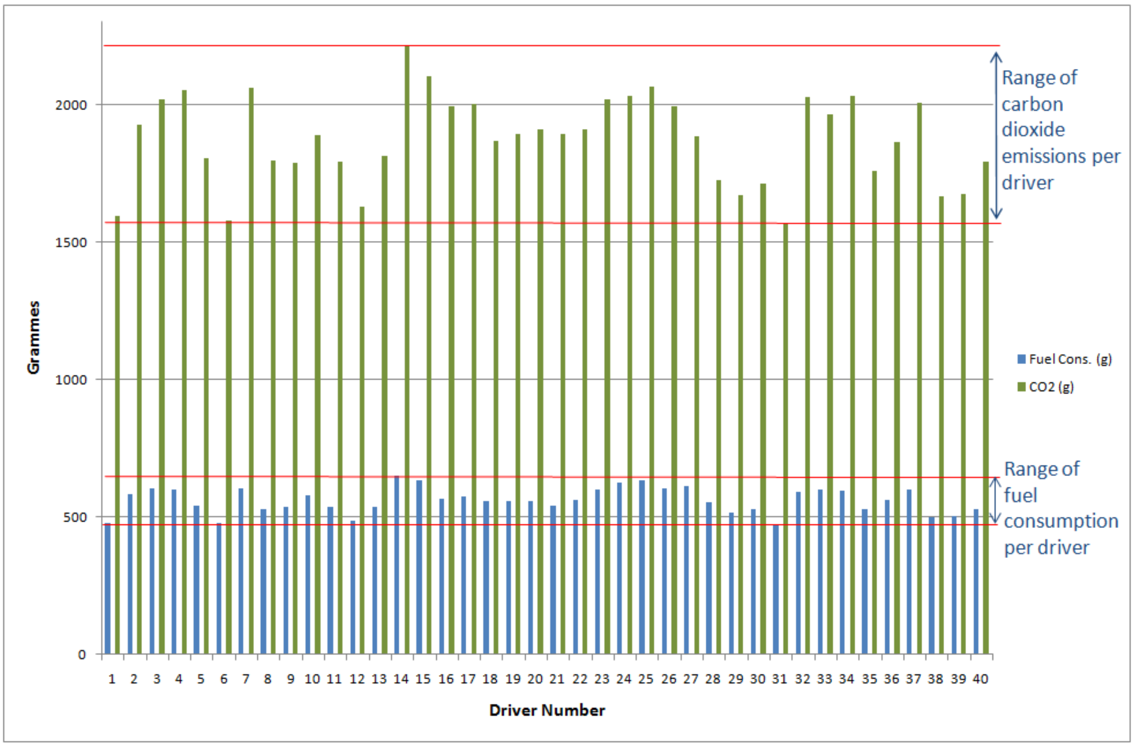



**Figure 2: Range of variation in aggregate $CO_2$ emissions and fuel consumption**

Table 2 provides a summary of the total tail pipe emissions (CO, $CO_2$, HC, and fuel consumption) in grams generated by each driver for a complete measurement sequence of nine laps. Descriptive statistics are also included. It should be noted that the data in this table contains some variability due to 'events' which occurred during the driving cycle (e.g. pausing to allow an oncoming vehicle to pass, slowing down for a cat crossing the road etc). However, the number of these 'events' in the data set is small, because the route was a very quiet suburban road with relatively little interaction with other vehicles, and their influence on variability in emissions across drivers is small compared to the larger variability due to driver behaviour. It can also be argued that the response of an individual driver to an 'event' will vary and that, for example, an oncoming vehicle may generate a response in one driver (e.g. deceleration), but no response in a second driver, due to differing perceptions of risk and gap acceptance. Whilst some events are likely to generate a reasonably uniform response across drivers (e.g. the road completely blocked), other occurrences (e.g. a slight narrowing of the carriageway) may generate no response in some drivers, and varying responses in others. The 'maximum' and 'minimum' emissions values per variable have been highlighted in the table to aid interpretation.

Firstly, it is notable that there is significant variability in the number of one second observations (n), and hence the average journey time. Nine loops of the test route equates to approximately 5.4 kilometres in total for each driver. The 'fastest' driver completed the nine loops in 572 seconds, giving an average speed of 9.4 metres per second or 34 kph. The 'slowest' driver completed the 5.4 kilometres in 946 seconds, giving an average speed of 5.7 metres per second or 20.5 kph. The mean speed was 26 kph, whilst the median speed was 26.7 kph.

Some outliers are observed in the carbon monoxide data, with driver 15 generating an extreme value of 73.21 grams over the test cycle. A small number of other drivers (e.g. 10, 14, 24, and 27) generate high values in the range 14.97 grams to 20.41 grams. With such a high value for driver 15, explanations such as validity of sensor response should not be immediately discounted, and required further investigation. However, examination of the data does suggest that the driving style did influence the high emissions values observed. Overall, the mean carbon monoxide value was 8.15 grams, with a median value of 5.72 grams, suggesting that most drivers generated much lower amounts of CO, as observed in Table 2. Drivers 9, 35, 34, and 31 generated the lowest total amounts of CO at 1.12g, 1.36g, 1.43g, and 1.66g respectively.

Again, driver 15 was responsible for the highest total hydrocarbon emissions at 2.47 grams, with drivers 10 and 14 generating 1.87g and 1.64g respectively. Drivers 17, 3, and 22 generated the least HC at 0.13g, 0.13g, and 0.18g respectively. The mean HC value was 0.85g, with a median value of 0.78g.

As is to be expected, there is a high degree of consistency between fuel consumption and carbon dioxide emissions, but a high degree of variation was observed across the drivers in the sample. Figure 2 illustrates the variability in fuel consumption and $CO_2$ emissions across the sample.

Driver 31 used the least fuel at 472 grams, and produced the least $CO_2$ at 1569 grams. Other notable low producers of $CO_2$ included drivers 6 and 1, at 1577 grams and 1593 grams respectively. At the other extreme, driver 14 had the highest fuel consumption at 652 grams, and the highest $CO_2$ emissions at 2214 grams. Other high $CO_2$ emitters included drivers 15 (2104g) 25 (2066g), 7 (2060g), and 4 (2053g). An important observation to make at this stage is that high total fuel consumption and $CO_2$ emissions were observed for drivers with both high average speeds (e.g. driver 15 at 34kph), and low average speeds (e.g. driver 14 at 20.5kph). Thus, high or low average speed is not of itself an indicator of economical and environmentally sympathetic driving. Of more relevance is the product of the rate of $CO_2$ emissions or fuel consumption (g/sec), and the total journey time. On the other hand, the most economical drivers do appear to be clustered in the range 23.2kph to 25.5kph in the context of this trial (but such average speeds do not necessarily themselves imply ‘eco-driving’).

Perhaps the most notable practical observation to make on this aspect of the data set is that the least economical driver consumed 38% more fuel than the most economical driver, and produced 41% more $CO_2$. Clearly such extremes can be a little misleading if taken out of context, but it does demonstrate that significant benefits may be possible if driving behaviour can be rationalised (if not optimised).

Overall, based on this aggregate assessment, it can be observed that certain drivers appear to display behaviours which may be coarsely categorised as ‘environmentally efficient’ (e.g. drivers 12, 17, 29, 31, and 35), whereas other drivers display behaviours which may be coarsely categorised as ‘environmentally inefficient’ (e.g. drivers 7, 10, 14, 15, and 24). Again, it should be emphasised that the underlying behaviours which result in these outcomes (especially for inefficient drivers) may be very different. Care should be taken not to generalise too much, since the generation process for individual pollutants varies, and variations in pollutant generation rates can be explained by more than one driver behaviour characteristic (for example, high levels of various emissions can be generated by both excessively aggressive drivers, and by inexperienced or overly cautious drivers). These more complex relationships will be the subject later discussion.

### 2.6 Variability in Tailpipe Emissions and Vehicle Metrics across Drivers

Figure 3 presents a box plot of the 1Hz carbon dioxide ($CO_2$) emissions measurements for each driver. The data has been sorted in rank order of 75th percentile values (the top of the inter-quartile range) to aid interpretation. Interpretation of this plot can provide an insight into the shape of the distribution of the data points for each driver, and the degree of variability. Seventeen of the forty drivers exhibit outliers beyond 1.5 times the inter-quartile range, but outliers only exist beyond the upper quartile (as is perhaps to be expected).

Drivers 14 and 33 in particular exhibit a larger number of outliers. There is significant variation in the inter-quartile range (IQR) across drivers, the IQR being 2 – 3 times larger for drivers 15 and 25, when compared to drivers 13 or 31, for example. Overall, the median (50th percentile) values tend to occur in the lower half of the IQR's, indicating that the distribution tends to be skewed, although there are some exceptions, for example driver 36.

Figure 4 presents box plots of the 1Hz carbon monoxide (CO) emissions measurements. In this case, there is far more variability in the data, particularly in the outliers and extreme outliers (more than three IQR's above the upper limit). For this reason, two plots have been presented, one plot for the ten drivers with the largest extreme outliers, and one plot for the other thirty drivers. Please note that the y-axis scales for these two plots are different by a factor of ten to accommodate these differences.

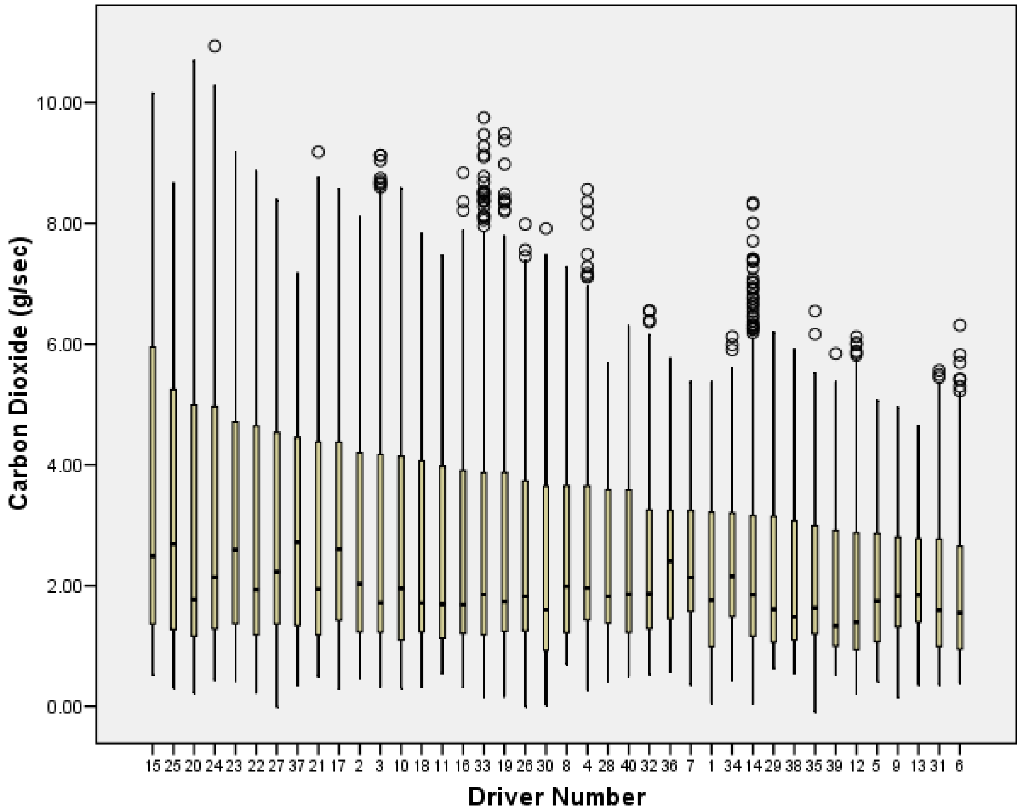
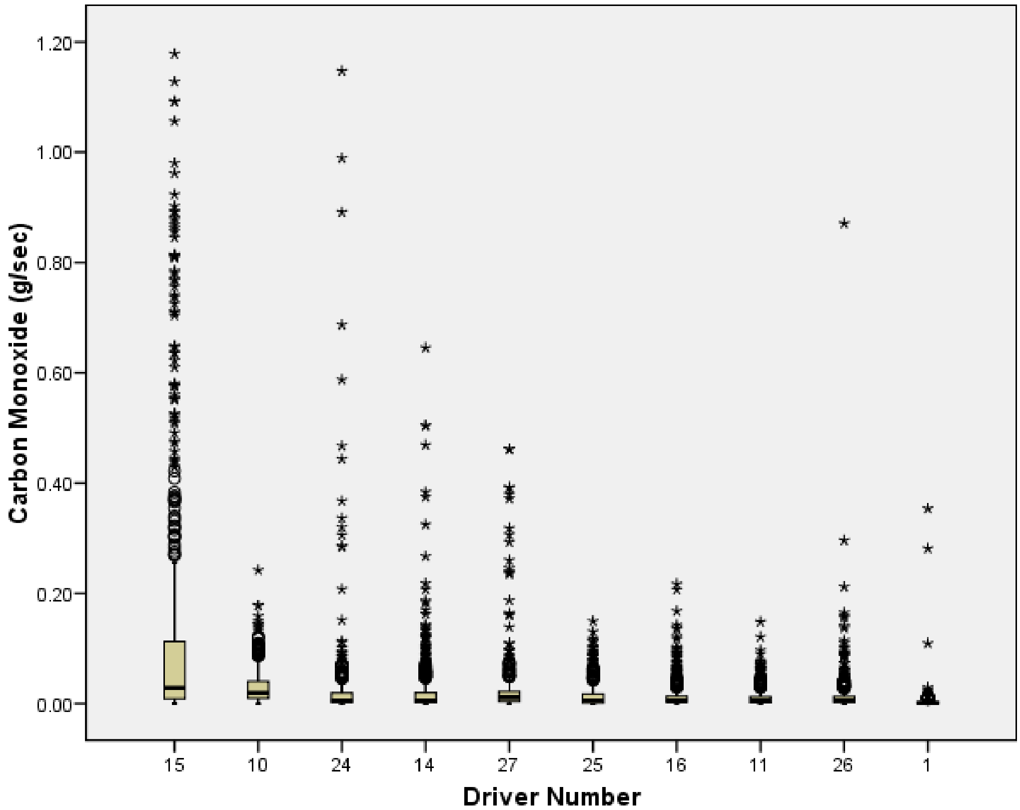



**Figure 3: Box plot of carbon dioxide emissions across drivers, ranked by 75th percentile values**



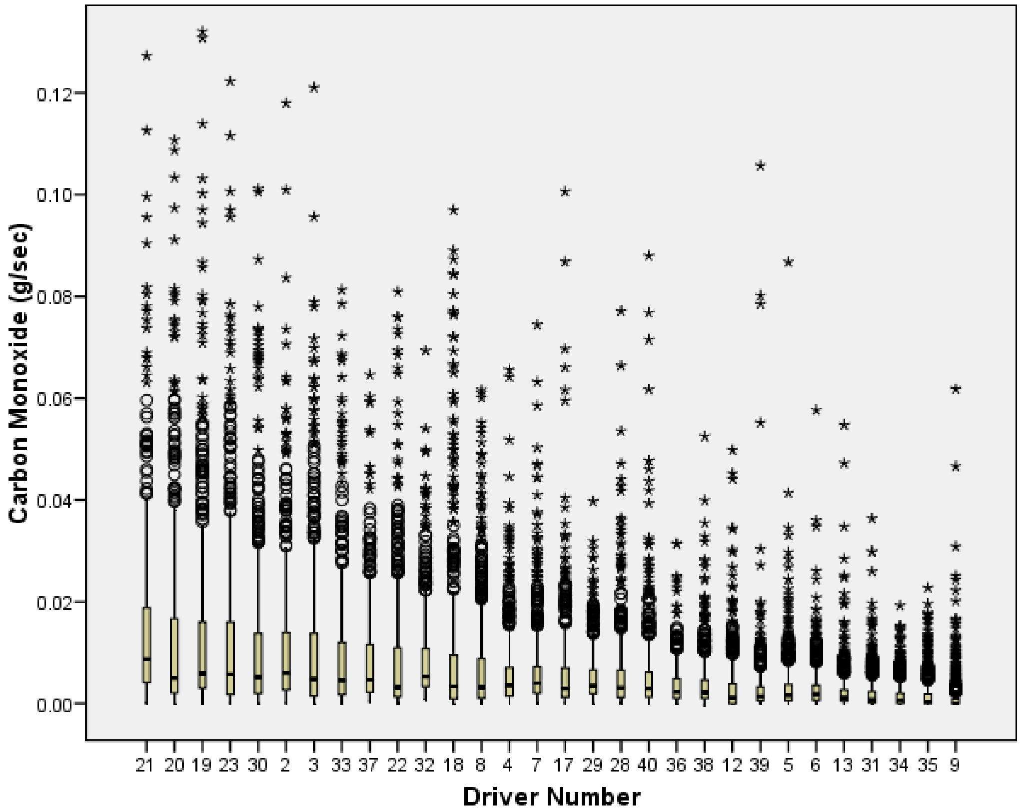




**Figure 4: Box plot of carbon monoxide emissions across drivers, ranked by 75$^{th}$ percentile values**

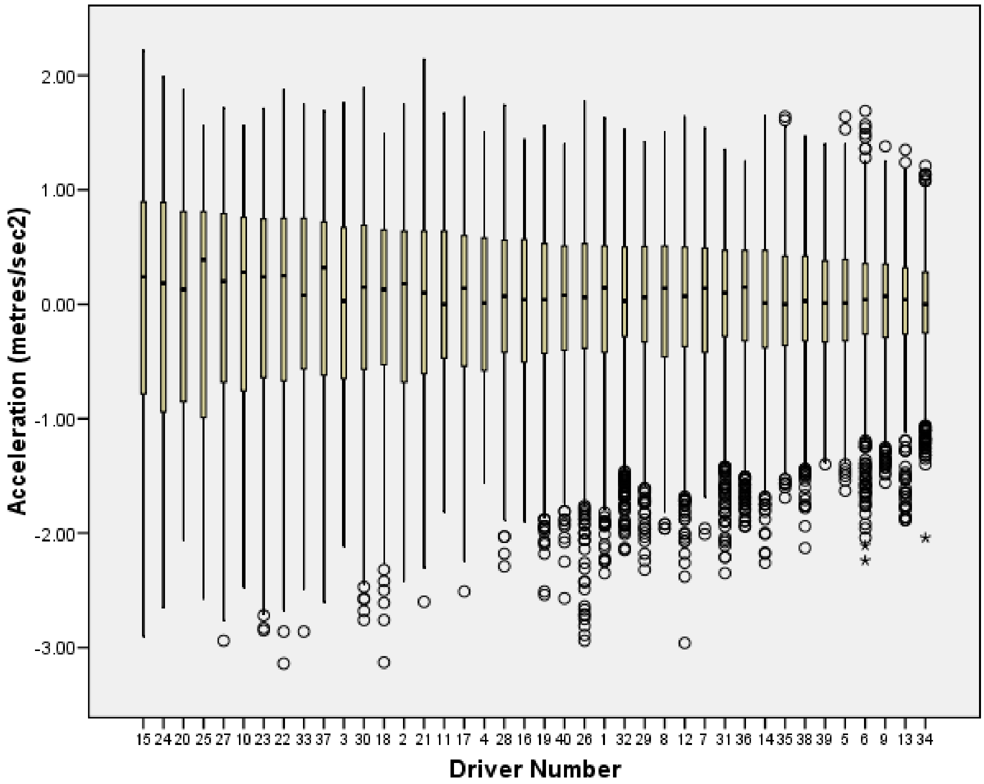



**Figure 5: Box plot of vehicle acceleration across drivers, ranked by 75th percentile values**

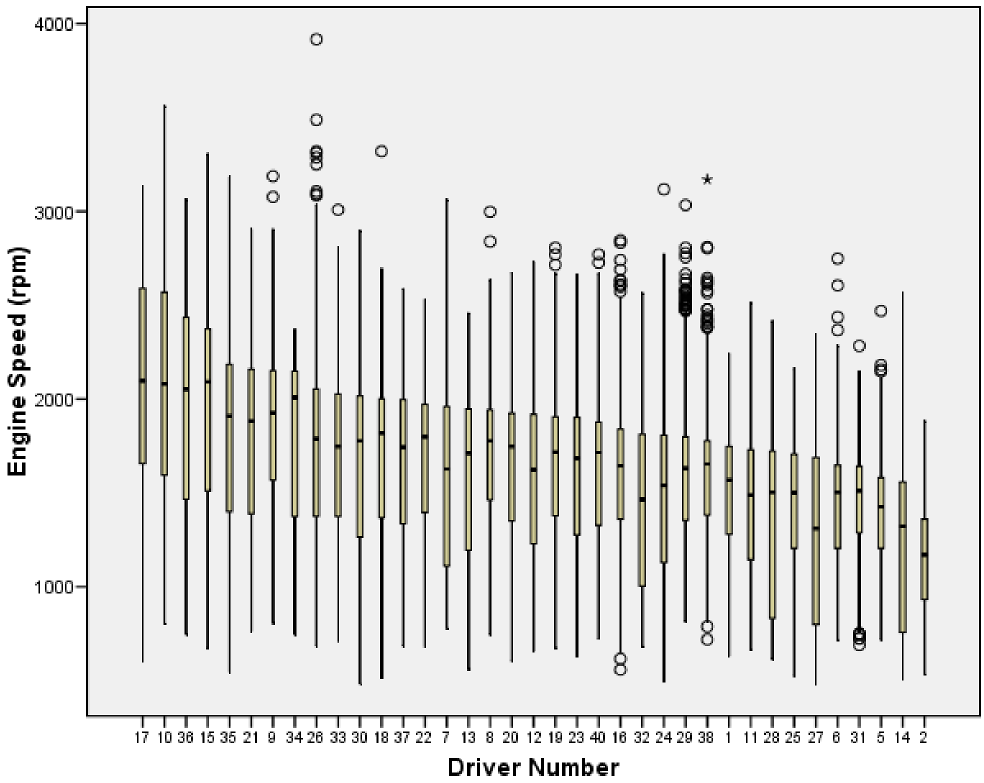



**Figure 6: Box plot of vehicle engine speed across drivers, ranked by 75th percentile values**

It can be seen from the data that whilst there is significant variability overall in the IQR, the data is characterised by the large number of outliers and extreme outliers beyond the upper limit. Driver 15 in particular exhibits a much larger IQR than the other drivers, and a range of extreme outliers rivalled only by drivers 14, 24, 26, and 27. The size of the IQR varies significantly across drivers, and the median values again tend to be skewed towards the bottom half of the IQR.

Figure 5 presents a box plot of vehicle acceleration in metres per second squared (both positive and negative) for all drivers. In this plot the 75th percentile values tend to be more stable across the drivers, in the approximate range +0.3 to +0.9m/s$^2$. There are few outliers in +ve acceleration, and these tend to be observed in drivers who are otherwise characterised as very gentle accelerators, for example drivers 6, 13, and 34. However, there is a much higher number of outliers during -ve acceleration (braking), but again these tend to be observed in drivers who are otherwise characterised as gentle brakers. For drivers who are gentle brakers and accelerators, the median values (50th percentile values) tend to be found in the centre of the IQR. For drivers who are more aggressive brakers and accelerators with larger IQR's, the median tends to be skewed towards the upper quartile.

Finally, Figure 6 presents a box plot of engine speed in revolutions per minute (rpm) for all drivers. This plot illustrates the very significant variability in the driver's choice of engine speed (and implicitly, gear selection). It is notable that the 75th percentile values of drivers 2 and 14 are below the 25th percentile values of drivers 10 and 17. Significant variability is observed in the inter-quartile ranges, with some drivers characterised by a narrower IQR at high engine rpm, some drivers with a narrower IQR at low engine rpm, and other drivers with a wide IQR across a wider range of engine rpm. As is to be expected, where outliers are observed in the plot, they tend to be found above the upper limit, not below the lower limit (with some minor exceptions).

## 2.7 Characteristics of Environmentally 'Efficient' and 'Inefficient' Drivers

These issues were explored in more depth, by selecting two drivers for more detailed analysis. Driver 7 was selected as a relatively 'inefficient' driver, and Driver 31 was selected as a relatively 'efficient' driver. These two drivers were selected as illustrations because they were reasonably representative of the high and low ranges. No 'a priori' assumptions were made about the reasons why they exhibited these characteristics.

To investigate further the causality behind these contrasting results, the relationship between engine speed and vehicle speed (and hence gear selection) has been explored. Figure 7 presents the frequency distribution of engine speed (rpm) over the test cycle for each driver. It can be seen that the distributions are quite different.

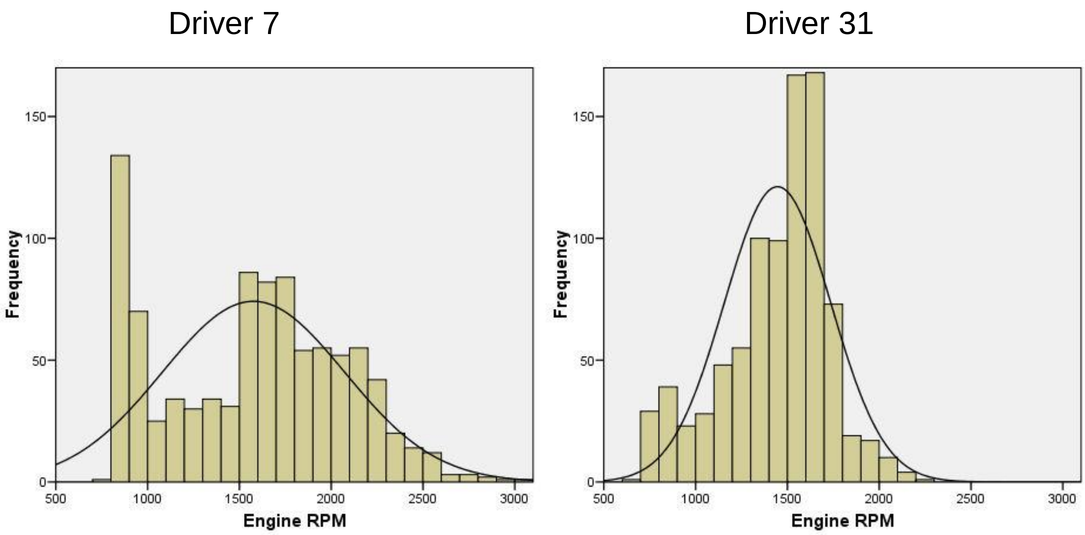



**Figure 7: Frequency distribution of engine rpm for Driver 7 and Driver 31**

Driver 7 exhibits a large peak at engine idle speeds (below 1000 rpm), and a relatively wide spread of engine rpm up to 3000rpm. In contrast, Driver 31 exhibits a relatively small proportion of engine speed below 1000 rpm, and a relatively narrower spread of engine speeds up to 2300 rpm, with peaks in the range 1500 – 1700 rpm.

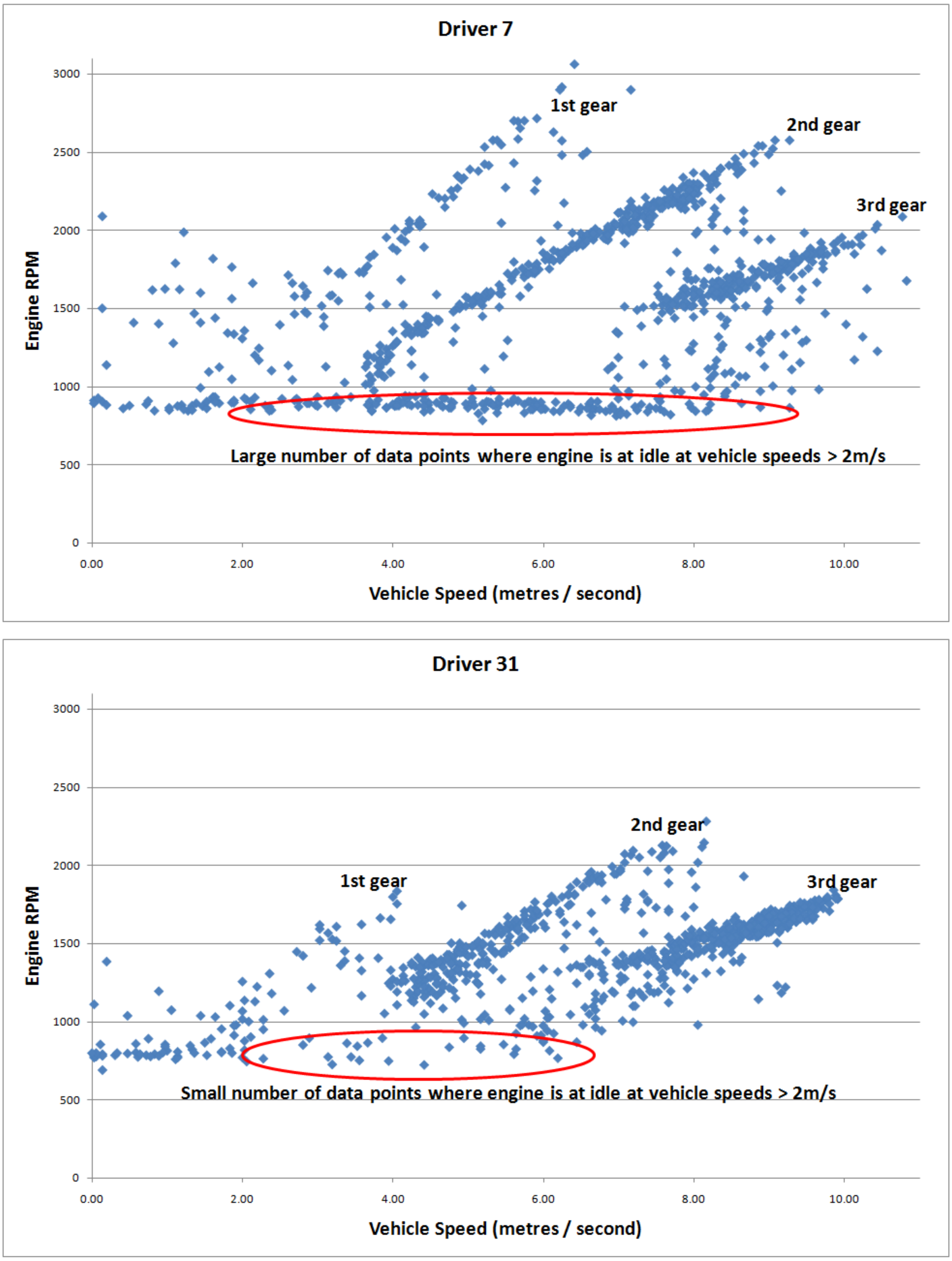



**Figure 8: Relationship between engine speed and vehicle speed**

Figure 8 presents the relationship between engine speed and vehicle speed for Driver 7 and Driver 31 respectively. A clear difference can be seen between the gear selection / engine speed choices of Drivers 7 and 31. Driver 7 tends to use higher engine speeds (up to 3000 rpm) and in particular retains first gear at engine speeds in excess of 2000 rpm. The three gears used predominantly by Driver 7 (1st gear, 2nd gear, and 3rd gear) are clearly visible as the three diagonal linear clusters with a positive slope (with 1st gear to the left with a steeper slope, and 3rd gear to the right with a lesser gradient). In contrast, Driver 31 very rarely exceeds 2000 rpm engine speed. Driver 31 makes very little use of 1st gear, apparently changing into 2nd gear almost immediately the vehicle is moving. Indeed, the width of the 2nd gear data cluster at engine speeds below 1500 rpm suggests that some slippage of the clutch is taking place to facilitate an early ‘up change’ from 1st gear to 2nd gear (although this may also be a time synchronisation issue). It can be seen that the clustering on the 2nd gear slope becomes narrower as engine speed increases. Another notable contrast between the two drivers is the high incidence of data points for Driver 7 at idling engine speeds, i.e. below 1000 rpm (across the full range of vehicle speeds). In contrast, Driver 31 has relatively few such data points. This suggests that Driver 7 is depressing the clutch pedal and / or taking the vehicle out of gear across a wide range of vehicle speeds during deceleration. Further investigation is required to assess the significance of this difference in driver behaviour on emissions characteristics.

### 2.8 Observations on Temporal Sampling Resolution

The data in this case study were collected at a sampling frequency of 1Hz across all variables. However, independent variables relevant to the prediction of fuel consumption and exhaust emissions may have a maximum frequency of greater than 1Hz, and the frequency of relevant variables may vary. In addition, recent research has shown that transient ‘spikes’ in exhaust emissions from modern passenger cars fitted with three way catalysts often have a frequency of the order of 3 to 5Hz, and that consequently a sampling frequency of the order of 10Hz is recommended (Weilenmann et al, 2003).

The Nyquist-Shannon Sampling Theorem provides a theoretical basis for determining the appropriate sampling rate of a variable. Mathematically;

$$f_s \geq 2f_c \quad (1)$$

where $f_s$ is the sampling frequency, and $f_c$ is the highest frequency contained in the signal. If $f_s < 2f_c$, then 'aliasing' can occur where a misleading/false understanding of the form of the original signal can be arrived at.

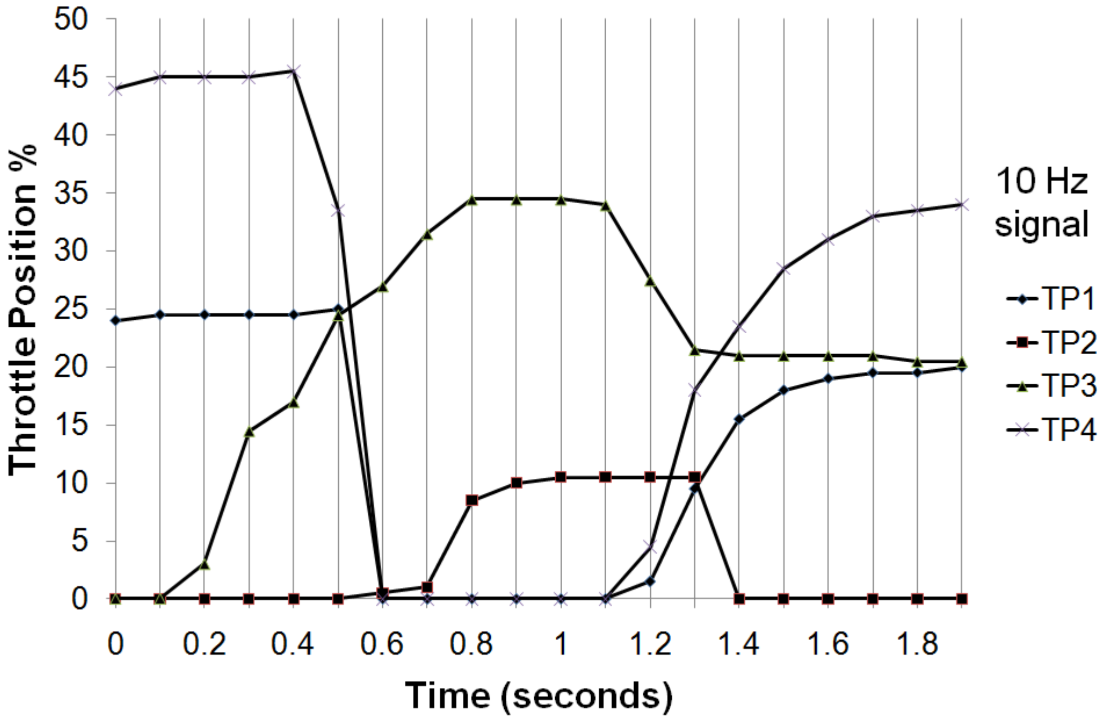



**Figure 9: Illustrative example of variability in throttle position at 10Hz**

The highest frequency contained in a signal can be determined by measurement. A simple but relevant illustrative example is presented in Figure 9. Changes in throttle (accelerator) position were measured at a sampling frequency ($f_s$) of 10Hz on an instrumented vehicle during normal driving. Figure 9 presents four short (2 second duration) samples of 10Hz data (TP1 – TP4) from these measurements. By observation, it can be seen that significant transitions in throttle position (+/- 20 to 40%) can occur within time periods of 0.3 to 0.1 seconds (3Hz - 10Hz). From this simple example, it can be seen that if throttle position was a significant independent variable in our analysis, it should be sampled at a rate of perhaps $f_s$ = 20Hz to capture transitions taking place at $f_c$ = 10Hz, or $f_s$ = 10Hz to capture transitions taking place at $f_c$ = 5Hz. This raises practical concerns for experimental design about achieving consistency of sampling frequency if, for example, sensor response times for some variables are constrained by limitations of technology. However, this insight suggests that the sampling frequency of 1Hz utilised in this study is likely to miss higher frequency transient signals in both inputs (e.g. throttle position) and outputs (e.g. exhaust emission spikes), and that future experiments should sample at a frequency of at least 10Hz.

## 2.9 Temporal Synchronisation

According to INRETS (2006), there are a number of potential systematic problems associated with the measurement of instantaneous emissions. The emissions signals recorded by exhaust gas analysers are delayed in time and smoothed compared to the emission events at the location of formation due to:

1. The transport of the exhaust gas to the analysers;
2. The mixing of exhaust gas, especially in the vehicle silencer and measurement equipment;
3. The response time of the analysers.

The use of data from sensor measurements which have not been corrected for time alignment and signal smoothing will potentially lead to errors in the allocation of emissions to corresponding engine operating conditions. Le Anh et al (2006) present mathematical techniques to attempt to address these issues by dynamically explaining the change of the emission value from its location of formation to the exhaust gas analyser signal by formula, and then by inverting these formulae to obtain equations which transform the analyser signal into the engine out (or catalyst-out) emission value. This technique has been used within the EU 5th Framework ARTEMIS project by both the Technical University of Graz and by the EMPA research institute in Switzerland (INRETS 2006).

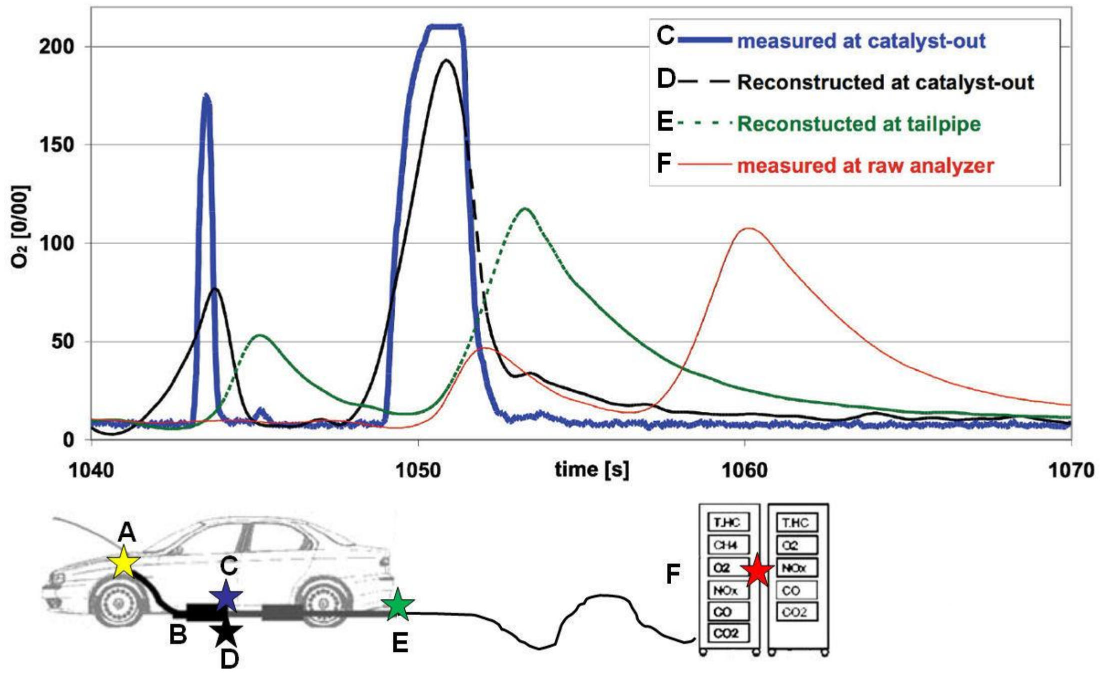



**Figure 10: Variability of time alignment between engine operation and measured emission signal, and reconstruction of source emissions using sensor signal inversion techniques example of variability in throttle position at 10Hz**

*Adapted from INRETS (2006), and Ajtay et al (2004).*

Figure 10 is adapted from the ARTEMIS work, and illustrates both the emissions signal time offset and smoothing effects, and the signal reconstruction using the equation inversion approach. In this example, an oxygen signal at the catalyst outlet (measured at location 'C') is reconstructed from the analyser signal (measured at location 'F'). One of the conclusions drawn from this work is that the use of data from sensor measurements which have not been corrected for time alignment and signal smoothing will potentially lead to errors in the allocation of emissions to corresponding engine operating conditions (INRETS 2006). Static time alignment may be appropriate in some circumstances where engine operation is constant in terms of engine speed, load, and resultant gas transit times in the vehicle exhaust and measurement system. However, in the real world, engine speed and load have the potential to be highly variable due to:

- The designed operational range of the vehicle's engine;

- Fuel type (diesel engines tend to operate over a narrower and lower engine speed range than petrol engines);
- Variability of behaviour within individual drivers;
- Variability of behaviour across drivers within the wider population.

The data utilised within this case study were originally processed within the RETEMM project employing techniques described in Ropkins et al (2007). A static time offset was assumed which accounted for the delay time due to gas transit from the point of sample measurement at the tailpipe to the sensor, including sensor response times. However, it was recognised by the researchers that this approach did not explicitly take account of variation due to the dynamic nature of gas transit times within the vehicle exhaust system due to changes in engine speed and load. Also, the fact that the data is at 1Hz frequency severely constrains the potential to apply dynamic alignment techniques because such required corrections are likely to be at higher frequencies. For this reason, static time alignment was retained within this analysis, but an attempt was made to account for inter-driver variability.

The constrained nature of the route used to collect the data in this case study could limit the range of variability between drivers one might expect to observe, as reflected in temporal offset between emission generation and emission measurement. Nevertheless, variability is observed within the sample of 40 drivers. To investigate this phenomena further, a simple linear correlation was carried out between emissions (grams/sec), and vehicle acceleration (-/+$m/s^2$) and throttle position (0-100%) with varying static time offsets. Similar techniques have been used by North et al (2006). A time offset range of -5 seconds (before the measured emissions event) to +5 seconds (after the measured emissions event) was explored in 1 second steps. Table 3 presents the number of drivers at each time offset for throttle position and acceleration, determined at the location of maximum correlation for each driver. Figure 11 illustrates the relationships between correlation and time offset for $CO_2$ and hydrocarbons (HC) across the 40 drivers. This analysis has the potential both to indicate the appropriate static time offset between prospective dependent and independent variables, and to highlight variability between drivers, but also to indicate where linear relationships (positive or negative) might exist, although of course the relationships may not be linear.

| Throttle Position | | $CO_2$ | CO | HC | $NO_x$ | Acceleration | | $CO_2$ | CO | HC | $NO_x$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Δt= -1 | Min | - | 0.34 | - | - | Δt= -3 | Min | - | 0.08 | - | - |
| | Max | - | 0.42 | - | - | | Max | - | 0.47 | - | - |
| | Mean | - | 0.38 | - | - | | Mean | - | 0.32 | - | - |
| | Median | - | 0.38 | - | - | | Median | - | 0.42 | - | - |
| | n | - | 2 | - | - | | n | - | 3 | - | - |
| Δt= 0 | Min | 0.78 | 0.09 | 0.12 | 0.48 | Δt= -2 | Min | 0.66 | 0.18 | 0.12 | 0.47 |
| | Max | 0.90 | 0.69 | 0.79 | 0.84 | | Max | 0.78 | 0.55 | 0.66 | 0.72 |
| | Mean | 0.86 | 0.44 | 0.54 | 0.66 | | Mean | 0.74 | 0.37 | 0.44 | 0.60 |
| | Median | 0.85 | 0.46 | 0.59 | 0.67 | | Median | 0.76 | 0.37 | 0.54 | 0.62 |
| | n | 39 | 36 | 26 | 39 | | n | 8 | 25 | 3 | 25 |
| Δt= +1 | Min | 0.79 | 0.50 | 0.33 | 0.48 | Δt= -1 | Min | 0.62 | 0.16 | 0.17 | 0.42 |
| | Max | 0.79 | 0.77 | 0.72 | 0.48 | | Max | 0.82 | 0.56 | 0.64 | 0.66 |
| | Mean | 0.79 | 0.63 | 0.51 | 0.48 | | Mean | 0.74 | 0.37 | 0.43 | 0.57 |
| | Median | 0.79 | 0.63 | 0.51 | 0.48 | | Median | 0.75 | 0.38 | 0.44 | 0.58 |
| | n | 1 | 2 | 7 | 1 | | n | 32 | 12 | 28 | 15 |

**Table 3: Static temporal alignment of throttle position and vehicle acceleration with tailpipe emissions derived from linear correlation (r)**

*N.B. Negative and indeterminate coefficients (for the purpose of determining temporal alignment) relating to hydrocarbons (HC) have been excluded, resulting in sum of n<40. See Figure 11.*

Carbon dioxide emissions display the strongest positive correlation with both acceleration and throttle position. Most (39) drivers displayed the strongest correlation for $CO_2$ with throttle position at Δt=0 time offset ('r' typically in the range 0.84 to 0.88). The majority of drivers (32) displayed the strongest correlation with acceleration at Δt=-1 time offset ('r' typically in the range 0.72 to 0.77), although 8 drivers were observed to have the strongest correlation at Δt=-2. It should be noted that acceleration in this context is calculated as the first derivative of velocity (sampled at 1Hz), not measured directly instantaneously.

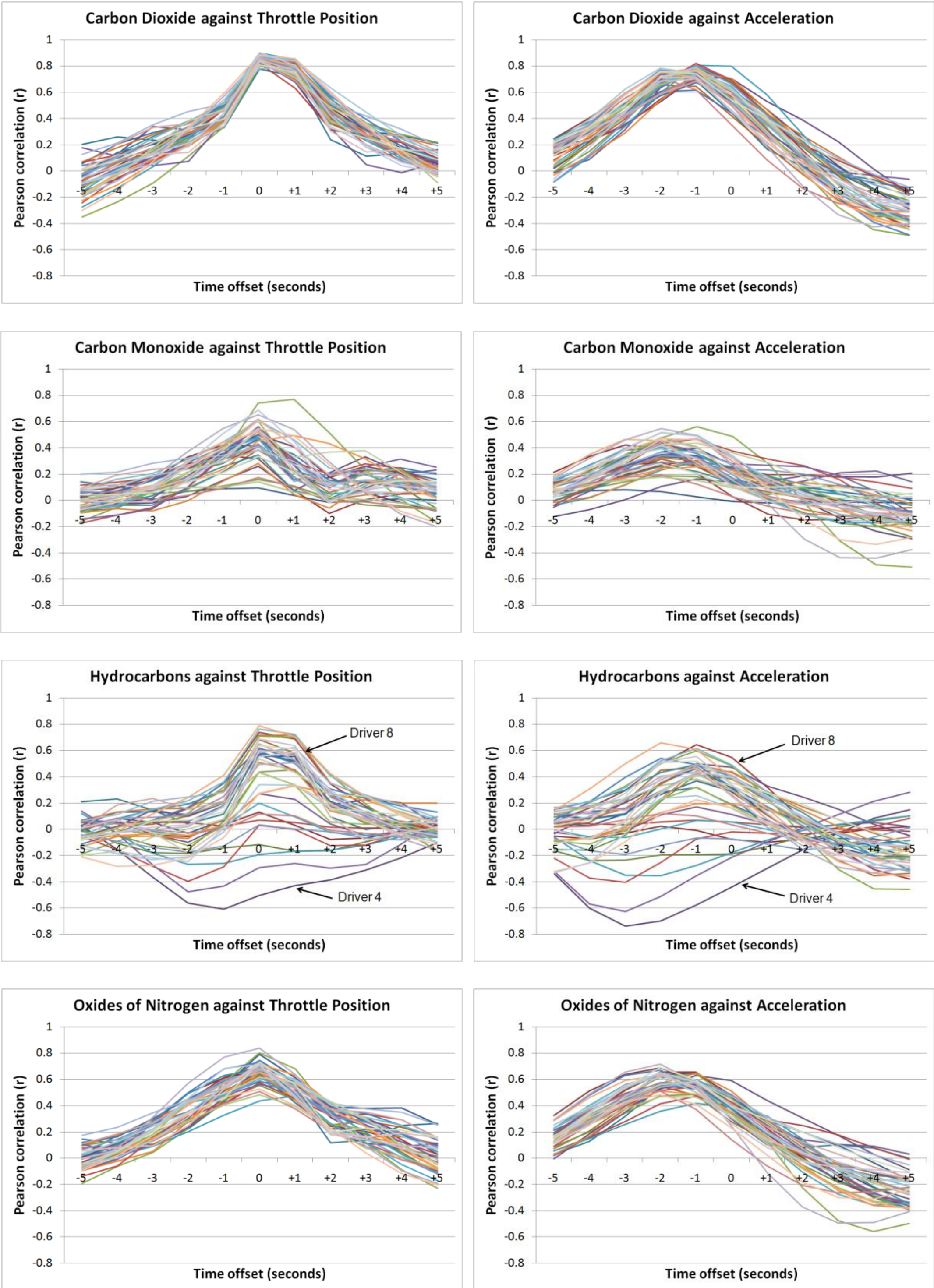



**Figure 11: Investigation into variation in static time offsets using linear correlation**

Oxides of nitrogen were observed to display the next strongest positive correlation with both throttle position and acceleration. N.B. The $NO_x$ emissions values should be interpreted with caution. It has been demonstrated that the sensor utilised in the experiment is in some circumstances cross-sensitive to ammonia ($NH_3$), rendering measurements sometimes unreliable, especially under rich engine operating conditions (Ropkins et al 2008).The majority of drivers (39) displayed the strongest positive correlation for $NO_x$ with throttle position at $\Delta$t=0 time offset (typically 0.60 to 0.72), although 1 driver was observed to have the strongest correlation at $\Delta$t=+1. The majority of drivers (25) displayed the strongest correlation with acceleration at $\Delta$t=-2 time offset, although 15 drivers were observed to have the strongest correlation at $\Delta$t=-1 (typically 0.55 to 0.65).

The correlation between carbon monoxide and throttle position/acceleration was less strong than for $CO_2$ or $NO_x$, but a positive correlation was observed (throttle position $\Delta$t in the range -1 to +1, and acceleration $\Delta$t in the range -1 to -3 with the majority of drivers at $\Delta$t=-2).

The results for hydrocarbons, as presented in Figure 11, are interesting and warrant further investigation to better understand the relationships. Whilst a positive correlation can be observed for many drivers (typically throttle position $\Delta$t=0, acceleration $\Delta$t=-1), the strength of the correlation is highly variable. In addition, a small number of drivers display a negative correlation together with a longer time lag. This can be partly explained by the fact that the nature of the correlation coefficient ‘r’ is such that it imparts no information about the magnitude of the variables being analysed, only the extent to which ‘x’ increases or decreases with changes in ‘y’ (and of course implies no causality). In the hydrocarbon plots in Figure 11, two drivers have been highlighted; Driver 8 displaying a more typical positive correlation, and Driver 4 displaying a less typical negative correlation.

Figure 12 presents scatter plots of hydrocarbons against throttle position and acceleration respectively for these two drivers. It can be seen that the rate of hydrocarbon emissions for Driver 4 is an order of magnitude lower (mean 0.00027grams/sec) than Driver 8 (mean 0.00207grams/sec), and that the higher levels generated by Driver 8 result in a better defined positive relationship with the independent variables (especially during positive acceleration), whereas the plot for Driver 4 displays a negative correlation (hydrocarbon emissions during positive acceleration are lower than during deceleration). There is insufficient information in the 1Hz data to fully understand the reasons for these differences, but it may be related to differences between drivers in the rate of change of throttle position with respect to time, which could only be investigated at higher sampling frequencies (10-20Hz).

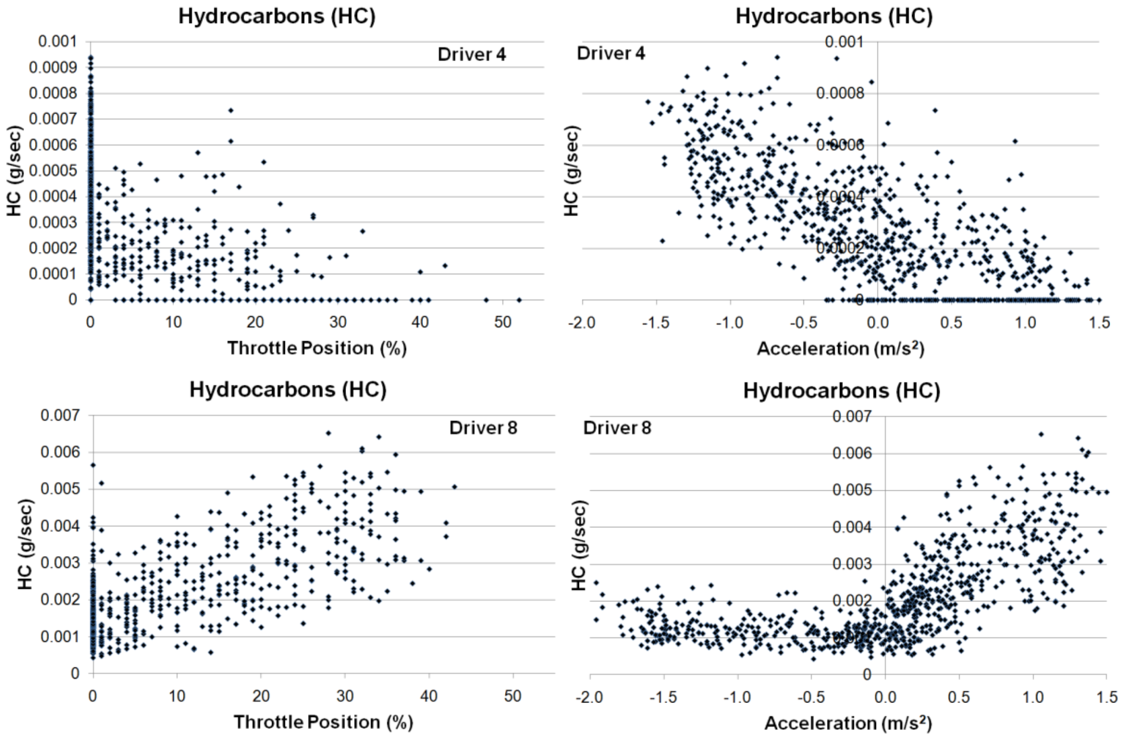



**Figure 12: Scatter plots of hydrocarbons against throttle position and acceleration respectively: Drivers 4 and 8.**

Figure 13 presents a scatter plot of total hydrocarbons (grams) for each driver plotted against the associated correlation coefficient (hydrocarbons (gram/sec) vs acceleration ($m/s^2$)). This serves to demonstrate that stronger positive correlations are generally associated with higher total hydrocarbon emissions. For drivers producing the lowest levels of total hydrocarbons, emissions during acceleration tend to be as low, or lower than during deceleration, resulting in a consequent indeterminate or indeed negative correlation. Driver 14 is seen as an outlier; this individual was a novice driver and was seen in the surveys to exhibit a rather jerky and hesitant driving style.

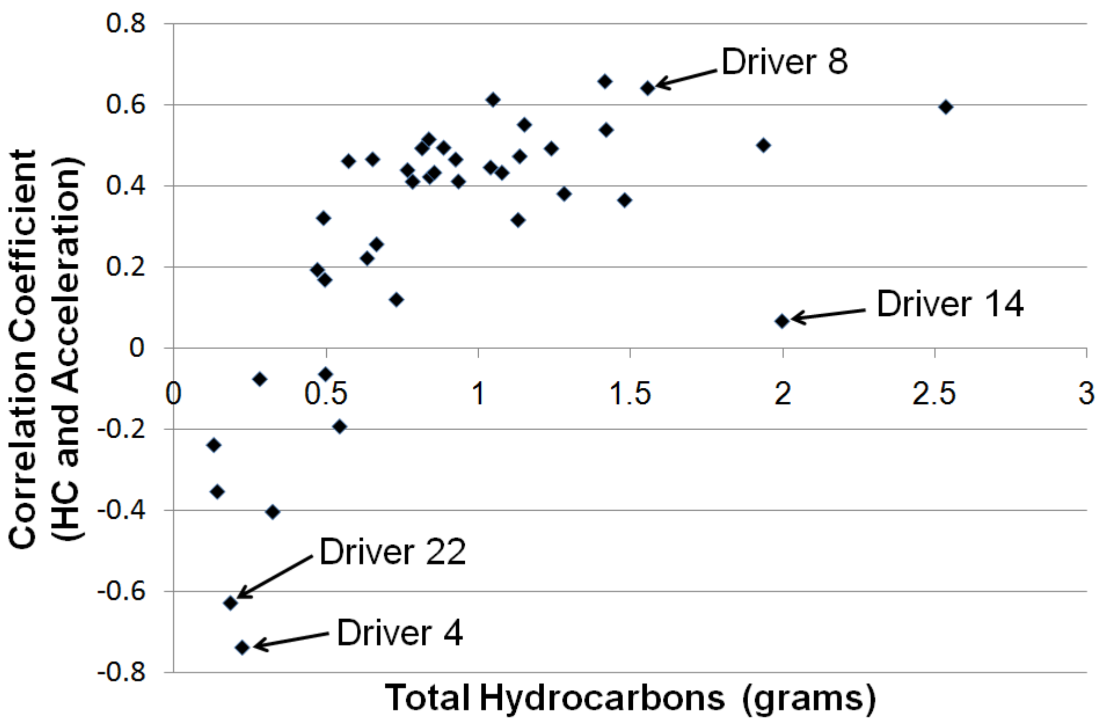



**Figure 13: Scatter plot of total hydrocarbons for each driver plotted against the associated correlation coefficient.**

This analysis shows that whilst linear correlation can be used to derive static time alignment of dependent and independent variables in a limited fashion, it should be used cautiously, and with knowledge of the distribution and magnitude of the underlying data.

## 2.10 Frequency Distribution of Aggregate Data by Operating Mode

When the frequency distributions of emissions data ($CO_2$, HC, $NO_x$, CO etc) are examined, they are often seen to exhibit significant skew and kurtosis (Zhang et al, 1994), and occasionally more than one local maxima. Such characteristics can inhibit the efficacy of ‘standard’ data transformations used traditionally to address issues of non-normality. De-convolution of the frequency distribution into vehicle operating modes has been observed to result in uni-modal distributions which are more amenable to statistical analysis and modelling. There is a practical rationale for such de-convolution since the independent variables/emissions precursors may be different in each operating mode.

Figure 14 presents the aggregate emissions data summed over the 40 drivers, illustrating the multi-component nature of the frequency distributions for $CO_2$, HC, CO, and $NO_x$ for four vehicle operating modes; acceleration, cruise, deceleration, and stop.

| | | |
|---|---|---|
| Acceleration | – | where acceleration (m/s$^2$) > 0 |
| Cruise | – | where velocity (m/s) > 0, and acceleration (m/s$^2$) = 0 |
| Deceleration | – | where acceleration (m/s$^2$) < 0 |
| Stop | – | where velocity (m/s) = 0, and acceleration (m/s$^2$) = 0 |

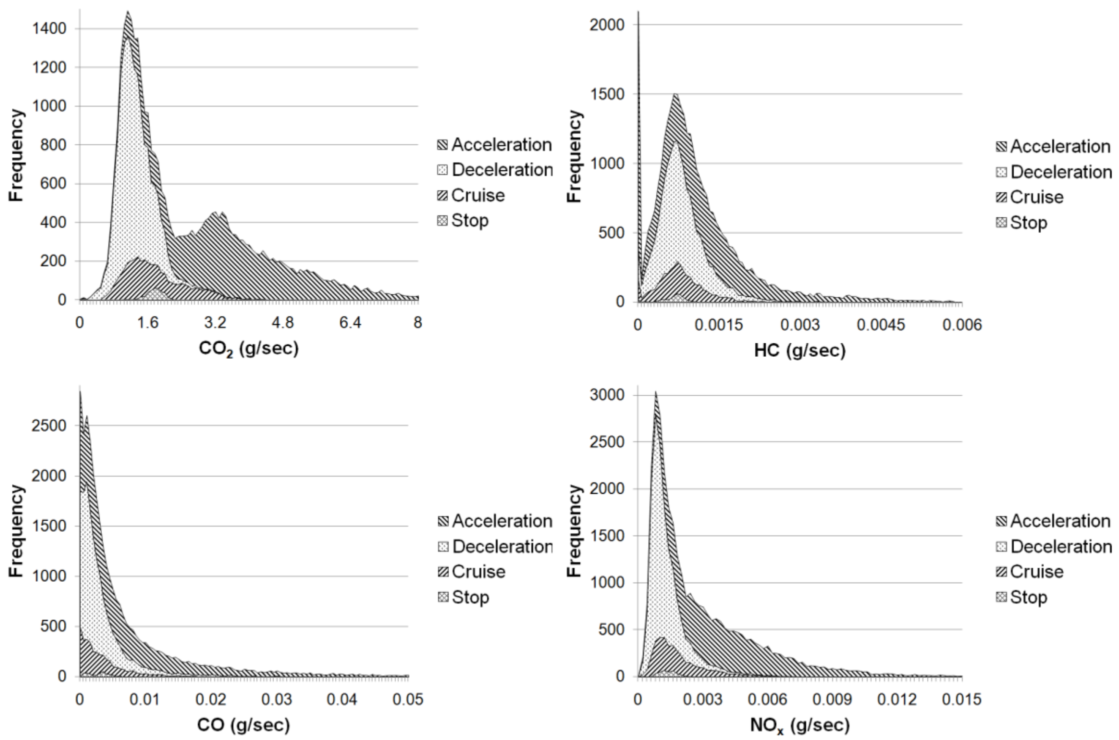



**Figure 14: Cumulative frequency distribution of emissions by operating mode.**

It can be seen clearly from Figure 15 that the frequency distribution of total $CO_2$ (g/sec) (sum of acceleration, deceleration, cruise, and stop) has two local maxima, one at approximately 1.12 g/sec, and a second at approximately 3.2 g/sec. However, it is clear that the peak at 3.2 g/sec is generated largely by the ‘acceleration’ component of vehicle operation, whereas the peak at 1.2 g/sec is dominated by the ‘deceleration’ component.

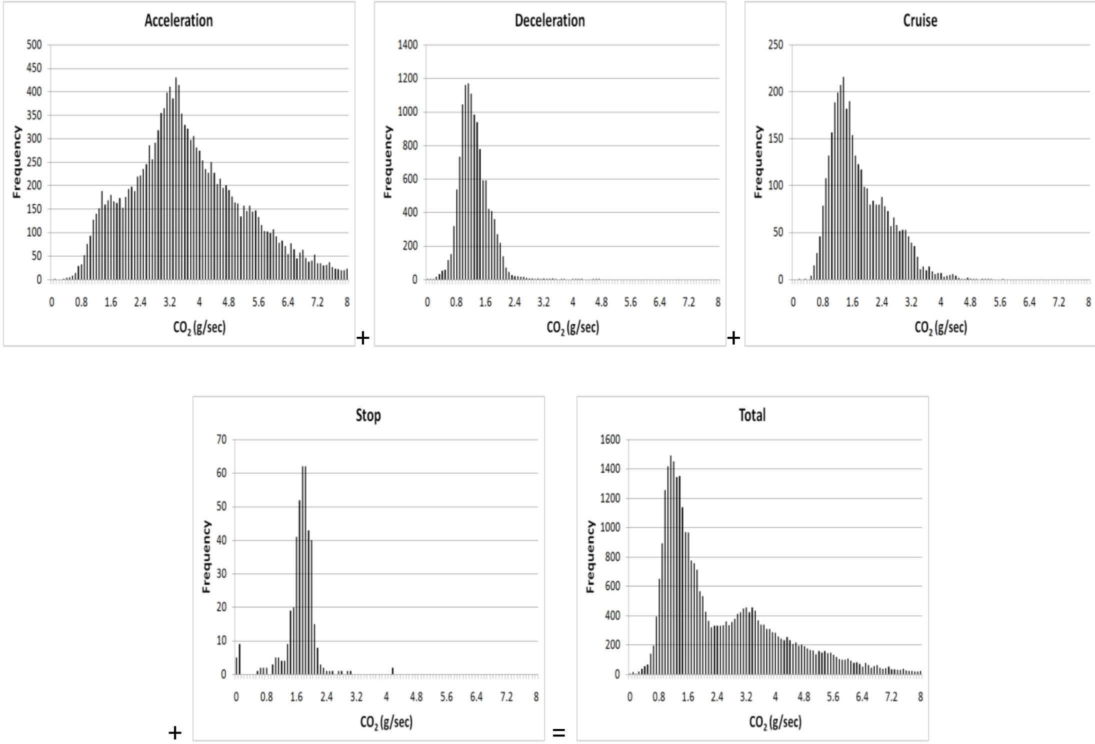



**Figure 15: Modal components of $CO_2$ (g/sec) exhaust emissions frequency distribution.**

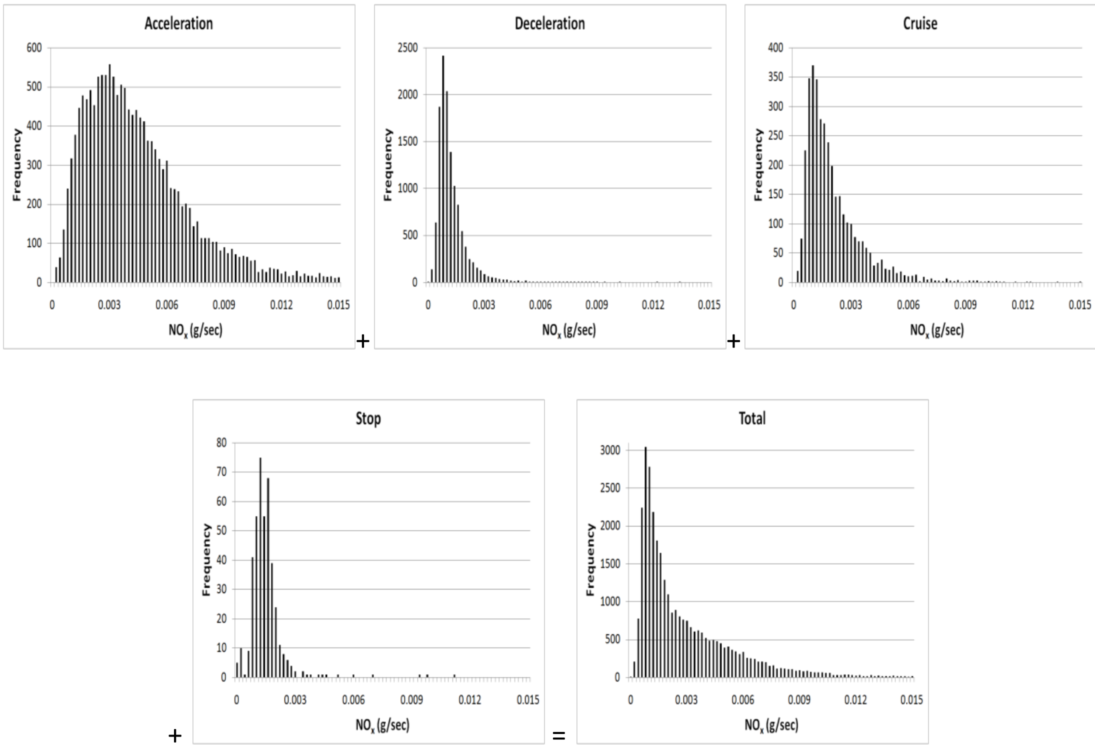



**Figure 16: Modal components of $NO_x$ (g/sec) exhaust emissions frequency distribution.**

On the other hand, the frequency distribution of total $NO_x$ g/sec emissions in Figure 16 is uni-modal and highly skewed. However, it can be seen that the individual operating mode components are quite distinct. As is perhaps to be expected, 'acceleration' dominates the right hand tail of the distribution, and whilst still skewed, the 'acceleration' distribution approximates more closely to a Gaussian distribution than the other components. 'Deceleration' and 'stop' modes have similar distributions, whereas the 'cruise' mode has a denser right hand tail.

This type of analysis is useful, not only because it provides guidance on the most appropriate statistical techniques to adopt (and possible data transformations), but also because it can provide indications regarding which operating modes are most dominant, and therefore where the analyst should be focusing attention when specifying predictive models of instantaneous tailpipe emissions.

### 2.11 Heterogeneity in Driver Behaviour

With current vehicle technology, heterogeneity in driver behaviour (i.e. how drivers operate the primary vehicle controls such as the accelerator, gears, brake, clutch etc.) may have a significant influence on exhaust emissions, both green house gases and local pollutants. Knowledge of such variability, its nature and extent, is necessary if reliable predictive emissions models are to be developed and used as part of a wider modelling framework to, for example, predict local air quality. Relatively little research data is currently available regarding the nature and extent of such variability in the 'amateur' (non-professional) driver population because of the practical challenges of data collection.

Cluster analysis techniques were used to analyse data collected as part of this case study, grouping driver cases with similar attributes or characteristics. Hierarchical cluster analysis was applied to the driver behaviour data to investigate how engine speed (rpm), throttle position (%), and vehicle acceleration (positive or negative m/s$^2$) could be used to group drivers. The environmental efficiency of these clusters of drivers was then investigated to provide an insight into the relationship between driver behaviour and environmental performance.

The distributions of the behavioural data for each variable by driver were standardised by generating percentile values at intervals of 5%. These percentile values were then utilised in the cluster analysis. The average (between-group) linkage cluster method was adopted, with squared Euclidean distance being used as the measure of similarity. Separate cluster analyses were carried out for each variable, engine speed, throttle position, and acceleration respectively. Data from 37 of the 40 drivers were included in the analysis, 3 drivers being discarded due to instrumentation reliability issues. Hierarchical cluster analysis (unlike other methods such as k-means clustering) makes no prior assumptions about the number of clusters to be generated. The number of clusters is determined by the analyst using metrics from the analysis such as the measure of proximity between clusters. In this case, four clusters of drivers were identified for each variable respectively. The individual drivers were allocated to clusters as presented in Table 4.

| | Cluster (R1) | Cluster (R2) | Cluster (R3) | Cluster (R4) |
|---|---|---|---|---|
| **(R) Engine speed** | 10, 15, 17, 36 | 7, 8, 9, 12, 13, 16, 18, 19, 20, 21, 22, 23, 26, 29, 30, 33, 34, 35, 37, 38, 40 | 1, 5, 6, 11, 24, 25, 31, 32 | 2, 14, 27, 28 |
| | **Cluster (T1)** | **Cluster (T2)** | **Cluster (T3)** | **Cluster (T4)** |
| **(T) Throttle Position** | 15* | 20, 22, 24, 25, 27 | 2, 8, 10, 11, 14, 16, 17, 18, 19, 21, 23, 26, 28, 30, 33, 37 | 1, 5, 6, 7, 9, 12, 13, 29, 31, 32, 34, 35, 36, 38, 40 |
| | **Cluster (A1)** | **Cluster (A2)** | **Cluster (A3)** | **Cluster (A4)** |
| **(A) Vehicle acceleration** | 15, 20, 24 | 2, 10, 18, 21, 22, 23, 25, 27, 30, 33, 37 | 1, 7, 8, 11, 12, 14, 16, 17, 19, 26, 28, 29, 31, 32, 36, 40 | 5, 6, 9, 13, 34, 35, 38 |

**N.B. Driver 15 was an outlier for the Throttle Position variable, and was allocated to its own cluster.*

**Table 4: Clustering of drivers by variable**

Investigation of the clusters generated by the analysis determined that they could be characterised by the attributes presented in Table 5 and illustrated in Figure 17.

| | | Cluster (R1) | Cluster (R2) | Cluster (R3) | Cluster (R4) |
|---|---|---|---|---|---|
| **(R) Engine speed (RPM)** | Mean 25th %tile | 1561 rpm | 1343 rpm | 1184 rpm | 825 rpm |
| | Mean 50th %tile | 2094 rpm | 1754 rpm | 1493 rpm | 1311 rpm |
| | Mean 75th %tile | 2500 rpm | 1970 rpm | 1706 rpm | 1573 rpm |
| | Mean 95th %tile | 2896 rpm | 2359 rpm | 2021 rpm | 1927 rpm |
| | | | | | |
| | | **Cluster (T1)** | **Cluster (T2)** | **Cluster (T3)** | **Cluster (T4)** |
| **(T) Throttle Position (%)** | Mean 65th %tile | 21% | 19% | 12% | 6% |
| | Mean 75th %tile | 35% | 28% | 20% | 11% |
| | Mean 85th %tile | 73% | 36% | 28% | 15% |
| | Mean 95th %tile | 98% | 47% | 38% | 22% |
| | | | | | |
| | | **Cluster (A1)** | **Cluster (A2)** | **Cluster (A3)** | **Cluster (A4)** |
| **(A) Vehicle acceleration ($m/s^2$)** | Mean 5th %tile | -1.97 $m/s^2$ | -1.82 $m/s^2$ | -1.45 $m/s^2$ | -1.10 $m/s^2$ |
| | Mean 25th %tile | -0.86 $m/s^2$ | -0.66 $m/s^2$ | -0.40 $m/s^2$ | -0.30 $m/s^2$ |
| | Mean 75th %tile | 0.85 $m/s^2$ | 0.72 $m/s^2$ | 0.52 $m/s^2$ | 0.36 $m/s^2$ |
| | Mean 95th %tile | 1.60 $m/s^2$ | 1.34 $m/s^2$ | 1.09 $m/s^2$ | 0.92 $m/s^2$ |

**Table 5: Behavioural attributes of clustered drivers by variable**

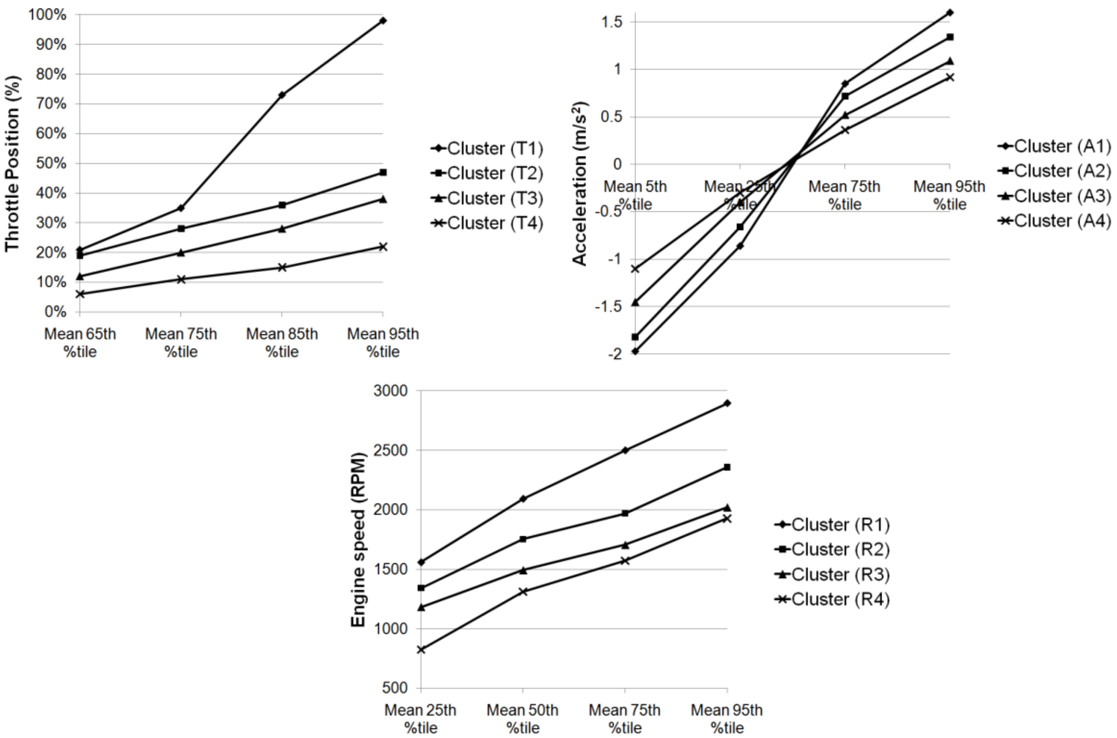



**Figure 17: Behavioural attributes of clustered drivers by variable**

When interpreting the data, it should be remembered that the context of the measurements was a low speed suburban route with short links connected by left-hand turns at priority junctions. Drivers were generally either accelerating or decelerating between corners with little opportunity to ‘cruise’. Gear selection was dominated by 2nd and 3rd gears.

Throttle position varies from 22% (Cluster T4) to 47% (Cluster T2) at the 95th percentile. As previously noted, Cluster T1 comprises only one outlier (Driver 15) who exhibited extreme throttle application compared to the other drivers (85th percentile 73% throttle, 95th percentile 98% throttle).

Acceleration (positive and negative) across the sample of drivers exhibits a symmetrical characteristic, with Cluster A1 displaying the greatest acceleration and deceleration, whereas Cluster A4 displays the lowest acceleration and deceleration i.e. drivers who accelerate harder also tend to brake harder, and vice versa. Normal road cars are generally capable of higher levels of deceleration than acceleration, and this is observed in the data. The mean 5th percentile values range from -2m/s$^2$ (Cluster A1) to -1.1 m/s$^2$ (Cluster A4), whilst the mean 95th percentile values range from +1.6m/s$^2$ (Cluster A1) to +0.9m/s$^2$ (Cluster A4).

The engine speed statistics are influenced by two main factors: (a) the choice of gear and vehicle speed when the engine is engaged with the transmission; and (b) the extent to which the driver depresses or ‘rides’ the clutch when the vehicle is in motion. Figure 18 presents information on the extent to which individual drivers depressed the clutch pedal whilst the vehicle was above a speed threshold of 10mph (16kph). Clearly, the nature of the test route means that frequent transient use of the clutch pedal for gear changing is to be expected. However, depression of the clutch pedal above a certain speed threshold for significant proportions of the journey indicates a different behavioural characteristic, that of disengaging the engine from the transmission during deceleration. The extent of variation in this statistic, from <1% (Driver 9) to 29% (Driver 27) is remarkable. The mean value across all drivers on the test route is 8%. Cluster group ‘R4’ has been highlighted in Figure 18, showing that three of the four members of the cluster (Drivers 2, 27, and 28) operated with the clutch pedal depressed, disengaging the engine from the transmission, for over 25% of the journey time. From Figure 17 it can be seen that engine speed cluster ‘R4’ is differentiated from cluster ‘R3’ by a lower mean engine speed, especially at the 25th percentile level. The fourth member of cluster ‘R4’ is Driver 14 (previously identified as a novice driver) who appears to display lower engine speed characteristics because of operating in too high a gear, possibly labouring the engine.

The significance of such variation in the use of the clutch pedal for fuel consumption and emissions depends on the engine mapping parameters for the vehicle, but modern engine management systems will seek to minimise unnecessary fuel consumption by switching off the fuel injectors above certain engine speed thresholds when the kinetic energy of the vehicle is driving the engine during deceleration, when the engine is connected to the transmission. However, with the clutch pedal depressed and the engine disengaged from the transmission, the engine management system must continue to supply fuel to maintain engine idle conditions. In principle, this could result in higher fuel consumption and emissions.

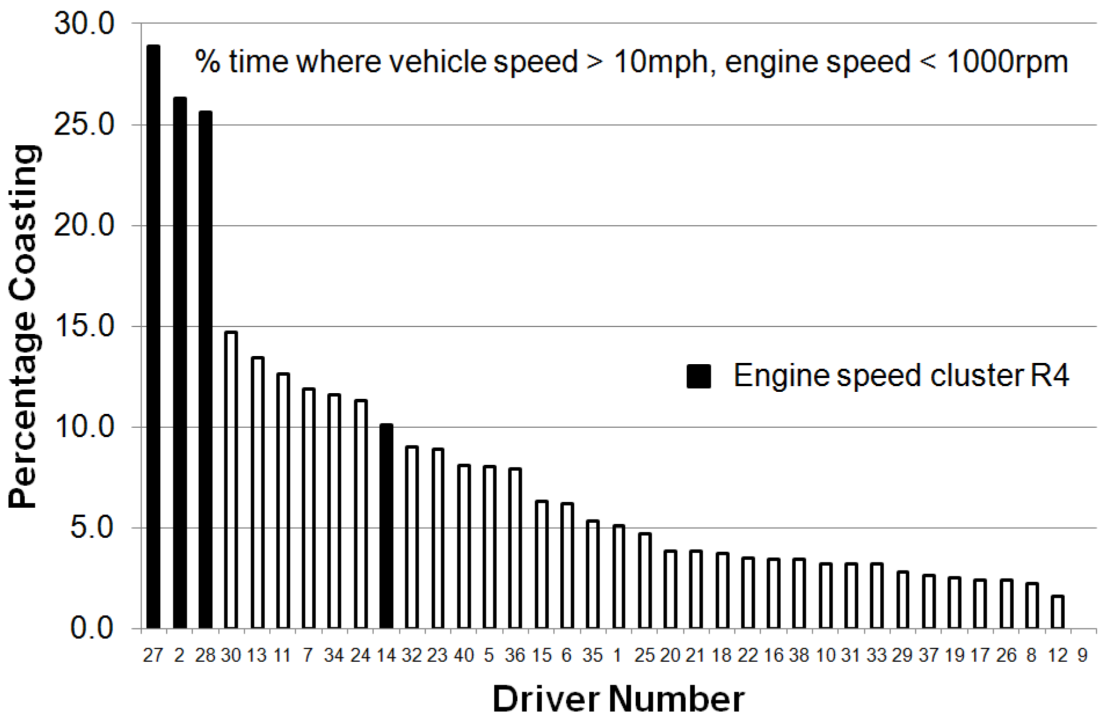



**Figure 18: Proportion of time individual drivers spent ‘coasting’.**

## 2.12 Fuel Consumption and Emissions

In principle, the production of 4 clusters of drivers for each of the 3 variables produces 43 (64) potential cluster combinations. However, with a relatively small sample of 37 drivers, the three dimensional cluster matrix could not be fully populated. In addition, some combinations of driver behaviour clusters may have a greater probability than others, and others may not be feasible in practice. It transpired that when the clusters of drivers by variable are cross-tabulated, 18 of the possible 64 matrix cells are populated, 11 of these by individual drivers.

The environmental ‘performance’ of these 18 cluster cells is presented in Table 6 in terms of $CO_2$ emissions, fuel consumption (FC), and pollutant emissions HC, CO, and $NO_x$.

Measured fuel consumption and $CO_2$ emissions would be expected to be significantly higher than ‘typical’ rates for mixed driving conditions, because of the constrained nature of the test route, and the fact that instrumentation increased the operating mass of the vehicle towards its type approved maximum. The main objective of the analysis is to assess the degree of variability displayed by drivers when presented with these constrained driving conditions, the vehicle and the highway geometry being held constant (ambient traffic conditions were extremely light with very little interaction with other traffic).

It is clear that the throttle application behaviour of Driver 15 was extreme relative to the other drivers. This behaviour tended to result in very high levels of fuel consumption and emissions for all pollutants, especially carbon monoxide. Generally, lower rates of fuel consumption and $CO_2$ emissions are associated with lighter throttle applications and lower rates of acceleration. The engine appeared to operate more efficiently in the R2 and R3 engine speed clusters when combined with light throttle application and low levels of acceleration, although some of the lowest emissions results for HC, CO, and

$NO_x$ were associated with the R1 engine speed cluster when combined with light throttle application (T3, T4) and low levels of acceleration (A3).

| | **Carbon dioxide** | | **Fuel Consumption** | | **Hydrocarbons** | | **Carbon monoxide** | | **Oxides of nitrogen** | |
|---|---|---|---|---|---|---|---|---|---|---|
| Cluster cell | Mean rate (g/sec) | Mean rate (g/km) | Mean rate (g/sec) | Mean rate (g/km) | Mean rate (g/sec) | Mean rate (g/km) | Mean rate (g/sec) | Mean rate (g/km) | Mean rate (g/sec) | Mean rate (g/km) |
| T1_A1_R1 (n=1) | 3.67 | 389 | 1.10 | 116 | 0.00412 | 0.44 | 0.1219 | 12.90 | 0.0122 | 1.29 |
| T2_A1_R2 (n=1) | 3.11 | 350 | 0.91 | 102 | 0.00049 | 0.06 | 0.0126 | 1.42 | 0.0027 | 0.30 |
| T2_A1_R3 (n=1) | 3.21 | 373 | 0.99 | 114 | 0.00069 | 0.08 | 0.0233 | 2.71 | 0.0041 | 0.47 |
| T2_A2_R2 (n=1) | 2.87 | 350 | 0.84 | 102 | 0.00026 | 0.03 | 0.0083 | 1.02 | 0.0023 | 0.28 |
| T2_A2_R3 (n=1) | 3.22 | 379 | 0.98 | 116 | 0.00079 | 0.09 | 0.0131 | 1.55 | 0.0035 | 0.42 |
| T2_A2_R4 (n=1) | 2.89 | 346 | 0.93 | 112 | 0.00184 | 0.22 | 0.0219 | 2.63 | 0.0043 | 0.51 |
| T3_A2_R1 (n=1) | 2.72 | 347 | 0.83 | 107 | 0.00261 | 0.33 | 0.0277 | 3.54 | 0.0059 | 0.76 |
| T3_A2_R2 (n=6) | 2.79 | 351 | 0.83 | 105 | 0.00114 | 0.14 | 0.0104 | 1.31 | 0.0030 | 0.38 |
| T3_A2_R4 (n=1) | 2.77 | 353 | 0.84 | 107 | 0.00038 | 0.05 | 0.0112 | 1.42 | 0.0041 | 0.52 |
| T3_A3_R1 (n=1) | 3.02 | 369 | 0.87 | 106 | 0.00020 | 0.02 | 0.0056 | 0.68 | 0.0020 | 0.25 |
| T3_A3_R2 (n=4) | 2.60 | 353 | 0.76 | 103 | 0.00133 | 0.18 | 0.0114 | 1.56 | 0.0030 | 0.41 |
| T3_A3_R3 (n=1) | 2.51 | 331 | 0.75 | 99 | 0.00161 | 0.21 | 0.0107 | 1.42 | 0.0033 | 0.44 |
| T3_A3_R4 (n=2) | 2.35 | 362 | 0.72 | 111 | 0.00154 | 0.24 | 0.0133 | 2.04 | 0.0036 | 0.56 |
| T4_A3_R1 (n=1) | 2.41 | 343 | 0.72 | 103 | 0.00077 | 0.11 | 0.0033 | 0.47 | 0.0014 | 0.20 |
| T4_A3_R2 (n=4) | 2.22 | 329 | 0.66 | 98 | 0.00131 | 0.19 | 0.0049 | 0.72 | 0.0025 | 0.37 |
| T4_A3_R3 (n=3) | 2.11 | 315 | 0.63 | 94 | 0.00088 | 0.13 | 0.0047 | 0.71 | 0.0027 | 0.41 |
| T4_A4_R2 (n=5) | 2.14 | 333 | 0.63 | 99 | 0.00094 | 0.15 | 0.0024 | 0.38 | 0.0017 | 0.26 |
| T4_A4_R3 (n=2) | 1.93 | 310 | 0.58 | 94 | 0.00110 | 0.18 | 0.0032 | 0.51 | 0.0030 | 0.48 |
| All drivers (n=37) | 2.50 | 344 | 0.75 | 103 | 0.00117 | 0.16 | 0.0110 | 1.51 | 0.0030 | 0.42 |

**Table 6: Summary of valid emissions measurements and vehicles identified**

It should also be noted that there is sometimes a trade-off between the rate of emissions in g/sec and the rate of emissions in g/km, where average speed is a factor. Total emissions for a journey can be high, even with a low rate g/sec, if average speed is very low, as illustrated in Figure 19. This implies that over-cautious, hesitant driving can increase emissions in g/km for a total journey, relative to a more competent driver who maintains a reasonable g/sec emissions rate, and completes the journey expeditiously, resulting in a lower g/km.

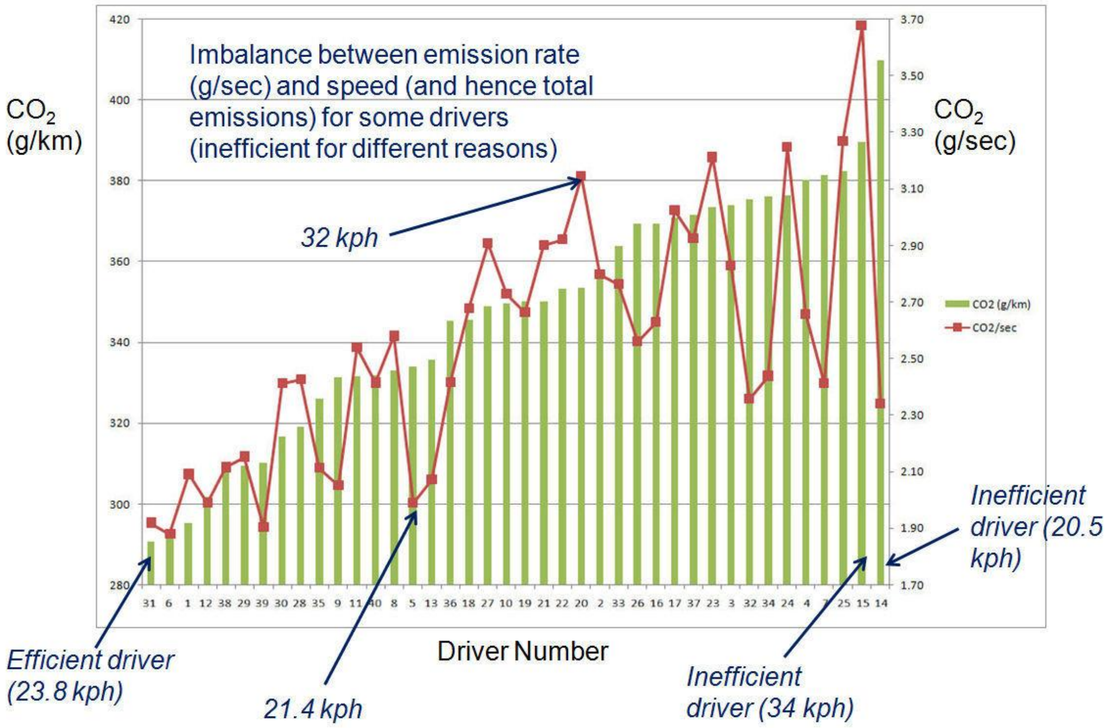



**Figure 19: Illustration of possible imbalance between $CO_2$ emission rate per unit time and per unit distance**

It is notable that the maximum fuel consumption rate (g/km) is 23% higher than the minimum, and 13% higher than the mean. The maximum $CO_2$ rate (g/km) is 25% higher than the minimum, and 13% higher than the mean.

Figure 20 presents the three dimensional cluster array (throttle, acceleration, and engine speed) populated with $CO_2$ emission rates (g/sec). Colour coding has been added to highlight the influence of vehicle operating regime on carbon dioxide emissions.

| T1 | A1 | A2 | A3 | A4 |
|---|---|---|---|---|
| R1 | 3.67 | | | |
| R2 | | | | |
| R3 | | | | |
| R4 | | | | |

| T2 | A1 | A2 | A3 | A4 |
|---|---|---|---|---|
| R1 | | | | |
| R2 | 3.11 | 2.87 | | |
| R3 | 3.21 | 3.22 | | |
| R4 | | 2.89 | | |

| T3 | A1 | A2 | A3 | A4 |
|---|---|---|---|---|
| R1 | | 2.72 | 3.02 | |
| R2 | | 2.79 | 2.60 | |
| R3 | | | 2.51 | |
| R4 | | 2.77 | 2.34 | |

| T4 | A1 | A2 | A3 | A4 |
|---|---|---|---|---|
| R1 | | | 2.41 | |
| R2 | | | 2.22 | 2.14 |
| R3 | | | 2.11 | 1.93 |
| R4 | | | | |

**Figure 20: $CO_2$ emissions (g/sec) by driver cluster**

Figure 21 and Figure 22 present the fuel consumption and emissions data for each cluster cell of drivers in the form of radar plots. The data has been normalised such that the minimum value for each variable equals zero (at the centre of the plot), and the maximum value for each variable equals one (at the periphery of the plot). Figure 21 presents grams per second, and Figure 22 presents grams per kilometre.

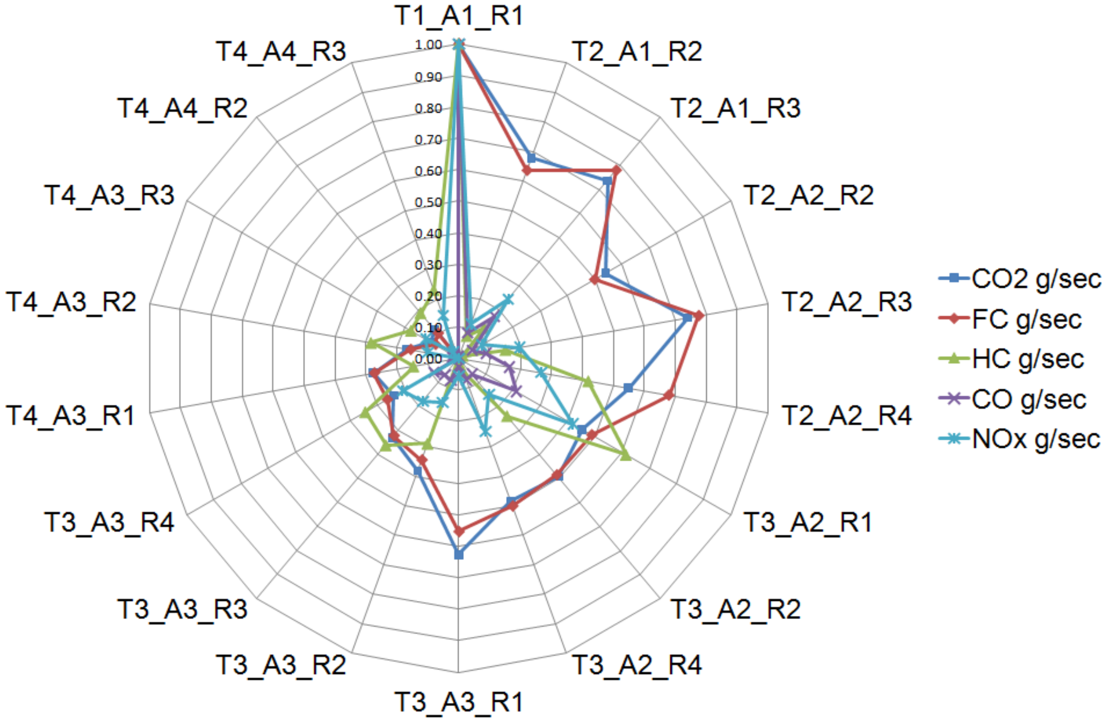



**Figure 21: Radar plot of emissions and fuel consumption (g/sec)**

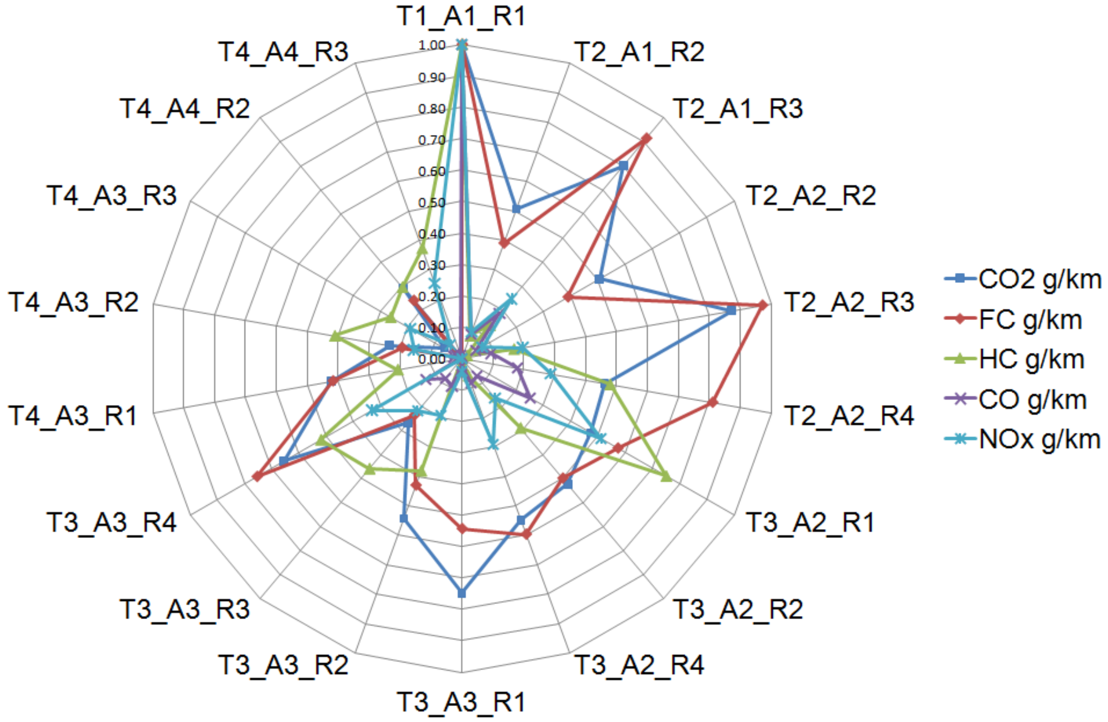



**Figure 22: Radar plot of emissions and fuel consumption (g/km)**

Comparing the two figures, the influence of average speed is clear when contrasting grams per second and grams per kilometre. For example, the cluster cell T3_A3_R4 (two drivers) has a relatively efficient fuel consumption rate per second, but a relatively high fuel consumption rate per kilometre because of a lower average speed, and higher journey time. In this small sample of drivers, the upper left quadrant in both plots (corresponding to the T4 throttle position cluster) dominates in terms of low fuel consumption and low emissions, indicating the significance of moderate throttle application for successful eco-driving.

## 2.13 Discussion

This chapter has presented a simple illustrative analysis of the variability in driver behaviour over a sample of forty drivers utilising the same vehicle over a common test route. The chapter has provided an indication of the consequences of such variability on vehicle tail pipe emissions and fuel consumption. Clearly, such a small sample of drivers is not necessarily representative of the whole driver population, but it is a subset of the UK driver population. The highway network used for the measurements is also only a subset of the total UK network. Nevertheless, the research has provided an insight into the nature and potential scale of driver behaviour variability in the population, and can be used to inform future experimental design.

Determination of the most appropriate sampling frequency to capture both system inputs and outputs is an important consideration in experimental design. This analysis suggests that a sampling frequency of 1Hz is generally too coarse to capture the detail of driver behaviour and associated exhaust emissions. A sampling rate of 10Hz (or perhaps even 20Hz) is likely to be more productive in future research, but there will of course be consequent implications for data processing and handling. Temporal synchronisation of driver inputs, vehicle dynamics, and exhaust emissions measurements will be facilitated by sampling at higher frequencies, but the choice of static or dynamic alignment techniques would have to be made on a case-by-case basis, depending on the characteristics of the vehicle, and variability in engine speed and load. Dynamic temporal synchronisation offers a more robust solution in the laboratory, but may be more challenging to implement for on-road emissions measurements. Ropkins et al (2009) have suggested a possible alternative approach using correlation optimised warping, but this technique has potential drawbacks with respect to signal area conservation. Knowledge of the distribution and magnitude of the underlying data is important in determining the most appropriate techniques to adopt. De-convolution of the frequency distribution of emissions data by operating mode has benefits in terms of identifying which modes are most significant in emissions generation for a given context (recognising that these relationships can vary for different operating conditions, road types, and drivers). This often also assists in data transformation to facilitate the application of parametric tests where normality is assumed.

The detail of variation in driver behaviour observed within this data set provides some useful insights into the factors relevant for the development of eco-driving techniques and guidance. Perhaps unsurprisingly, throttle application (as a precursor of both acceleration and engine speed), is seen to be a significant factor, although sampling at 1Hz precluded any detailed investigation of the significance of the rate of change of throttle position with respect to time for fuel consumption and emissions. It was clear that throttle application, if kept below 25% at the 95th percentile level (40% of drivers in this very limited context and sample) was associated with much reduced levels of fuel consumption and emissions. However, a trade-off was also observed for some drivers between the rate of emissions per unit time and per unit distance, with hesitant driving resulting in higher rates of emission per kilometre, even with relatively moderate rates of emission per second. Details of variability in driver behaviour, such as the degree of variation in the use of the clutch (disengaging the engine from the transmission during deceleration), deserve further research to determine whether this is a result of driver training, or some other factors.

The results suggest that there may be a range of defining characteristics of ‘efficient’ and ‘inefficient’ driving which relate to the degree of alignment between vehicle operation as determined by the driver, and the ‘efficient’ operating regime for the vehicle (for example, determined by efficient areas of the engine map as highlighted by Felstead et al 2008). The research may have a positive contribution to make in the fields of driver training and vehicle design. Certainly, there is scope for vehicle manufacturers to provide more information to the driver on the environmental efficiency of the prevailing vehicle operating regime, and perhaps to constrain vehicle operation within more environmentally efficient ranges.

Eco-driving, with the objective of reducing or minimising either fuel consumption or exhaust emissions, offers the potential for realising environmental benefits with little if any associated additional costs. Researchers such as Beusen et al (2009) have investigated the use of on-board logging devices to study the longer-term impact of driver education, in particular eco-driving guidance. Chapter 3 presents a short case study based on a system developed by a major vehicle manufacturer, assessing the efficacy of a smart phone based eco-driving application. The application calculates eco-driving scores based on speed and acceleration data collected by the GPS module in the smart phone. The application also provides guidance on the driving behaviours to adopt to achieve reduced fuel consumption in particular. The case study is limited in terms of scale and time period, but presents a statistical assessment of the efficacy of the system, and a wider discussion of some of the issues encountered.

# Chapter 3. Influencing Driver Behaviour: A Case Study.

## 3.1 Introduction

This chapter describes an evaluation of a prototype commercial Eco-Driving smart phone application (App) produced by a vehicle manufacturer. To evaluate the App, Newcastle University and the University of Southampton were requested to undertake limited trials of the App to understand what impact it could make on users' driving style and to assess user opinions on the system. The work reported here relates only to the quantitative assessment of the impact of the App on users' driving style. This statistical analysis was carried out by the author.

In the context of the impact on driving style, the objectives of the App evaluation were as follows:

- Determine whether users can 'improve' their driving manner during use of the App.  This is based on an evaluation of their 'Eco-score', assuming that a higher Eco-score equates to a 'better' driving manner.
- Assess the extent to which users maintain their motivation for eco-driving over the course of the study. This was assessed by measuring any discernible trends in the Eco-score over the course of the study.

This chapter presents the outcomes of these trials and associated analysis.

## 3.2 System Description

The Eco-Driving smart phone App operates on an Android phone incorporating a GPS device. It is a standalone device which utilises GPS position measurements to quantify speed. Acceleration can be calculated as a first derivative of speed. The application provides:

a) An eco-driving diagnostic function after driving

b) An eco-driving score ranking function

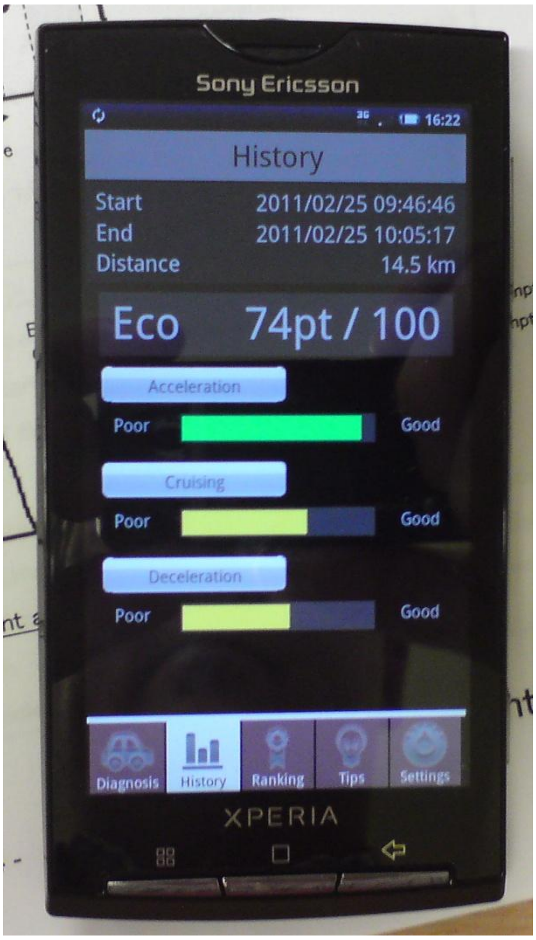



**Figure 23: Eco-driving app on an android phone**

Feedback to the driver on the eco-driving score is not in real time, but provided after each trip. However, instantaneous feedback on fuel economy is displayed while driving, but drivers are not required to observe. Driving behaviour is divided into 3 scenes: “start”, “cruise” and “deceleration”. The application provides a diagnosis for each scene, indicating whether the measured driving behaviour is close to an ‘ideal’ pattern. The system logic assumes that:

- “Start”: smooth acceleration is consistent with economical driving
- “Cruise”: keeping constant speed is consistent with economical driving
- “Deceleration”: smooth deceleration is consistent with economical driving

Eco-driving is scored on a maximum scale of 10 points for each section, and total score is calculated on a maximum scale of 100 points. Car type, road type and traffic conditions are not considered in this diagnosis.

## 3.3 Approach to Assessment

The trial of the Eco-Driving App and the subsequent assessment was based upon a one month trial by eight volunteers. The volunteers were staff members at both the University of Southampton and Newcastle University. Volunteers were recruited by personal request or by group email. A key requirement in the recruitment of volunteers was that they commute on a consistent route. This allowed for a more controlled comparison of speed data and consequent eco-driving performance. The complete quantitative evaluation was based upon:

- Driving speed profiles collected at 1Hz
- Aggregate eco-scores

It was planned that the speed data recorded at 1 second intervals by the phone GPS would be passed through a pre-existing App Eco-driving 'simulator' spreadsheet to derive what the suggested ideal 'target' speed would be for a given 'actual' recorded speed value and also to identify the phase assigned to a given speed value (e.g. acceleration, cruising, deceleration, stop) – this dataset is known as the Simulated Dataset. However, when the App simulator was received from the vehicle manufacturer and reviewed, it was found that the simulator aggregated output data into phases or 'scenes'. This meant that whilst comparison of estimated and ideal energy consumption within each phase or 'scene' was still possible, the simulator did not output the suggested 'target' or ideal speed for each 1Hz data point.

There remained some questions over the logic behind the system within a UK / European context, but as validation of the algorithm was not the subject of investigation, they were commented on but not examined in detail.

The use of a ranking system will not correlate directly to fuel consumption since the vehicle to vehicle variations, variations in road type, traffic conditions, weather, and other confounding factors cannot be accounted for in a system of this type. The system will not be sensitive to gear changing behaviour, choice of engine speed, and propensity to ‘coast’, which can have a significant influence on fuel consumption (e.g. cruising in third gear will have very different fuel consumption to cruising at the same speed in fifth gear).

The manufacturer accepted that in such a limited study, over a very constrained time frame with a small number of subjects, the outcome of the study may be that the efficacy of the system was ‘not proven’. The study was one step in the development of the application, and further trials (outside the scope of the current study) might be required at a later date.

## 3.4 Initial Findings on System Performance

### *3.4.1 Comparison of Smartphone App eco-scores with Simulator output*

Samples of the GPS speed data were passed through the Simulator spreadsheet to attempt to replicate the original eco-drive scores calculated by the phone App. It was known that the data sets used to calculate the App and Simulator scores would not be identical since the GPS data obtained from the vehicle manufacturer had been to some extent post-processed to remove instances where GPS data were invalid (the phone App did not have this data validation function). It might also be the case that the algorithm in the App on the Smartphone was not completely identical to the algorithm in the spreadsheet simulator. To understand how this might impact subsequent analysis of the GPS data, a simple comparison exercise was undertaken.

The comparison analysis is based upon data collected on Feb 9th 2011. The intention of the investigation was to discover the consistency in operation and output of both the App and the Smartphone GPS systems. Three phones were placed in the same location in a vehicle which was then driven for a period of 25 minutes. Table 7 summarises how the three results compared to each other from the App, whilst Table 8 presents the results of passing the GPS speed traces obtained from the vehicle manufacturer through the spreadsheet based simulator.

| Phone ID | Start Time | End time | Duration (s) | Distance (km) | App Eco-score | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | Accel | Cruise | Decel | Overall |
| Phone 3 | 09:20:36 | 09:44:35 | 1439 | 15.2 | 98 | 68 | 99 | 77 |
| Phone 5 | 09:20:37 | 09:44:35 | 1438 | 15.0 | 99 | 61 | 88 | 69 |
| Phone 6 | 09:20:37 | 09:44:36 | 1439 | 15.0 | 97 | 58 | 97 | 65 |

**Table 7: Summary of output from three simultaneous runs of the App**

| Phone ID | Sim Data length (s) | Actual length (s) | Missing data (s) | Ave speed ($kmh^{-1}$) | Distance (km) | Simulator Eco-score | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Accel | Cruise | Decel | Overall |
| Phone 3 | 1422 | 1439 | 17 | 37.7 | 14.9 | 98 | 71 | 95 | 78 |
| Phone 5 | 1427 | 1438 | 11 | 37.6 | 14.9 | 98 | 62 | 83 | 69 |
| Phone 6 | 1418 | 1439 | 21 | 37.8 | 14.9 | 98 | 60 | 97 | 66 |

**Table 8: Summary of output from runs of Simulator based on data from server**

Based on this very simple comparison, the overall eco-scores calculated by the simulator spreadsheet were very close (within 1%) to the eco-scores generated by the Smartphone application, although there is a greater degree of variability within the driving states (acceleration, cruise, and deceleration). A significant source of variability appears to be degradation / loss of the GPS signal in the vicinity of structures and in heavy traffic congestion (where the amount of metal in surrounding vehicles, trucks, buses may be having an influence).

### 3.4.2 Comparison of Smartphone App GPS positional consistency across phones

Below are presented some illustrations of comparisons of Phone 3, Phone 5, and Phone 6 positional accuracy (data collected simultaneously on the same trip on February 9th 2011). These have been plotted using Google Earth Pro.


**Figure 24: Comparison of GPS positional consistency (1)**

*Comparison of Phone 3 (red), Phone 5 (yellow), and Phone 6 (blue) on the same journey (data collected simultaneously on February 9th 2011). All phones lose GPS signal under tunnel structure.*


**Figure 25: Comparison of GPS positional consistency (2)**

*In urban area in congested traffic, all phones seem to lose GPS accuracy, but especially Phone 3 in this example.*


**Figure 26: Comparison of GPS positional consistency (3)**

*Again, in heavy traffic congestion, accuracy of spatial positioning is reduced.*

### *3.4.3 Observations on spreadsheet simulator analysis*

The journeys recorded during the trial were input to the spreadsheet simulator in order to gain a better understanding of the ‘driving phase’ being assigned to each data point. The simulator did not output a ‘target’ speed for each data point, but calculated the ‘ideal’ consumed energy for a particular driving phase or ‘scene’, which can be one data point, or a group of many data points depending on the context. The aggregating nature of this process is illustrated below.

Figure 27 plots a section of a journey obtained from Phone 7. The 1Hz data points are colour coded according to speed (kph) in eight speed bands, with higher speeds coloured green, and lower speeds coloured red. It can be seen that there is significant variation in speed, both positive and negative) as the vehicle travels from south to north through the network. Transitions from red through to green with respect to time indicate acceleration; transitions from green through to red with respect to time indicate deceleration.


**Figure 27: Sample of Phone 7 vehicle speed data**

Figure 28 presents the same data, but in this case the data points are colour coded according to their driving phase or ‘scene’, as determined by the spreadsheet simulator. In this diagram, blue = ‘deceleration’, green = ‘cruise’, yellow = ‘acceleration’, and red = ‘stopped’. A key observation from this analysis is that the ‘cruise’ scene often contains significant variation in speed (and hence acceleration and deceleration events), according to the programmed logic of the algorithm. Generally, it is understood from documentation obtained from the manufacturer that the ‘cruise’ phase includes all data above 10kph, as long as it is not in a transition from below 10kph to a higher speed (which would be an ‘acceleration’ or pull away phase), or in a transition to a speed below 10kph from a higher speed (which would be a ‘deceleration’ phase).

This definition of acceleration and deceleration may have the potential to confuse some users of the eco-driving application, who might define acceleration as any increase in speed with respect to time, regardless of the absolute level of speed. The term ‘pull away’, as used in some of the documentation, is perhaps a more representative term to describe the operation of the algorithm. Similarly, users may not appreciate that decelerating from 100kph to 40 kph would be interpreted by the eco-drive algorithm as variation in ‘cruise’, and not ‘deceleration’.


**Figure 28: Corresponding Phone 7 driving phase or 'scene'**

### 3.5 Quantitative Assessment of Driver Behaviour

The data collection from the trial participants in Southampton ceased on March 11th 2011. The data collection from the trial participants in Newcastle ceased on March 18th 2011, but data collection commenced a week later than Southampton, so the two datasets both cover approximately one month.

The data were cleaned before analysis to remove as far as practical any trips undertaken which were not journeys to and from work i.e. limiting the analysis to commute trips. This was done to try to ensure that the eco-score comparisons were carried out across the same road type for each trip, although of course it was not possible to control for traffic conditions and congestion (which might have a significant influence on eco-scores attained).

There was one important difference in the manner the data were collected in the two regions. In Newcastle, trial participants were asked to collect data using the App for a period of time (up to February 27th 2011) without consciously changing their driving styles. This period was labelled ‘Phase A’. The objective was to attempt to obtain a base line of ‘normal’ driving data against which eco-driving data could be compared. From February 28th 2011 onwards, the trial participants were asked to take note of the eco-driving scores generated by the phone App, and attempt to improve their eco-driving scores to the extent that they felt it possible and appropriate. The period from February 28th to March 18th was split into two further phases, ‘Phase B’ and ‘Phase C’, with the remaining trip data for each driver being allocated in equal proportions. This permitted the study to address the research questions:

- Determine whether users can ‘improve’ their driving manner during use of the App.
- Assess the extent to which users maintain their motivation for eco-driving over the course of the study.

In Southampton, the trial participants were not required to attempt to generate a base line dataset, but were simply asked to utilise the phone App from the beginning of the trial. In the case of the data from the Southampton trial participants, the data for each driver were simply divided into three approximately equal temporal phases, ‘Phase A’, ‘Phase B’, and ‘Phase C’. This permitted some degree of assessment of the extent to which the drivers improved their eco-driving over time, and also the extent to which they maintained their motivation. With such a small sample of drivers over a relatively short survey period, the results need to be interpreted with caution.

Unfortunately it was found that one trial participant (utilising Phone 8) generated relatively few trips, and these tended to be across a range of different geographic routes. The data from this driver could not readily be utilised to address the objectives of the research, so this driver was removed from the analysis, resulting in a final sample of seven drivers, four in Newcastle and three in Southampton. In the following discussion, Newcastle trial participants have the prefix ‘NCL’ and Southampton trial participants have the prefix ‘TRG’.

The routes driven by the volunteers in the Smartphone eco-drive application trials in Newcastle and Southampton cover a range of road types and standards, from motorways with a 70mph speed limit, to urban distributor roads with a 20mph speed limit. The proportion of each road type in each route varies, with some routes such as that driven by TRG Laura (Phone 9) almost entirely motorway, whilst other routes such as those driven by NCL Lindsey (Phone 3) and TRG Linda (Phone 7) are entirely urban and suburban.

The following section presents details of the primary journey to work trips driven by each of the volunteers during the survey period, and the aggregate eco-scores for each trip as generated by the Smartphone application. The results are presented in the following standardised manner for each driver:

- A figure illustrating the primary route utilised for the journey to / from work;
- A line chart presenting the eco-driving scores by trip and Phase (A, B, C) for each driving mode (acceleration, cruising, deceleration, and total score); and
- A brief statistical summary based on an analysis of the raw 1Hz speed data generated by the Smartphone App (mean, 'Q1' 25th percentile, median 50th percentile, 'Q3' 75th percentile). This includes speed during 'cruise' mode (i.e. where speed is greater than zero, and acceleration is approximately zero); speed across all driving modes; acceleration; and deceleration. Non-parametric pairwise Mann-Whitney tests were applied to determine any statistically significant differences in the samples across Phases A, B, and C at 95% confidence level. In addition to the test for statistical significance, an estimate of the effect size (magnitude of the observed effect) is also reported, in this case using the measure $r = z/\sqrt{n}$, where an effect size of $r=0.1$ is considered to be a small effect, $r=0.3$ a medium effect, and $r=0.5$ a large effect.
- A short commentary interpreting the results, and identifying whether the driver had (a) adopted a more eco-friendly driving style as a result of

using the Smartphone app, and (b) whether the driver had maintained the changes in driving style (if any) throughout the duration of the trial.

During the analysis, it was found that the speed data generated by the application, whilst being continuous in nature, tended to be stored at intervals of 1m/s (converted into kph). Thus when acceleration and deceleration values are calculated from these speed data, there is a tendency for the results to be dominated by values which are coincident with multiples of these intervals e.g. -0.25m/s$^2$, +0.25m/s$^2$, +0.5m/s$^2$ etc. This is particularly noticeable in the quartile values reported for acceleration and deceleration and may obscure some of the detailed variation in the driver behaviour.

## 3.6 Eco-driving Results

### *3.6.1 NCL Lindsey (Phone 3)*

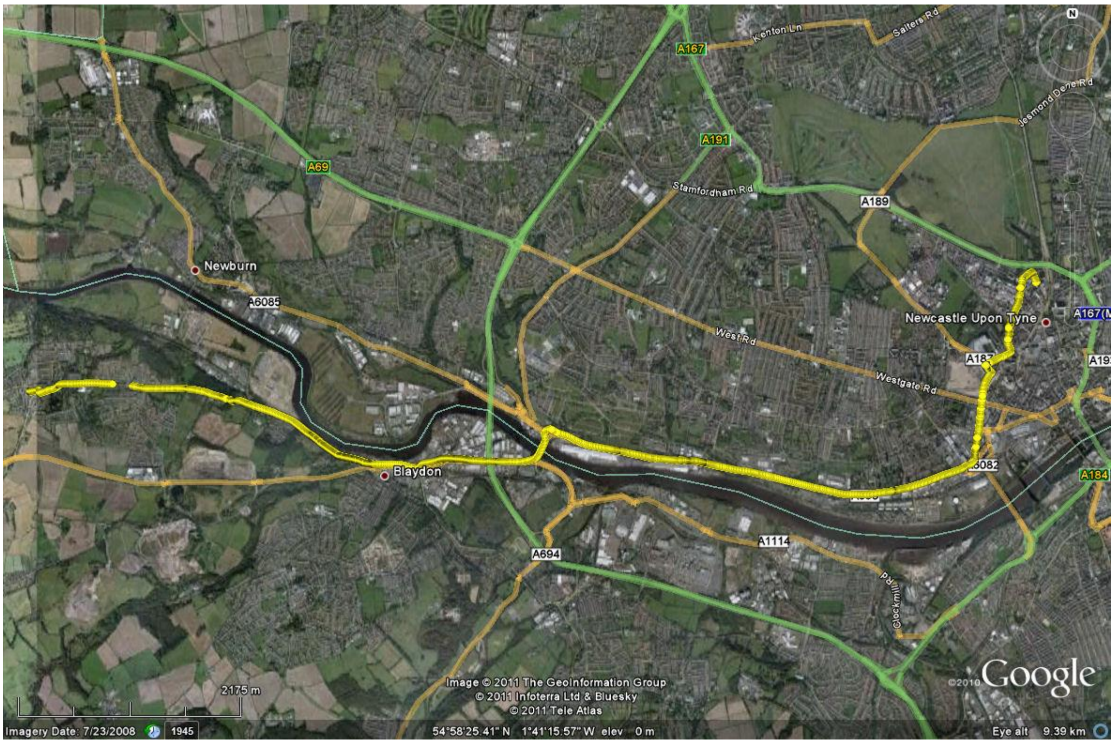



**Figure 29: NCL Lindsey primary route to / from work**

NCL Lindsey commuted on a route which is predominantly urban and suburban in nature. On such a route, overall speeds tend to be dominated by highway geometry and traffic conditions. Figure 29 illustrates the primary route from home to the west of Newcastle, south of the River Tyne, into the city centre.

Figure 30 presents the eco-driving scores by trip and Phase. Overall, there appears to be an improvement in the mean total eco-driving score from Phase A (62) to Phase B (66), followed by a deterioration in Phase C (58). The improvement in Phase B appears to be generated by improvements in the mean acceleration (94) and deceleration (91) scores relative to their values in Phase A (86 and 82 respectively), whilst the mean cruise score for Phase B is actually marginally worse than Phase A. There is a general deterioration in the mean cruise score over time from Phase A (54) to Phase C (45).

When the statistical summary of the 1Hz data is examined in Table 9, it can be seen that there is a small but statistically significant change in the cruise mode speed (Table 9a) with the mean value reducing from 40.6kph to 38.7kph in Phase B, whilst the Q1 (25th percentile) speed reduces from 21.6kph to 16.2kph. The changes in speed across all driving modes reported in Table 9b are very small but statistically significant, probably because of the relatively large sample size. However, whilst the eco-driving scores for acceleration (pull away) and deceleration (stop) in Figure 30 display an improvement in Phase B, it is clear from Table 9c and Table 9d that there is no significant change in the overall acceleration or deceleration data across the three Phases A, B, and C. This suggests that the changes in eco-driving score for acceleration (pull away) and deceleration (stop) utilised in the algorithm may be more sensitive to departures from the ‘ideal’ driving profile, and variability around this ‘ideal’ profile, than to overall changes in the acceleration or deceleration behaviours.

In summary, NCL Lindsey displayed a small improvement in eco-driving score in Phase B, but this improvement was not maintained into Phase C where overall scores lapsed below those recorded in Phase A. The statistical analysis identified some small but statistically significant changes in speed, but there were no statistically significant changes in overall acceleration or deceleration rates.

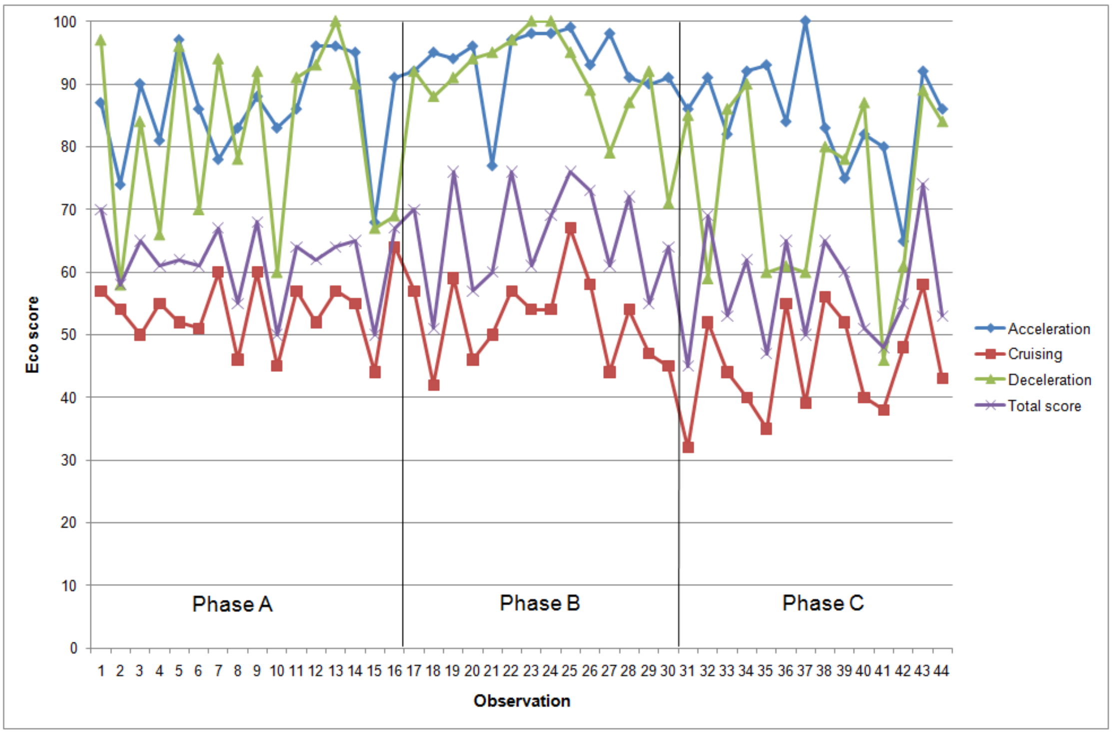



**Figure 30: NCL Lindsey eco-driving scores by trip and phase**

| Phase | n | Mean (kph) | Q1 (kph) | Median (kph) | Q3 (kph) |
|---|---|---|---|---|---|
| A | 5225 | 40.60 | 21.64 | 44.10 | 56.70 |
| B | 4548 | 38.70 | 16.20 | 42.30 | 55.83 |
| C | 4276 | 38.06 | 16.20 | 39.60 | 56.70 |

| Pairwise comparison | Mann-Whitney U | Z | Significance (2-tailed) | Effect size r |
|---|---|---|---|---|
| A – B | 11354852 | -3.787 | *p* < 0.001 | -0.04 |
| B - C | 9584133 | -1.166 | *ns* | - |
| A - C | 10494302 | -5.088 | *p* < 0.001 | -0.05 |

**a) Cruise mode speed (kph)** – velocity equal to or greater than 0.25m/s, acceleration -0.1 to +0.1 $m/s^2$

| Phase | n | Mean (kph) | Q1 (kph) | Median (kph) | Q3 (kph) |
|---|---|---|---|---|---|
| A | 22423 | 29.61 | 7.42 | 29.70 | 46.80 |
| B | 20451 | 28.07 | 6.30 | 26.10 | 45.90 |
| C | 19501 | 30.15 | 9.00 | 27.90 | 47.73 |

| Pairwise comparison | Mann-Whitney U | Z | Significance (2-tailed) | Effect size r |
|---|---|---|---|---|
| A – B | 2.2E+008 | -7.235 | *p* < 0.001 | -0.03 |
| B - C | 1.9E+008 | -9.453 | *p* < 0.001 | -0.05 |
| A - C | 2.2E+008 | -2.426 | *p* = 0.015 | -0.01 |

**b) Speed across all driving modes (kph)**

| Phase | n | Mean ($m/s^2$) | Q1 ($m/s^2$) | Median ($m/s^2$) | Q3 ($m/s^2$) |
|---|---|---|---|---|---|
| A | 6999 | 0.59 | 0.25 | 0.50 | 0.75 |
| B | 6495 | 0.58 | 0.25 | 0.50 | 0.75 |
| C | 6426 | 0.60 | 0.25 | 0.50 | 0.75 |

| Pairwise comparison | Mann-Whitney U | Z | Significance (2-tailed) | Effect size r |
|---|---|---|---|---|
| A – B | 22638705 | -0.416 | *ns* | - |
| B - C | 20739385 | -0.632 | *ns* | - |
| A - C | 22262611 | -1.042 | *ns* | - |

**c) Acceleration ($m/s^2$)** – Speed equal to or greater than 0.25m/s, acceleration equal to or greater than plus 0.1$m/s^2$

| Phase | n | Mean ($m/s^2$) | Q1 ($m/s^2$) | Median ($m/s^2$) | Q3 ($m/s^2$) |
|---|---|---|---|---|---|
| A | 6506 | -0.60 | -0.75 | -0.50 | -0.25 |
| B | 5947 | -0.60 | -0.75 | -0.50 | -0.25 |
| C | 6105 | -0.61 | -0.75 | -0.50 | -0.25 |

| Pairwise comparison | Mann-Whitney U | Z | Significance (2-tailed) | Effect size r |
|---|---|---|---|---|
| A – B | 19141417 | -1.054 | *ns* | - |
| B - C | 18147340 | -0.032 | *ns* | - |
| A - C | 19652497 | -1.050 | *ns* | - |

**d) Deceleration ($m/s^2$)** – Speed equal to or greater than 0.25m/s, deceleration equal to or less than minus 0.1$m/s^2$

**Table 9: NCL Lindsey statistical summary**

### 3.6.2 NCL Glyn (Phone 4)

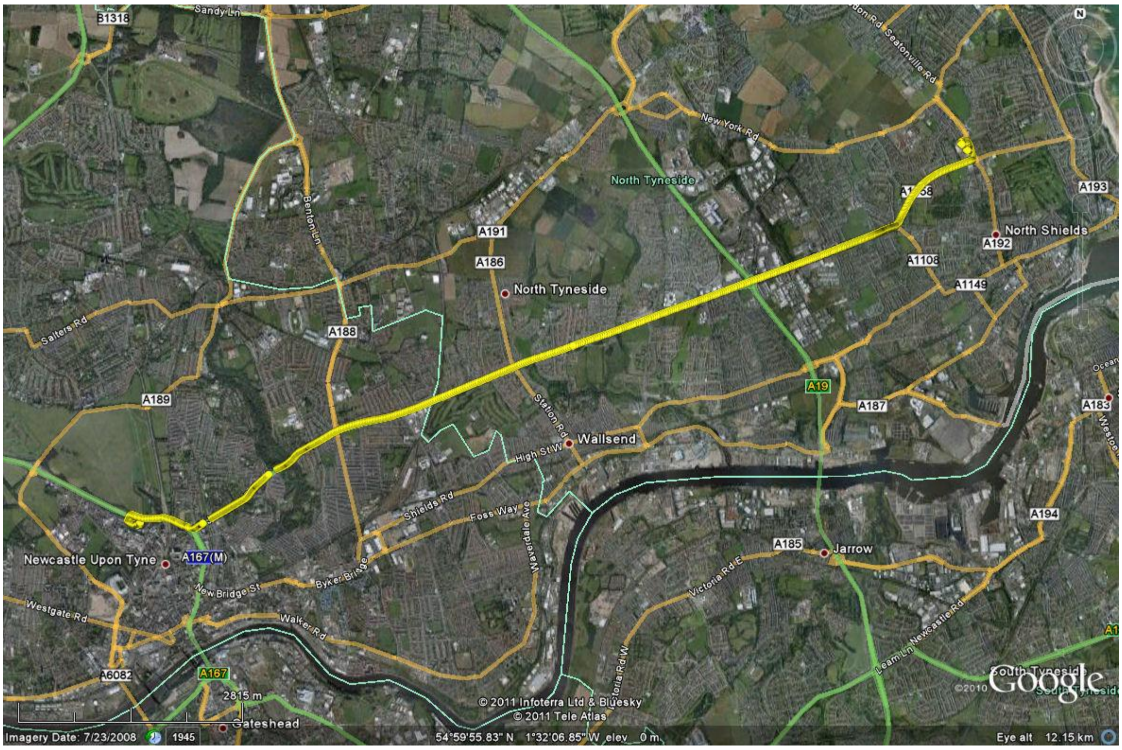



**Figure 31: NCL Glyn primary route to / from work**

NCL Glyn commuted on a route which is a mix of urban, suburban, and interurban road types. The interurban element of the route is a major part of the total trip. Figure 31 illustrates the primary route from home to the east of Newcastle, north of the River Tyne, into the city centre.

Figure 32 presents the eco-driving scores by trip and Phase. Overall, there appears to be little improvement in the mean total eco-driving scores from Phases A, B and C (63, 63 and 65 respectively). However, there was a great deal of day-to-day variability in eco-driving scores, particularly in the 'deceleration' scores. The dominance of the interurban element of the route results in a relatively high correlation between the 'cruise' score and the 'total' score, although the 'cruise' score tended to be slightly lower than the total (the overall total score being elevated by higher acceleration and deceleration scores). The mean deceleration scores in Phases B and C are considerably higher than the score achieved in Phase A, suggesting an improvement in deceleration behaviour.

This observation is borne out by statistical analysis presented in Table 10d, where there is a small but statistically significant reduction in deceleration rates (Phase A, mean -0.62m/s$^2$, median -0.50m/s$^2$; Phase B, mean -0.58m/s$^2$, median -0.45m/s$^2$). Interestingly, there is also a statistically significant reduction in cruise speed in Phase B (Table 10a) where the mean reduces from 66.6kph to 53.4kph, which is also observed in the speed measured across all driving modes (Table 10b). Speeds observed in Phases B and C are generally significantly lower than in Phase A, but this is not reflected in a significant increase in the 'cruise' score for eco-driving (Phase A, 58; Phase B, 56; Phase C, 59). It would appear that the scoring algorithm may be more sensitive to variability around the 'ideal' energy profile, and relatively less sensitive to changes in absolute velocity overall.

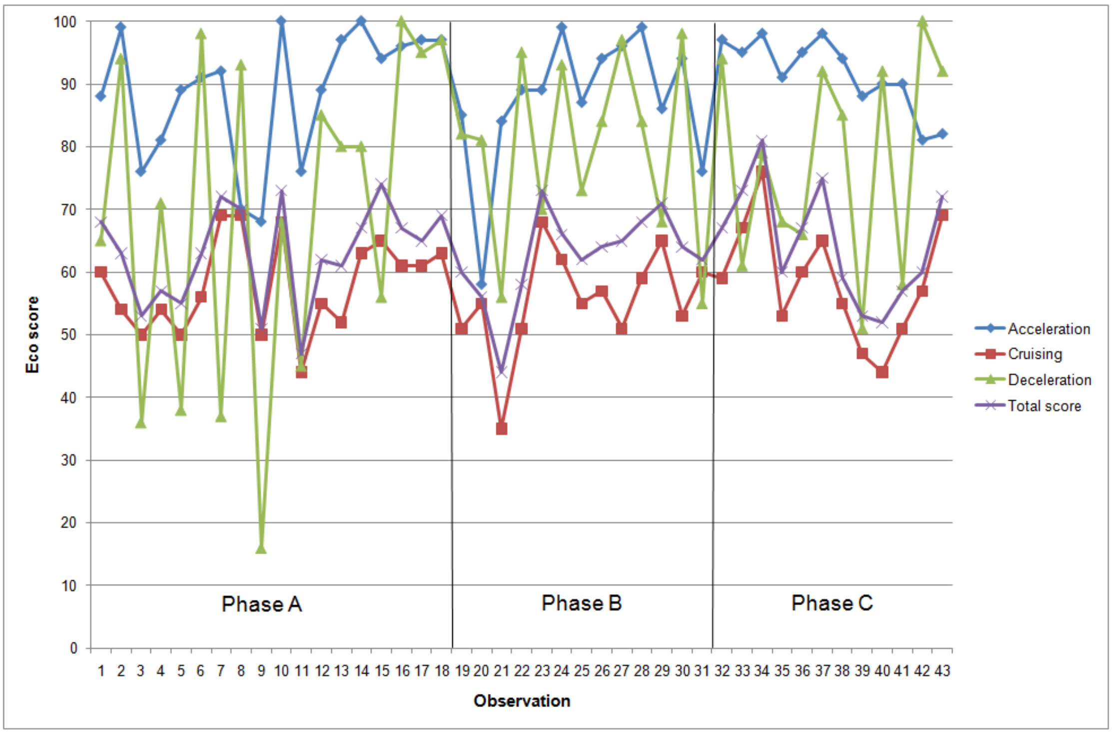



**Figure 32: NCL Glyn eco-driving scores by trip and phase**

In summary, NCL Glyn displayed quite a significant improvement in 'deceleration' score from Phase A to Phase B, which was maintained into Phase C. However, because the overall score was dominated by the 'cruise' score (and this was the majority of the route), there was little improvement in the overall eco-driving score. Nevertheless, the statistical analysis highlighted a reduction in speed overall in Phase B, partially maintained in Phase C, which was not obviously reflected in the reported eco-driving scores.

| Phase | n | Mean (kph) | Q1 (kph) | Median (kph) | Q3 (kph) |
|---|---|---|---|---|---|
| A | 5115 | 66.62 | 40.50 | 69.30 | 98.10 |
| B | 4135 | 53.39 | 14.40 | 47.70 | 90.90 |
| C | 3708 | 57.84 | 27.90 | 55.83 | 92.70 |

| Pairwise comparison | Mann-Whitney U | Z | Significance (2-tailed) | Effect size r |
|---|---|---|---|---|
| A – B | 8413344 | -16.931 | $p < 0.001$ | -0.18 |
| B - C | 7128298 | -5.374 | $p < 0.001$ | -0.06 |
| A - C | 8179533 | -11.039 | $p < 0.001$ | -0.12 |

**a) Cruise mode speed (kph)** – velocity equal to or greater than 0.25m/s, acceleration -0.1 to +0.1 m/s$^2$

| Phase | n | Mean (kph) | Q1 (kph) | Median (kph) | Q3 (kph) |
|---|---|---|---|---|---|
| A | 19047 | 47.12 | 17.10 | 42.30 | 72.92 |
| B | 16565 | 39.19 | 8.10 | 30.60 | 63.90 |
| C | 13989 | 42.40 | 10.80 | 37.80 | 68.40 |

| Pairwise comparison | Mann-Whitney U | Z | Significance (2-tailed) | Effect size r |
|---|---|---|---|---|
| A – B | 1.4E+008 | -23.451 | $p < 0.001$ | -0.12 |
| B - C | 1.1E+008 | -9.290 | $p < 0.001$ | -0.05 |
| A - C | 1.2E+008 | -12.839 | $p < 0.001$ | -0.07 |

**b) Speed across all driving modes (kph)**

| Phase | n | Mean (m/s$^2$) | Q1 (m/s$^2$) | Median (m/s$^2$) | Q3 (m/s$^2$) |
|---|---|---|---|---|---|
| A | 6373 | 0.57 | 0.25 | 0.50 | 0.75 |
| B | 5266 | 0.57 | 0.25 | 0.50 | 0.75 |
| C | 4578 | 0.56 | 0.25 | 0.50 | 0.75 |

| Pairwise comparison | Mann-Whitney U | Z | Significance (2-tailed) | Effect size r |
|---|---|---|---|---|
| A – B | 16637748 | -0.820 | *ns* | - |
| B - C | 11898691 | -1.149 | *ns* | - |
| A - C | 14276028 | -1.988 | $p = 0.052$ | -0.02 |

**c) Acceleration (m/s$^2$)** – Speed equal to or greater than 0.25m/s, acceleration equal to or greater than plus 0.1m/s$^2$

| Phase | n | Mean (m/s$^2$) | Q1 (m/s$^2$) | Median (m/s$^2$) | Q3 (m/s$^2$) |
|---|---|---|---|---|---|
| A | 5838 | -0.62 | -0.75 | -0.50 | -0.25 |
| B | 5072 | -0.58 | -0.75 | -0.45 | -0.25 |
| C | 4270 | -0.59 | -0.75 | -0.48 | -0.25 |

| Pairwise comparison | Mann-Whitney U | Z | Significance (2-tailed) | Effect size r |
|---|---|---|---|---|
| A – B | 14007919 | -5.080 | $p < 0.001$ | -0.05 |
| B - C | 10682136 | -1.184 | *ns* | - |
| A - C | 11968036 | -3.568 | $p < 0.001$ | -0.04 |

**d) Deceleration (m/s$^2$)** – Speed equal to or greater than 0.25m/s, deceleration equal to or less than minus 0.1m/s$^2$

## Table 10: NCL Glyn statistical summary

### 3.6.3 NCL James (Phone 5)

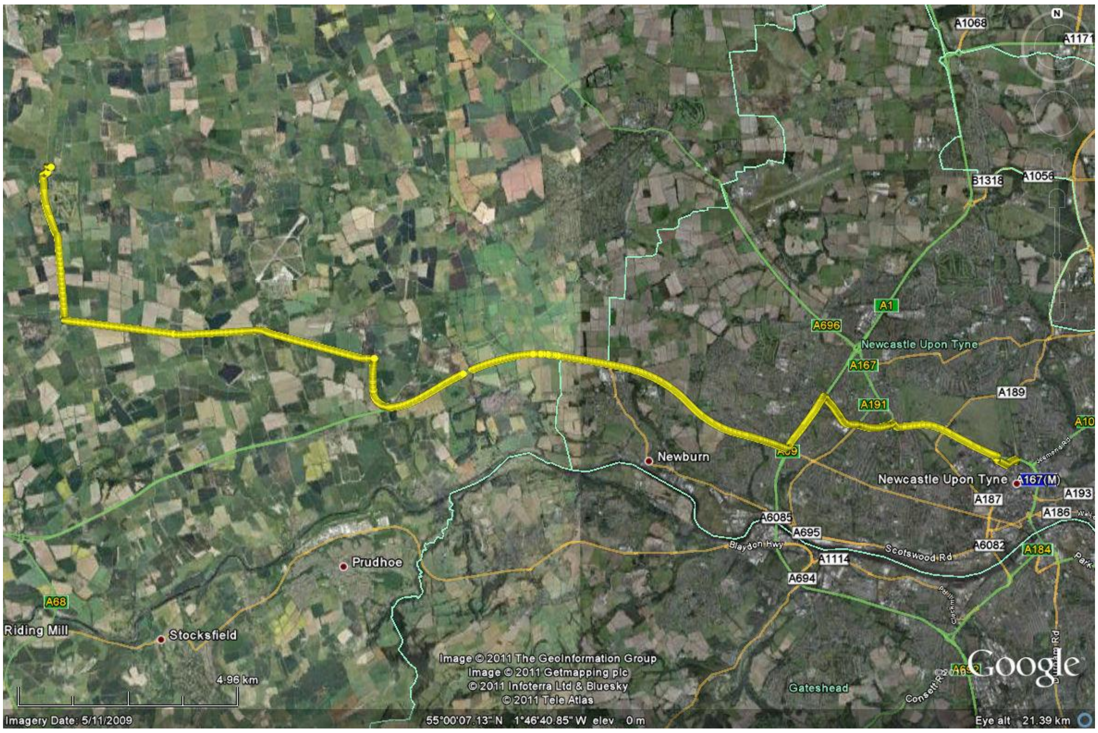



**Figure 33: NCL James primary route to / from work**

NCL James commuted on a route which is a mix of urban, interurban, and rural road types. The interurban element of the route is a major part of the total trip. Figure 33 illustrates the primary route from home to the west of Newcastle, north of the River Tyne, into the city centre.

Figure 34 presents the eco-driving scores by trip and Phase. It can be seen that there is a very strong correlation between the ‘cruise’ score and the ‘total’ score, reflecting the dominance of the interurban element of the route. It is also notable that there is significant variation in ‘acceleration’ and particularly ‘deceleration’ eco-driving scores. Some ‘deceleration’ scores approach zero; this issue is investigated further later in this chapter. Overall, there appears to be an improvement in the mean total eco-driving score in Phase B (64) which is maintained in Phase C (64), relative to the Phase A score (60). The main source of the improvement appears to be in the ‘acceleration’ scores, where the mean values for Phases A, B, and C are 69, 87, and 81 respectively. There is a small gradual improvement in the ‘cruise’ score (progressively 60, 61, and 62), but the deceleration score is more variable.

From Table 11a, it is clear that there is a statistically significant reduction in speed from Phase A (cruise mean 82.8kph) to Phase B (cruise mean 72.8kph), which is partially maintained in Phase C (cruise mean 76.4kph). Interestingly, whilst there is a small reduction in the mean rate of acceleration (Table 11c) from Phase A (0.58m/s$^2$) to Phase B (0.55m/s$^2$), this is not found to be statistically significant.

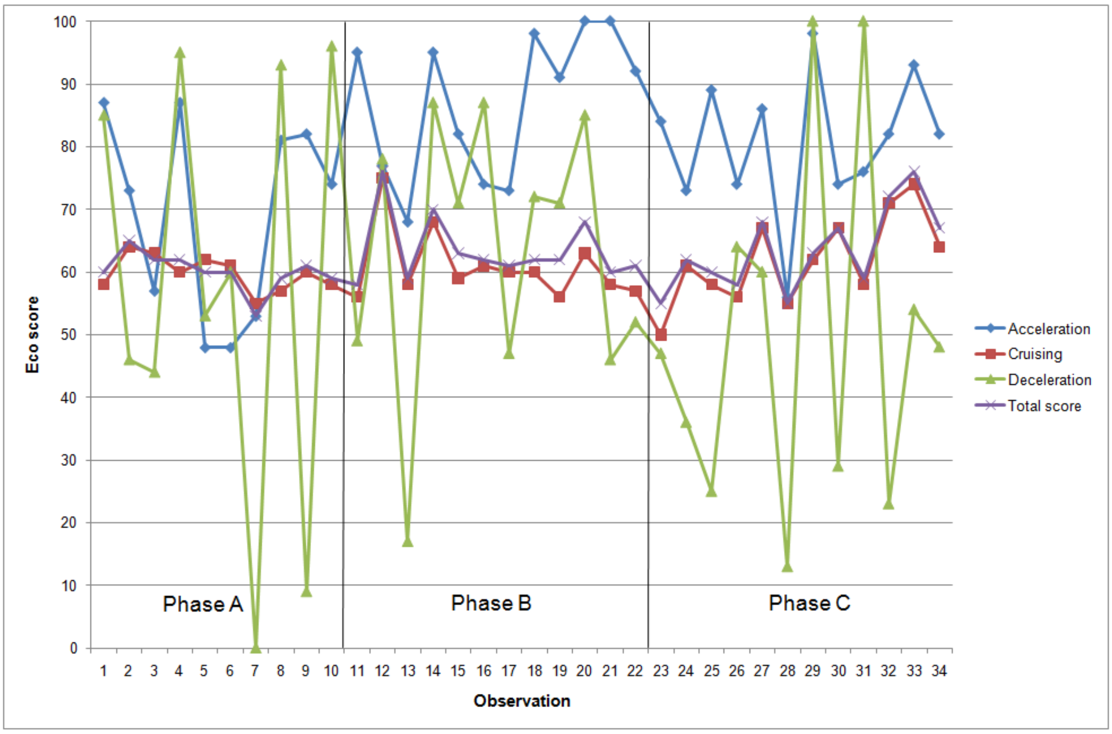



**Figure 34: NCL James eco-driving scores by trip and phase**

In summary, a small improvement in ‘cruise’ eco-driving scores, and a larger improvement in ‘acceleration’ scores, results in an overall improvement in mean ‘total’ eco-driving score from 60 in Phase A to 64 in Phases B and C. The statistical analysis highlights a reduction in speed in Phase B which is partially maintained in Phase C. However, the observed small variations in acceleration and deceleration rates were not found to be statistically significant. The improvement in ‘acceleration’ eco-driving score appears to be related more to the relationship between the ‘ideal’ and observed driving profile than to any overall reduction in acceleration rates.

| Phase | n | Mean (kph) | Q1 (kph) | Median (kph) | Q3 (kph) |
|---|---|---|---|---|---|
| A | 5475 | 82.78 | 73.80 | 91.80 | 102.60 |
| B | 7800 | 72.84 | 61.23 | 83.72 | 89.10 |
| C | 7464 | 76.41 | 67.52 | 84.62 | 93.60 |

| Pairwise comparison | Mann-Whitney U | Z | Significance (2-tailed) | Effect size r |
|---|---|---|---|---|
| A – B | 14289451 | -32.496 | $p < 0.001$ | -0.28 |
| B - C | 25491253 | -13.297 | $p < 0.001$ | -0.11 |
| A - C | 15712318 | -22.487 | $p < 0.001$ | -0.20 |

**a) Cruise mode speed (kph)** – velocity equal to or greater than 0.25m/s, acceleration -0.1 to +0.1 $m/s^2$

| Phase | n | Mean (kph) | Q1 (kph) | Median (kph) | Q3 (kph) |
|---|---|---|---|---|---|
| A | 14683 | 68.30 | 44.10 | 78.32 | 93.60 |
| B | 20683 | 58.81 | 33.35 | 67.50 | 84.68 |
| C | 19598 | 62.23 | 37.80 | 72.09 | 88.22 |

| Pairwise comparison | Mann-Whitney U | Z | Significance (2-tailed) | Effect size r |
|---|---|---|---|---|
| A – B | 1.2E+008 | -33.382 | $p < 0.001$ | -0.18 |
| B - C | 1.9E+008 | -13.820 | $p < 0.001$ | -0.07 |
| A - C | 1.2E+008 | -21.669 | $p < 0.001$ | -0.12 |

**b) Speed across all driving modes (kph)**

| Phase | n | Mean ($m/s^2$) | Q1 ($m/s^2$) | Median ($m/s^2$) | Q3 ($m/s^2$) |
|---|---|---|---|---|---|
| A | 4625 | 0.58 | 0.25 | 0.27 | 0.75 |
| B | 6435 | 0.55 | 0.25 | 0.27 | 0.75 |
| C | 6139 | 0.55 | 0.25 | 0.27 | 0.75 |

| Pairwise comparison | Mann-Whitney U | Z | Significance (2-tailed) | Effect size r |
|---|---|---|---|---|
| A – B | 14684973 | -1.229 | *ns* | - |
| B - C | 19630823 | -0.620 | *ns* | - |
| A - C | 13927827 | -1.754 | *ns* | - |

**c) Acceleration ($m/s^2$)** – Speed equal to or greater than 0.25m/s, acceleration equal to or greater than plus 0.1$m/s^2$

| Phase | n | Mean ($m/s^2$) | Q1 ($m/s^2$) | Median ($m/s^2$) | Q3 ($m/s^2$) |
|---|---|---|---|---|---|
| A | 4235 | -0.61 | -0.75 | -0.26 | -0.25 |
| B | 5850 | -0.59 | -0.75 | -0.26 | -0.25 |
| C | 5453 | -0.60 | -0.75 | -0.26 | -0.25 |

| Pairwise comparison | Mann-Whitney U | Z | Significance (2-tailed) | Effect size r |
|---|---|---|---|---|
| A – B | 12385825 | -0.011 | *ns* | - |
| B - C | 15873716 | -0.459 | *ns* | - |
| A - C | 11491841 | -0.421 | *ns* | - |

**d) Deceleration ($m/s^2$)** – Speed equal to or greater than 0.25m/s, deceleration equal to or less than minus 0.1$m/s^2$

**Table 11: NCL James statistical summary**

### 3.6.4 NCL Bryn (Phone 6)

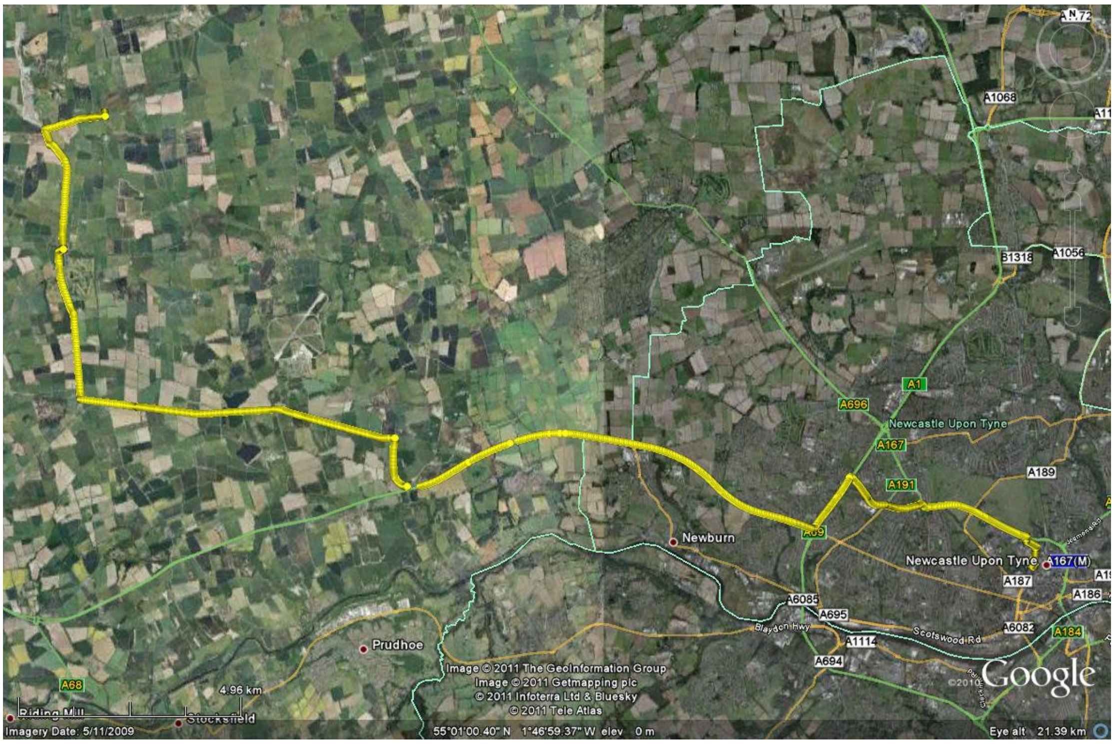



**Figure 35: NCL Bryn primary route to / from work**

NCL Bryn commuted on essentially the same route as NCL James, a route which is a mix of urban, interurban, and rural road types. The interurban element of the route is a major part of the total trip. Figure 35 illustrates the primary route from home to the west of Newcastle, north of the River Tyne, into the city centre.

Figure 36 presents the eco-driving scores by trip and Phase. NCL Bryn was arguably the most extreme driver in the trial, in terms of his variability in driving style and his potential to improve. Again, it can be seen that there is a very strong correlation between the ‘cruise’ score and the ‘total’ score, reflecting the dominance of the interurban element of the route. It is also notable that there is significant variation in ‘acceleration’ and particularly ‘deceleration’ eco-driving scores. However, it is also very clear from Figure 36 that with this driver there has been a significant improvement in total eco-driving score in Phase B, which has been generally maintained in Phase C (although there is evidence of a drop-off in performance in the last two or three trips of the trial).

Overall mean total eco-driving scores for Phase A, B, and C improved progressively from 23, to 43, and finally 50. Whilst much lower than the scores achieved by NCL James on the same route, the improvement is notable. Progressive improvements are observed in each of the three driving modes, ‘acceleration’, ‘cruise’, and ‘deceleration’.

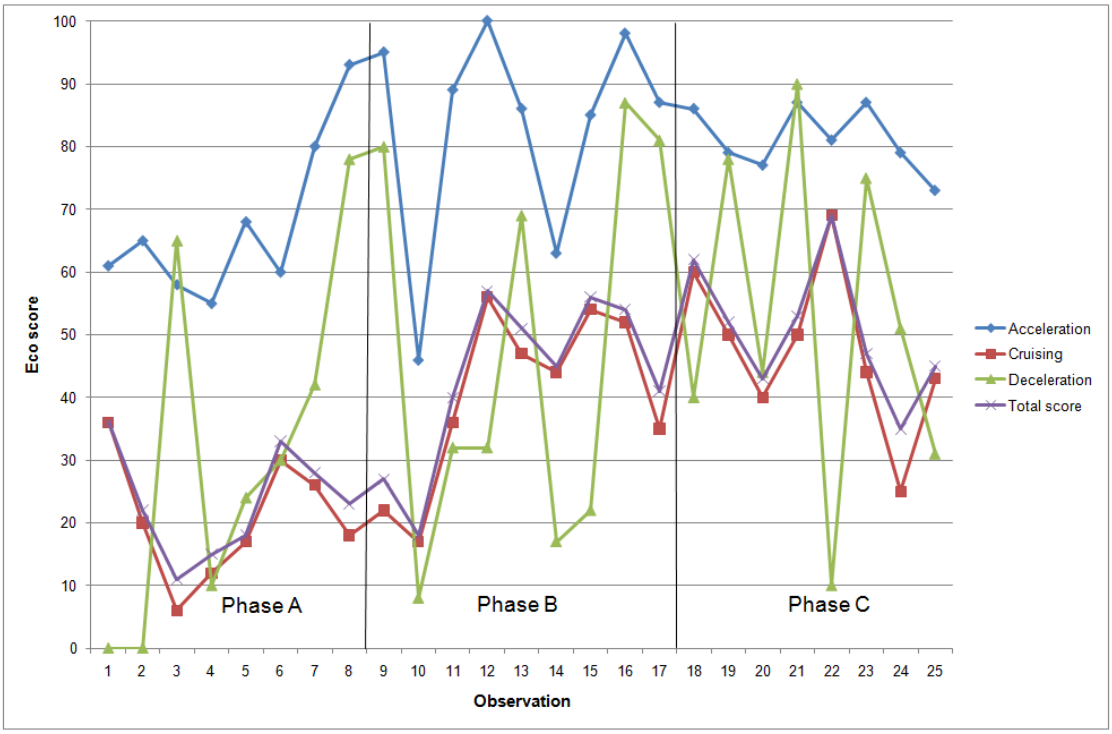



**Figure 36: NCL Bryn eco-driving scores by trip and phase**

The statistical summary presented in Table 12 reinforces this picture. Mean cruise speeds decreased significantly from Phase A (67.6kph) to Phase B (57.5kph) in particular. There were statistically significant reductions in the mean rate of acceleration from Phase A (0.75m/s$^2$), to Phase B (0.59m/s$^2$), and Phase C (0.57m/s$^2$). There were also statistically significant reductions in the mean rate of deceleration from Phase A (-0.77m/s$^2$), to Phase B (-0.64m/s$^2$), and Phase C (-0.63m/s$^2$).

In summary, NCL Bryn achieved and maintained improved eco-driving scores across ‘acceleration’, ‘cruise’, and ‘deceleration’ modes throughout the trial.

These results are confirmed by the statistical analysis of the 1Hz speed data for each Phase.

| Phase | n | Mean (kph) | Q1 (kph) | Median (kph) | Q3 (kph) |
|---|---|---|---|---|---|
| A | 2790 | 67.58 | 45.04 | 62.13 | 89.12 |
| B | 4453 | 57.45 | 45.90 | 61.20 | 70.20 |
| C | 5069 | 57.90 | 45.94 | 62.10 | 72.00 |

| Pairwise comparison | Mann-Whitney U | Z | Significance (2-tailed) | Effect size r |
|---|---|---|---|---|
| A – B | 5429993 | -9.030 | $p < 0.001$ | -0.11 |
| B - C | 10953933 | -2.482 | $p = 0.012$ | -0.03 |
| A - C | 6304878 | -7.963 | $p < 0.001$ | -0.09 |

**a) Cruise mode speed (kph)** – velocity equal to or greater than 0.25m/s, acceleration -0.1 to +0.1 m/s$^2$

| Phase | n | Mean (kph) | Q1 (kph) | Median (kph) | Q3 (kph) |
|---|---|---|---|---|---|
| A | 13406 | 61.35 | 40.50 | 60.33 | 84.60 |
| B | 16293 | 52.44 | 38.70 | 57.60 | 68.40 |
| C | 16541 | 49.71 | 35.10 | 54.90 | 67.52 |

| Pairwise comparison | Mann-Whitney U | Z | Significance (2-tailed) | Effect size r |
|---|---|---|---|---|
| A – B | 92565005 | -22.642 | $p < 0.001$ | -0.13 |
| B - C | 1.3E+008 | -8.881 | $p < 0.001$ | -0.05 |
| A - C | 88805025 | -29.668 | $p < 0.001$ | -0.17 |

**b) Speed across all driving modes (kph)**

| Phase | n | Mean (m/s$^2$) | Q1 (m/s$^2$) | Median (m/s$^2$) | Q3 (m/s$^2$) |
|---|---|---|---|---|---|
| A | 5147 | 0.75 | 0.25 | 0.50 | 1.00 |
| B | 5988 | 0.59 | 0.25 | 0.50 | 0.75 |
| C | 5754 | 0.57 | 0.25 | 0.50 | 0.75 |

| Pairwise comparison | Mann-Whitney U | Z | Significance (2-tailed) | Effect size r |
|---|---|---|---|---|
| A – B | 13217548 | -13.254 | $p < 0.001$ | -0.13 |
| B - C | 16692047 | -3.010 | $p = 0.003$ | -0.03 |
| A - C | 12279583 | -15.812 | $p < 0.001$ | -0.15 |

**c) Acceleration (m/s$^2$)** – Speed equal to or greater than 0.25m/s, acceleration equal to or greater than plus 0.1m/s$^2$

| Phase | n | Mean (m/s$^2$) | Q1 (m/s$^2$) | Median (m/s$^2$) | Q3 (m/s$^2$) |
|---|---|---|---|---|---|
| A | 4844 | -0.77 | -1.00 | -0.50 | -0.25 |
| B | 5361 | -0.64 | -0.75 | -0.50 | -0.25 |
| C | 5005 | -0.63 | -0.75 | -0.50 | -0.25 |

| Pairwise comparison | Mann-Whitney U | Z | Significance (2-tailed) | Effect size r |
|---|---|---|---|---|
| A – B | 11683441 | -8.959 | $p < 0.001$ | -0.09 |
| B - C | 12956846 | -3.111 | $p = 0.002$ | -0.03 |
| A - C | 10530407 | -11.589 | $p < 0.001$ | -0.12 |

**d) Deceleration (m/s$^2$)** – Speed equal to or greater than 0.25m/s, deceleration equal to or less than minus 0.1m/s$^2$

**Table 12: NCL Bryn statistical summary**

### 3.6.5 TRG Linda (Phone 7)

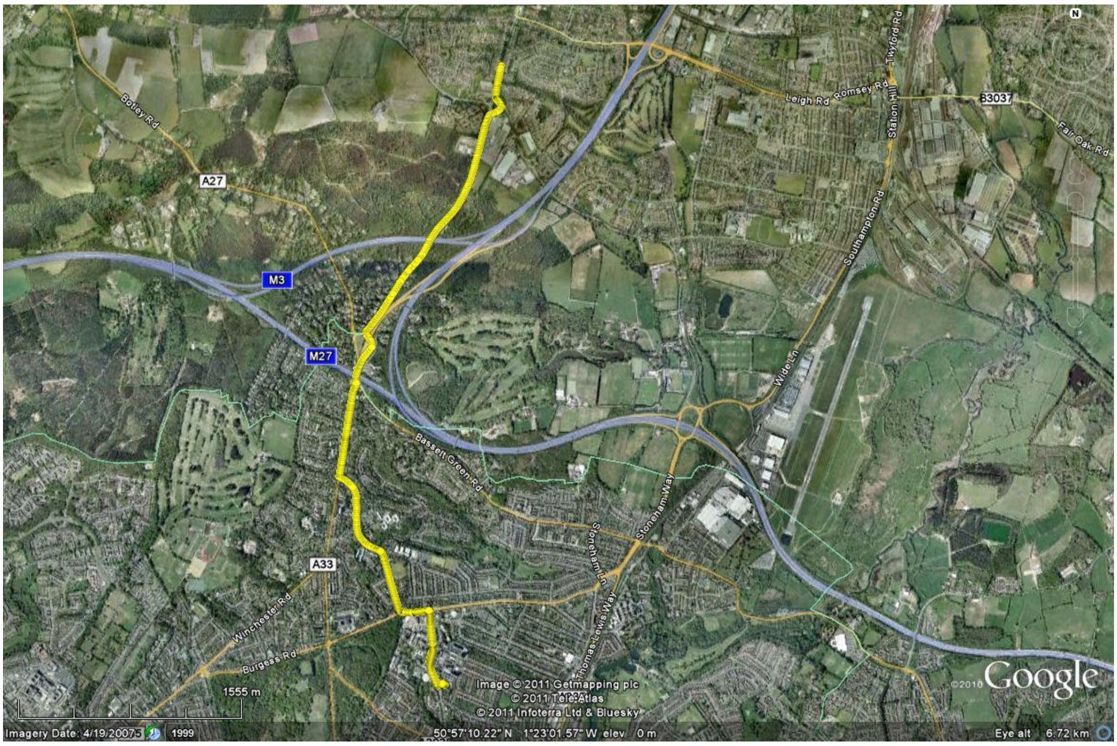


**Figure 37: TRG Linda primary route to / from work**

TRG Linda commuted on a route which is predominantly urban and suburban in nature. On such a route, overall speeds tend to be dominated by highway geometry and traffic conditions. Figure 37 illustrates the primary route from home just to the north of Southampton, into the University campus.

Figure 38 presents the eco-driving scores by trip and Phase. Overall, there appears to be a no improvement in the mean ‘total’ eco-driving score from Phase A (42), to Phase B (38), and Phase C (39), indeed the trend appears to be for the eco-driving scores to get worse. When the individual driving modes are reviewed, it can be seen that whilst there is an improvement in the ‘acceleration’ score from Phase A (58) to Phase B (69), this is offset by deteriorating scores in the ‘cruise’ mode (Phase A, 35; Phase B, 25) and in the ‘deceleration’ mode (Phase A, 80; Phase B, 71).

From the statistical summary presented in Table 13, it can be seen that there is a small reduction in the mean cruise speed (from 36.9kph to 34.17kph), and a larger reduction from Phase A to Phase B (from 45kph to 36.9kph) in the median cruise speed. The mean acceleration rate essentially remains constant throughout the trial in the range 0.73m/s$^2$ to 0.69m/s$^2$. Mean deceleration rates actually increase from Phase A (-0.63m/s$^2$) to Phase B (-0.71m/s$^2$), and remain at -0.67m/s$^2$ in Phase C.

In summary, it is difficult to conclude from the data that the eco-driving application has had any significant influence on the driving behaviour of TRG Linda. However, taking into account the nature of the route, it may be the case that the driving behaviour and consequent eco-driving scores were primarily determined in this case by prevailing traffic conditions, congestion, and highway infrastructure characteristics.

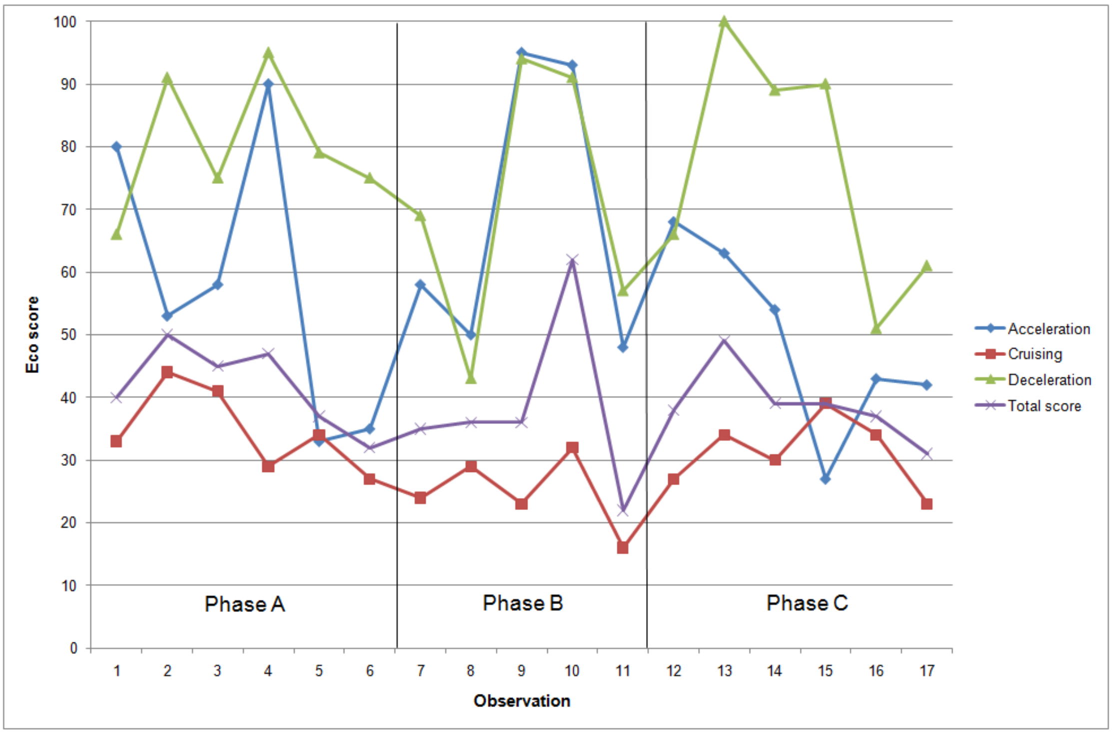



**Figure 38: TRG Linda eco-driving scores by trip and phase**

| Phase | n | Mean (kph) | Q1 (kph) | Median (kph) | Q3 (kph) |
|---|---|---|---|---|---|
| A | 736 | 36.90 | 15.30 | 45.00 | 54.90 |
| B | 578 | 34.17 | 9.72 | 36.90 | 53.10 |
| C | 787 | 35.70 | 9.90 | 41.40 | 54.00 |

| Pairwise comparison | Mann-Whitney U | Z | Significance (2-tailed) | Effect size r |
|---|---|---|---|---|
| A – B | 196317 | -2.401 | $p = 0.018$ | -0.07 |
| B - C | 215374 | -1.678 | *ns* | - |
| A - C | 284169 | -0.635 | *ns* | - |

**a) Cruise mode speed (kph)** – velocity equal to or greater than 0.25m/s, acceleration -0.1 to +0.1 m/s$^2$

| Phase | n | Mean (kph) | Q1 (kph) | Median (kph) | Q3 (kph) |
|---|---|---|---|---|---|
| A | 4288 | 25.35 | 0.90 | 22.50 | 46.80 |
| B | 3728 | 23.96 | 0.90 | 17.34 | 43.20 |
| C | 4796 | 23.40 | 0.00 | 16.70 | 45.00 |

| Pairwise comparison | Mann-Whitney U | Z | Significance (2-tailed) | Effect size r |
|---|---|---|---|---|
| A – B | 7662240 | -3.221 | $p = 0.001$ | -0.04 |
| B - C | 8806304 | -1.195 | *ns* | - |
| A - C | 9726674 | -4.492 | $p < 0.001$ | -0.05 |

**b) Speed across all driving modes (kph)**

| Phase | n | Mean (m/s$^2$) | Q1 (m/s$^2$) | Median (m/s$^2$) | Q3 (m/s$^2$) |
|---|---|---|---|---|---|
| A | 1193 | 0.73 | 0.25 | 0.50 | 1.00 |
| B | 1133 | 0.71 | 0.25 | 0.50 | 0.96 |
| C | 1321 | 0.69 | 0.25 | 0.50 | 0.89 |

| Pairwise comparison | Mann-Whitney U | Z | Significance (2-tailed) | Effect size r |
|---|---|---|---|---|
| A – B | 648613 | -1.718 | *ns* | - |
| B - C | 745881 | -0.145 | *ns* | - |
| A - C | 753249 | -1.959 | $p = 0.047$ | -0.04 |

**c) Acceleration (m/s$^2$)** – Speed equal to or greater than 0.25m/s, acceleration equal to or greater than plus 0.1m/s$^2$

| Phase | n | Mean (m/s$^2$) | Q1 (m/s$^2$) | Median (m/s$^2$) | Q3 (m/s$^2$) |
|---|---|---|---|---|---|
| A | 1347 | -0.63 | -0.75 | -0.50 | -0.25 |
| B | 1074 | -0.71 | -0.98 | -0.50 | -0.25 |
| C | 1353 | -0.67 | -0.75 | -0.50 | -0.25 |

| Pairwise comparison | Mann-Whitney U | Z | Significance (2-tailed) | Effect size r |
|---|---|---|---|---|
| A – B | 667597 | -3.334 | $p = 0.001$ | -0.07 |
| B - C | 689185 | -2.232 | $p = 0.024$ | -0.05 |
| A - C | 890419 | -1.056 | *ns* | - |

**d) Deceleration (m/s$^2$)** – Speed equal to or greater than 0.25m/s, deceleration equal to or less than minus 0.1m/s$^2$

## Table 13: TRG Linda statistical summary

### 3.6.6 TRG Laura (Phone 9)

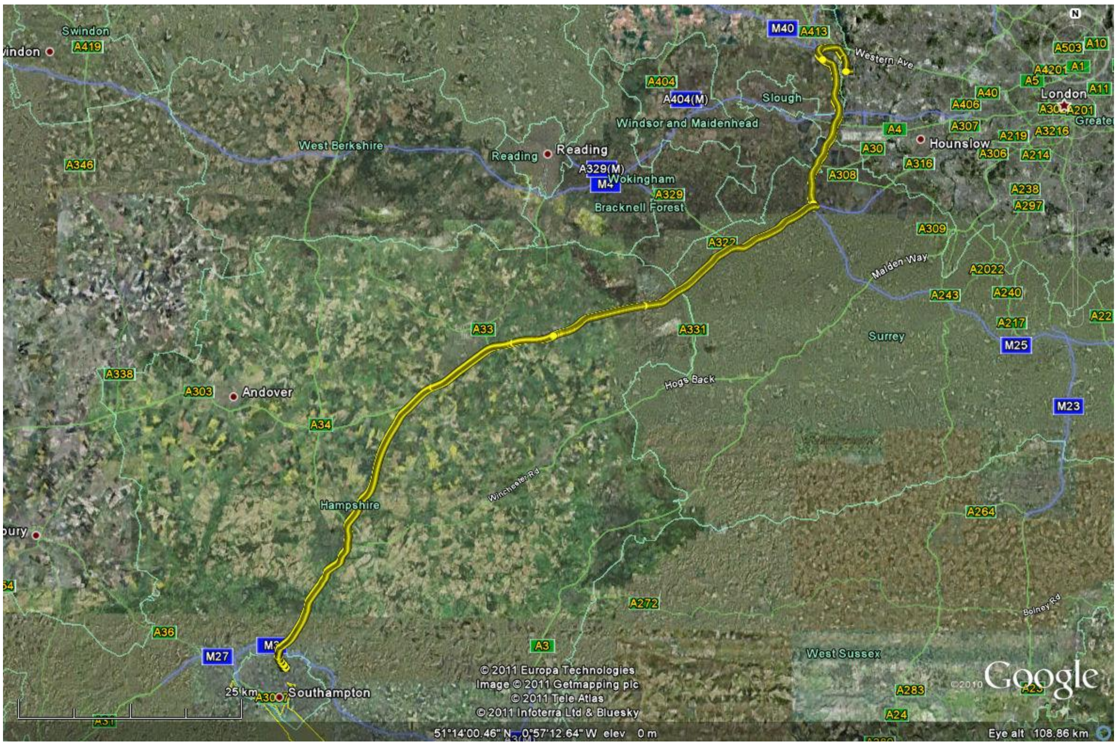



**Figure 39: TRG Laura primary route to / from work**

TRG Laura commuted on a route which was almost completely interurban motorway, the route length being approximately 106km, from west London to Southampton along the M25 and M3 motorways. Figure 39 illustrates the primary route from home in London to Southampton.

Figure 40 presents the eco-driving scores by trip and Phase. Unsurprisingly, there is an almost perfect correlation between the ‘cruise’ eco-driving score, and the ‘total’ score. Logic would suggest that the options for eco-driving interventions in such circumstances (in the context of the trial) would be limited to reducing variability in speed, and reducing absolute speed. Overall, the mean ‘total’ eco-driving score improved from 84 in Phase A to 85 in Phases B and C. The ‘cruise’ scores equalled the ‘total’ scores, whilst there was a slight improvement in the mean ‘acceleration’ scores, and a deterioration in the mean ‘deceleration’ scores.

With reference to Table 14, a little surprisingly, there was a statistically significant increase in mean speed from Phase A to Phase B. Mean speeds in Phases B and C are both higher than Phase A.

In summary, whilst there appears to be a slight improvement in the ‘acceleration’ scores, there was little change in ‘cruise’ scores, and a deterioration in ‘deceleration’ scores. It would appear that for motorway journeys, with relatively constant speeds, and few if any ‘acceleration’ and ‘deceleration’ events (where speed drops below 20kph, a threshold level for the eco-driving algorithm), the eco-driving scores tend to be inherently high (generally above 80), and with little variation, with the exception of the ‘deceleration’ metric. In this case, the eco-driving application does not appear to have had a significant influence on the outcome, based on the data available.

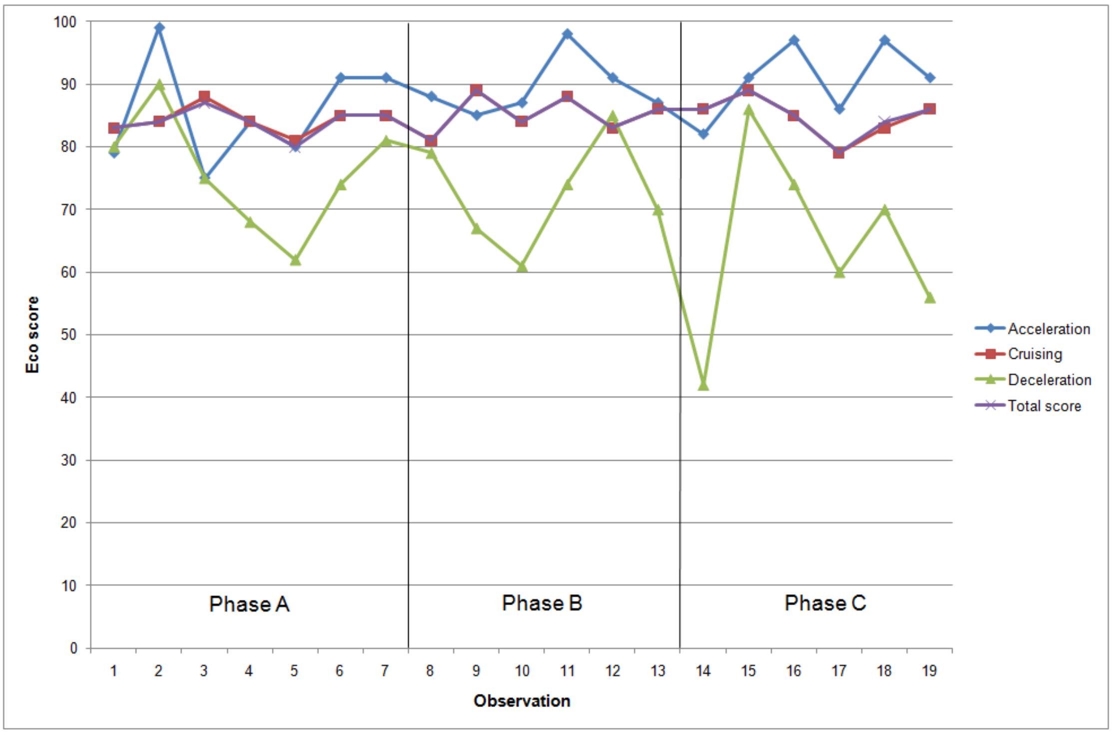



**Figure 40: TRG Laura eco-driving scores by trip and phase**

| Phase | n | Mean (kph) | Q1 (kph) | Median (kph) | Q3 (kph) |
|---|---|---|---|---|---|
| A | 15023 | 95.87 | 91.82 | 104.42 | 111.60 |
| B | 12973 | 99.51 | 97.20 | 108.90 | 116.10 |
| C | 12927 | 97.75 | 93.62 | 106.22 | 114.30 |

| Pairwise comparison | Mann-Whitney U | Z | Significance (2-tailed) | Effect size r |
|---|---|---|---|---|
| A – B | 81149193 | -24.171 | $p < 0.001$ | -0.14 |
| B - C | 77639120 | -10.326 | $p < 0.001$ | -0.06 |
| A - C | 88136993 | -13.329 | $p < 0.001$ | -0.08 |

**a) Cruise mode speed (kph)** – velocity equal to or greater than 0.25m/s, acceleration -0.1 to +0.1 m/s$^2$

| Phase | n | Mean (kph) | Q1 (kph) | Median (kph) | Q3 (kph) |
|---|---|---|---|---|---|
| A | 35099 | 80.25 | 53.10 | 98.12 | 108.90 |
| B | 28907 | 82.01 | 51.30 | 101.70 | 112.51 |
| C | 29105 | 81.74 | 53.10 | 100.80 | 111.60 |

| Pairwise comparison | Mann-Whitney U | Z | Significance (2-tailed) | Effect size r |
|---|---|---|---|---|
| A – B | 4.6E+008 | -18.292 | $p < 0.001$ | -0.07 |
| B - C | 4.1E+008 | -5.747 | $p < 0.001$ | -0.02 |
| A - C | 4.8E+008 | -12.282 | $p < 0.001$ | -0.05 |

**b) Speed across all driving modes (kph)**

| Phase | n | Mean (m/s$^2$) | Q1 (m/s$^2$) | Median (m/s$^2$) | Q3 (m/s$^2$) |
|---|---|---|---|---|---|
| A | 9300 | 0.41 | 0.25 | 0.25 | 0.50 |
| B | 7273 | 0.41 | 0.25 | 0.25 | 0.50 |
| C | 7491 | 0.40 | 0.25 | 0.25 | 0.50 |

| Pairwise comparison | Mann-Whitney U | Z | Significance (2-tailed) | Effect size r |
|---|---|---|---|---|
| A – B | 33807699 | -0.045 | *ns* | - |
| B - C | 27152069 | -0.405 | *ns* | - |
| A - C | 34707165 | -0.475 | *ns* | - |

**c) Acceleration (m/s$^2$)** – Speed equal to or greater than 0.25m/s, acceleration equal to or greater than plus 0.1m/s$^2$

| Phase | n | Mean (m/s$^2$) | Q1 (m/s$^2$) | Median (m/s$^2$) | Q3 (m/s$^2$) |
|---|---|---|---|---|---|
| A | 8402 | -0.44 | -0.50 | -0.25 | -0.25 |
| B | 6528 | -0.44 | -0.50 | -0.25 | -0.25 |
| C | 6844 | -0.43 | -0.50 | -0.25 | -0.25 |

| Pairwise comparison | Mann-Whitney U | Z | Significance (2-tailed) | Effect size r |
|---|---|---|---|---|
| A – B | 27360046 | -0.281 | *ns* | - |
| B - C | 21927273 | -2.139 | $p = 0.033$ | -0.02 |
| A - C | 28149135 | -2.574 | $p = 0.010$ | -0.02 |

**d) Deceleration (m/s$^2$)** – Speed equal to or greater than 0.25m/s, deceleration equal to or less than minus 0.1m/s$^2$

**Table 14: TRG Laura statistical summary**

### *3.6.7 TRG Nick (Phone 11)*

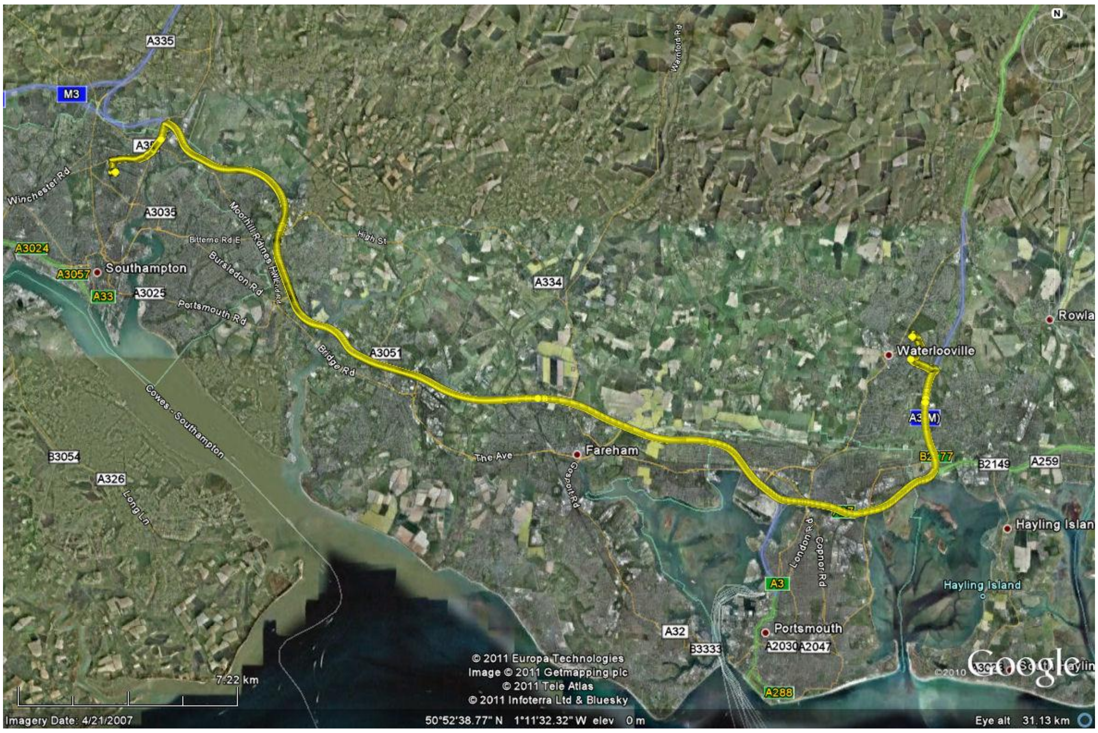



**Figure 41: TRG Nick primary route to / from work**

TRG Nick commuted on a route which was mainly interurban motorway, with short urban and suburban sections. Figure 41 illustrates the primary route from home near Waterlooville in the east to Southampton in the west.

Figure 42 presents the eco-driving scores by trip and Phase. Unsurprisingly, there is again an almost perfect correlation between the ‘cruise’ eco-driving score, and the ‘total’ score, because of the dominance of the ‘cruise’ element of the journey. There is a small increase in the overall mean ‘total’ eco-driving’ score from Phase A (72), to Phase B (75), and Phase C (75). The mean ‘acceleration’ score actually gets progressively worse from Phase A (95), to Phase B (93), and Phase C (86). It is notable that the ‘deceleration’ scores are influenced by a small number of low scores for individual trips in Phases A and C. This results in a higher mean ‘deceleration’ score for Phase B (87), relative to the other two Phases.

The statistical summary presented in Table 15 highlights the fact that mean speeds consistently and progressively increased from Phase A (cruise speed 76.6kph) through to Phase C (cruise speed 87.5kph). This increase in speed does not appear to have had a negative impact on the resulting eco-driving score for the 'cruise' mode. Very small reductions in both acceleration and deceleration rates were observed, but these changes were barely significant.

In summary, TRG Nick was observed to produce a modest improvement in overall total eco-driving score over the course of the trial, but acceleration scores were observed to get worse, and deceleration scores appeared to be influenced by outliers (low values).

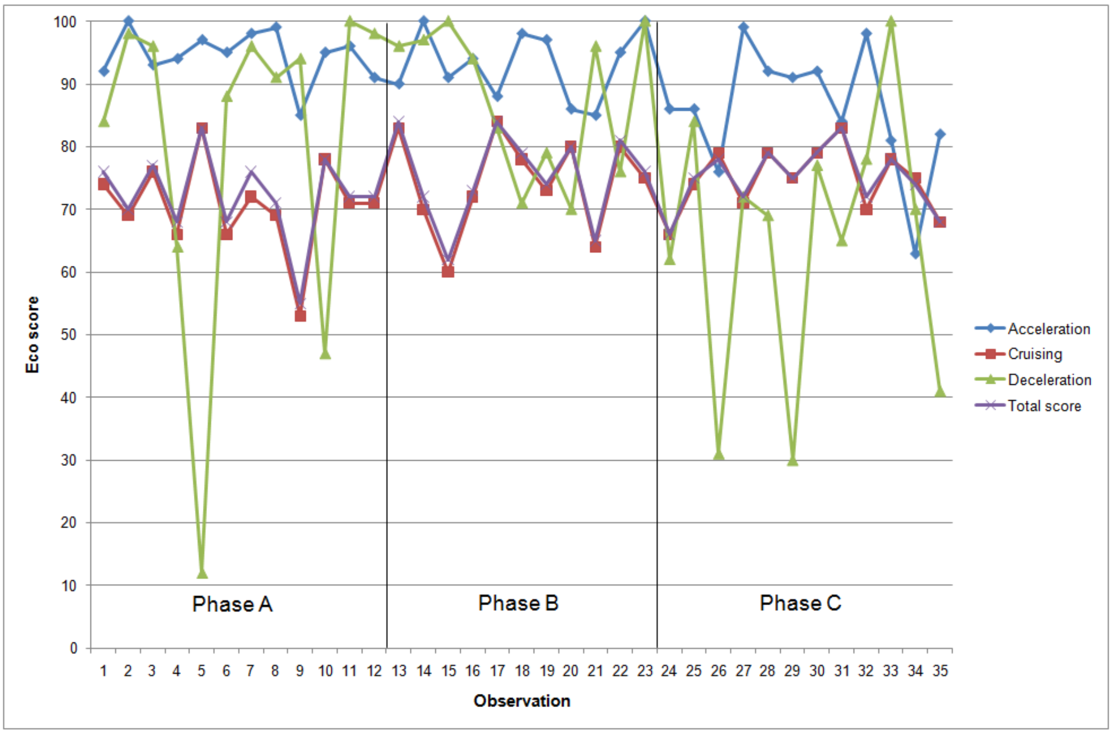



**Figure 42: TRG Nick eco-driving scores by trip and phase**

| Phase | n | Mean (kph) | Q1 (kph) | Median (kph) | Q3 (kph) |
|---|---|---|---|---|---|
| A | 8946 | 76.60 | 50.40 | 90.02 | 103.52 |
| B | 7992 | 82.55 | 60.30 | 96.30 | 105.32 |
| C | 8234 | 87.50 | 74.72 | 99.92 | 108.00 |

| Pairwise comparison | Mann-Whitney U | Z | Significance (2-tailed) | Effect size r |
|---|---|---|---|---|
| A – B | 31813907 | -12.385 | $p < 0.001$ | -0.10 |
| B - C | 29323420 | -12.000 | $p < 0.001$ | -0.09 |
| A - C | 28870027 | -24.514 | $p < 0.001$ | -0.19 |

**a) Cruise mode speed (kph)** – velocity equal to or greater than 0.25m/s, acceleration -0.1 to +0.1 $m/s^2$

| Phase | n | Mean (kph) | Q1 (kph) | Median (kph) | Q3 (kph) |
|---|---|---|---|---|---|
| A | 26888 | 62.93 | 32.40 | 65.70 | 96.37 |
| B | 22429 | 68.85 | 41.40 | 74.72 | 101.70 |
| C | 22972 | 74.42 | 45.00 | 89.10 | 104.42 |

| Pairwise comparison | Mann-Whitney U | Z | Significance (2-tailed) | Effect size r |
|---|---|---|---|---|
| A – B | 2.7E+008 | -19.223 | $p < 0.001$ | -0.09 |
| B - C | 2.3E+008 | -18.148 | $p < 0.001$ | -0.09 |
| A - C | 2.5E+008 | -37.778 | $p < 0.001$ | -0.17 |

**b) Speed across all driving modes (kph)**

| Phase | n | Mean ($m/s^2$) | Q1 ($m/s^2$) | Median ($m/s^2$) | Q3 ($m/s^2$) |
|---|---|---|---|---|---|
| A | 9000 | 0.43 | 0.25 | 0.25 | 0.50 |
| B | 7196 | 0.42 | 0.25 | 0.25 | 0.50 |
| C | 7391 | 0.41 | 0.25 | 0.25 | 0.50 |

| Pairwise comparison | Mann-Whitney U | Z | Significance (2-tailed) | Effect size r |
|---|---|---|---|---|
| A – B | 31897542 | -1.819 | *ns* | - |
| B - C | 25995942 | -2.635 | $p = 0.008$ | -0.02 |
| A - C | 32021371 | -4.594 | $p < 0.001$ | -0.04 |

**c) Acceleration ($m/s^2$)** – Speed equal to or greater than 0.25m/s, acceleration equal to or greater than plus 0.1$m/s^2$

| Phase | n | Mean ($m/s^2$) | Q1 ($m/s^2$) | Median ($m/s^2$) | Q3 ($m/s^2$) |
|---|---|---|---|---|---|
| A | 7799 | -0.49 | -0.50 | -0.25 | -0.25 |
| B | 6233 | -0.48 | -0.50 | -0.25 | -0.25 |
| C | 6593 | -0.47 | -0.50 | -0.25 | -0.25 |

| Pairwise comparison | Mann-Whitney U | Z | Significance (2-tailed) | Effect size r |
|---|---|---|---|---|
| A – B | 23780023 | -2.393 | $p = 0.018$ | -0.02 |
| B - C | 20087273 | -2.407 | $p = 0.016$ | -0.02 |
| A - C | 24573712 | -4.997 | $p < 0.001$ | -0.04 |

**d) Deceleration ($m/s^2$)** – Speed equal to or greater than 0.25m/s, deceleration equal to or less than minus 0.1$m/s^2$

**Table 15: TRG Nick statistical summary**

### 3.7 Investigation of Low / Zero Deceleration Scores

It was noted during the analysis that a number of trial participants generated occasional very low or zero eco-driving scores for the ‘deceleration’ mode. Such extreme values were generally not observed for the ‘acceleration’ mode. It is of course possible to generate much higher rates of deceleration through hard / emergency braking, whereas positive acceleration rates are limited by the power and traction of the vehicle. A small number of examples were investigated to gain a better understanding of the circumstances under which such low / zero deceleration scores would be generated. This was done using the spreadsheet simulator.

An instance of a zero ‘deceleration’ score occurred with driver NCL James on February 24th 2011, trip commencing at 11:06am. The spreadsheet simulator was run on this 1Hz data set. Figure 43 reproduces the contents of the ‘Section1.csv’ simulator output file, with some amendments from the author to aid interpretation.

The simulator calculates the eco-driving scores for ‘Pulling away’, ‘Cruising’, and ‘Braking’ to be 63, 55, and -10 respectively. This is calculated using the following equation for each driving mode:

***Eco-driving score*** *= (1-((Total energy consumed – Total ‘ideal’ energy consumed) * γn) / Total energy consumed) * 100*

Where gamma (γ)n is a parameter specific to each driving mode, in this case assumed to be 1.7 in all cases, based on information provided by the vehicle manufacturer.

It is important to note the following assumptions:

a) In the calculation of the eco-driving score, if the actual energy consumption is calculated to be less than the ‘ideal’ energy consumption, the ‘ideal’ energy consumption value is used; and

b) If the eco-driving score is calculated to be less than zero, it is assumed to be zero; and
c) If the eco-driving score is calculated to be greater than 100, it is assumed to be 100.

Thus, in the case of Figure 43, the calculated ‘deceleration’ eco-driving score of -10 would be reported as zero. In Figure 43 attention is drawn to the three lines in the ‘Braking’ scene that are highlighted with an asterisk. These are three braking events where the energy consumed is significantly higher than the calculated ‘ideal’ values.

Scene start 199; consumed energy 10.61; ‘ideal’ energy 0.92
Scene start 499; consumed energy 5.82; ‘ideal’ energy 1.10
Scene start 1306; consumed energy 9.93; ‘ideal’ energy 0.92

As a sensitivity test, if these three values are reset to be approximately 110% of the ‘ideal’ energy consumption value, the ‘Braking’ eco-driving score for the whole trip increases from -10 to +71, as illustrated in Figure 44. These three braking events have a total combined duration of approximately 51 seconds. The single braking ‘event’ commencing at scene start 199 is reproduced in Table 16 below.

| Time | Speed (m/s) | Deceleration (m/s$^2$) |
|---|---|---|
| 199 | 25.25 | |
| 200 | 24.51 | -0.75 |
| 201 | 23.76 | -0.75 |
| 202 | 23.00 | -0.76 |
| 203 | 22.00 | -1.00 |
| 204 | 19.01 | -2.99 |
| 205 | 16.00 | -3.01 |
| 206 | 12.50 | -3.50 |
| 207 | 8.75 | -3.75 |
| 208 | 7.00 | -1.75 |
| 209 | 2.30 | -4.70 |
| 210 | 0.25 | -2.05 |
| 211 | 0.00 | -0.25 |
| 212 | 0 | 0.00 |

**Table 16: Example braking event**

Clearly, if the speed measurements derived from the smart phone GPS are accurate, then the deceleration rates observed are quite severe, particularly those in excess of $-3 m/s^2$ ($\approx 0.3g$). However, it should be noted that there will be error associated with the speed measurements, and such error will inevitably feed into any derived calculations of acceleration and deceleration. In addition, it is clear from these examples that in the eco-driving score algorithm as currently specified, a small number of braking events of relatively short duration can have a very significant impact on the overall ‘deceleration’ score calculated.

| Scene | Scene start | Number of data | Dist for scene (m) | Duration for scene | Consumed energy | Ideal consumed energy | Consumed minus Ideal | Consumed energy (assumed) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 5 | 23.1 | 4 | 3.57 | 3.66 | -0.09 | 3.66 | | | | |
| 1 | 17 | 11 | 47.0 | 10 | 8.67 | 7.79 | 0.88 | 8.67 | | | | |
| 1 | 37 | 15 | 83.4 | 14 | 11.51 | 12.83 | -1.32 | 12.83 | | | | |
| 1 | 215 | 7 | 20.5 | 6 | 13.90 | 3.33 | 10.58 | 13.90 | | | | |
| 1 | 512 | 15 | 95.1 | 14 | 16.05 | 13.24 | 2.81 | 16.05 | | | | |
| 1 | 1116 | 9 | 38.6 | 8 | 7.58 | 5.45 | 2.13 | 7.58 | | | | |
| 1 | 1189 | 9 | 29.2 | 8 | 5.34 | 4.52 | 0.82 | 5.34 | | **Scene 1: Pulling away** | | |
| 1 | 1206 | 8 | 37.6 | 7 | 7.64 | 4.83 | 2.81 | 7.64 | | | | |
| 1 | 1319 | 8 | 35.7 | 7 | 8.58 | 5.03 | 3.55 | 8.58 | | | | |
| 1 | 1330 | 12 | 79.6 | 11 | 13.64 | 11.32 | 2.33 | 13.64 | | | | |
| 1 | 1383 | 4 | 9.7 | 3 | 1.68 | 1.92 | -0.24 | 1.92 | | | | |
| 1 | 1393 | 10 | 21.4 | 9 | 3.24 | 6.05 | -2.81 | 6.05 | | | | |
| 1 | 1419 | 8 | 10.7 | 7 | 2.42 | 3.82 | -1.40 | 3.82 | | | | |
| 1 | 1431 | 3 | 0.3 | 2 | 0.39 | 0.53 | -0.15 | 0.53 | | | | |
| 1 | 1437 | 5 | 5.2 | 4 | 1.29 | 1.82 | -0.53 | 1.82 | | | | |
| 1 | 1446 | 2 | 0.1 | 1 | 0.30 | 0.29 | 0.01 | 0.30 | | | | |
| 1 | 1452 | 3 | 2.0 | 2 | 0.83 | 0.91 | -0.08 | 0.91 | | | | |
| 1 | 1461 | 6 | 1.8 | 5 | 0.99 | 2.08 | -1.09 | 2.08 | | | | |
| 1 | 1467 | 4 | 1.4 | 3 | 0.70 | 0.95 | -0.25 | 0.95 | | | | |
| 1 | 1474 | 4 | 0.8 | 3 | 0.63 | 0.95 | -0.32 | 0.95 | | | | |
| 1 | 1478 | 2 | 0.3 | 1 | 0.21 | 0.24 | -0.03 | 0.24 | | | | |
| 1 | 1483 | 2 | 0.3 | 1 | 0.21 | 0.24 | -0.03 | 0.24 | | | | |
| 1 | 1491 | 2 | 0.0 | 1 | 0.20 | 0.21 | -0.02 | 0.21 | | Gamma1= | | 1.7 |
| 1 | 1493 | 2 | 0.0 | 1 | 0.20 | 0.21 | -0.02 | 0.21 | | Accel score = | | 63 |
| 1 | 1497 | 2 | 0.0 | 1 | 0.20 | 0.21 | -0.02 | 0.21 | | Accel score used = | | 63 |
| 1 | 1500 | 5 | 0.8 | 4 | 0.76 | 1.47 | -0.70 | 1.47 | | Energy Actual | Ideal | |
| 1 | 1505 | 2 | 0.0 | 1 | 0.20 | 0.21 | -0.02 | 0.21 | | 120.0 | 94.1 | |
| 2 | 4 | 8 | 32.8 | 6.9 | 2.45 | 1.94 | 0.51 | 2.45 | | | | |
| 2 | 27 | 3 | 19.1 | 2.0 | 1.59 | 0.71 | 0.87 | 1.59 | | **Scene 2: Cruising** | | |
| 2 | 51 | 149 | 3189.4 | 147.9 | 204.94 | 116.30 | 88.64 | 204.94 | | | | |
| 2 | 221 | 279 | 6889.3 | 278.2 | 345.15 | 288.12 | 57.03 | 345.15 | | Gamma2= | | 1.7 |
| 2 | 526 | 583 | 13242.3 | 582.4 | 675.17 | 505.65 | 169.52 | 675.17 | | Cruise score = | | 55 |
| 2 | 1124 | 48 | 536.7 | 46.9 | 29.15 | 18.25 | 10.90 | 29.15 | | | | 55 |
| 2 | 1213 | 94 | 2348.1 | 93.0 | 146.13 | 101.10 | 45.03 | 146.13 | | Energy Actual | Ideal | |
| 2 | 1341 | 38 | 325.7 | 37.4 | 15.06 | 12.85 | 2.21 | 15.06 | | 1419.6 | 1044.9 | |
| 5 | 11 | 7 | 18.6 | 5.6 | 0.92 | 0.92 | 0.00 | 0.92 | | | | |
| 5 | 29 | 9 | 57.1 | 9.4 | 1.28 | 0.92 | 0.36 | 1.28 | | | | |
| **5** | **199** | **13** | **181.8** | **17.0** | **10.61** | **0.92** | **9.70** | **10.61** | * | | | |
| **5** | **499** | **14** | **172.2** | **16.4** | **5.82** | **1.10** | **4.73** | **5.82** | * | | | |
| 5 | 1108 | 9 | 70.1 | 10.2 | 2.15 | 0.92 | 1.23 | 2.15 | | | | |
| 5 | 1171 | 18 | 150.7 | 16.6 | 0.92 | 0.92 | 0.00 | 0.92 | | | | |
| 5 | 1197 | 10 | 47.0 | 9.0 | 0.73 | 0.73 | 0.00 | 0.73 | | **Scene 5: Braking** | | |
| **5** | **1306** | **14** | **220.5** | **17.3** | **9.93** | **0.92** | **9.01** | **9.93** | * | | | |
| 5 | 1326 | 5 | 31.8 | 5.0 | 1.63 | 0.55 | 1.08 | 1.63 | | | | |
| 5 | 1378 | 6 | 15.6 | 4.2 | 0.37 | 0.37 | 0.00 | 0.37 | | | | |
| 5 | 1386 | 8 | 19.4 | 6.3 | 0.92 | 0.92 | 0.00 | 0.92 | | | | |
| 5 | 1402 | 9 | 16.1 | 6.1 | 0.92 | 0.92 | 0.00 | 0.92 | | | | |
| 5 | 1426 | 5 | 8.7 | 4.3 | 0.73 | 0.73 | 0.00 | 0.73 | | | | |
| 5 | 1433 | 2 | 0.2 | 1.0 | 0.18 | 0.18 | 0.00 | 0.18 | | | | |
| 5 | 1441 | 5 | 5.8 | 3.7 | 0.55 | 0.55 | 0.00 | 0.55 | | | | |
| 5 | 1447 | 4 | 1.8 | 2.5 | 0.18 | 0.18 | 0.00 | 0.18 | | | | |
| 5 | 1454 | 6 | 6.7 | 4.6 | 0.37 | 0.37 | 0.00 | 0.37 | | | | |
| 5 | 1466 | 2 | 0.5 | 1.2 | 0.18 | 0.18 | 0.00 | 0.18 | | | | |
| 5 | 1470 | 3 | 1.7 | 2.2 | 0.37 | 0.37 | 0.00 | 0.37 | | | | |
| 5 | 1477 | 2 | 0.7 | 1.1 | 0.18 | 0.18 | 0.00 | 0.18 | | | | |
| 5 | 1479 | 5 | 1.2 | 2.5 | 0.18 | 0.18 | 0.00 | 0.18 | | | | |
| 5 | 1484 | 5 | 1.2 | 2.7 | 0.18 | 0.18 | 0.00 | 0.18 | | | | |
| 5 | 1492 | 2 | 0.2 | 1.0 | 0.18 | 0.18 | 0.00 | 0.18 | | Gamma3= | | 1.7 |
| 5 | 1494 | 2 | 0.2 | 1.0 | 0.18 | 0.18 | 0.00 | 0.18 | | Decel score = | | -10 |
| 5 | 1498 | 2 | 0.2 | 1.0 | 0.18 | 0.18 | 0.00 | 0.18 | | Decel score used = | | 0 |
| 5 | 1504 | 2 | 0.2 | 1.0 | 0.18 | 0.18 | 0.00 | 0.18 | | Energy Actual | Ideal | |
| 5 | 1506 | 2 | 0.2 | 1.0 | 0.18 | 0.18 | 0.00 | 0.18 | | 40.2 | 14.1 | |
| | | | | | | | | | | | | |
| | | | | | | | | | | Gamma4 = | | 1.7 |
| | | | | | | | | | | Overall eco-score = | | 54 |
| | | | | | | | | | | | | |
| | | | | | | | | | | Energy Actual | Ideal | |
| | | | | | | | | | | 1579.9 | 1153.1 | |

**Figure 43: NCL James: Feb 24th 2011 11:06am Section file**

| Scene | Scene start | Number of data | Dist for scene (m) | Duration for scene | Consumed energy | Ideal consumed energy | Consumed minus Ideal | Consumed energy (assumed) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 5 | 23.1 | 4 | 3.57 | 3.66 | -0.09 | 3.66 | | | |
| 1 | 17 | 11 | 47.0 | 10 | 8.67 | 7.79 | 0.88 | 8.67 | | | |
| 1 | 37 | 15 | 83.4 | 14 | 11.51 | 12.83 | -1.32 | 12.83 | | | |
| 1 | 215 | 7 | 20.5 | 6 | 13.90 | 3.33 | 10.58 | 13.90 | | | |
| 1 | 512 | 15 | 95.1 | 14 | 16.05 | 13.24 | 2.81 | 16.05 | | | |
| 1 | 1116 | 9 | 38.6 | 8 | 7.58 | 5.45 | 2.13 | 7.58 | | | |
| 1 | 1189 | 9 | 29.2 | 8 | 5.34 | 4.52 | 0.82 | 5.34 | **Scene 1: Pulling away** | | |
| 1 | 1206 | 8 | 37.6 | 7 | 7.64 | 4.83 | 2.81 | 7.64 | | | |
| 1 | 1319 | 8 | 35.7 | 7 | 8.58 | 5.03 | 3.55 | 8.58 | | | |
| 1 | 1330 | 12 | 79.6 | 11 | 13.64 | 11.32 | 2.33 | 13.64 | | | |
| 1 | 1383 | 4 | 9.7 | 3 | 1.68 | 1.92 | -0.24 | 1.92 | | | |
| 1 | 1393 | 10 | 21.4 | 9 | 3.24 | 6.05 | -2.81 | 6.05 | | | |
| 1 | 1419 | 8 | 10.7 | 7 | 2.42 | 3.82 | -1.40 | 3.82 | | | |
| 1 | 1431 | 3 | 0.3 | 2 | 0.39 | 0.53 | -0.15 | 0.53 | | | |
| 1 | 1437 | 5 | 5.2 | 4 | 1.29 | 1.82 | -0.53 | 1.82 | | | |
| 1 | 1446 | 2 | 0.1 | 1 | 0.30 | 0.29 | 0.01 | 0.30 | | | |
| 1 | 1452 | 3 | 2.0 | 2 | 0.83 | 0.91 | -0.08 | 0.91 | | | |
| 1 | 1461 | 6 | 1.8 | 5 | 0.99 | 2.08 | -1.09 | 2.08 | | | |
| 1 | 1467 | 4 | 1.4 | 3 | 0.70 | 0.95 | -0.25 | 0.95 | | | |
| 1 | 1474 | 4 | 0.8 | 3 | 0.63 | 0.95 | -0.32 | 0.95 | | | |
| 1 | 1478 | 2 | 0.3 | 1 | 0.21 | 0.24 | -0.03 | 0.24 | | | |
| 1 | 1483 | 2 | 0.3 | 1 | 0.21 | 0.24 | -0.03 | 0.24 | | | |
| 1 | 1491 | 2 | 0.0 | 1 | 0.20 | 0.21 | -0.02 | 0.21 | Gamma1= | | 1.7 |
| 1 | 1493 | 2 | 0.0 | 1 | 0.20 | 0.21 | -0.02 | 0.21 | Accel score = | | 63 |
| 1 | 1497 | 2 | 0.0 | 1 | 0.20 | 0.21 | -0.02 | 0.21 | Accel score used = | | 63 |
| 1 | 1500 | 5 | 0.8 | 4 | 0.76 | 1.47 | -0.70 | 1.47 | Energy Actual | Ideal | |
| 1 | 1505 | 2 | 0.0 | 1 | 0.20 | 0.21 | -0.02 | 0.21 | 120.0 | 94.1 | |
| 2 | 4 | 8 | 32.8 | 6.9 | 2.45 | 1.94 | 0.51 | 2.45 | | | |
| 2 | 27 | 3 | 19.1 | 2.0 | 1.59 | 0.71 | 0.87 | 1.59 | **Scene 2: Cruising** | | |
| 2 | 51 | 149 | 3189.4 | 147.9 | 204.94 | 116.30 | 88.64 | 204.94 | | | |
| 2 | 221 | 279 | 6889.3 | 278.2 | 345.15 | 288.12 | 57.03 | 345.15 | Gamma2= | | 1.7 |
| 2 | 526 | 583 | 13242.3 | 582.4 | 675.17 | 505.65 | 169.52 | 675.17 | Cruise score = | | 55 |
| 2 | 1124 | 48 | 536.7 | 46.9 | 29.15 | 18.25 | 10.90 | 29.15 | | | 55 |
| 2 | 1213 | 94 | 2348.1 | 93.0 | 146.13 | 101.10 | 45.03 | 146.13 | Energy Actual | Ideal | |
| 2 | 1341 | 38 | 325.7 | 37.4 | 15.06 | 12.85 | 2.21 | 15.06 | 1419.6 | 1044.9 | |
| 5 | 11 | 7 | 18.6 | 5.6 | 0.92 | 0.92 | 0.00 | 0.92 | | | |
| 5 | 29 | 9 | 57.1 | 9.4 | 1.28 | 0.92 | 0.36 | 1.28 | | | |
| **5** | **199** | **13** | **181.8** | **17.0** | **1.00** | **0.92** | **0.09** | **1.00** * | | | |
| **5** | **499** | **14** | **172.2** | **16.4** | **1.20** | **1.10** | **0.10** | **1.20** * | | | |
| 5 | 1108 | 9 | 70.1 | 10.2 | 2.15 | 0.92 | 1.23 | 2.15 | | | |
| 5 | 1171 | 18 | 150.7 | 16.6 | 0.92 | 0.92 | 0.00 | 0.92 | | | |
| 5 | 1197 | 10 | 47.0 | 9.0 | 0.73 | 0.73 | 0.00 | 0.73 | **Scene 5: Braking** | | |
| **5** | **1306** | **14** | **220.5** | **17.3** | **1.00** | **0.92** | **0.09** | **1.00** * | | | |
| 5 | 1326 | 5 | 31.8 | 5.0 | 1.63 | 0.55 | 1.08 | 1.63 | | | |
| 5 | 1378 | 6 | 15.6 | 4.2 | 0.37 | 0.37 | 0.00 | 0.37 | | | |
| 5 | 1386 | 8 | 19.4 | 6.3 | 0.92 | 0.92 | 0.00 | 0.92 | | | |
| 5 | 1402 | 9 | 16.1 | 6.1 | 0.92 | 0.92 | 0.00 | 0.92 | | | |
| 5 | 1426 | 5 | 8.7 | 4.3 | 0.73 | 0.73 | 0.00 | 0.73 | | | |
| 5 | 1433 | 2 | 0.2 | 1.0 | 0.18 | 0.18 | 0.00 | 0.18 | | | |
| 5 | 1441 | 5 | 5.8 | 3.7 | 0.55 | 0.55 | 0.00 | 0.55 | | | |
| 5 | 1447 | 4 | 1.8 | 2.5 | 0.18 | 0.18 | 0.00 | 0.18 | | | |
| 5 | 1454 | 6 | 6.7 | 4.6 | 0.37 | 0.37 | 0.00 | 0.37 | | | |
| 5 | 1466 | 2 | 0.5 | 1.2 | 0.18 | 0.18 | 0.00 | 0.18 | | | |
| 5 | 1470 | 3 | 1.7 | 2.2 | 0.37 | 0.37 | 0.00 | 0.37 | | | |
| 5 | 1477 | 2 | 0.7 | 1.1 | 0.18 | 0.18 | 0.00 | 0.18 | | | |
| 5 | 1479 | 5 | 1.2 | 2.5 | 0.18 | 0.18 | 0.00 | 0.18 | | | |
| 5 | 1484 | 5 | 1.2 | 2.7 | 0.18 | 0.18 | 0.00 | 0.18 | | | |
| 5 | 1492 | 2 | 0.2 | 1.0 | 0.18 | 0.18 | 0.00 | 0.18 | Gamma3= | | 1.7 |
| 5 | 1494 | 2 | 0.2 | 1.0 | 0.18 | 0.18 | 0.00 | 0.18 | Decel score = | | 71 |
| 5 | 1498 | 2 | 0.2 | 1.0 | 0.18 | 0.18 | 0.00 | 0.18 | Decel score used = | | 71 |
| 5 | 1504 | 2 | 0.2 | 1.0 | 0.18 | 0.18 | 0.00 | 0.18 | Energy Actual | Ideal | |
| 5 | 1506 | 2 | 0.2 | 1.0 | 0.18 | 0.18 | 0.00 | 0.18 | 17.0 | 14.1 | |
| | | | | | | | | | | | |
| | | | | | | | | | Gamma4 = | | 1.7 |
| | | | | | | | | | Overall eco-score = | | 56 |
| | | | | | | | | | | | |
| | | | | | | | | | Energy Actual | Ideal | |
| | | | | | | | | | 1556.7 | 1153.1 | |

**Figure 44: NCL James: Feb 24th 2011 11:06am Sensitivity test**

## 3.8 Summary

The Eco-Driving App was trialled by 8 volunteers over an approximately 6 week period in February – March 2011. The participants were asked to use the App whilst driving, in particular, along their regular commuting route (though they were permitted to use it for all their driving, only their regular commuting routes were examined in the analysis of the GPS and eco-score data). The drivers were instructed to use the App as they would normally use it (i.e. take note of the App scores and make any adjustments they felt necessary to their driving style to achieve better scores). The limitations of the sample size and duration of trial must be recognised, but nevertheless some valid observations can be made.

NCL Lindsey displayed a small improvement in eco-driving score, but this was not maintained over time. NCL Glyn displayed a quite significant improvement in ‘deceleration’ score which was maintained over time. However, because the overall score was dominated by the cruise score (the majority of the driven route), there was little improvement in the overall score. Nevertheless, the statistical analysis highlighted a reduction in speed overall, partially maintained over time, which was not obviously reflected in the reported eco-driving scores from the App. This is an area for possible refinement of the algorithm. NCL James displayed a small improvement in ‘cruise’ eco-driving scores, and a larger improvement in ‘acceleration’ scores, resulting in an overall improvement in mean ‘total’ eco-driving score. The statistical analysis highlighted a reduction in speed which was partially maintained over time. The improvement in ‘acceleration’ eco-driving score appeared to be related more to the relationship between the manufacturers’ ‘ideal’ and observed driving profile than to any overall reduction in acceleration rates. This may be an area where the algorithm could be refined. NCL Bryn achieved and maintained improved eco-driving scores across ‘acceleration’, ‘cruise’, and ‘deceleration’ modes throughout the trial. These results were confirmed by the statistical analysis of the 1Hz speed data. It was difficult to conclude that the App had any influence on the eco-driving scores of TRG Linda, but the nature of the driven route and associated traffic conditions may have a significant bearing in such circumstances. Further research is required to gain a better understanding of such factors on eco-driving performance. Both TRG Laura and TRG Nick drove predominantly on the interurban motorway network. Eco-driving scores generated on this road type were observed to be higher than on other road types, generally because the total score is dominated by the cruise mode, and the current version of the App appeared in some circumstances to be less sensitive to changes in the absolute level of speed than to variability in speed. This is a possible area for refinement of the energy calculation.

It was notable that zero and very low deceleration scores could be generated in the data, and that these deceleration 'events', when they occur, tend to dominate the overall deceleration score. In some circumstances one or two brief deceleration events can result in a deceleration score of 70 reducing to below zero. This may be an aspect of the eco-driving algorithm that would benefit from further refinement.

The objectives of the App evaluation in this context were as follows:

a) Determine whether users can 'improve' their driving manner during use of the App.
b) Assess the extent to which users maintain their motivation for eco-driving over the course of the study.

It was observed in the sample of trial participants that the users of the App could improve their driving manner. The extent to which this is possible depends to some extent on the 'normal' driving behaviour of the individual, but NCL Bryn was an example where very significant improvements in eco-driving were possible and achievable within a very short period of time, utilising feedback from the App. The extent to which other drivers were able to improve depended to some extent on the road type and prevailing traffic conditions. Further refinement of the App would be required to internalise some of these factors.

The duration of the trial was a limitation in assessing reliably the degree to which users maintained their motivation. The results were mixed, with some drivers maintaining some aspects of eco-driving techniques, whilst other drivers indicated a tendency to revert to previous behaviour over time. A longer term trial, perhaps with a larger sample of participants, would be required to provide a more definitive conclusion. The eco-scoring algorithm, as currently specified, tended to be dominated by certain aspects of driving behaviour such as deceleration events. This can serve to undermine confidence in the system by trial participants. Future developments of the system could be refined by tailoring the eco-scoring algorithm to the make and model of car being driven. This would be relatively straightforward to achieve by creating an online database of vehicles, perhaps based on existing VCA and / or SMMT databases, extracting relevant information to refine the eco-scoring algorithm (such as fuel type, transmission type, number of gears, power output, and maximum speed). The user would select their make and model of vehicle, and obtain tailored results (and eco-driving guidance). This would provide a scoring system which was bespoke. Using this information, the system developers could also estimate what level of eco-driving performance was achievable in theory, and compare this with observed reported outcomes.

Chapter 4 moves on from variability in driver behaviour per se to address the issue of characterising the exhaust emissions from the wider UK road vehicle fleet. A remote sensing technique was adopted which measures the ‘in-use’ exhaust emission rates from road vehicles. Such remote sensing measurements encompass all of the factors influencing exhaust emissions, including variability in driver behaviour across the observed population (both in terms of the primary vehicle controls, and secondary systems such as air conditioning), vehicle types, vehicle ages, emission control technology, and fuel technologies. The measurement technique therefore captures the full range of factors which influence exhaust emissions from road vehicles.

# Chapter 4. Remote Sensing Data Collection and Fleet Characterisation

## 4.1 Introduction

Atmospheric pollutants have been the subject of regulation through national and international legislation for a number of years. The European Union has recently adopted Directive 2008/50/EC on ambient air quality and cleaner air for Europe, consolidating previous legislation, which sets out limit values for a range of pollutants considered harmful to human health. These include limit values for nitrogen dioxide ($NO_2$) and particulates ($PM_{10}$). In urban environments, $NO_2$ and particulates are the two main air pollutants of concern. Most particulate emissions come from road transport (engine emissions, and tyre and brake wear). Road transport and heating systems are the main sources of $NO_2$. In London, United Kingdom, these two pollutants are the main focus of attention within the Mayor’s Air Quality Strategy (Greater London Authority, 2010). The Mayor’s Air Quality Strategy notes that whilst $NO_2$ is of most concern due to its impact on health, the control of total $NO_x$ ($NO_2$ + NO) is essential because of the ease with which nitric oxide (NO) converts to $NO_2$ in the atmosphere.

The European Union has adopted increasingly stringent regulations to control the composition of exhaust emissions within the vehicle type approval process, because of the significance of road transport as a source of air pollution. Current European vehicle type approval legislation regulates levels of $NO_x$ (oxides of nitrogen) in exhaust emissions, but not specifically $NO_2$, an apparent discontinuity in European regulatory policy highlighted by Carslaw and Beevers (2004). This issue has become more significant in the UK in recent years because of the increasing proportion of diesel fuelled passenger cars in the UK fleet. In the UK, 33% of new passenger cars registered in 2004 were diesel; in 2009, this percentage increased to 41% (DoT, 2010). Diesel (compression ignition) engines tend to produce higher levels of $NO_x$ and particulates compared to petrol (spark ignition) engines. Diesel engines also emit a higher proportion of their $NO_x$ as $NO_2$ compared with petrol engines (Alvarez et al., 2008). Vehicle manufacturers have utilised a range of exhaust treatment technologies to achieve compliance with the increasingly stringent type approval limits. However, researchers such as Carslaw (2005) and Grice et al. (2009) have highlighted the significance of diesel particulate filters, and other exhaust after treatment systems for diesel engine vehicles, in the increasing formation of primary $NO_2$, and a subsequent increase in the local $NO_2/NO_x$ ratio due to road traffic.

Given the dynamic nature of the UK vehicle fleet, and the significance of the environmental challenges facing policy makers, there is relatively little detailed current information available in the literature about the ‘in-use’ environmental characteristics of road vehicles in the UK. Some studies were carried out in London in the 1990’s measuring carbon monoxide (CO) and hydrocarbons (HC) (Sadler et al., 1996; Muncaster et al., 1996; Revitt et al., 1999), using roadside remote sensing, but both instrumentation and fleet characteristics have evolved over the intervening period. A European Joint Commission Services Study into ‘In-use vehicle emission controls’, carried out in 1994-1998, included roadside remote sensing measurements at a number of locations, including two locations in the UK. The study assessed the effectiveness of remote sensing as a method of screening the vehicle fleet for high emitters (Barlow, 1998). The EU FP5 REVEAL project developed a low cost roadside remote sensing device (RSD) to collect data on overall car fleet emissions characteristics and gross emitters, which included a field trial in London in 2003 (REVEAL, 2004). The REVEAL RSD was later used in Winchester, UK in 2006 to research driver motivation for voluntary vehicle emissions related maintenance (Felstead, 2007).

Ropkins et al. (2009) provide a comprehensive critical review of the techniques utilised to monitor real-world vehicle exhaust emissions. Real-world measurements (measurements of exhaust emissions from vehicles in operation on the highway network) differ from laboratory based measurements (typically using test cycles) because they have a more realistic potential to capture the range of variability typically encountered in real-world driving, including variability in driver behaviour, interactions with other road users, and interactions with highway infrastructure, all of which have the potential to influence exhaust emissions. Real-world measurements using techniques such as remote sensing also have the potential to monitor a representative cross section of vehicle ages and levels of maintenance (including faulty vehicles), sampling many thousands of vehicles, which would not be practical or cost effective to attempt in laboratory conditions. The disadvantages of remote sensing in this context relate to the variability in ambient atmospheric conditions, variation in size and location of exhaust plume, and limitations on the levels of absolute accuracy achievable in practice using such methods. Remote sensing can be seen as a useful complement to more detailed measurements using laboratory based chassis dynamometers or engine test beds, or on-road instrumented vehicles. Other researchers have identified its potential to provide statistically robust fleet emission characteristics through repeat measurements over a sustained period of time (McCrae et al., 2005).

This chapter explores the exhaust emissions characteristics of a large sample of vehicles operating in London, UK in 2008, based on data collected using roadside remote sensing absorption spectroscopy techniques (infrared and ultraviolet), combined with Automatic Number Plate Recognition (ANPR) for vehicle identification, and vehicle speed/acceleration measurement. Using this information, the ‘in-use’ emissions characteristics of the observed vehicles can be determined, by vehicle class, fuel type, vehicle age, and other parameters. Vehicle age is used as a proxy to classify the observed vehicles by Euro emissions standard. This information facilitates the estimation of the relative environmental impact of each vehicle category by Euro emissions standard for each atmospheric pollutant, allowing policy makers to evaluate the real-world effectiveness of increasingly stringent vehicle exhaust emissions standards. The research has the potential to inform the development of air quality improvement strategies, including possible interventions such as vehicle scrappage incentive schemes, and access restrictions to localities with air quality problems for certain categories of high polluting vehicles.

This is the first time that such a comprehensive analysis has been carried out and reported in a UK context, determining the 'real-world' exhaust emission characteristics of a significant sample within the UK vehicle fleet operating in urban traffic conditions at a point in time. A section of this work relating specifically to light vehicles has been published in Rhys-Tyler et al. (2011).

## 4.2 Remote Sensing Surveys

The study utilises a pre-existing dataset supplied by colleagues at the London Borough of Southwark. The data were collected in 2008 using an RSD (Remote Sensing Device) 4600 on-road vehicle emissions testing device manufactured by Environmental Systems Products (www.esp-global.com). The equipment was owned and operated by Enviro Technology (www.et.co.uk) under contract (Merelles, 2008). The development and application of this equipment and measurement technique is described extensively in the literature (Bishop et al, 1989; Guenther et al, 1995; Burgard et al, 2006; Bishop and Stedman 2008), so only a brief overview is presented here.

The RSD 4600 comprises three main functional components:

- An infrared (for CO, $CO_2$, and HC) and ultraviolet (for NO) source/detector module and mirror for measuring absorption in the beam path across the road, through the ambient air in front of the passing vehicle, and through the exhaust plume at the rear of the vehicle;
- A speed/acceleration module, triggered when the passing vehicle interrupts a laser beam;
- A camera which captures a digital image of the rear of the vehicle, which is then used to acquire the vehicle licence plate / registration number.

When a vehicle passes the survey site, the equipment takes approximately 48 absorption measurements within 0.5 seconds, at a frequency of around 100Hz. Simultaneously, a digital image is captured of the rear of the vehicle, and an ANPR algorithm interprets the licence plate. Vehicle speed and acceleration are measured. All of these data items are stored electronically in a database for subsequent analysis. The system software includes data validity checks which accept or reject measurements according to predefined criteria (Burgard et al, 2003). Figure 45 provides an illustration of the equipment deployment for a typical survey site. Figure 46 provides an example of the digital image taken of the rear of the passing vehicle, whilst Figure 47 illustrates the associated image used for processing by the ANPR algorithm.

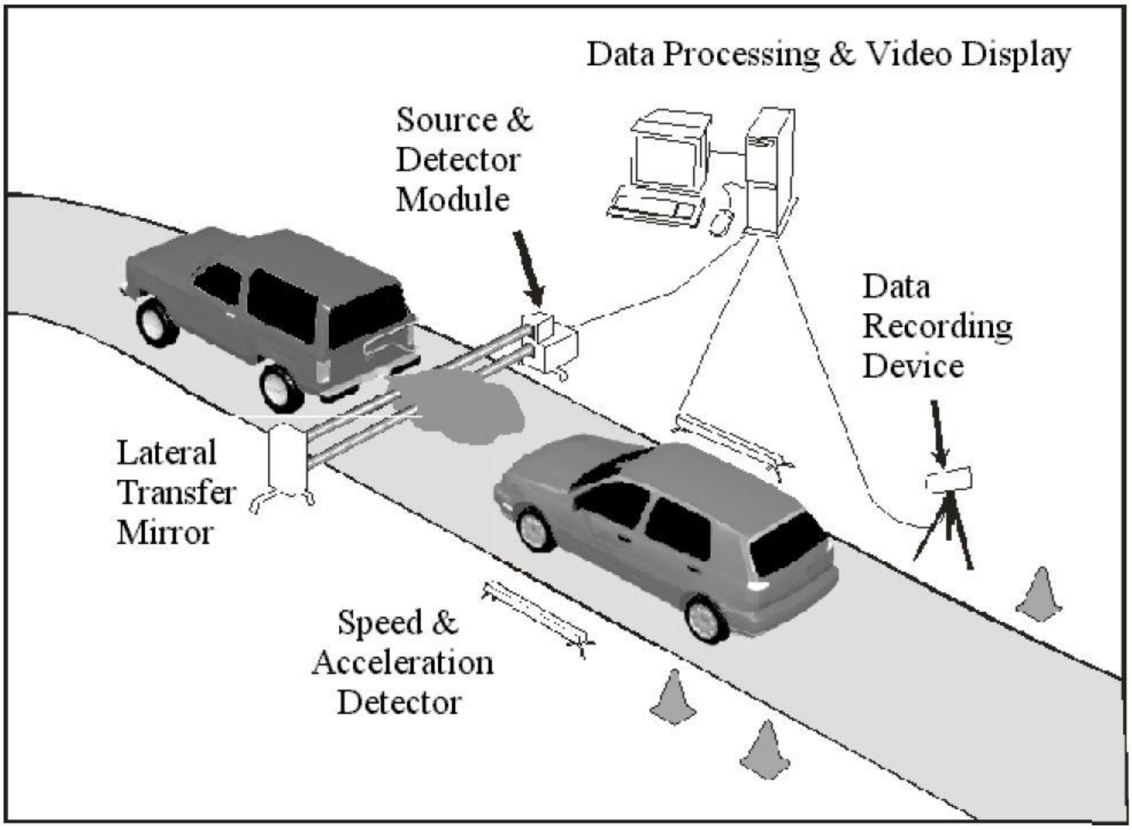



**Figure 45: Schematic of RSD deployment (Source: ESP 2007)**

It can be seen that the digital image presented in Figure 46 includes the following parameters from the measurement instrumentation superimposed along the bottom of the photograph, from left to right:

- Vehicle speed (mph)
- Vehicle acceleration (mph/sec)
- Speed / acceleration flag (V=Valid, X=Invalid)
- CO concentration (%) per combustion equation

- $CO_2$ concentration (%) per combustion equation
- HC (propane) concentration (ppm) per combustion equation
- NO concentration (ppm) per combustion equation
- Smoke factor (grams of smoke / 100grams of fuel)
- Maximum plume size (%cm $CO_2$)
- Number of exhaust plume samples (maximum of 48 at 100Hz)
- Gas measurement flag (V=Valid, X=Invalid)


**Figure 46: Example digital image captured by RSD 4600**


**Figure 47: Example image used for ANPR processing**

The instrumentation can be set up by the operator to collect speed and acceleration data either in imperial (US) units, or in metric (SI) units, so care must be taken to determine this issue prior to performing any data analysis. A flag in the data file (‘samflag’) is set to either ‘E’ for English (mph and mph/s) or ‘M’ for Metric (kph and kph/s). In the case of this analysis, the ‘samflag’ was set to ‘E’ for all data files, so appropriate factors were applied to convert from mph to m/s, and from mph/s to m/s$^2$.

The RSD 4600 measures three gas ratios; $CO/CO_2$, $HC/CO_2$, and $NO/CO_2$. These ratios are used in a combustion equation in real time (making reasonable assumptions about fuel composition, and air/fuel ratio for stoichiometric combustion) to produce estimates of the values of CO%(vol), $CO_2$%(vol), HCppm, and NOppm. $NO_2$ is not measured directly. The instrument also measures smoke, reported in units of grams of diesel particulate per 100 grams fuel, based on opacity measurements made at ultraviolet wavelengths in the 230 nm UV spectral range (Stedman and ESP, 2004; ESP, 2005). The accuracy specifications published by the manufacturer for the instrumentation are; CO% (±0.1 or ±10%, whichever is greater); HCppm (±100 or ±10%, whichever is greater); NOppm (±150 or ±10%, whichever is greater); and, smoke number (±0.05 or ±10%, whichever is greater) (ESP, 2005). Instrument calibration was carried out in accordance with manufacturers’ instructions.

The surveys were carried out at 8 sites in Ealing in March/April 2008, and 5 sites in Southwark in June/July/August 2008, over a total of 29 survey days, resulting in over 119 000 observations. The survey locations are illustrated in Figure 48 and Figure 49. The survey sites within these local authority areas were chosen to be reasonably representative of the range of urban road conditions, constrained by the practicality of finding survey locations with sufficient space for instrumentation to be deployed safely. Surveys were limited to daylight hours, typically 8.30am to 6.30pm, thus capturing morning and evening peak flow conditions, in addition to off-peak daytime flow conditions. Instrumentation was set up to intercept primarily light vehicle exhaust plumes (in terms of the height of the UV/IR beam, 250-300mm from the road surface), although data was also collected successfully from a significant number of larger vehicles (but these would generally be under-represented in the final data set). Vehicles with vertical or side facing exhaust pipes would not be represented in the final data set. The instrumentation as deployed was not very successful in measuring exhaust emissions from motorcycles due to their variability in position on the road, and poor ANPR success rate.

The mean vehicle speed through the survey sites was 32.4 kph (std. deviation 9.1kph, std. error of mean 0.04), and the mean vehicle acceleration was +0.2 $m/s^2$ (std. deviation $0.6m/s^2$, std. error of mean 0.003). The road network in question was subject to a 30mph (48kph) legal speed limit for all survey sites, but speeds through the survey sites would be influenced by local context and traffic management measures used for the surveys (e.g. signing, traffic cones etc.). The majority of survey sites had moderately positive (uphill) gradients where the engine of the vehicle would be under moderate load.

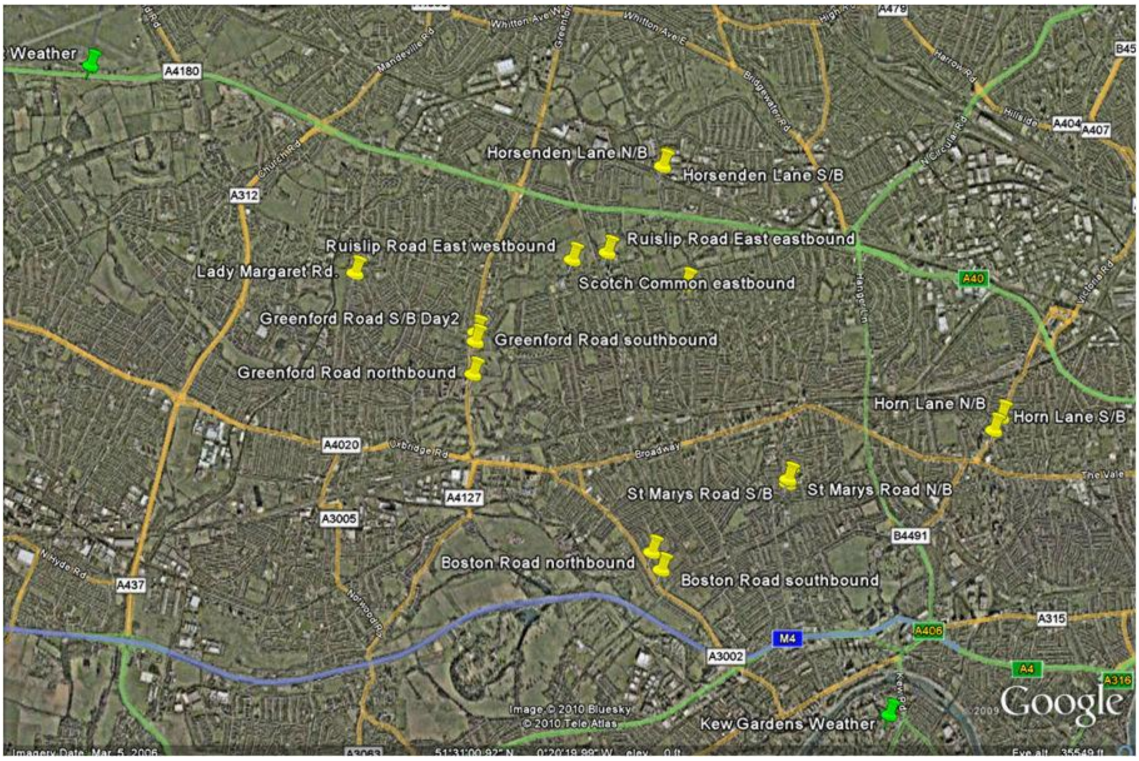



**Figure 48: Ealing remote sensing survey locations**

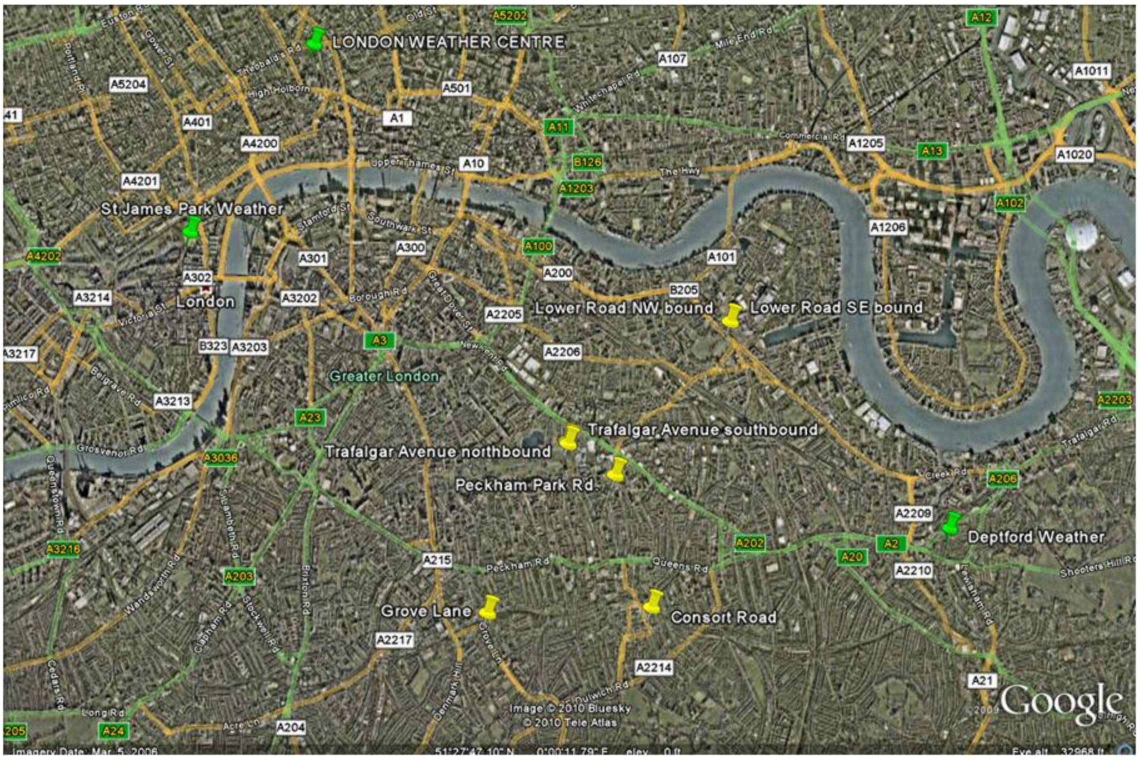



**Figure 49: Southwark remote sensing survey locations**

The different survey seasons resulted in a range of mean ambient temperature, from 5.8°C to 27.0°C, and a range of relative humidity, from 39% to 86%, which has potential implications for use of vehicle ancillaries such as air conditioning, and for duration of cold start operating conditions. Other studies in the literature which were carried out specifically to monitor 'hot' vehicle emissions (e.g. Sjodin and Andreasson, 2000; Ekstrom et al., 2004), selected survey sites where vehicles were generally warmed-up (i.e. with the catalytic converter operating at optimum temperature). Given that this analysis utilises a pre-existing dataset, it was not possible to control the survey design, and it is considered likely that the data contains a proportion of vehicles operating in cold-start mode. It can be considered that the surveys were therefore measuring the exhaust emissions from road vehicles on the urban road network in London operating across the range of operating modes, including cold starts, and their consequent overall contribution to local air quality in London.

Table 17 summarises the 2008 survey sites, timings, and relevant parameters. References E1-E15 and S1-S14 have been utilised to conveniently label the survey locations and dates for the London Borough of Ealing (E) and the London Borough of Southwark (S) respectively.

| Ref | Location | Direction | Latitude | Longitude | Date | Time | Road gradient (degrees)[1] | Mean Temperature (°C)[2] | Mean relative humidity (%)[2] | Mean speed (m/s) | Mean acceleration ($m/s^2$) | Total Observations |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| E1 | Lady Margaret Road | N/B | 51d 31m 36.20s N | 0d 22m 25.10s W | 03/03/2008 | 07:34 - 18:43 | 0.4 | 6.7 | 57 | 9.2 | 0.3 | 5986 |
| E2 | Ruislip Road | W/B | 51d 31m 39.43s N | 0d 20m 20.13s W | 17/03/2008 | 07:57 - 18:50 | -0.6 | 6.7 | 57 | 10.3 | 0.4 | 4737 |
| E3 | Ruislip Road | E/B | 51d 31m 41.70s N | 0d 19m 59.98s W | 18/03/2008 | 07:19 - 18:47 | -0.4 | 5.8 | 62 | 9.9 | 0.3 | 6935 |
| E4 | Greenford Road | N/B | 51d 30m 59.37s N | 0d 21m 18.52s W | 19/03/2008 | 07:28 - 18:44 | 0.7 | 6.6 | 60 | 10.3 | 0.2 | 6298 |
| E5 | Greenford Road | S/B | 51d 31m 11.02s N | 0d 21m 16.77s W | 20/03/2008 | 07:31 - 14:13 | 1.2 | 7.2 | 75 | 9.2 | 0.2 | 3335 |
| E6 | Boston Road | N/B | 51d 29m 54.54s N | 0d 19m 38.20s W | 25/03/2008 | 07:58 - 18:42 | 0 | 6.0 | 56 | - | - | 5624 |
| E7 | Boston Road | S/B | 51d 29m 48.22s N | 0d 19m 33.06s W | 26/03/2008 | 08:19 - 15:03 | 0 | 9.2 | 76 | 10.1 | 0.2 | 3071 |
| E8 | Scotch Common | E/B | 51d 31m 29.56s N | 0d 19m 15.51s W | 28/03/2008 | 07:12 - 17:43 | 0.5 | 9.4 | 79 | 9.6 | 0.4 | 3514 |
| E9 | Horsenden Lane | N/B | 51d 32m 11.96s N | 0d 19m 27.19s W | 31/03/2008 | 07:16 - 18:46 | 0.5 | 11.1 | 68 | 7.9 | 0.5 | 2958 |
| E10 | Horsenden Lane | S/B | 51d 32m 13.20s N | 0d 19m 25.50s W | 01/04/2008 | 09:46 - 11:32 | -0.5 | 13.6 | 57 | 8.2 | 0.4 | 461 |
| E11 | Greenford Road | S/B | 51d 31m 14.30s N | 0d 21m 16.00s W | 01/04/2008 | 13:38 - 18:04 | 1.3 | 14.5 | 48 | 9.3 | 0.3 | 2462 |
| E12 | St. Mary`s Road | N/B | 51d 30m 19.50s N | 0d 18m 19.50s W | 02/04/2008 | 07:09 - 18:42 | 0.2 | 12.0 | 77 | 10.1 | 0.2 | 4792 |
| E13 | St. Mary`s Road | S/B | 51d 30m 18.00s N | 0d 18m 19.20s W | 03/04/2008 | 07:28 - 18:43 | -0.2 | 13.6 | 71 | 9.3 | 0.0 | 4526 |
| E14 | Horn Lane | N/B | 51d 30m 39.90s N | 0d 16m 16.60s W | 04/04/2008 | 07:17 - 17:42 | 0 | 14.9 | 67 | 6.7 | 0.3 | 4431 |
| E15 | Horn Lane | S/B | 51d 30m 35.30s N | 0d 16m 20.60s W | 08/04/2008 | 07:27 - 18:28 | -0.7 | 8.2 | 54 | 5.9 | 0.1 | 4966 |
| S1 | Grove Lane | S/B | 51d 28m 5.46s N | 0d 5m 11.72s W | 23/06/2008 | 08:59 - 18:26 | 2.6 | 20.1 | 39 | 8.3 | 0.0 | 3571 |
| S2 | Trafalgar Avenue | N/B | 51d 29m 1.52s N | 0d 4m 26.84s W | 24/06/2008 | 08:33 - 18:30 | 0 | 20.9 | 42 | 10.1 | 0.4 | 2196 |
| S3 | Peckham Park Road | N/B | 51d 28m 50.05s N | 0d 4m 1.92s W | 25/06/2008 | 09:05 - 18:28 | 0.3 | 20.9 | 45 | 7.3 | 0.1 | 2651 |
| S4 | Lower Road | SE/B | 51d 29m 39.88s N | 0d 2m 58.76s W | 26/06/2008 | 08:42 - 18:19 | 0.6 | 19.9 | 48 | 9.4 | 0.3 | 4101 |
| S5 | Lower Road | NW/B | 51d 29m 39.74s N | 0d 2m 58.95s W | 27/06/2008 | 08:55 - 12:31 | -0.6 | 18.2 | 72 | 9.7 | 0.1 | 1821 |
| S6 | Lower Road | SE/B | 51d 29m 39.88s N | 0d 2m 58.76s W | 28/07/2008 | 08:41 - 18:31 | 0.6 | 27.0 | 53 | 8.9 | 0.3 | 4602 |
| S7 | Lower Road | NW/B | 51d 29m 39.74s N | 0d 2m 58.95s W | 29/07/2008 | 08:40 - 18:30 | -0.6 | 21.2 | 60 | 10.4 | 0.1 | 5169 |
| S8 | Lower Road | SE/B | 51d 29m 39.88s N | 0d 2m 58.76s W | 30/07/2008 | 08:25 - 18:27 | 0.6 | 25.4 | 42 | 8.6 | 0.2 | 5000 |
| S9 | Trafalgar Avenue | S/B | 51d 29m 0.92s N | 0d 4m 26.58s W | 31/07/2008 | 08:45 - 18:20 | 0 | 25.3 | 60 | 9.6 | 0.2 | 2777 |
| S10 | Trafalgar Avenue | N/B | 51d 29m 1.52s N | 0d 4m 26.84s W | 01/08/2008 | 08:20 - 11:20 | 0 | 20.2 | 61 | 10.1 | 0.2 | 800 |
| S11 | Consort Road | S/B | 51d 28m 5.97s N | 0d 3m 44.48s W | 04/08/2008 | 08:45 - 18:29 | 0.2 | 19.8 | 63 | 8.7 | 0.2 | 6500 |
| S12 | Consort Road | S/B | 51d 28m 5.97s N | 0d 3m 44.48s W | 05/08/2008 | 08:09 - 17:14 | 0.2 | 18.2 | 86 | 8.7 | 0.1 | 4335 |
| S13 | Consort Road | S/B | 51d 28m 5.97s N | 0d 3m 44.48s W | 06/08/2008 | 08:17 - 18:09 | 0.2 | 24.2 | 61 | 8.8 | 0.1 | 6500 |
| S14 | Consort Road | S/B | 51d 28m 5.97s N | 0d 3m 44.48s W | 07/08/2008 | 08:28 - 18:24 | 0.2 | 21.7 | 65 | 8.7 | 0.1 | 5200 |
| **Total** | | | | | | | | | | | | **119319** |

**Table 17: Summary of roadside remote sensing surveys of vehicle exhaust emissions**

1. EDINA Digimap Collections (UK Ordnance Survey). http://edina.ac.uk/digimap/ accessed May 29th 2010.
2. UK Meteorological Office. MIDAS Land Surface Stations data, British Atmospheric Data Centre. http://badc.nerc.ac.uk accessed May 29th 2010.

## 4.3 Data Processing

### *4.3.1 ANPR data cleaning and matching*

Vehicles are uniquely identified using the vehicle registration plate (or licence plate) number. Identification of vehicle registration plates using automatic number plate recognition (ANPR) is subject to error, dependent on factors such as instrumentation setup, local site conditions, and the physical attributes of the plate itself. The ANPR system can either fail to recognise and read the registration plate completely, or it can misinterpret alpha-numeric characters, leading to a failure to identify the vehicle correctly. Typical misinterpretation, for example, includes interchanging alpha and numeric characters 'S' and '5', 'O' and '0', 'G' and '6', 'D' and 'O'. Such errors have the potential to introduce systematic geo-spatial bias in the data in a UK context because the first two letters of the registration in the current UK system define the local geographic registration office.

The survey dataset included a digital photograph of the rear of the vehicle, as illustrated in Figure 46. Using these images, it was possible to carry out visual data cleaning and validation of the ANPR process. The ANPR data had apparently been subject to some cleaning and correction prior to supply (although no supporting documentation was available), but extensive additional visual comparison of the photographs with the ANPR data was carried out as part of this work (constrained by available resources) to increase (if not maximise) the validity and size of the sample. The cleaning and validation process corrected many errors due to ANPR misinterpretation, in addition to more fundamental errors such as reading non-licence plate text on vehicles, as illustrated in Figure 50. This manual checking process added or corrected around 11,500 vehicle registration plates to the dataset.

The sample size for large buses was augmented by utilising the vehicle fleet number for vehicle identification where visible, when the vehicle licence plate was not visible. This often occurs when vehicle licence plates are mounted in the upper corner of the vehicle, where the ANPR system often fails. Correspondence between fleet numbers and licence plate numbers was obtained from a number of internet sources. An example is presented in Figure 51 (Fleet number 9005 is vehicle licence plate BX54DHN, a Volvo B7TL with a Wright 'Eclipse' body). The use of bus vehicle fleet numbers in addition to visible licence plates served to increase the identified bus sample by around 14%. Foreign registered vehicles were excluded from the process, since it would not be feasible to access registration details outside the UK.


**Figure 50: Example ANPR error reading 'Keep Clear' sign**

A total of 99,847 vehicle registration licence plate numbers were generated from this process. These ‘cleaned’ licence plate numbers were then matched against the central UK vehicle registration database maintained by the Driver and Vehicle Licensing Agency (DVLA), an executive agency of the Department for Transport. For logistical reasons, the matching was carried out by CDL Vehicle Information Services Ltd in February 2010, under a commercial contract. 94,328 matches (identified vehicles) were obtained from this process, a match rate of over 94%. This included some limited multiple observations of the same vehicles, either within sites or across sites.


**Figure 51: Bus licence plate not visible, but fleet number visible top right**

Not all survey observations were necessarily valid gas measurements or validated ANPR observations. Table 18 summarises both the valid gas (emissions) measurements, and the validated vehicles identified from the ‘cleaned’ ANPR data through the DVLA data matching process. It can be seen that 56% of the total observations had valid emissions measurements, as determined by the instrumentation acceptance criteria (Stedman and Bishop, 2003). In contrast, 79% of observations were matched successfully to the DVLA database. Overall, 46% of observations had both valid emissions measurements and vehicle identification.

| Ref | Total Observations | Total Valid Emissions Measurements | | Total Valid Vehicles Identified | | Total Valid Emissions Measurements & Vehicles Identified | |
|---|---|---|---|---|---|---|---|
| | | Count | % | Count | % | Count | % |
| E1 | 5986 | 2994 | 50 | 2118 | 35 | 1110 | 19 |
| E2 | 4737 | 2433 | 51 | 4347 | 92 | 2197 | 46 |
| E3 | 6935 | 3898 | 56 | 5684 | 82 | 3547 | 51 |
| E4 | 6298 | 3288 | 52 | 4536 | 72 | 2848 | 45 |
| E5 | 3335 | 1742 | 52 | 2314 | 69 | 1455 | 44 |
| E6 | 5624 | 3606 | 64 | 4516 | 80 | 3096 | 55 |
| E7 | 3071 | 1370 | 45 | 1522 | 50 | 736 | 24 |
| E8 | 3514 | 1843 | 52 | 2698 | 77 | 1641 | 47 |
| E9 | 2958 | 2054 | 69 | 1463 | 49 | 987 | 33 |
| E10 | 461 | 192 | 42 | 245 | 53 | 94 | 20 |
| E11 | 2462 | 898 | 36 | 2243 | 91 | 791 | 32 |
| E12 | 4792 | 2536 | 53 | 3661 | 76 | 2256 | 47 |
| E13 | 4526 | 1823 | 40 | 2661 | 59 | 1099 | 24 |
| E14 | 4431 | 2998 | 68 | 1856 | 42 | 1217 | 27 |
| E15 | 4966 | 2900 | 58 | 3809 | 77 | 2548 | 51 |
| S1 | 3571 | 3157 | 88 | 3321 | 93 | 2948 | 83 |
| S2 | 2196 | 1124 | 51 | 2050 | 93 | 1055 | 48 |
| S3 | 2651 | 1674 | 63 | 2488 | 94 | 1559 | 59 |
| S4 | 4101 | 1737 | 42 | 3527 | 86 | 1437 | 35 |
| S5 | 1821 | 656 | 36 | 1647 | 90 | 580 | 32 |
| S6 | 4602 | 2071 | 45 | 4053 | 88 | 1730 | 38 |
| S7 | 5169 | 1985 | 38 | 4641 | 90 | 1728 | 33 |
| S8 | 5000 | 2144 | 43 | 4404 | 88 | 1806 | 36 |
| S9 | 2777 | 1275 | 46 | 2574 | 93 | 1193 | 43 |
| S10 | 800 | 333 | 42 | 744 | 93 | 311 | 39 |
| S11 | 6500 | 4458 | 69 | 6139 | 94 | 4209 | 65 |
| S12 | 4335 | 2996 | 69 | 4066 | 94 | 2806 | 65 |
| S13 | 6500 | 4466 | 69 | 6076 | 93 | 4169 | 64 |
| S14 | 5200 | 3653 | 70 | 4925 | 95 | 3446 | 66 |
| **Total** | **119319** | **66304** | **56** | **94328** | **79** | **54599** | **46** |

**Table 18: Summary of valid emissions measurements and vehicles identified**

A number of checks were carried out to ensure that the matching of registration licence plates to vehicles was implemented correctly. This included adding a small number of ‘known’ vehicles to the dataset submitted to CDL for processing. All ‘known’ vehicles were correctly identified by the process.

A very small number of licence plates (<10) in the dataset were identified as being associated with more than one vehicle. On investigation, it was found that this tended to occur with ‘cherished’ licence plates which had been transferred from one vehicle to another in the period between implementation of the surveys and processing of the data. Use of the digital images collected during the surveys allowed the correct vehicle to be linked with the licence plate (and with the associated emissions measurement).

A small number of DVLA database errors were discovered, utilising appropriate logic checks, which included:

- Vehicle manufacture dates recorded as being in the future (in one case year 3002);
- Vehicles with obviously incorrect year of manufacture (e.g. Triumph Heralds and Morris Minors with recorded year of manufacture after year 2000, possibly a consequence of the SORN process;
- Vehicles with obviously incorrect engine capacities recorded.

Where possible, such errors were corrected. Where correction was not possible with any level of confidence, the data record was discarded.

### *4.3.2 Vehicle classification*

Commission Directive 2001/116/EC (European Parliament, 2001) set out classifications for the purpose of vehicle type approval (Table 19). These classifications are used, in particular in this context, for the application of emissions standards. The data were classified using these categories. In addition, category M1 was further subdivided to allow separate analysis of the emissions characteristics of London taxis (black cabs). Mopeds, motorcycles and quadricycles (categories L1, L3, and L7 respectively) were also classified, although numbers tended to be too small for meaningful statistical analysis.

| Category | Description |
|---|---|
| M1 | Vehicles designed and constructed for the carriage of passengers and comprising no more than eight seats in addition to the driver's seat. |
| M2 | Vehicles designed and constructed for the carriage of passengers, comprising more than eight seats in addition to the driver's seat, and having a maximum mass not exceeding 5 tonnes. |
| M3 | Vehicles designed and constructed for the carriage of passengers, comprising more than eight seats in addition to the driver's seat, and having a maximum mass exceeding 5 tonnes. |
| N1 | Vehicles designed and constructed for the carriage of goods and having a maximum mass not exceeding 3.5 tonnes. |
| N2 | Vehicles designed and constructed for the carriage of goods and having a maximum mass exceeding 3.5 tonnes but not exceeding 12 tonnes. |
| N3 | Vehicles designed and constructed for the carriage of goods and having a maximum mass exceeding 12 tonnes. |

**Table 19: European classifications for vehicle type approval**

The DVLA data included date of manufacture for the matched vehicles. This was used to estimate applicable European emission standards as set out in Table 20[2].

| Vehicle Category | Pre-Euro | Euro 1 | Euro 2 | Euro 3 | Euro 4 |
|---|---|---|---|---|---|
| M1 | Pre 1993 | 1993-1996 | 1997-2000 | 2001-2005 | 2006-2008 |
| M2 | Pre 1993 | 1993-1995 | 1996-2000 | 2001-2005 | 2006-2008 |
| M3 | Pre 1993 | 1993-1995 | 1996-2000 | 2001-2005 | 2006-2008 |
| | **Pre-Euro** | **Euro I** | **Euro II** | **Euro III** | **Euro IV** |
| N1 | Pre 1994 | 1994-1998 | 1999-2000 | 2001-2005 | 2006-2008 |
| N2 | Pre 1993 | 1993-1995 | 1996-2000 | 2001-2005 | 2006-2008 |
| N3 | Pre 1993 | 1993-1995 | 1996-2000 | 2001-2005 | 2006-2008 |

**Table 20: European emissions standards by vehicle category (year of manufacture)**

Table 21 presents the number of observations which were successfully identified through matching of ANPR data with the DVLA database, and which had valid emissions measurements, allocated to Euro emissions standard. Vehicles are allocated to Euro emissions standards based on the date of manufacture of the vehicle (Table 20), an approximation in the absence of more reliable data. These sample sizes will inform the analysis of the emissions data.

[2] Based on Boulter et al (2009) and DoT (2007), utilising 'in-use' dates.

Generally, sample bins with less than 100 vehicles are discarded, consistent with practise in similar studies.

| Vehicle type | Fuel type | Vehicle category | Emissions standard (allocated by vehicle date of manufacture, Table 20) | | | | |
|---|---|---|---|---|---|---|---|
| | | | **Pre Euro** | **Euro 1** | **Euro 2** | **Euro 3** | **Euro 4** |
| Car | Petrol | M1 | 1306 | 4271 | 10811 | 13312 | 4647 |
| Car | Diesel | M1 | 88 | 499 | 1012 | 3537 | 2861 |
| Car | Hybrid electric | M1 | 0 | 0 | 1 | 26 | 120 |
| London taxi | Diesel | M1 | 22 | 121 | 213 | 209 | 121 |
| Minibus | Petrol | M2 | 2 | 0 | 0 | 0 | 0 |
| Minibus | Diesel | M2 | 1 | 0 | 0 | 0 | 63 |
| Bus | Diesel | M3 | 9 | 2 | 901 | 850 | 62 |
| | | | **Pre Stage** | **Stage I** | **Stage II** | **Stage III** | |
| Motorcycle | Petrol | L1 + L3 | 18 | 24 | 16 | 11 | |
| | | | **Pre Euro** | **Euro I** | **Euro II** | **Euro III** | **Euro IV** |
| Light commercial | Petrol | N1 | 63 | 57 | 47 | 145 | 116 |
| Light commercial | Diesel | N1 | 58 | 916 | 840 | 3540 | 2761 |
| Medium commercial | Diesel | N2 | 5 | 14 | 48 | 245 | 127 |
| Heavy commercial | Diesel | N3 | 0 | 0 | 7 | 51 | 32 |

**Table 21: Number of observations with valid identification and valid emissions measurement, by Euro emissions standard**

The DVLA/CDL data also included vehicle fuel type and engine size for all identified vehicles in the observed sample. Additional technical data was available for a subset of the sample, including vehicle mass, transmission type, number of cylinders, and number of valves, all of which are potentially useful as dependent variables in emissions estimation.

### *4.3.3 Hydrocarbon (HC) offset calculation and adjustment*

Previous studies have identified the need to calculate and apply an offset correction to the hydrocarbon measurements from the RSD equipment. The developers of the instrumentation state that diagnosis of the underlying cause of this discrepancy has proved difficult, but that the adjustment facilitates comparisons across different survey sites and/or different data collection years for the same site. Calculation of the offset is accomplished by computing the mode and means of the newest model year vehicles and, assuming these vehicles emit negligible levels of hydrocarbons, using the lowest of either of these values as the offset. The offset is then subtracted from all of the hydrocarbon data. It is assumed that the newest / cleanest vehicles emit little hydrocarbons, and that therefore such an adjustment "will only err slightly towards clean because the true offset will be a value somewhat less than the average of the cleanest model year and make." (Burgard et al, 2003, Burgard et al, 2006).

The HC offset was derived using the subset of data containing both valid gas measurements and vehicle identification. Vehicles with a year of manufacture of 2007 and 2008 were defined as the 'newest/cleanest' vehicles, as 2007 was the most recent complete year for which data were available. Table 22 presents the mode and mean values of HCppm for these observations.

| Site Ref. | n | Mode(s) | Mean | Median | Site Ref. | n | Mode(s) | Mean | Median |
|---|---|---|---|---|---|---|---|---|---|
| E1 | 83 | -10, -40 | -17 | -27 | S1 | 391 | -10 | 9 | 2 |
| E2 | 174 | -40 | -7 | -33 | S2 | 121 | -10 | -10 | -13 |
| E3 | 289 | -30 | 12 | -27 | S3 | 131 | -10 | -8 | -11 |
| E4 | 304 | -20 | 7 | -3 | S4 | 252 | -10 | 21 | 1 |
| E5 | 142 | -10, -20 | 0 | -13 | S5 | 93 | -20 | 6 | -6 |
| E6 | 290 | -10 | 16 | -2 | S6 | 311 | -20 | 14 | 5 |
| E7 | 69 | -30 | -11 | -23 | S7 | 289 | -20 | -7 | -11 |
| E8 | 162 | -50 | -12 | -39 | S8 | 313 | -10 | 11 | 3 |
| E9 | 98 | -20 | 14 | 1 | S9 | 172 | -10 | 11 | -3 |
| E10 | 9 | - | -46 | -42 | S10 | 43 | -30 | -9 | -11 |
| E11 | 82 | -40 | -47 | -43 | S11 | 590 | -10 | 3 | -11 |
| E12 | 258 | -20 | -4 | -19 | S12 | 386 | -20 | -6 | -14 |
| E13 | 128 | -40 | -27 | -36 | S13 | 572 | -10 | 9 | -9 |
| E14 | 175 | -10 | -5 | -11 | S14 | 458 | -20 | 1 | -14 |
| E15 | 260 | -40 | 9 | -28 | | | | | |

**Table 22: Derivation of HC offset (ppm) from observed vehicles manufactured in 2007 and 2008**

To make the calculation of the mode more tractable, the HC values were rounded to the nearest 10ppm. Where more than one mode was identified, all modes are reported. The calculated median values are also presented for comparison. It can be seen that the derived HC offsets across all survey sites are in a relatively stable range of -10ppm to -50ppm. This compares with calculated HC offset values reported by, for example, Burgard et al (2003) of 70, 100, 5, 60 and -50ppm for measurements conducted at a site in Denver in 1996, 1997, 1999, 2000, and 2001 respectively. As an example, Figure 52 illustrates the HC offset calculation for survey site S11. Where the HC emissions values are discussed later in this thesis, it will be made clear whether adjusted or unadjusted values are used.

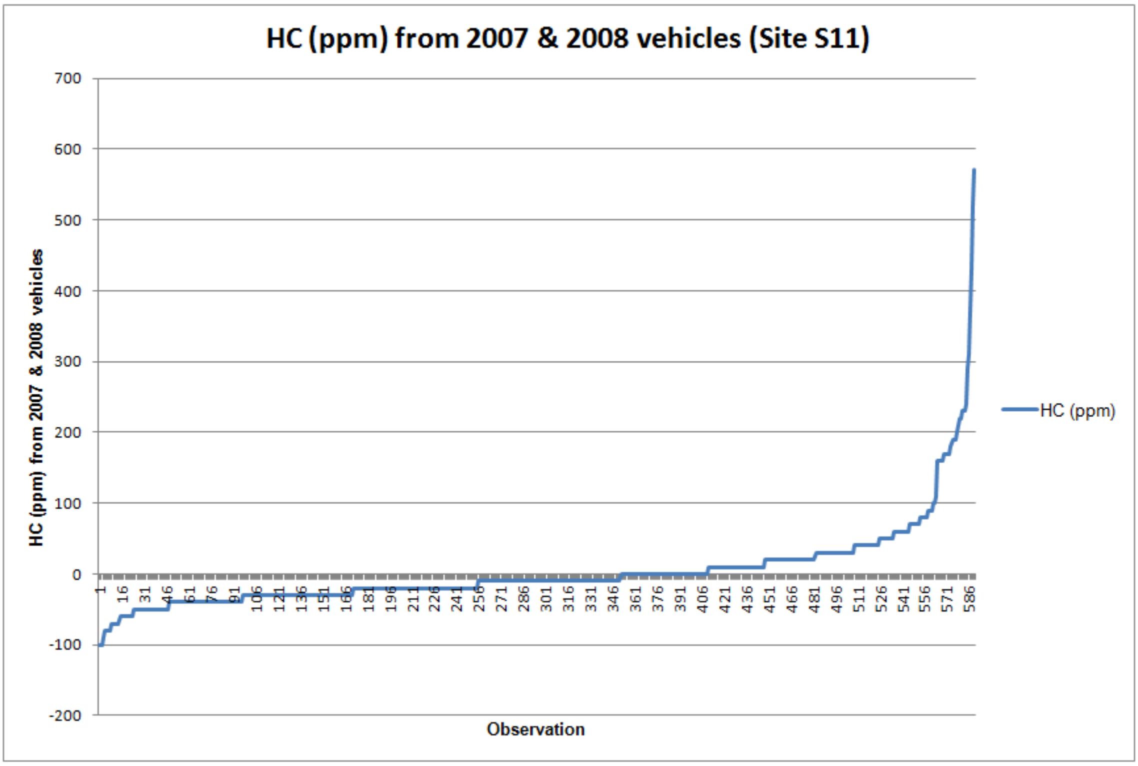



**Figure 52: Example calculation of HC offset (Site Ref. S11)**

## 4.4 Technical Characteristics of the Observed Vehicles

### *4.4.1 Vehicle types and age profiles*

Table 23 presents a summary of the observed vehicles by survey site, vehicle category, and fuel type. 79.8% of the observed vehicles were category M1 (cars and taxis), whilst 16% of vehicles were category N1 (light commercial vehicles). As is to be expected in an urban environment, the numbers of medium and heavy commercial vehicles (category N2 and N3) are relatively small. The proportion of large buses (category M3) ranged from 0.1% to 6.8% of total traffic, depending on location.

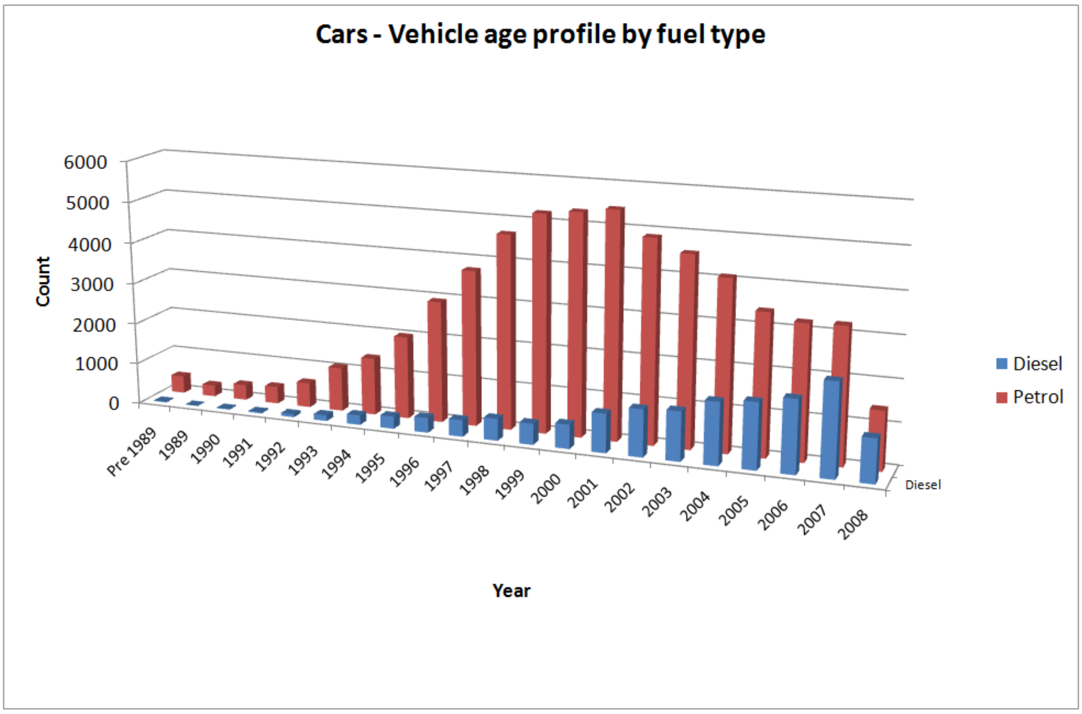



**Figure 53: Passenger car year of manufacture by fuel type**

As noted previously, there are growing concerns about some of the environmental disbenefits associated with the ‘dieselisation’ of the passenger car fleet in the UK, in particular relating to production of $NO_x$, primary $NO_2$ and particulates. Figure 53 presents the passenger car age profile of the observed fleet by the main fuel types, petrol and diesel. For vehicles manufactured in 1997, 9.7% are diesel; for vehicles manufactured in 2007, 40.8% are diesel.

This figure increases to 42.7% in 2008, broadly consistent with total UK fleet statistics.

Table 24 presents the average ages of the observed vehicle fleet. It is noteworthy that the average age of petrol cars is between 7.4 and 7.5 years, whereas the average age of diesel cars is between 4.7 and 5.0 years. This reflects the growing popularity of diesel powered vehicles in recent years, consistent with Figure 53. Therefore, on average, diesel cars in the observed fleet will tend to have newer technology, including emissions control technology, compared to petrol cars. Figure 54 presents the public transport vehicle (M3 category large buses and M1 London taxis) age profile of the observed fleet. The average age of the observed London taxis (black cabs) is 7.1 years, marginally longer than the overall age of the total car fleet. The average age of the observed large (M3) buses was 6.8 years, but it is notable from Figure 54 that fleet acquisition tends to be in tranches (and that particular groups of vehicles will tend to be allocated to particular routes, and thus be observed on multiple occasions).

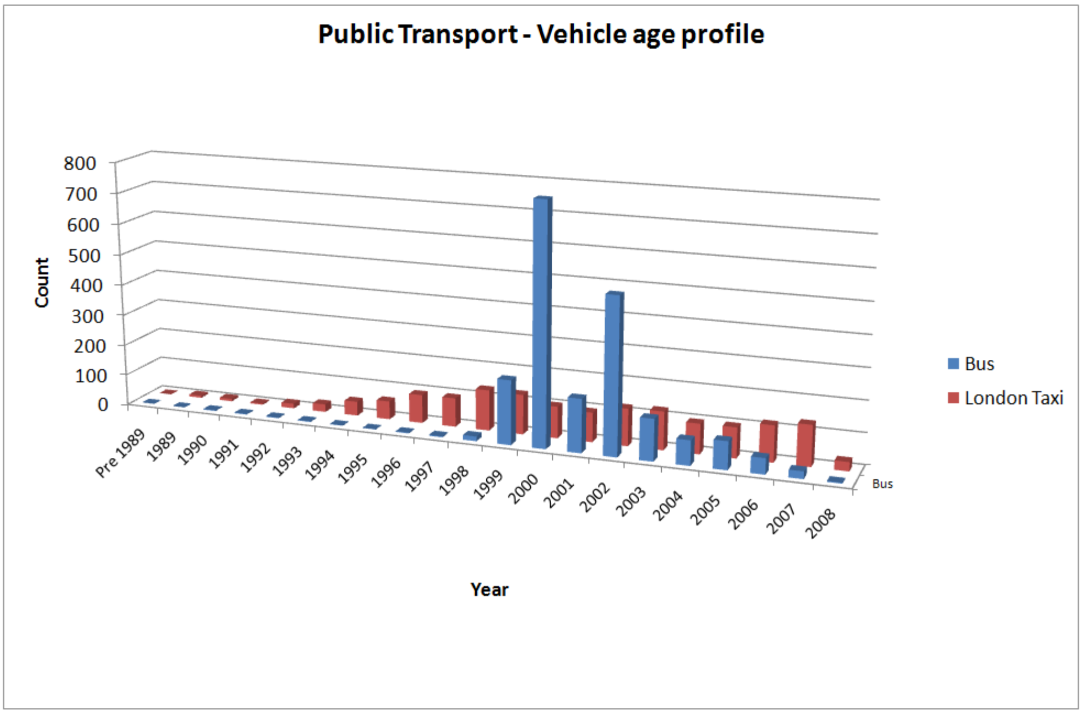



**Figure 54: Public transport vehicles year of manufacture**

| | Car (M1) | | | Light commercial (N1) | | | London Taxi (M1) | | Minibus (M2) | | Bus (M3) | N2 | N3 | Motorcycle | Quadricycle | Count |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Ref** | **Petrol** | **Diesel** | **Other** | **Petrol** | **Diesel** | **Other** | **Diesel** | **Other** | **Petrol** | **Diesel** | **Diesel** | **Diesel** | **Diesel** | **Petrol** | **Petrol** | |
| **E1** | 1662 | 323 | 5 | 8 | 83 | 0 | 0 | | | | 33 | 1 | 1 | 2 | | **2118** |
| **E2** | 2876 | 651 | 8 | 27 | 521 | 4 | 16 | | | 3 | 197 | 24 | 3 | 17 | | **4347** |
| **E3** | 4010 | 810 | 11 | 27 | 555 | 6 | 20 | | | 1 | 201 | 23 | 8 | 10 | 2 | **5684** |
| **E4** | 3066 | 751 | 21 | 17 | 561 | 6 | 8 | | | 1 | 55 | 39 | 7 | 4 | | **4536** |
| **E5** | 1472 | 360 | 6 | 12 | 353 | 7 | 6 | | | | 75 | 16 | 4 | 3 | | **2314** |
| **E6** | 3009 | 719 | 16 | 27 | 666 | 4 | 16 | | | | 4 | 31 | 9 | 15 | | **4516** |
| **E7** | 1084 | 251 | 9 | 12 | 142 | 4 | 7 | | | | 5 | 3 | 5 | | | **1522** |
| **E8** | 1874 | 455 | 8 | 24 | 259 | 2 | 22 | | | 1 | 35 | 8 | 1 | 9 | | **2698** |
| **E9** | 1043 | 212 | 8 | 6 | 160 | 4 | 8 | | | | 20 | 1 | | 1 | | **1463** |
| **E10** | 181 | 23 | 1 | 2 | 29 | 0 | 1 | | | | 7 | 1 | | | | **245** |
| **E11** | 1536 | 374 | 7 | 2 | 237 | 1 | 5 | | | | 54 | 9 | 2 | 16 | | **2243** |
| **E12** | 2490 | 648 | 18 | 28 | 353 | 4 | 30 | | | 6 | 59 | 14 | | 11 | | **3661** |
| **E13** | 2024 | 370 | 10 | 12 | 201 | 2 | 6 | | | | 28 | 7 | 1 | | | **2661** |
| **E14** | 1147 | 393 | 12 | 12 | 252 | 7 | 12 | | | | 14 | 4 | | 3 | | **1856** |
| **E15** | 2517 | 626 | 18 | 22 | 531 | 24 | 9 | | | 1 | 28 | 15 | 7 | 11 | | **3809** |
| **S1** | 1917 | 521 | 22 | 14 | 446 | 13 | 60 | 1 | | 9 | 175 | 31 | 6 | 106 | | **3321** |
| **S2** | 1143 | 319 | 15 | 19 | 265 | 9 | 36 | | | 4 | 139 | 18 | 4 | 79 | | **2050** |
| **S3** | 1644 | 289 | 9 | 31 | 385 | 27 | 12 | | 2 | 3 | 46 | 16 | 2 | 22 | | **2488** |
| **S4** | 1729 | 543 | 17 | 30 | 729 | 21 | 195 | 1 | | 1 | 137 | 46 | 15 | 63 | | **3527** |
| **S5** | 723 | 284 | 12 | 19 | 377 | 10 | 103 | 1 | | 1 | 56 | 20 | 2 | 39 | | **1647** |
| **S6** | 1975 | 642 | 14 | 42 | 824 | 27 | 231 | | | 1 | 141 | 38 | 14 | 104 | | **4053** |
| **S7** | 2327 | 717 | 24 | 34 | 978 | 26 | 274 | | | 2 | 148 | 31 | 6 | 74 | | **4641** |
| **S8** | 2122 | 732 | 25 | 51 | 891 | 22 | 197 | 2 | | 2 | 168 | 30 | 18 | 144 | | **4404** |
| **S9** | 1403 | 396 | 21 | 24 | 414 | 22 | 51 | | | 6 | 160 | 15 | 4 | 58 | | **2574** |
| **S10** | 413 | 107 | 7 | 6 | 110 | 4 | 11 | | | 1 | 48 | 7 | 1 | 29 | | **744** |
| **S11** | 3883 | 932 | 25 | 47 | 1012 | 32 | 57 | | | 10 | 6 | 36 | 9 | 89 | 1 | **6139** |
| **S12** | 2510 | 591 | 14 | 51 | 749 | 29 | 29 | | | 8 | 4 | 37 | 3 | 41 | | **4066** |
| **S13** | 3828 | 845 | 20 | 69 | 1072 | 37 | 54 | 1 | | 9 | 7 | 46 | 5 | 83 | | **6076** |
| **S14** | 3121 | 696 | 22 | 42 | 816 | 28 | 44 | 1 | | 9 | 20 | 46 | 15 | 65 | | **4925** |
| **Count** | **58729** | **14580** | **405** | **717** | **13971** | **382** | **1520** | **7** | **2** | **79** | **2070** | **613** | **152** | **1098** | **3** | **94328** |

**Table 23: Observed vehicles by survey site, category, and fuel type**

| Vehicle Type | Age (years) | | |
|---|---|---|---|
| | Ealing | Southwark | UK average 2008 (DoT, 2010) |
| Cars – Petrol (M1) | 7.5 | 7.4 | - |
| Cars – Diesel (M1) | 5.0 | 4.7 | - |
| Cars – Total (M1) | 7.1 | 6.8 | 7.0 |
| Light commercial – Petrol (N1) | 8.2 | 6.0 | - |
| Light commercial – Diesel (N1) | 5.1 | 4.6 | - |
| Light commercial – Total (N1) | 5.3 | 4.6 | 6.8 |
| Motorcycles (L1 and L3) | 5.6 | 5.9 | 10.4 |
| London taxis (Black cabs – M1) | 7.7 | 7.0 | - |
| Buses (M3) | 7.2 | 6.6 | 9.0 |

**Table 24: Average age of observed vehicles**

### *4.4.2 Vehicle technical parameters*

Additional technical information relevant to exhaust emissions can be derived from the DVLA/CDL vehicle dataset. Figure 55 presents information on engine capacity (cc's), maximum vehicle mass (kg), average $CO_2$ emissions (g/km type approval value used for taxation purposes), and vehicle engine power (bhp) respectively (it should be noted that vehicle mass, $CO_2$ rating, and vehicle engine power are only available for a subset of the data). There is a reducing trend over time in the mean engine capacities of both petrol and diesel powered cars. Observed mean engine capacities for petrol and diesel cars (M1) manufactured in 1997 were 1.73 litres and 2.08 litres respectively; for cars manufactured in 2007, the corresponding figures are 1.63 litres and 2.02 litres.

In contrast, it would appear that mean car weight (maximum permitted) is tending to increase slightly over time. Observed mean weights for petrol and diesel cars (M1) manufactured in 1997 were 1630kg and 1980kg respectively; for cars manufactured in 2007, the corresponding figures are 1700kg and 2110kg.

In response to European legislation, and vehicle taxation incentives, the UK average $CO_2$ emissions of passenger cars are reducing over time. This is confirmed by the observed data in London. Observed mean $CO_2$ emissions (type approval value recorded on the vehicle registration document for taxation purposes) for petrol and diesel cars (M1) manufactured in 1998 were 181g/km and 208g/km respectively; for cars manufactured in 2008, the corresponding figures are 165g/km and 161g/km.

Finally, the data indicates that mean engine power (brake horse power - bhp) for passenger cars is tending to increase with time, most notably for diesel fuelled cars. Observed mean engine power for petrol and diesel cars (M1) manufactured in 1997 was 105bhp and 97bhp respectively; for cars manufactured in 2007, the corresponding figures are 115bhp and 136bhp. This may reflect the increasing adoption of turbo-charging technology over the last ten years, particularly for diesel vehicles where it is becoming ubiquitous.

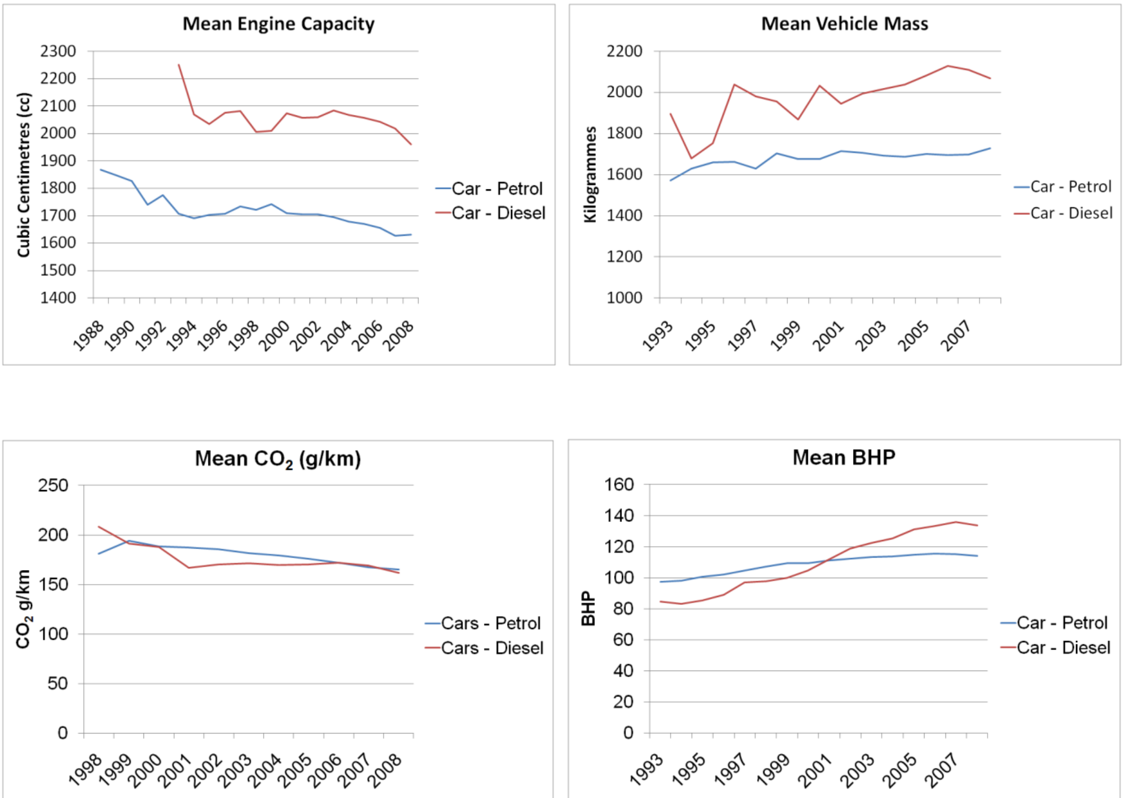



**Figure 55: Observed passenger car technical parameters by year of manufacture and fuel type**

### 4.5 Summary

The overall picture this paints is that whilst vehicles are tending to become heavier, possibly in response to the adoption of additional safety technology and higher specification of equipment levels, engines are becoming both more powerful and more fuel efficient, with more power being generated from smaller cubic capacities. This serves to illustrate the tensions and trade-offs that exist in motor vehicle design and manufacture between factors such as energy policy, safety policy, environmental policy, and consumer demand.

# Chapter 5. Exhaust Emissions Characteristics of the Observed Fleet

## 5.1 Overview of Measured Emissions

Table 27 presents a summary of observed vehicle exhaust pollutant emission concentrations by vehicle type, fuel type, and emissions standard, where data sample bins contain generally more than 100 observations. Mean and median values are presented for carbon monoxide (CO), hydrocarbons (HC), nitric oxide (NO), and smoke number. All HC values are offset adjusted. The divergence of mean and median values is indicative of the presence and influence of large values in the tails of the distribution of data. Previous studies have identified the skewed and leptokurtic nature of the distribution of emissions data (Zhang et al, 1994), and that a relatively small number of gross emitters tend to generate the majority of total fleet pollutant (Sjodin and Andreasson, 2000). The results should be interpreted with due cognisance of the limitations of the measurement instrumentation, as highlighted in the previous chapter.

In addition to CO% (by volume), HCppm, and NOppm values, pollutant in units of grams per kilogram of fuel burnt is also reported in Table 28. The following equations were used to estimate the mass of pollutant generated, following the form used by Pokharel et al (2002) and Burgard et al (2006):

$$\frac{gCO}{kgFuel} = \frac{28 \times Q \times 860}{(1 + Q + (2 \times 3Q')) \times 12}$$

$$\frac{gHC}{kgFuel} = \frac{2 \times 44 \times Q' \times 860}{(1 + Q + (2 \times 3Q')) \times 12}$$

$$\frac{gNO}{kgFuel} = \frac{30 \times Q'' \times 860}{(1 + Q + (2 \times 3Q')) \times 12}$$

where $Q = \frac{CO\%}{CO2\%}$, $Q' = \frac{HC\%}{CO2\%}$, and $Q'' = \frac{NO\%}{CO2\%}$

and assuming a fuel carbon fraction of 86%, 12g/mole for carbon, 28g/mole for carbon monoxide, 44g/mole for HC (propane $C_3H_8$), 30g/mole for nitric oxide, and 3 carbon atoms per molecule of fuel (propane is typically the calibration gas). A factor of 2 is applied to Q’ because the non-dispersive infrared HC measurement calibrated with propane only determines around 50% of the HC mass compared to flame ionisation detector (FID) techniques (Singer et al, 1998).

The calculated mean and median values for Q, Q’, and Q” from the London 2008 dataset are compared to typical values observed in recent surveys in Denver, USA in Table 25 below (Burgard et al, 2006):

| | London | | Denver | |
|---|---|---|---|---|
| | **Mean** | **Median** | **Mean** | **Median** |
| **Q** | 0.0227 | 0.0025 | 0.0200 | 0.009 |
| **Q’** | 0.0011 | 0.0001 | 0.0010 | - |
| **Q”** | 0.0024 | 0.0009 | 0.0020 | - |

**Table 25: Comparison of Q, Q', and Q" values from London and Denver**

With reference to the values of Q, Q’, and Q”, Burgard et al (2006) state that “In Denver, as well as in all cities we measure, the medians are less than half the means because the means are dominated by a few high emitters.”

To facilitate comparison with some other studies which have reported exhaust emissions in terms of grams of pollutant per litre of fuel burnt, these values have also been calculated. However, fuel density varies with changes in temperature, so correction factors were derived (Bosch 2007), taking into account the mean ambient temperature recorded on the day of survey. Temperature data were obtained from MIDAS (Met Office Integrated Data Archive System) Land Surface Stations data, British Atmospheric Data Centre, UK Meteorological Office. Coefficients of thermal expansion of 0.00084 and 0.00095 per ºC for diesel and petrol respectively were assumed.

Table 26 presents density values for petrol and diesel fuel over a range of ambient temperatures.

| Fuel type | Temperature ºC | | | | | | |
|---|---|---|---|---|---|---|---|
| | 0ºC | 5ºC | 10ºC | 15ºC | 20ºC | 25ºC | 30ºC |
| **Petrol** | 751 | 747 | 744 | 740 | 736 | 733 | 730 |
| **Diesel** | 840 | 837 | 833 | 830 | 827 | 823 | 820 |

**Table 26: Assumed variation in fuel density with temperature (grams/litre)**

## 5.2 Passenger Cars (M1)

### *5.2.1 Emissions from passengers cars*

CO, HC, and NO emissions from petrol cars are all seen to display a decreasing trend with the introduction of each successive (and more stringent) Euro standard. The mean and median CO and HC values for Euro 4 are both approaching zero. Indeed, the median HC value for Euro 4 is recorded as -3ppm. It should be pointed out at this juncture that negative measurements are routinely observed with remote sensing technology of this type for two main reasons; firstly, it is possible that the level of pollutant measured at the front of the vehicle (supposedly ambient) is in fact higher than the pollutant measured through the exhaust plume at the rear of the vehicle because of other vehicles passing in front of the subject vehicle, in cases where vehicle headways are so small that pollutant from the leading vehicle has not had time to disperse, or because the leading vehicle is a gross polluter.

Secondly, when pollutant concentrations are very low (common with the most modern vehicle technologies, where values can approach zero), the measurement accuracy of the instrumentation can become a factor. The manufacturer reports the following instrument accuracy for $CO_2$ plumes greater than 20%-cm.

| | | | |
|---|---|---|---|
| CO% | ±0.1 | or | ±10% of reading, whichever is greater |
| HC (propane)ppm | ±100 | or | ±10% of reading, whichever is greater |
| NOppm | ±150 | or | ±10% of reading, whichever is greater |

So it can be seen that when CO, HC, and NO values fall below 0.1%, 100ppm, and 150ppm respectively, some negative measurement values are to be expected, due to measurement error. If the true HC value was 50ppm, one would expect to observe values in the range -50ppm to 150ppm, with a mean of 50ppm.

| Vehicle Type | Fuel | Emissions Class | n | Carbon Monoxide (CO) Mean %vol | Carbon Monoxide (CO) Median %vol | Hydrocarbons (HC) Mean ppm | Hydrocarbons (HC) Median ppm | Nitric Oxide (NO) Mean ppm | Nitric Oxide (NO) Median ppm | Smoke Number Mean | Smoke Number Median |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **M1 (Car)** | Petrol | Pre Euro | 1306 | 1.853 | 0.946 | 983 | 564 | 955 | 595 | 0.20 | 0.18 |
| | | Euro 1 | 4271 | 0.806 | 0.289 | 356 | 126 | 451 | 179 | 0.05 | 0.02 |
| | | Euro 2 | 10811 | 0.490 | 0.130 | 206 | 41 | 320 | 84 | 0.03 | 0.01 |
| | | Euro 3 | 13312 | 0.168 | 0.033 | 56 | 4 | 105 | 23 | 0.01 | 0.01 |
| | | Euro 4 | 4647 | 0.066 | 0.019 | 14 | -3 | 49 | 12 | 0.00 | 0.00 |
| | | Total Petrol | 34347 | 0.399 | 0.067 | 170 | 16 | 240 | 48 | 0.03 | 0.01 |
| | Diesel | Pre Euro | 88 | 0.067 | 0.035 | 78 | 47 | 510 | 434 | 0.24 | 0.16 |
| | | Euro 1 | 499 | 0.071 | 0.042 | 73 | 37 | 476 | 410 | 0.23 | 0.16 |
| | | Euro 2 | 1012 | 0.061 | 0.037 | 78 | 52 | 628 | 535 | 0.20 | 0.15 |
| | | Euro 3 | 3537 | 0.039 | 0.013 | 37 | 25 | 486 | 376 | 0.15 | 0.10 |
| | | Euro 4 | 2861 | 0.020 | 0.010 | 23 | 16 | 294 | 203 | 0.08 | 0.06 |
| | | Total Diesel | 7997 | 0.037 | 0.015 | 40 | 24 | 435 | 331 | 0.14 | 0.09 |
| | Hybrid Electric | Euro 4 | 120 | 0.072 | 0.020 | 16 | -4 | 1 | 0 | 0.00 | 0.00 |
| | Total Cars* | | 42603 | 0.330 | 0.046 | 145 | 18 | 276 | 78 | 0.05 | 0.02 |
| **M1 (London Taxi)** | Diesel | Euro 1 | 121 | 0.008 | 0.008 | 31 | 17 | 975 | 881 | 0.12 | 0.10 |
| | | Euro 2 | 213 | 0.012 | 0.009 | 19 | 13 | 928 | 858 | 0.14 | 0.11 |
| | | Euro 3 | 209 | 0.006 | -0.002 | 48 | 27 | 414 | 311 | 0.43 | 0.36 |
| | | Euro 4 | 121 | -0.001 | 0.006 | 17 | 14 | 327 | 249 | 0.19 | 0.12 |
| | Total Taxis* | | 690 | 0.013 | 0.007 | 31 | 18 | 665 | 612 | 0.23 | 0.14 |

**Table 27: Observed vehicle exhaust emission concentrations by type, fuel, and Euro standard**

* Values include additional data from small sample bins

(continued overleaf)

| Vehicle Type | Fuel | Emissions Class | n | Carbon Monoxide (CO) Mean %vol | Carbon Monoxide (CO) Median %vol | Hydrocarbons (HC) Mean ppm | Hydrocarbons (HC) Median ppm | Nitric Oxide (NO) Mean ppm | Nitric Oxide (NO) Median ppm | Smoke Number Mean | Smoke Number Median |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **M3 (Bus)** | Diesel | Euro 2 | 901 | 0.013 | 0.012 | 70 | 50 | 841 | 777 | 0.08 | 0.04 |
| | | Euro 3 | 850 | 0.017 | 0.015 | 88 | 50 | 1001 | 884 | 0.12 | 0.05 |
| | Total Buses* | | 1824 | 0.016 | 0.014 | 80 | 51 | 946 | 853 | 0.10 | 0.05 |
| **N1 (Light commercial)** | Petrol | Euro III | 145 | 0.374 | 0.062 | 199 | 6 | 178 | 53 | 0.02 | 0.01 |
| | | Euro IV | 116 | 0.153 | 0.033 | 3 | -4 | 130 | 15 | 0.00 | 0.00 |
| | | Total Petrol* | 428 | 0.747 | 0.109 | 370 | 24 | 378 | 85 | 0.06 | 0.02 |
| | Diesel | Euro I | 916 | 0.074 | 0.051 | 116 | 71 | 711 | 566 | 0.28 | 0.18 |
| | | Euro II | 840 | 0.070 | 0.042 | 91 | 59 | 687 | 568 | 0.25 | 0.16 |
| | | Euro III | 3540 | 0.055 | 0.021 | 60 | 33 | 623 | 497 | 0.23 | 0.16 |
| | | Euro IV | 2761 | 0.031 | 0.010 | 40 | 22 | 363 | 253 | 0.15 | 0.09 |
| | | Total Diesel* | 8115 | 0.050 | 0.020 | 63 | 33 | 557 | 428 | 0.21 | 0.14 |
| | Total N1* | | 8814 | 0.092 | 0.022 | 90 | 24 | 536 | 401 | 0.20 | 0.13 |
| **N2 (Medium commercial)** | Diesel | Euro III | 245 | 0.081 | 0.060 | 78 | 42 | 1412 | 1205 | 0.14 | 0.12 |
| | | Euro IV | 127 | 0.069 | 0.039 | 49 | 30 | 1327 | 1226 | 0.09 | 0.06 |
| | Total N2* | | 439 | 0.081 | 0.055 | 87 | 46 | 1407 | 1232 | 0.15 | 0.11 |
| **All observed vehicles*** | | | 54599 | 0.279 | 0.038 | 136 | 22 | 357 | 137 | 0.08 | 0.03 |

**Table 27: Observed vehicle exhaust emission concentrations by type, fuel, and Euro** standard

* Values include additional data from small sample bins

(continued from previous page)

| Vehicle Type | Fuel | Emissions Class | n | Carbon Monoxide (CO) Mean g/kg of fuel | Carbon Monoxide (CO) Median g/kg of fuel | Hydrocarbons (HC) Mean g/kg of fuel | Hydrocarbons (HC) Median g/kg of fuel | Nitric Oxide (NO) Mean g/kg of fuel | Nitric Oxide (NO) Median g/kg of fuel | Smoke Number Mean | Smoke Number Median |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **M1 (Car)** | Petrol | Pre Euro | 1306 | 216.9 | 121.9 | 34.2 | 22.4 | 13.0 | 7.9 | 0.20 | 0.18 |
| | | Euro 1 | 4271 | 98.5 | 38.2 | 13.4 | 5.2 | 6.3 | 2.5 | 0.05 | 0.02 |
| | | Euro 2 | 10811 | 60.9 | 17.3 | 7.9 | 1.7 | 4.5 | 1.2 | 0.03 | 0.01 |
| | | Euro 3 | 13312 | 21.6 | 4.4 | 2.2 | 0.1 | 1.5 | 0.3 | 0.01 | 0.01 |
| | | Euro 4 | 4647 | 8.7 | 2.6 | 0.6 | -0.1 | 0.7 | 0.2 | 0.00 | 0.00 |
| | | Total Petrol | 34347 | 49.2 | 8.8 | 6.4 | 0.7 | 3.4 | 0.7 | 0.03 | 0.01 |
| | Diesel | Pre Euro | 88 | 8.8 | 4.6 | 3.2 | 2.0 | 7.3 | 6.2 | 0.24 | 0.16 |
| | | Euro 1 | 499 | 9.3 | 5.6 | 3.0 | 1.6 | 6.8 | 5.9 | 0.23 | 0.16 |
| | | Euro 2 | 1012 | 8.1 | 5.0 | 3.2 | 2.2 | 9.0 | 7.6 | 0.20 | 0.15 |
| | | Euro 3 | 3537 | 5.1 | 1.8 | 1.5 | 1.0 | 6.9 | 5.4 | 0.15 | 0.10 |
| | | Euro 4 | 2861 | 2.6 | 1.2 | 1.0 | 0.7 | 4.2 | 2.9 | 0.08 | 0.06 |
| | | Total Diesel | 7997 | 4.9 | 2.0 | 1.7 | 1.0 | 6.2 | 4.7 | 0.14 | 0.09 |
| | Hybrid Electric | Euro 4 | 120 | 9.5 | 2.6 | 0.6 | -0.2 | 0.0 | 0.0 | 0.00 | 0.00 |
| | Total Cars* | | 42603 | 40.8 | 6.2 | 5.5 | 0.8 | 3.9 | 1.1 | 0.05 | 0.02 |
| **M1 (London Taxi)** | Diesel | Euro 1 | 121 | 1.0 | 1.0 | 1.3 | 0.7 | 14.0 | 12.6 | 0.12 | 0.10 |
| | | Euro 2 | 213 | 1.6 | 1.2 | 0.8 | 0.6 | 13.3 | 12.3 | 0.14 | 0.11 |
| | | Euro 3 | 209 | 0.8 | -0.2 | 2.0 | 1.1 | 5.9 | 4.4 | 0.43 | 0.36 |
| | | Euro 4 | 121 | -0.2 | 0.8 | 0.7 | 0.6 | 4.7 | 3.6 | 0.19 | 0.12 |
| | Total Taxis* | | 690 | 1.7 | 0.9 | 1.3 | 0.8 | 9.5 | 8.7 | 0.23 | 0.14 |

**Table 28: Observed vehicle exhaust mass emissions by type, fuel, and Euro standard**

* Values include additional data from small sample bins

(continued overleaf)

| Vehicle Type | Fuel | Emissions Class | n | Carbon Monoxide (CO) | | Hydrocarbons (HC) | | Nitric Oxide (NO) | | Smoke Number | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Mean g/kg of fuel | Median g/kg of fuel | Mean g/kg of fuel | Median g/kg of fuel | Mean g/kg of fuel | Median g/kg of fuel | Mean | Median |
| **M3 (Bus)** | Diesel | Euro 2 | 901 | 1.8 | 1.6 | 2.9 | 2.1 | 12.0 | 11.1 | 0.08 | 0.04 |
| | | Euro 3 | 850 | 2.2 | 2.0 | 3.6 | 2.1 | 14.3 | 12.6 | 0.12 | 0.05 |
| | Total Buses* | | 1824 | 2.2 | 1.8 | 3.3 | 2.1 | 13.5 | 12.2 | 0.10 | 0.05 |
| **N1 (Light commercial)** | Petrol | Euro III | 145 | 46.8 | 8.2 | 7.4 | 0.2 | 2.5 | 0.8 | 0.02 | 0.01 |
| | | Euro IV | 116 | 20.0 | 4.4 | 0.1 | -0.1 | 1.9 | 0.2 | 0.00 | 0.00 |
| | | Total Petrol* | 428 | 88.1 | 14.5 | 12.8 | 1.0 | 5.2 | 1.2 | 0.06 | 0.02 |
| | Diesel | Euro I | 916 | 9.7 | 6.8 | 4.8 | 3.0 | 10.1 | 8.0 | 0.28 | 0.18 |
| | | Euro II | 840 | 9.2 | 5.6 | 3.8 | 2.5 | 9.8 | 8.1 | 0.25 | 0.16 |
| | | Euro III | 3540 | 7.2 | 2.8 | 2.5 | 1.4 | 8.9 | 7.1 | 0.23 | 0.16 |
| | | Euro IV | 2761 | 4.0 | 1.4 | 1.6 | 0.9 | 5.2 | 3.6 | 0.15 | 0.09 |
| | | Total Diesel* | 8115 | 6.6 | 2.6 | 2.6 | 1.4 | 7.9 | 6.1 | 0.21 | 0.14 |
| | Total N1* | | 8814 | 11.5 | 3.0 | 3.2 | 1.4 | 7.6 | 5.7 | 0.20 | 0.13 |
| **N2 (Medium commercial)** | Diesel | Euro III | 245 | 10.8 | 8.0 | 3.2 | 1.8 | 20.2 | 17.2 | 0.14 | 0.12 |
| | | Euro IV | 127 | 9.1 | 5.2 | 2.1 | 1.3 | 19.0 | 17.5 | 0.09 | 0.06 |
| | Total N2* | | 439 | 10.8 | 7.2 | 3.6 | 1.9 | 20.1 | 17.6 | 0.15 | 0.11 |
| **All observed vehicles*** | | | 54599 | 34.4 | 5.0 | 5.0 | 0.9 | 5.0 | 1.9 | 0.08 | 0.03 |

**Table 28: Observed vehicle exhaust mass emissions by type, fuel, and Euro standard**

* Values include additional data from small sample bins

(continued from previous page)

CO values for Euro 4 petrol cars have a mean of 0.066%, whereas mean CO values for all observed diesel powered vehicle types and Euro standards are below 0.1%. However, because over 54% of the observed vehicles were petrol powered Euro 3 or earlier, the observed mean CO value for all petrol cars was 0.399%, and the observed mean CO value for all vehicles combined was 0.279%.

Mean HC values for all vehicle classes except petrol cars (pre Euro to Euro 3), Euro 1 light commercial diesel vehicles (N1), and pre-Euro IV light commercial petrol vehicles (N1) were below 100ppm. Again, the large number of petrol powered cars (pre Euro to Euro 3) results in a mean HC value for petrol cars of 170ppm, and a mean HC value for all observed vehicles of 136ppm.

To more fully understand the nature of the distribution of exhaust emissions in the observed sample, Figure 56 presents the observed emissions data for petrol and diesel cars in the form of box plots, where the centre horizontal line is the median ($50^{th}$ percentile) value, the top and the bottom of the box are the $75^{th}$ and $25^{th}$ percentile values, and the ends of the whiskers are at 1.5 times the inter quartile range (or the maximum and minimum values if these data lie within the 1.5 inter quartile range). Outliers and extreme outliers have been excluded from the diagrams for reasons of presentational clarity.

Figure 57 and Figure 58 present observed exhaust emissions by vehicle year of manufacture in the form of deciles (means), for petrol and diesel cars respectively. These plots serve to illustrate more clearly both the changes in emissions characteristics by year of manufacture, and the change in the shape of the emissions distribution (i.e. the relative contribution of each decile to the total emissions). The form of the emissions distribution varies by year of manufacture, pollutant, and fuel type. CO and HC distributions for petrol cars have a similar form, with absolute levels of pollutant decreasing significantly with the introduction of increasingly stringent Euro standards to 2008. The form of the distribution for NO is slightly different, with higher values persisting in the eighth and ninth deciles until around 2001 when the Euro 3 standard penetrated the fleet.

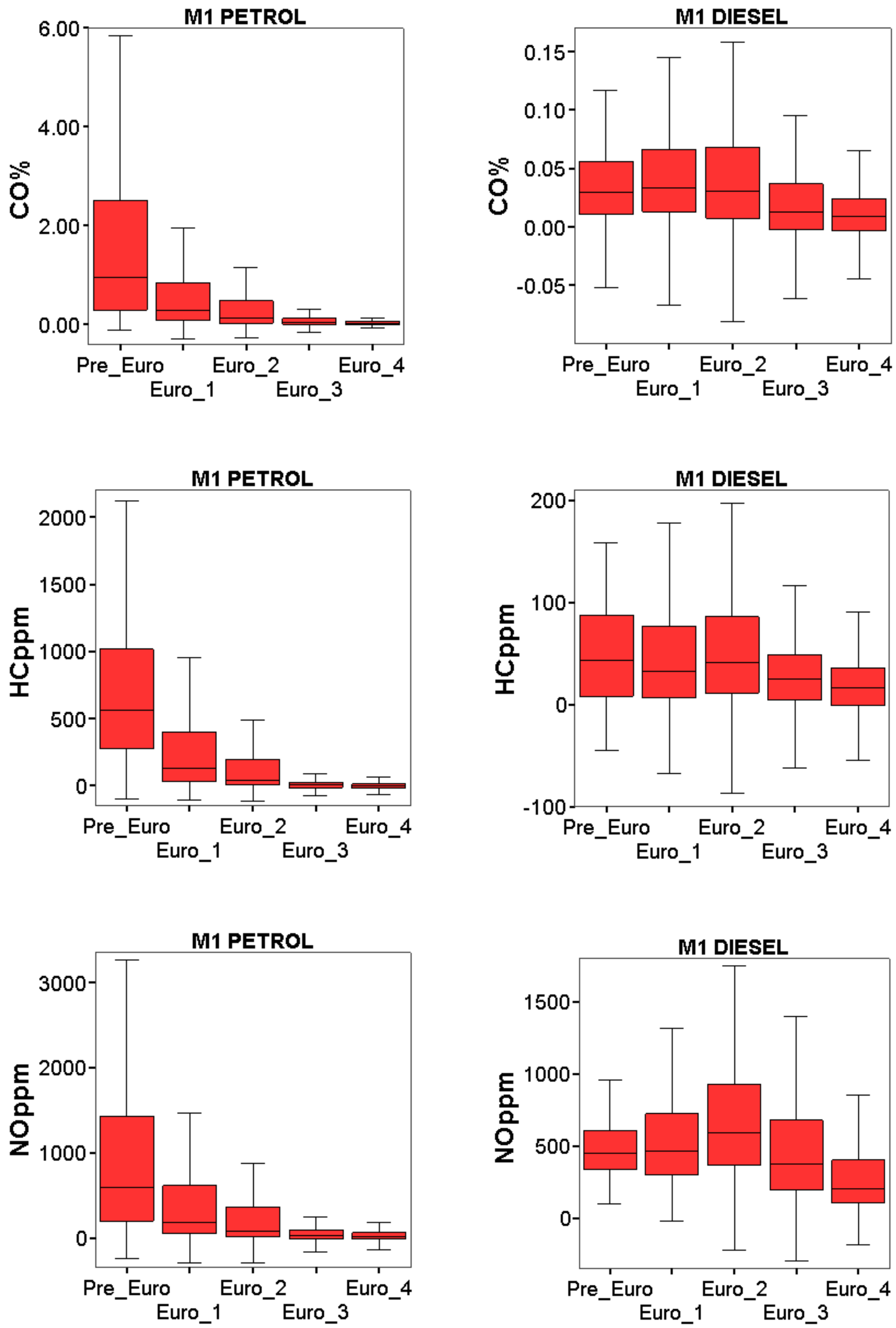



**Figure 56: Box plot comparison of petrol and diesel M1 vehicle class exhaust emissions by Euro standard**

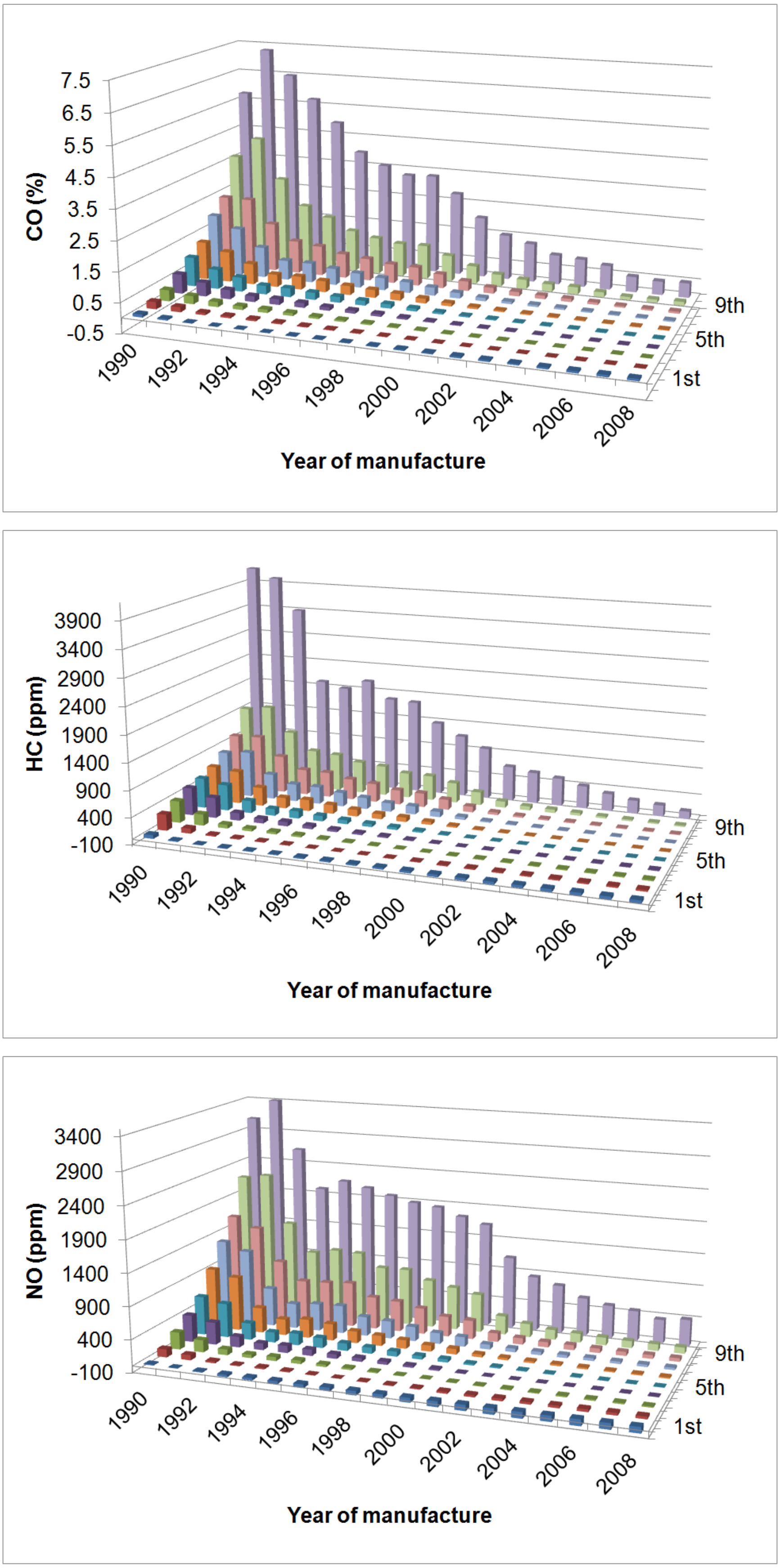



**Figure 57: Petrol cars: Mean emissions (deciles) by year of manufacture**

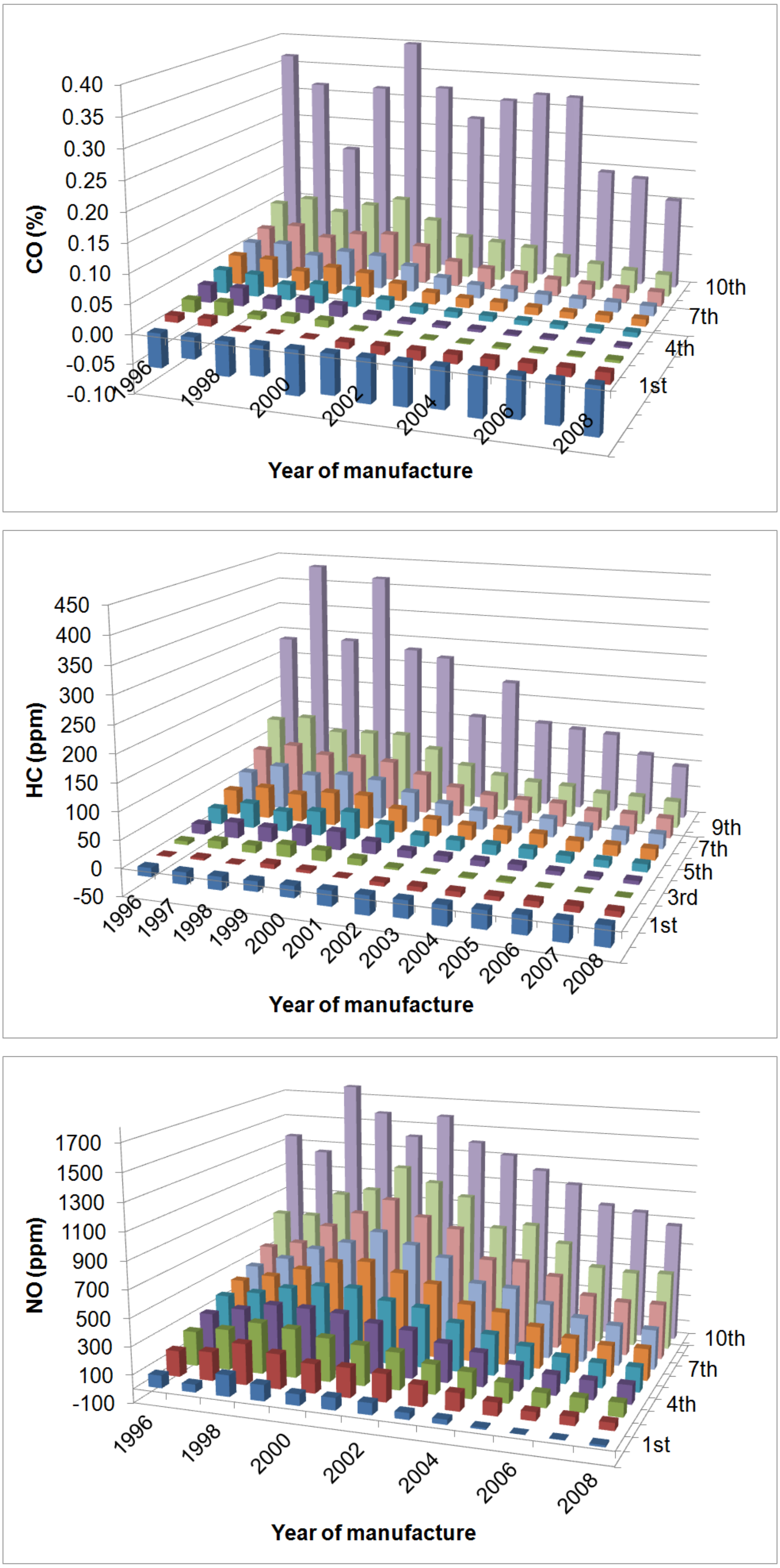



**Figure 58: Diesel cars: Mean emissions (deciles) by year of manufacture**

The form of the distributions for CO and HC for diesel cars in Figure 58 is influenced by the very low levels of pollutant observed, relative to the values observed for petrol cars. The degree of reduction over time with increasing Euro standards is less pronounced because of the lower absolute values, the measurements being more constrained by the sensitivity limitations of the measurement instrumentation, as discussed previously, with a higher proportion of negative values in the data. It is interesting to observe that the mean and median HC emissions for Euro 4 petrol cars are lower than the equivalent HC emissions for diesel cars (measurement constraints notwithstanding), a reversal of the situation compared to earlier Euro standards. The distribution of NO emissions for diesel cars has a very different form. From Euro 1 standard onwards, NO emissions from diesel cars are higher than petrol cars, and one does not observe the level and rate of NO emission reduction as is observed in the petrol fleet. The distribution is relatively less skewed and more platykurtic in nature.

Observations of NO for diesel passenger cars (M1) display an interesting characteristic which merits further investigation. NO emissions increase from Euro 1 to Euro 2, before decreasing when the Euro 3 standard is applied. This phenomenon becomes clearer when the emissions data are reviewed on an annual basis, by year of manufacture, as presented in Figure 59. When interpreting these data, one should be aware that the sample size is increasing by year of manufacture, as diesel powered vehicles become a larger proportion of the fleet (see Table 27 for sample sizes). NO emissions from diesel cars increase from year 1995 (mean 457ppm, median 400ppm) to a maximum in year 2000 (mean 676ppm, median 596ppm), then gradually decline to 2008 (mean 283ppm, median 200ppm). Explanations for this are speculative, but may be related to the prevailing type approval emissions standard in force at the time.

Table 29 presents the relevant emissions standards for diesel cars during this period. The transition from Euro 1 to Euro 2 introduced a significant reduction in the carbon monoxide limit value from 2.72g/km to 1.00g.km over the test cycle.

There was also a tightening of the particulate (PM) limit, and a reduction in the combined HC+$NO_x$ limit.

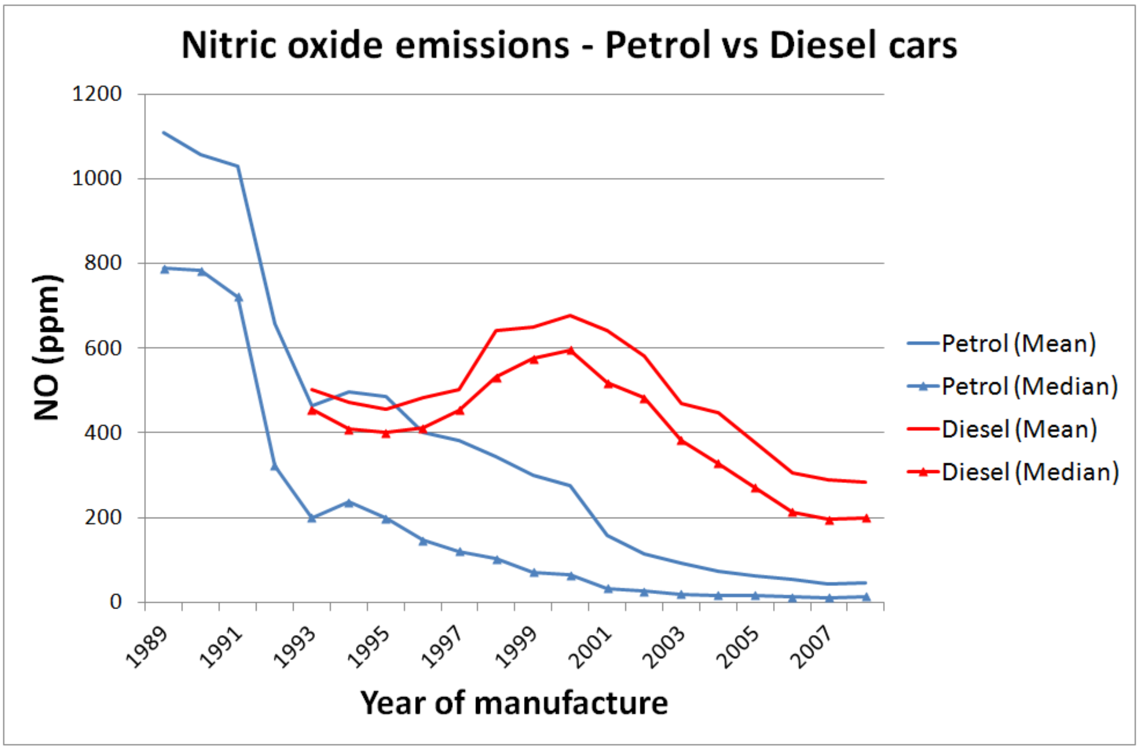



**Figure 59: Nitric oxide emissions for petrol and diesel cars by year of manufacture**

| EU Directive | Engine / fuel type* | Limit values (g/km) | | | | | Implementation dates | |
|---|---|---|---|---|---|---|---|---|
| | | CO | HC | $NO_x$ | HC+$NO_x$ | PM | Type approval | In-use |
| Euro 1 | D-IDI | 2.72 | | | 1.0 | 0.14 | | |
| | D-DI | 2.72 | | | 1.4 | 0.20 | 1/7/1992 | 31/12/1992 |
| | D-DI | 2.72 | | | 1.0 | 0.14 | 1/7/1994 | 31/12/1994 |
| Euro 2 | D-IDI | 1.00 | | | 0.7 | 0.08 | | |
| | D-DI | 1.00 | | | 0.9 | 0.10 | 1/1/1996 | 1/1/1997 |
| | D-DI | 1.00 | | | 0.7 | 0.08 | 1/10/1998 | 1/10/1999 |
| Euro 3 | D | 0.64 | | 0.50 | 0.56 | 0.05 | 1/1/2000 | 1/1/2001 |
| Euro 4 | D | 0.50 | | 0.25 | 0.30 | 0.025 | 1/1/2005 | 1/1/2006 |

**Table 29: European type approval emissions standards for diesel cars (M1)**

Source: UK DoT (2007): * D=Diesel, D-DI=Diesel direct injection, D-IDI=Diesel indirect injection

However, it should be noted that an individual limit for $NO_x$ was not introduced until the Euro 3 standard was adopted. Therefore, it is possible that under Euro

2, $NO_x$ was allowed to increase by the vehicle manufacturers, as long as the combined HC+$NO_x$ value complied with the Euro 2 standard. When Euro 3 was introduced with an explicit $NO_x$ limit value, $NO_x$ was reduced. Samuel et al (2004) have highlighted the issue of vehicle manufacturers developing engine maps to meet the emission limit values (g/km) of the relevant type approval drive cycle. It is not unreasonable to assume that adjustments are made by vehicle manufacturers to the engine mapping for each new vehicle model and engine type to ensure that it passes the prevailing type approval tests, whilst also achieving other objectives such as drivability, reliability, and economy. An alternative explanation might relate to the manner in which the technologies perform with increasing age, and possibly deteriorating maintenance regimes as the vehicles get older. It is worth noting that the UK annual vehicle inspection (MoT test) does not currently include an $NO_x$ measurement.

Ekstrom et al (2004) observed a similar profile for NO from diesel cars, with values of approximately 8.2, 11.8, and 9.6 grams of $NO_x$ (NO) per litre of fuel burnt for Euro 1, Euro 2 and Euro 3 vehicles respectively. (N.B. Ekstrom et al (2004) measured NO using remote sensing, but reported the figures as $NO_x$, making the assumption that the proportion of $NO_2$ in total $NO_x$ at the time of the surveys was very low).The corresponding values from the London data set are 6.8, 8.0 and 5.7 grams of NO per litre of fuel burnt. Inventories such as the EMEP/EEA air pollutant emission inventory guidebook (European Environment Agency, 2009), which is used in the COPERT model (Gkatzoflias et al 2007), include a similar peak in the $NO_x$ profile, although in the case of COPERT, the peak value (measured in grams per kilometre) occurs at Euro 3, before reducing with the introduction of Euro 4.

A small number of hybrid electric passenger cars (predominantly Toyota Prius) are included in the observed data. It is not possible to determine with any degree of certainty whether such vehicles were operating in electric or petrol engine mode when observed. However, it is interesting to compare the ‘in-use’ emissions of the hybrid vehicles with comparable petrol and diesel vehicles at the survey sites. Figure 60 and Table 27 present a comparison of the emissions from Euro 4 petrol, diesel, and hybrid electric vehicles. It should be noted that the hybrid electric vehicle sample is only 120 observations, compared with 4647 petrol vehicles, and 2861 diesel vehicles. Generally, both CO and HC emissions from all three Euro 4 propulsion classes are very low (mean CO petrol 0.066%, diesel 0.020%, hybrid 0.072%; mean HC petrol 14ppm, diesel 23ppm, hybrid 16ppm). The most notable difference is seen in the NO results where the mean NO for petrol was 49ppm, diesel 294ppm, and hybrid 1ppm. Such small values for both petrol and hybrid should be interpreted in the context of the known instrument sensitivity and accuracy, but it seems clear that NO emissions for Euro 4 diesel vehicles are measurably higher.

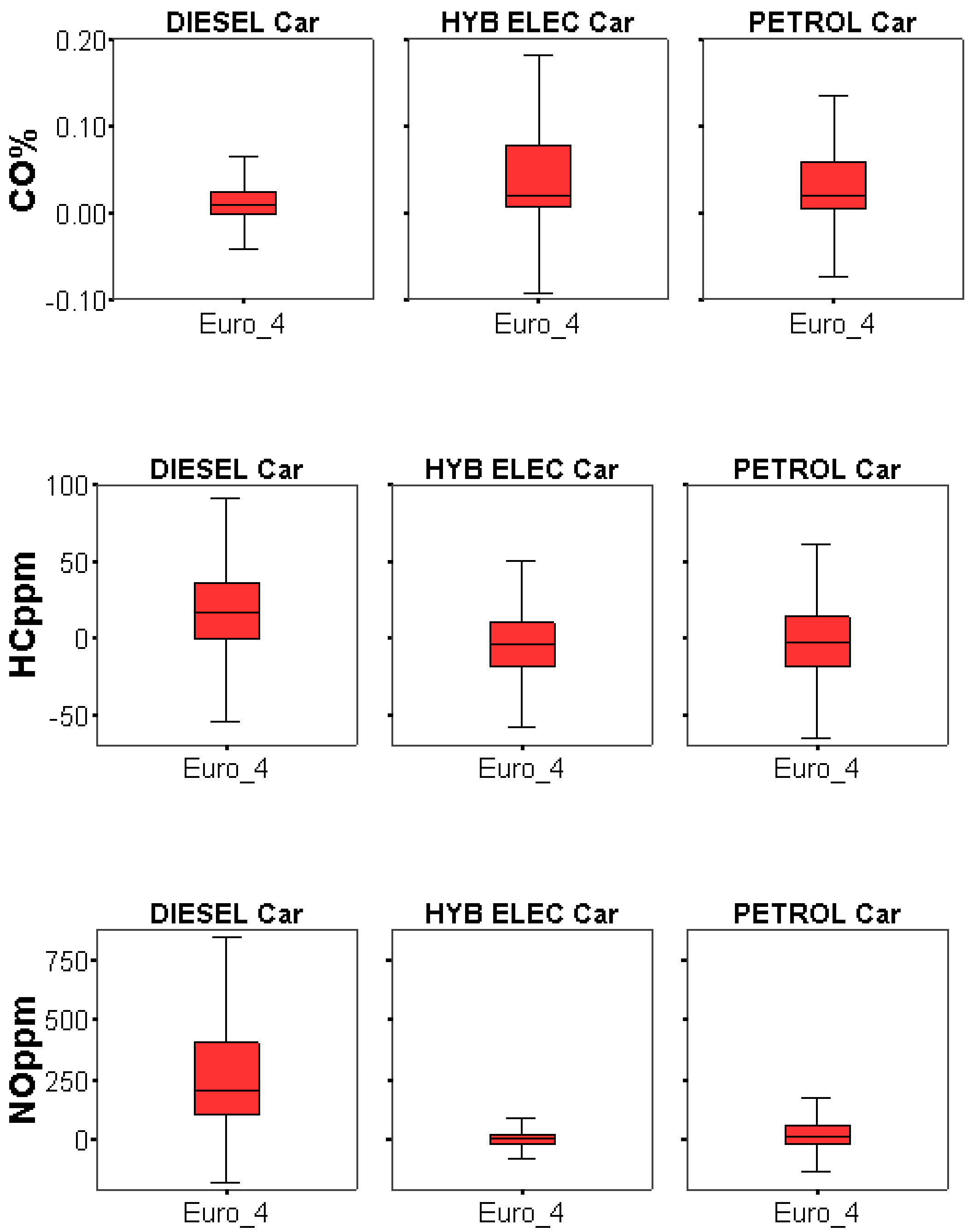



**Figure 60: Comparison of Euro 4 petrol, hybrid electric, and diesel car exhaust emissions**

### *5.2.2 Significance of differences between groups*

Since the data violate the assumptions of the independent *t*-test, non-parametric statistical tests were applied (Kruskal-Wallis and Mann Whitney rank-sum tests) to detect any statistically significant differences between emissions characteristics of the groups of vehicles, by Euro standard.

Passenger cars (category M1 excluding London taxis) comprised just over 82% of the total observed light vehicles. Of these, 34 347 were powered by petrol, and 7997 were powered by diesel fuel. The majority of petrol cars observed were either Euro 2 or Euro 3 emissions standard, whilst the majority of diesel cars were either Euro 3 or Euro 4 emissions standard. This reflects the increasing popularity, and increased market share, of diesel cars in the UK in recent years.

Applying a Kruskal-Wallis test to the petrol car exhaust emissions observations, grouped by Euro emissions standard for each pollutant, we obtain the following results.

| | |
|---|---|
| **CO:** | Kruskal-Wallis statistic $H$ (df=4) is 7367, with significance $p < 0.001$ |
| **HC:** | Kruskal-Wallis statistic $H$ (df=4) is 8700, with significance $p < 0.001$ |
| **NO:** | Kruskal-Wallis statistic $H$ (df=4) is 5603, with significance $p < 0.001$ |
| **Smoke:** | Kruskal-Wallis statistic $H$ (df=4) is 3557, with significance $p < 0.001$ |

In each case the Kruskal-Wallis test is found to be significant (critical value $p<0.05$), indicating that Euro emissions standard does significantly affect exhaust emissions from petrol cars.

Pairwise post hoc Mann-Whitney tests were used to follow up these findings to explore where within the data (between which emission standard categories) the statistically significant differences were located, the test statistics being presented in Table 30. A Bonferroni correction was applied to control the Type I error rate, so all effects are reported at a 0.0125 level of significance. CO, HC, NO, and smoke (particulate) emissions from petrol engine cars are all seen to display statistically significant reductions with the introduction of each new emissions standard, from Pre-Euro through to Euro 4 emissions standard, but the effect size (as measured by *r,* where $r = z / \sqrt{N}$), varied considerably between -0.05 and -0.44. An effect size *r*=0.1 is considered to be a small effect, *r*=0.3 a medium effect, and *r*=0.5 a large effect (Field, 2009). Generally, the change from Euro 3 to Euro 4 resulted in a smaller reduction in petrol car emissions than earlier changes in Euro standards (for example, from Euro 2 to Euro 3), but the reduction was still measured to be statistically significant.

| **Pollutant** | **Emission standard** | **Emission standard** | **Mann-Whitney *U*** | ***z*** | ***Significance (1-tailed)*** | **Effect size *r*** |
|---|---|---|---|---|---|---|
| CO (%) | Pre Euro | Euro 1 | 1696413 | -21.456 | $p < 0.001$ | -0.29 |
| | Euro 1 | Euro 2 | 17773305 | -22.057 | $p < 0.001$ | -0.18 |
| | Euro 2 | Euro 3 | 46976594 | -46.444 | $p < 0.001$ | -0.30 |
| | Euro 3 | Euro 4 | 24975712 | -19.570 | $p < 0.001$ | -0.15 |
| HC (ppm) | Pre Euro | Euro 1 | 1394113 | -27.393 | $p < 0.001$ | -0.37 |
| | Euro 1 | Euro 2 | 17139749 | -24.686 | $p < 0.001$ | -0.20 |
| | Euro 2 | Euro 3 | 43057475 | -53.730 | $p < 0.001$ | -0.35 |
| | Euro 3 | Euro 4 | 26120539 | -15.808 | $p < 0.001$ | -0.12 |
| NO (ppm) | Pre Euro | Euro 1 | 1747805 | -20.447 | $p < 0.001$ | -0.27 |
| | Euro 1 | Euro 2 | 18657053 | -18.388 | $p < 0.001$ | -0.15 |
| | Euro 2 | Euro 3 | 49710036 | -41.362 | $p < 0.001$ | -0.27 |
| | Euro 3 | Euro 4 | 27650241 | -10.780 | $p < 0.001$ | -0.08 |
| Smoke | Pre Euro | Euro 1 | 1101604 | -33.138 | $p < 0.001$ | -0.44 |
| | Euro 1 | Euro 2 | 19143797 | -16.368 | $p < 0.001$ | -0.13 |
| | Euro 2 | Euro 3 | 60084576 | -22.074 | $p < 0.001$ | -0.14 |
| | Euro 3 | Euro 4 | 29000496 | -6.343 | $p < 0.001$ | -0.05 |

**Table 30: Mann-Whitney test statistics for petrol passenger cars by emission standard for each pollutant**

Direct comparisons of measured differences between observed groups of vehicles of differing emissions standards (based on remote sensing), with the ‘expected’ reductions based on changes in the legislative (Euro) standards, can be problematic because the legal type approval standards are based on limit values (g/km) measured from a new vehicle on a chassis dynamometer over the legislated test cycle, whereas the individual remote sensing values are just a ‘snapshot’ of the concentration of pollutants in the exhaust plume as the vehicle passes the survey site. For example, the transition from Euro 1 to Euro 2 for petrol cars reduced the legal limit value for CO from 2.72g/km to 2.20g/km, whilst the limit value for combined $HC+NO_x$ reduced from 1.0g/km to 0.5g/km (DoT, 2007). From the observed data, the median CO reduced from 0.29%

(Euro 1) to 0.13% (Euro 2), whilst the median HC/NO reduced from 126ppm / 179ppm (Euro 1) to 41ppm / 84ppm (Euro 2). So there appears to be a stronger than expected impact on the CO and HC emissions, whereas the impact on NO emissions of the Euro 2 standard is broadly in line with expectations. Of course, as has been discussed earlier, NO is only one component of total $NO_x$, and in newer vehicles $NO_2$ is of growing concern.

The extent of the reduction in NO emissions by the introduction of each successive Euro standard is demonstrated clearly. The benefit of moving from earlier to later emissions standards to reduce overall NO emissions from petrol cars is clear, when the proportion of each category in the overall observed fleet is taken into account.

Given that the emissions of CO and HC from diesel engine vehicles are so small in absolute terms, and given the limitations of the remote sensing instrument sensitivity already discussed, the statistical tests for diesel engine vehicles were limited to the pollutants nitric oxide and smoke. Applying a Kruskal-Wallis test to the diesel car exhaust emissions observations, grouped by Euro emissions standard, indicates that NO and smoke emissions are influenced significantly by changing Euro standards.

**NO:** Kruskal-Wallis statistic $H$ (df=4) is 973, with $p < 0.001$
**Smoke:** Kruskal-Wallis statistic $H$ (df=4) is 1283, with $p < 0.001$

Post hoc Mann-Whitney tests were used to follow up these findings, the test statistics being presented in Table 31. Again, a Bonferroni correction is applied, so all effects in this case are reported at a 0.01 level of significance. It was found that the reduction in NO emissions from Pre Euro to Euro 1 was not statistically significant, but that the observed increase in NO from Euro 1 to Euro 2, and subsequent decreases from Euro 2 to Euro 3, and Euro 3 to Euro 4 were statistically significant, with varying effect size. Interestingly, NO emissions from Euro 1 and Euro 3 diesel cars were statistically similar with the Mann-Whitney test ($p > 0.01$).

| Pollutant | Emission standard | Emission standard | Mann-Whitney *U* | *z* | *Significance (1-tailed)* | Effect size *r* |
|---|---|---|---|---|---|---|
| NO (ppm) | Pre Euro | Euro 1 | 19562 | -1.632 | *ns* | -0.07 |
| | Euro 1 | Euro 2 | 190803 | -7.734 | $p < 0.001$ | -0.20 |
| | Euro 2 | Euro 3 | 1373253 | -11.305 | $p < 0.001$ | -0.17 |
| | Euro 3 | Euro 4 | 3337704 | -23.441 | $p < 0.001$ | -0.29 |
| | Euro 1 | Euro 3 | 854315 | -1.156 | *ns* | -0.02 |
| Smoke | Pre Euro | Euro 1 | 21198 | -0.517 | *ns* | -0.02 |
| | Euro 1 | Euro 2 | 246090 | -0.803 | *ns* | -0.02 |
| | Euro 2 | Euro 3 | 1252171 | -14.591 | $p < 0.001$ | -0.22 |
| | Euro 3 | Euro 4 | 3317897 | -23.711 | $p < 0.001$ | -0.30 |
| | Pre Euro | Euro 2 | 41902 | -0.919 | *ns* | -0.03 |

**Table 31: Mann-Whitney test statistics for diesel passenger cars by emission standard for nitric oxide and smoke**

Changes in smoke number from Pre Euro to Euro 1 and Euro 2 are not statistically significant, but changes from Euro 2 to Euro 3 and 4 are statistically significant, with low to medium effect size. When interpreting these London data, one should be aware that the diesel car sample size is increasing year on year, as diesel powered vehicles become a larger proportion of the total fleet. It is notable that the observed NO emissions from Euro 4 diesel cars are between 6 and 17 times higher than the equivalent Euro 4 petrol cars, depending on whether the comparison is based on the mean or median values. This may have significant implications for local air quality management.

## 5.3 London Taxis (M1)

### *5.3.1 Emissions from London taxis*

London taxis (black cabs) are subject to an annual licensing regime, which includes emissions standards. Since June 30$^{th}$ 2008, annual licences have only been issued to taxis that meet Euro 3 standards (TfL, 2010). This is achieved either by (a) operating a vehicle originally manufactured to Euro 3 standards, (b) retro-fitting approved emissions reduction equipment, or (c) using an LPG conversion. The taxi emissions strategy was implemented in two phases. At the time of the remote sensing surveys in 2008, all London Taxi International (LTI) type vehicles registered before September 16$^{th}$ 1998 should have been adapted to comply with the Euro 3 standard for $NO_x$ and $PM_{10}$. From July 1$^{st}$ 2007, annual licences were only issued if the vehicle was Euro 3 compliant for $NO_x$ and $PM_{10}$.

This highlights one of the limitations of using vehicle age as a proxy for Euro standard. Although some of the remote sensing surveys were carried out before the taxi emission strategy had been fully implemented, some degree of homogeneity might be expected in the results, as nearly all would have been technically Euro 3 compliant. However, it is clear from the results in Table 27 that large differences exist in NO and smoke emissions between London taxis that are Euro 2 standard by year of manufacture (but Euro 3 compliant after retro-fitting of emissions control equipment), and vehicles originally manufactured to Euro 3 standards.

**Figure 61: London taxi (black cab)**

London taxis were observed at nearly all survey sites. These vehicles are generally diesel powered. The sample size for the London taxis is significantly smaller than for the diesel cars (see Table 27). It should also be noted that the mean engine capacity for the diesel cars is 2.10 litres, whilst the mean engine capacity for the London taxis is 2.56 litres. The CO and HC emissions from both groups are low and broadly comparable, with mean CO emissions well below 0.1%, and mean HC emissions below 80ppm.

A more notable difference is in the profile of NO emissions by Euro standard. Figure 62 presents a comparison between the nitric oxide emissions of the observed diesel passenger cars and the London taxis, both vehicle category M1. The ‘peak’ in the NO emissions at Euro 2 for diesel cars has already been discussed. It can be seen that NO emissions from Euro 1 and 2 emissions standard London taxis are generally higher than from the diesel passenger car population, but that with the introduction of Euro 3 and 4, levels of NO emissions from the two groups of vehicles are similar. The London taxis display a more pronounced and clearly defined ‘step’ down from Euro 2 to Euro 3, with Euro 1 and Euro 2 emitting mean NO values of 975ppm and 928ppm respectively, and Euro 3 and Euro 4 emitting mean NO values of 414ppm and 327ppm respectively.

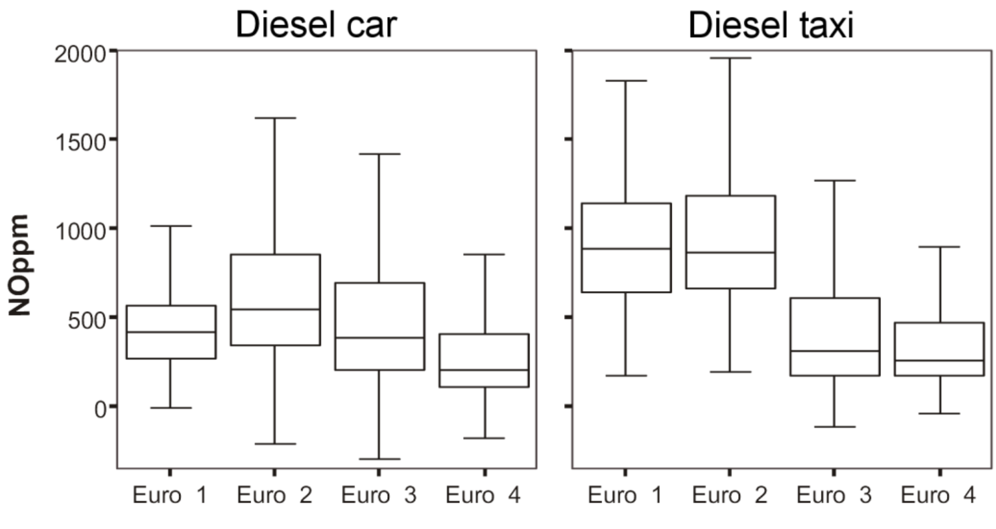



**Figure 62: Comparison of nitric oxide emissions from diesel passenger cars and London taxis**

Figure 63 compares the smoke number emissions of diesel London taxis with diesel passenger cars by Euro class (based on year of manufacture). The box plot illustrates a gradual reduction in smoke emissions from the diesel car population with the introduction of Euro 3 and 4, but a significant peak in London taxi smoke emissions at Euro 3.

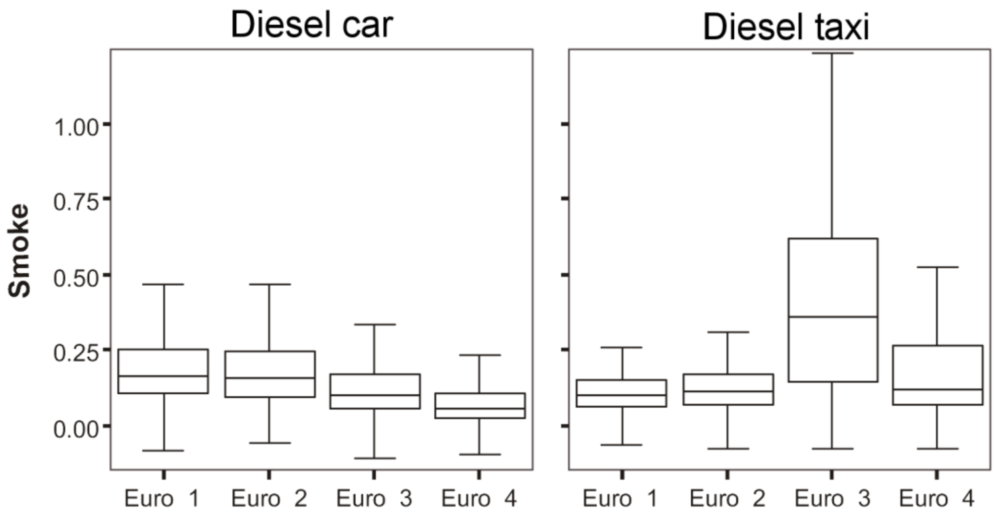



**Figure 63: Comparison of smoke emissions from diesel passenger cars and London taxis**

### *5.3.2 Significance of differences between groups*

Applying a Kruskal-Wallis test to the diesel London taxi (black cab) results by Euro standard (Euro 1 to Euro 4 inclusive, based on year of original manufacture) indicates that NO and smoke emissions are influenced significantly by changing Euro standards.

**NO:** Kruskal-Wallis statistic $H$ (df=3) is 273, with $p < 0.001$
**Smoke:** Kruskall-Wallis statistic $H$ (df=3) is 157, with $p < 0.001$

Post hoc Mann-Whitney tests were used to follow up these findings (all effects in this case are reported at a 0.0125 level of significance), the test statistics being reported in Table 32. It was found that the reduction in NO emissions from Euro 1 to Euro 2 was not statistically significant, but that the observed reduction in NO from Euro 2 to Euro 3 was statistically significant, with a large effect size (*r*=-0.59). The reduction in NO emissions from Euro 3 to Euro 4 was not statistically significant.

| Pollutant | Emission standard | Emission standard | Mann-Whitney *U* | *z* | *Significance (1-tailed)* | Effect size *r* |
|---|---|---|---|---|---|---|
| NO (ppm) | Euro 1 | Euro 2 | 12583 | -0.358 | *ns* | -0.02 |
| | Euro 2 | Euro 3 | 7005 | -12.177 | $p < 0.001$ | -0.59 |
| | Euro 3 | Euro 4 | 11357 | -1.542 | *ns* | -0.08 |
| Smoke | Euro 1 | Euro 2 | 11513 | -1.619 | *ns* | -0.09 |
| | Euro 2 | Euro 3 | 8713 | -10.814 | $p < 0.001$ | -0.53 |
| | Euro 3 | Euro 4 | 6466 | -7.398 | $p < 0.001$ | -0.41 |
| | Euro 2 | Euro 4 | 11654 | -1.453 | *ns* | -0.08 |

**Table 32: Mann-Whitney test statistics for diesel London taxis by emission standard for nitric oxide and smoke**

The increase in smoke number from Euro 1 to Euro 2 was not statistically significant, but the increase in smoke number from Euro 2 to Euro 3 was statistically significant, with a large effect size (*r*=-0.53). The subsequent reduction in smoke number from Euro 3 to Euro 4 was also statistically significant, with a medium-large effect size (*r*=-0.41). Interestingly, smoke emissions from Euro 2 and Euro 4 diesel taxis were statistically similar with the Mann-Whitney test ($p = 0.08$).

The mean and median smoke numbers for Euro 3 London taxis are more than double the other Euro classes. A more detailed analysis of the changes in vehicle technology in the London taxis suggest that changes in engine technology may explain the sharp transitions. Up until around 2002, the LTI TX1 London taxis were powered by a Nissan 2.7 litre engine (originally manufactured to Euro 2 standard). With the introduction of the LTI TXII taxi in around 2002, a Euro 3 compliant Ford 2.4 litre engine was adopted. Finally, the LTI TX4 taxi was introduced around 2006 with a Euro 4 compliant VM Motori 2.5 litre engine. If the data are grouped according to engine capacity rather than year of manufacture, the differences in emissions performance become clearer, as presented in Table 33. The differences in NO emissions from the Euro 3 (2.4 litre) and Euro 4 (2.5 litre) vehicles remain statistically insignificant, but the smoke emissions from the Euro 4 (2.5 litre) are now found to be statistically lower than the Euro 2 (2.7 litre) vehicles ($p$=0.001, with a modest effect size $r$ of -0.17).

| Engine make | Engine capacity (litres) | Emissions standard (as built) | n | **Nitric Oxide (NO)** **Mean** | ***Median*** | Smoke Number Mean | *Median* |
|---|---|---|---|---|---|---|---|
| | | | | **ppm** | ***ppm*** | | |
| Nissan | 2.7 | Euro 2 | 254 | **898** | ***848*** | 0.15 | *0.11* |
| Ford | 2.4 | Euro 3 | 206 | **323** | ***224*** | 0.48 | *0.42* |
| VM Motori | 2.5 | Euro 4 | 83 | **350** | ***271*** | 0.09 | *0.09* |

**Table 33: Observed nitric oxide and smoke exhaust emissions from London taxis (black cabs) by engine make and capacity**

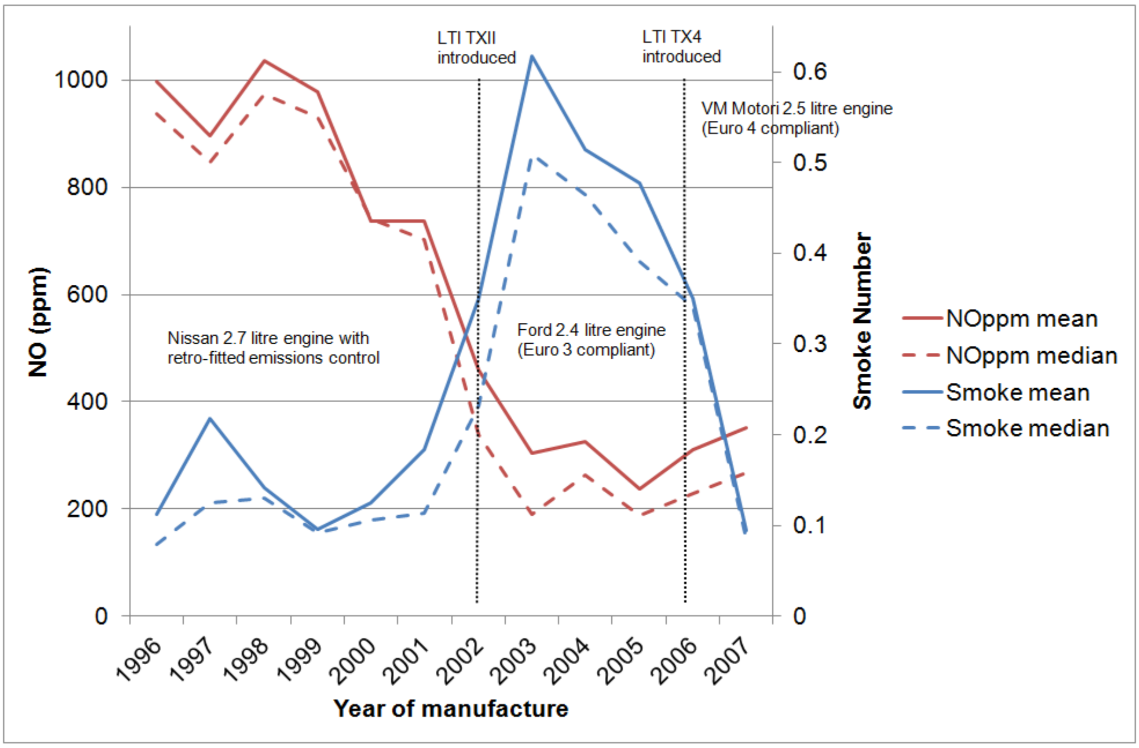



**Figure 64: Variation in NO and smoke emissions from London taxis with changes in engine technology**

This leads to the tentative conclusion that a pre 2002 model TX1 London taxi (Nissan engine with retro fitted emissions control equipment) will produce significantly lower smoke (particulate) exhaust emissions than a post 2002 LTI TXII model taxi (fitted with a Ford engine), but with much higher emissions of nitric oxide. Only with the introduction of the LTI TX4 model taxi (VM Motori engine) are both particulates and NO reduced together. This is illustrated in

Figure 64. Therefore, a simple policy of reducing the average age of the taxi fleet may in some circumstances result in a net increase in emissions of particulate matter, ceteris paribus. However, it should be noted that the sample size for the emissions measurements from London taxis in this study is significantly smaller than for the observed diesel cars, so the results should be interpreted with caution. In addition, it would be desirable to validate the opacity based measurement of smoke (particulate matter), as utilised in the remote sensing instrumentation, against other forms of particulate measurement instrumentation.

## 5.4 Buses (M3)

### *5.4.1 Emissions from buses*

Due to the way the London bus fleet (M3) is procured, most observed buses were either Euro 2 or Euro 3 based on year of manufacture (see Figure 54), being manufactured between 1999 and 2005. Table 27 and Table 28 present the mean and median emission values for each pollutant for the Euro 2 buses and Euro 3 buses. The measured CO values were extremely low (Euro 2 CO mean 0.013%, Euro 3 CO mean 0.017%). Observed HC values were also low (Euro 2 HC mean 70ppm, Euro 3 HC mean 88ppm), with identical median values of 50ppm, although the Euro 3 observations displayed more variability. A slightly clearer difference was observed in the NO measurements (Euro 2 NO mean 841ppm, Euro 3 NO mean 1001ppm). The higher emissions values for Euro 3 buses relative to Euro 2 buses were unexpected, so further investigations were carried out.

Bus (M3) is the only vehicle category that is geo-spatially constrained, i.e. buses are generally allocated to fixed routes. Some survey sites were implemented in Ealing in March/April 2008 (Spring), when average ambient daytime temperatures were around 10ºC, whereas the other survey sites were implemented in Southwark in June/July/August 2008 (Summer), when average ambient daytime temperatures were around 22ºC, as presented in Table 34. In addition, there was some variability across survey sites in terms of mean vehicle speed and acceleration.

| | | n | Temp | Speed | Accel. | CO | | HC | | NO | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | ºC<br>Mean | m/s<br>Mean | $m/s^2$<br>Mean | %<br>Mean | %<br>Median | ppm<br>Mean | ppm<br>Median | ppm<br>Mean | ppm<br>Median |
| Euro 2 | Spring | 429 | 10 | 8.8 | 0.16 | 0.008 | 0.009 | 56 | 44 | 714 | 656 |
| | Summer | 472 | 22 | 8.3 | 0.18 | 0.019 | 0.017 | 82 | 64 | 956 | 949 |
| Euro 3 | Spring | 284 | 10 | 8.2 | 0.22 | 0.012 | 0.014 | 107 | 52 | 1143 | 1033 |
| | Summer | 566 | 22 | 8.3 | 0.23 | 0.019 | 0.016 | 78 | 48 | 930 | 844 |

**Table 34: Summary of buses (M3) by Euro class and season of survey**

Inspection of the data reveals that Euro 2 and Euro 3 buses were not equally distributed across the Spring (Ealing) and Summer (Southwark) survey sites. A higher proportion of Euro 3 buses were observed at the summer survey sites when ambient temperatures were higher.

Previous work by Transport for London, reported in DEFRA (2007), indicates that there is a great deal of variation in emissions characteristics of bus vehicles, depending on bus type, Euro class, and emissions control technology. Table 35 presents an abstract from the Transport for London bus emission database (DEFRA 2007), including data for $NO_x$, primary $NO_2$, and particulates.

| Bus type | Tailpipe $NO_x$ (g $km^{-1}$) | f-$NO_2$ tailpipe (%) | PM (g $km^{-1}$) |
|---|---|---|---|
| Euro III buses fitted with DPF | | | |
| Volvo B7TL Double Deck | 12.42 | 53.4 | 0.014 |
| Scania Double Deck | 10.58 | 39.3 | 0.008 |
| Optare Solo Single Deck | 5.43 | 24.3 | 0.014 |
| Mercedes-Benz Citaro G Artic | 12.98 | 35.0 | 0.024 |
| Euro III buses fitted with DPF and SCR | | | |
| Dennis Dart single deck | 5.33 | 46.0 | 0.007 |
| Dennis Dart single deck | 4.89 | 54.3 | 0.015 |
| Euro IV buses without DPF | | | |
| Dennis Enviro 400 double deck | 7.26 | 3.7 | 0.052 |
| Dennis Dart single deck | 8.6 | 7.7 | 0.029 |

**Table 35: Extract from the TfL bus exhaust emission database**
Source: DEFRA 2007.

The data from the London surveys were disaggregated by bus type, Euro class, and location (season) to gain a better understanding of the observed emissions characteristics of these groups. A summary of NO and particulate (smoke) emissions is presented in Table 36.

| Make | Model | Year | Location | n | NO (ppm) | | Smoke number | |
|---|---|---|---|---|---|---|---|---|
| | | | | | Mean | Median | Mean | Median |
| Dennis | Single deck | 1996-2000 | Ealing (Spring) | 264 | 661 | 601 | 0.05 | 0.03 |
| Dennis | Single deck | 2001-2005 | Ealing (Spring) | 56 | 812 | 641 | 0.05 | 0.04 |
| Dennis | Double deck | 1996-2000 | Ealing (Spring) | 136 | 754 | 694 | 0.05 | 0.03 |
| Dennis | Double deck | 2006-2005 | Ealing (Spring) | 169 | 1338 | 1194 | 0.28 | 0.08 |
| Dennis | Double deck | 1996-2000 | Southwark (Summer) | 184 | 706 | 669 | 0.19 | 0.10 |
| Dennis | Double deck | 2001-2005 | Southwark (Summer) | 140 | 1042 | 902 | 0.16 | 0.09 |
| Volvo | Double deck | 2001-2005 | Ealing (Spring) | 54 | 913 | 874 | 0.08 | 0.05 |
| Volvo | Double deck | 1996-2000 | Southwark (Summer) | 229 | 1137 | 1106 | 0.04 | 0.03 |
| Volvo | Double deck | 2001-2005 | Southwark (Summer) | 430 | 903 | 839 | 0.06 | 0.04 |

**Table 36: Observed NO and smoke emissions by bus type and location**

It can be seen that all observed Dennis type vehicles manufactured in the period 2001-2005 (Euro 3) emit higher concentrations of nitric oxide than the equivalent models manufactured in the period 1996-2000 (Euro 2). The Dennis Euro 3 single deck buses operating in Ealing in the spring emit 23% more NO than the Euro 2 single deck buses operating at the same time and location (based on mean values). The Dennis Euro 3 double deck buses emit between 48% and 77% more NO than the Euro 2 double deck buses (again based on mean values) depending on season and location; the larger differential is apparent in the spring surveys in Ealing with lower ambient temperatures.

Conversely, all observed Volvo type double deck vehicles manufactured in the period 2001-2005 (Euro 3) emit lower concentrations of nitric oxide (21% lower on average) than the equivalent models manufactured in the period 1996-2000 (Euro 2).

In addition, Dennis double deck buses operating in Southwark in the summer months (with higher ambient temperatures) emit lower levels of nitric oxide than the equivalent generic type and age of vehicles operating in Ealing in the spring (with lower ambient temperatures).

There is insufficient information available regarding the type of emissions control equipment installed in this sample of vehicles. Therefore, the reasons for these differences cannot be explained with any degree of confidence. Also, since nitrogen dioxide was not measured during the remote sensing surveys, it is not possible to comment at this stage on emissions of primary $NO_2$, or total $NO_x$. Finally, as can be seen in Table 36, the sample size of observations for each group of vehicles is small, so the results should be treated with some caution. Nevertheless, the results demonstrate that there is notable variation in the nitric oxide and smoke emissions from the TfL bus fleet operating in Ealing and Southwark in 2008, and that for some groups of vehicles, newer buses are not necessarily cleaner in terms of their exhaust emissions of certain pollutants. Ambient temperature also appears to be a relevant factor.

## 5.5 Light Commercial Vehicles (N1)

### *5.5.1 Emissions from light commercial vehicles*

Table 27 and Table 28 present light commercial vehicle (N1) exhaust emissions by Euro standard for both petrol and diesel engine vehicles. It can be seen that there were far fewer petrol engine vehicles observed in the survey, with only Euro III and IV petrol vehicles exceeding 100 observations. The numbers of Euro III (3540) and IV (2761) diesel vehicles far exceeded any other groups. Given that the observed numbers of petrol engine vehicles were so low, this analysis will focus on vehicles powered by diesel engines.

As is to be expected with diesel engine vehicles, measured values of CO and HC for Euro I to IV vehicles are low (mean CO < 0.1%, mean HC < 120ppm), and display a downward trend with increasing Euro standard. Mean NO reduces from 711ppm (Euro I) to 363ppm (Euro IV). Figure 65 presents the observed emissions from N1 diesel vehicles in the form of box plots. The N1 diesel vehicles do not display the peak in NO emissions at Euro II that was seen for Euro 2 M1 diesel vehicles. Mean NO emissions from N1 class diesel vehicles were observed to be 28% higher than from M1 class diesel vehicles. Euro emissions standards for N1 class vehicles <1300kg are broadly consistent with Euro standards for M1 class vehicles, but Euro emissions standards for N1 class vehicles >1300kg are more relaxed (DoT 2007).

Figure 66 illustrates the differences between mean nitric oxide emissions from observed diesel light commercial vehicles (N1) and petrol and diesel passenger cars (M1), by year of manufacture. It can be seen that since the introduction of Euro emissions standards (circa 1993), NO emissions from diesel light commercial vehicles have tended to be higher than from diesel passenger cars. However, in the data for 2007 and 2008, it appears that the two classes of vehicles are converging, with the mean value for diesel light commercial vehicles actually marginally lower than the comparable value for diesel cars. Future surveys will tell us whether this trend continues.

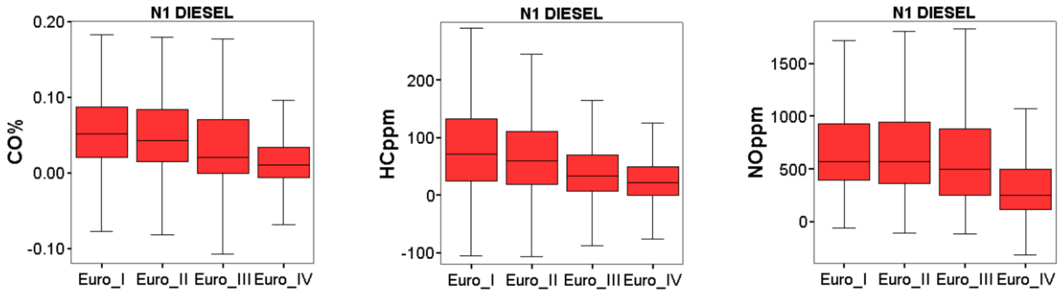



**Figure 65: Light commercial vehicle (N1) diesel exhaust emissions by Euro standard**

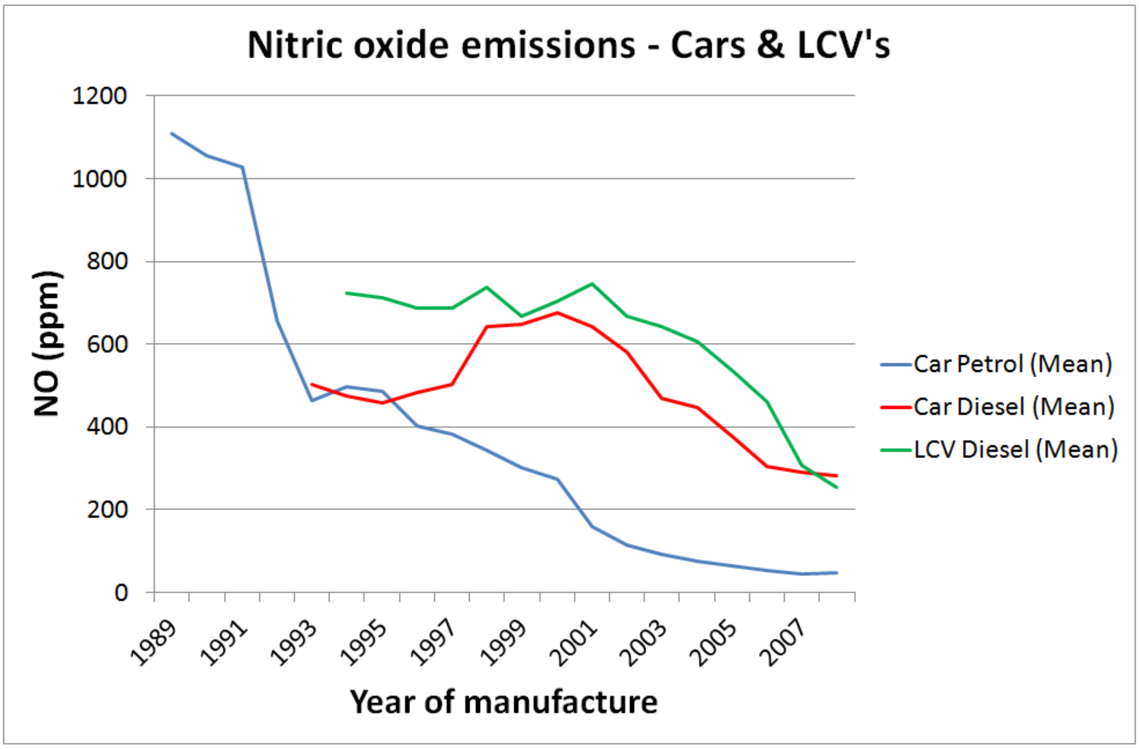



**Figure 66: Comparison of car and LCV nitric oxide emissions by year of manufacture**

### *5.5.2 Significance of differences between groups*

Diesel light commercial vehicles (category N1) represented just under 16% of all light vehicles observed in the surveys, but just over 50% of all diesel light vehicles observed. Approximately 78% of diesel N1 vehicles were either Euro III or Euro IV emissions standard.

Applying a Kruskal-Wallis test to the diesel light commercial vehicle results by Euro standard indicates that NO and smoke emissions are influenced significantly by changing Euro standards.

**NO:** Kruskal-Wallis statistic $H$ (df=3) is 1021, with $p < 0.001$

**Smoke:** Kruskal-Wallis statistic $H$ (df=3) is 706, with $p < 0.001$

Table 37 presents the post hoc Mann-Whitney test statistics, with effects reported at a 0.01 level of significance. It was found that the change in NO emissions from Euro I to Euro II was not statistically significant, but that the observed reductions in NO from Euro II to Euro III, and from Euro III to Euro IV were statistically significant, albeit with a larger effect size from Euro III to Euro IV (*r*=-0.32).

| **Pollutant** | **Emission standard** | **Emission standard** | **Mann-Whitney *U*** | ***z*** | ***Significance (1-tailed)*** | **Effect size *r*** |
|---|---|---|---|---|---|---|
| NO (ppm) | Euro I | Euro II | 374 895 | -0.926 | *ns* | -0.02 |
| | Euro II | Euro III | 1 308 439 | -5.413 | $p < 0.001$ | -0.08 |
| | Euro III | Euro IV | 3 075 580 | -25.283 | $p < 0.001$ | -0.32 |
| Smoke | Euro I | Euro II | 350 889 | -3.187 | $p = 0.001$ | -0.08 |
| | Euro II | Euro III | 1 479 858 | -0.211 | *ns* | -0.01 |
| | Euro III | Euro IV | 3 222 065 | -23.238 | $p < 0.001$ | -0.29 |

**Table 37: Mann-Whitney test statistics for diesel light commercial (N1) vehicles by emission standard for nitric oxide and smoke**

The reductions in smoke number from Euro I to Euro II ($p < 0.001$, *r*=-0.08), and from Euro III to Euro IV ($p < 0.001$, *r*=-0.29), were statistically significant, but the reduction from Euro II to Euro III was not statistically significant. Overall, the largest and most significant reduction in NO and smoke emissions from N1 diesel commercial vehicles occurred in the transition from Euro III to Euro IV emission standard. However, it should be noted that median NO emissions from Euro IV diesel N1 goods vehicles are approximately 25% higher than from Euro 4 diesel M1 passenger vehicles, reflecting the fact that the type approval $NO_x$ limit values for category N1 (<1305kg, 0.25g/km; 1305-1760kg, 0.33g/km; 1760-3500kg, 0.39g/km) are generally higher than the $NO_x$ limit value for category M1 (0.25g/km) (DoT, 2007).

## 5.6 Medium Commercial Vehicles (N2)

### *5.6.1 Emissions from medium commercial vehicles*

As can be seen from Table 21 and Table 27, the number of successful emissions measurements from medium commercial vehicles (N2) was very small, and the number for heavy commercial vehicles (N3) was even smaller. This was for two reasons. Firstly, the number of medium and especially heavy commercial vehicles operating through the survey sites in London was very small, so the opportunity to intercept them was limited. This is fairly typical of most urban areas. Secondly, the remote sensing instrumentation was deployed to capture exhaust emissions measurements from the bulk of the vehicle fleet (i.e. passenger cars), for example in terms of the height of the measurement IR/UV beam (circa 25-30cm above the ground). This meant that even if a medium (N2) or heavy (N3) vehicle passed through a survey site, a successful measurement was not as probable as for class M1 or N1 vehicles.

With cars and vans (and even buses to some extent), the configuration of the vehicle is relatively well defined (essentially a single metal box), and the position of the exhaust plume is generally predictable. So experimentally, the beam blocking and unblocking which is used to 'trigger' the gas data measurement can be set up with some confidence. With medium and heavy commercial vehicles, the variation in chassis configuration (rigid, articulated, drawbar trailers, flat beds, tippers etc.) will make the triggering of a successful measurement far more problematic.

a) The exhaust outlet is rarely conveniently at the back of the vehicle. It's often half way down the chassis, to one side, or even pointing straight up vertically.
b) Depending on how the measurement equipment is deployed, physical gaps in the vehicle configuration e.g. between the cab and the load area, have the potential to 'confuse' the system, perhaps triggering a measurement too early.

## 5.7 Gross Emitters and Overall Emissions Contribution by Vehicle Class / Euro Standard

As noted previously, earlier studies have shown that a relatively small proportion of the vehicle fleet produce the majority of polluting exhaust emissions. Table 38 presents the proportion of total emissions produced by the most polluting ‘x’% of observed vehicles, where ‘x’ is 10% and 5%.

| Vehicle type | 'x' | CO | HC | NO |
|---|---|---|---|---|
| | | | | |
| Petrol cars | 10%<br>5% | 65.1%<br>47.2% | 71.5%<br>52.3% | 65.1%<br>44.0% |
| Diesel cars | 10%<br>5% | 75.1%<br>58.7% | 52.7%<br>38.5% | 30.0%<br>17.4% |
| All cars | 10%<br>5% | 69.3%<br>51.3% | 73.9%<br>54.8% | 54.8%<br>36.1% |
| All observed vehicles | 10%<br>5% | 73.1%<br>55.5% | 73.3%<br>55.4% | 45.8%<br>29.1% |

**Table 38: Proportion of total exhaust emissions produced by the most polluting 'x'% of observed vehicles**

Around 73% of the measured CO and HC emissions from the total observed sample of vehicles were emitted by the most polluting 10% of vehicles. Approximately 46% of NO emissions were emitted by the most polluting 10% of vehicles. It can be seen from Table 38 that the emissions proportions for petrol and diesel powered cars are different, illustrating the differences in the underlying frequency distribution of the emissions data for different fuel types. As emissions limits become more stringent with each new Euro standard, the absolute level of emissions is decreasing, but CO and HC are still observed to display a skewed and peaked distribution. The NO (and to a lesser extent, HC) emissions of diesel cars are less skewed, with the most polluting 10% of cars emitting a far lower proportion of total emissions (30% of NO, and 53% of HC respectively).

Whilst a small number of older (Pre Euro) vehicles may individually be the most polluting in the fleet, the total emission contribution of each vehicle class and Euro standard is obtained by calculating the emissions weighted by the total number of vehicles in each class and the vehicle kilometres driven. Vehicle kilometres are not available directly within this study, although multiple observations at survey sites, for example for buses and taxis, provide some indication of *usage* rather than just vehicle stock. Table 39 presents the proportion of total mean exhaust emissions weighted by the observed number of vehicles. Petrol cars (all Euro classes) were observed to emit 89.9% of CO, 78.9% of HC, and 42.4% of NO. Diesel cars emitted 17.8% of NO, and diesel light commercial vehicles (N1) emitted 23.2% of NO. When individual Euro classes are considered, the most polluting emissions group is Euro 2 petrol cars which were observed to emit 34.7% of all CO, 30.1% of HC, and 17.8% of NO. At the survey sites, Euro 2 and 3 buses (M3) combined were observed to contribute 0.2% of CO, 1.9% of HC, and 8.3% of NO. London taxis (black cabs), Euro 1 to 4 inclusive, were observed to emit <0.1% of CO, 0.3% of HC, and 2.3% of NO.

Weighting by observed numbers of vehicles alone may not provide the full picture of emissions; the total vehicle kilometres driven by vehicle class on each road type should ideally also be taken specifically into account, but such data is not available in this study. Also, the relative proportions of vehicles by type observed at the survey sites may not be representative of the total vehicles operating on the network. Clearly, when considering public policy interventions to reduce exhaust emissions from road traffic, one should consider not only the emissions characteristics of different vehicle types and Euro classes, but also the absolute numbers of these vehicles operating by road type, the average age of each class (rate of fleet turnover), and the vehicle kilometres driven.

| Vehicle type | Euro standard | CO | HC | NO |
|---|---|---|---|---|
| Car - Petrol | Pre Euro | 15.9% | 17.3% | 6.4% |
| | Euro 1 | 22.6% | 20.5% | 9.9% |
| | Euro 2 | 34.7% | 30.1% | 17.8% |
| | Euro 3 | 14.7% | 10.0% | 7.2% |
| | Euro 4 | 2.0% | 0.9% | 1.2% |
| | Sub total | 89.9% | 78.9% | 42.4% |
| Car - Diesel | Pre Euro | 0.0% | 0.1% | 0.2% |
| | Euro 1 | 0.2% | 0.5% | 1.2% |
| | Euro 2 | 0.4% | 1.1% | 3.3% |
| | Euro 3 | 0.9% | 1.8% | 8.8% |
| | Euro 4 | 0.4% | 0.9% | 4.3% |
| | Sub total | 2.0% | 4.3% | 17.8% |
| Car – Hybrid Electric | Euro 4 | 0.1% | 0.0% | 0.0% |
| London Taxi | Euro 1 | 0.0% | 0.1% | 0.6% |
| | Euro 2 | 0.0% | 0.1% | 1.0% |
| | Euro 3 | 0.0% | 0.1% | 0.4% |
| | Euro 4 | 0.0% | 0.0% | 0.2% |
| | Sub total | 0.0% | 0.3% | 2.3% |
| Bus (M3) | Euro 2 | 0.1% | 0.8% | 3.9% |
| | Euro 3 | 0.1% | 1.0% | 4.4% |
| | Sub total | 0.2% | 1.9% | 8.3% |
| N1 - Petrol | Pre Euro | 1.1% | 0.9% | 0.4% |
| | Euro I | 0.4% | 0.6% | 0.1% |
| | Euro II | 0.2% | 0.2% | 0.1% |
| | Euro III | 0.4% | 0.4% | 0.1% |
| | Euro IV | 0.1% | 0.0% | 0.1% |
| | Sub total | 2.2% | 2.1% | 0.8% |
| N1 - Diesel | Pre Euro | 0.0% | 0.1% | 0.4% |
| | Euro I | 0.4% | 1.4% | 3.3% |
| | Euro II | 0.4% | 1.0% | 3.0% |
| | Euro III | 1.3% | 2.9% | 11.3% |
| | Euro IV | 0.6% | 1.5% | 5.1% |
| | Sub total | 2.7% | 6.9% | 23.2% |
| N2 - Diesel | Euro III | 0.1% | 0.3% | 1.8% |
| | Euro IV | 0.1% | 0.1% | 0.9% |
| | Sub total | 0.2% | 0.3% | 2.6% |
| Other vehicle classes and Euro standards | | 2.9% | 5.2% | 2.6% |
| | | 100% | 100% | 100% |

**Table 39: Proportion of total mean exhaust emissions weighted by observed number of vehicles**

## 5.8 Comparisons with Previous Studies in London

Sadler et al (1996) report a study where CO and HC data were collected with similar remote sensing equipment in Abbey Street and the Old Kent Road, both in the London Borough of Southwark. Mean speeds were in the range 5.6m/s and 6.9m/s. Only CO results for petrol vehicles are reported. It is reported in the 1996 study that the 90th percentile CO value for the whole data set was 4.1%. This compares with an observed 90$^{th}$ percentile CO value for petrol vehicles in the 2008 data set of 1.04%. In the 1996 study, it was reported that 50% of the CO was emitted from 11.5% of the petrol vehicles; in the 2008 study, 50% of the CO emitted by petrol vehicles was emitted from 4.95% of the petrol vehicles.

Muncaster et al (1996) report a remote sensing study where CO emissions were measured at Bounds Green Road, Haringey, London, between May 25$^{th}$ 1994 and June 1$^{st}$ 1994. Vehicles speeds were observed to range from 2.2m/s to 8.9m/s. Measurements were based on a sample of 7397 valid observations. The mean CO measurement for vehicles produced in 1993 (i.e. one year old vehicles) from the 1994 data set was 0.21%. The mean CO measurement for vehicles produced in 1993 (i.e. fifteen year old vehicles) from the 2008 data set was 0.92%, reflecting the effects of vehicle ageing, wear, and probable deterioration in maintenance regime over time. The mean CO emissions from one year old (2007) vehicles in the 2008 data set was 0.05%. Muncaster et al (1996) make the observation that older vehicles do not contribute significantly to total fleet emissions, the primary reasons being the small number of old vehicles on the road and the low mileage such vehicles undertake. This viewpoint is supported to some extent by the data presented in Table 39, but in the 2008 data set, cars (pre Euro emissions standard) were still observed to emit 15.9% of total CO, 17.4% of HC, and 6.6% of NO, not insignificant proportions of total road vehicle emissions.

Revitt et al (1999) report hydrocarbon (HC) fleet emissions from the Bounds Green Road, Haringey, survey site (May 1994) reported previously by

Muncaster et al (1996), and also HC results from an additional survey site at Abbey Road (*sic*), Southwark where data were collected in March and August 1995. Revitt et al (1999) report mean and median values for HC at the Haringey survey site (sample size 11,099) of 1000ppm and 590ppm respectively, and mean and median values for HC at the Southwark survey site (sample size 7,414) of 940ppm and 350ppm respectively. The observed mean and median HC values in the current 2008 total data set were 136ppm and 22ppm respectively. The observed mean HC values in the 2008 data set by individual survey site were in the range 94ppm to 303ppm; observed median HC values in the 2008 data set by individual survey site were in the range 8ppm to 40ppm.

It can be seen from these comparisons that mean CO emissions in 2008 are around 25% of the levels observed in the mid 1990's, and that mean HC emissions are around 14% of the levels observed in the mid 1990's. Median values have fallen even further, reflecting the change in frequency distribution over time.

### 5.9 European Comparisons

Ekstrom et al (2004) present a comparison of road vehicle exhaust emissions measurements from remote optical sensing in Gothenberg, Sweden in 2001 and 2002 with modelled results from COPERT III. Surveys were carried out at three sites with average speeds in the range 11.4m/s to 12.8m/s, and average accelerations in the range 0m/s$^2$ to +0.3m/s$^2$. Table 40 presents a comparison between the London 2008 data and the Gothenberg 2001/2 data for petrol engine cars in units of grams of emission per litre of fuel. Since the density of fuel changes with temperature, the London data were adjusted using the mean ambient temperature for each survey date and location. The Gothenburg survey locations were located to avoid interception of vehicles in cold start mode, whereas the London data will include some cold start observations. It is notable that the mean engine capacity for petrol cars in Gothenburg was much larger than in London (Gothenburg 61% > 2 litres; London 14% > 2 litres). However, when comparing Euro classes, a more significant factor may be the age of the vehicles observed. When the Gothenburg observations were made, the Euro 2 vehicles would have been between three and five years old; when the London observations were made, the Euro 2 vehicles were between eight and eleven years old. Sjodin and Andreasson (2000) and Bishop and Stedman (2008) have observed the phenomena of deterioration of emissions with increasing age of the vehicle, although the rate of deterioration it is not necessarily consistent with respect to age or year of manufacture. Such issues may explain much of the difference between the two data sets. For completeness, Table 41 presents the nitric oxide emissions results from the London 2008 surveys for diesel passenger cars (excluding London taxis), by COPERT engine capacity category; at the time of the Swedish surveys in 2001/2, the diesel car sample size (≈1100) reported in Ekstrom et al (2004) was too small to disaggregate by engine capacity.

| Pollutant | Engine capacity | Euro standard | Sample size (n) | Emissions (g/litre of fuel) | Sample size (n) | Emissions (g/litre of fuel) |
|---|---|---|---|---|---|---|
| | | | Gothenberg 2001/2 | | London 2008 | |
| CO | <1.4 litres | Pre Euro | 149 | 182.7 | 295 | 205.7 |
| | | Euro 1 | 306 | 44.2 | 1194 | 93.4 |
| | | Euro 2 | 155 | 13.8 | 2718 | 53.2 |
| | | Euro 3 | 214 | 2.8 | 4118 | 17.0 |
| | | Euro 4 | - | - | 1743 | 7.4 |
| | 1.4-2.0 litres | Pre Euro | 754 | 135.2 | 726 | 148.0 |
| | | Euro 1 | 2398 | 36.1 | 2472 | 68.0 |
| | | Euro 2 | 1943 | 15.4 | 6549 | 45.2 |
| | | Euro 3 | 1857 | 6.5 | 7377 | 16.2 |
| | | Euro 4 | - | - | 2484 | 6.2 |
| | >2.0 litres | Pre Euro | 271 | 136.2 | 285 | 145.2 |
| | | Euro 1 | 3215 | 27.0 | 606 | 52.3 |
| | | Euro 2 | 3752 | 6.8 | 1544 | 30.0 |
| | | Euro 3 | 4680 | 4.4 | 1817 | 12.7 |
| | | Euro 4 | - | - | 420 | 3.3 |
| HC | <1.4 litres | Pre Euro | 149 | 15.7 | 295 | 29.8 |
| | | Euro 1 | 306 | 4.0 | 1194 | 11.5 |
| | | Euro 2 | 155 | 0.9 | 2718 | 6.8 |
| | | Euro 3 | 214 | 0.3 | 4118 | 1.9 |
| | | Euro 4 | - | - | 1743 | 0.5 |
| | 1.4-2.0 litres | Pre Euro | 754 | 11.3 | 726 | 24.1 |
| | | Euro 1 | 2398 | 3.4 | 2472 | 9.9 |
| | | Euro 2 | 1943 | 0.9 | 6549 | 5.9 |
| | | Euro 3 | 1857 | 0.1 | 7377 | 1.6 |
| | | Euro 4 | - | - | 2484 | 0.4 |
| | >2.0 litres | Pre Euro | 271 | 15.9 | 285 | 23.6 |
| | | Euro 1 | 3215 | 2.7 | 606 | 7.0 |
| | | Euro 2 | 3752 | 0.3 | 1544 | 3.8 |
| | | Euro 3 | 4680 | -0.1 | 1817 | 1.2 |
| | | Euro 4 | - | - | 420 | 0.5 |
| NO | <1.4 litres | Pre Euro | 108 | 28.2 | 295 | 11.7 |
| | | Euro 1 | 207 | 11 | 1194 | 4.6 |
| | | Euro 2 | 114 | 1.7 | 2718 | 3.1 |
| | | Euro 3 | 166 | 1.4 | 4118 | 1.2 |
| | | Euro 4 | - | - | 1743 | 0.7 |
| | 1.4-2.0 litres | Pre Euro | 616 | 21.2 | 726 | 9.5 |
| | | Euro 1 | 1801 | 8.7 | 2472 | 4.9 |
| | | Euro 2 | 1417 | 2.7 | 6549 | 3.6 |
| | | Euro 3 | 1395 | 1.7 | 7377 | 1.2 |
| | | Euro 4 | - | - | 2484 | 0.4 |
| | >2.0 litres | Pre Euro | 211 | 22.0 | 285 | 7.8 |
| | | Euro 1 | 2733 | 6.9 | 606 | 3.9 |
| | | Euro 2 | 3213 | 2.4 | 1544 | 2.6 |
| | | Euro 3 | 3955 | 1.0 | 1817 | 0.7 |
| | | Euro 4 | - | - | 420 | 0.3 |

**Table 40: Comparison of exhaust emissions from petrol cars by COPERT engine capacity category: Gothenburg 2001/2 (Ekstrom et al 2004) and London 2008**

| Pollutant | Engine capacity | Euro standard | London 2008 | | |
|---|---|---|---|---|---|
| | | | Sample size (n) | Emissions (g/litre of fuel) | |
| | | | | Mean | Median |
| NO | <2.0 litres | Euro 1 | 244 | 6.3 | 5.4 |
| | | Euro 2 | 685 | 7.9 | 6.9 |
| | | Euro 3 | 2387 | 6.1 | 4.9 |
| | | Euro 4 | 1994 | 3.7 | 2.7 |
| | >2.0 litres | Euro 1 | 255 | 5.0 | 4.3 |
| | | Euro 2 | 327 | 6.5 | 5.5 |
| | | Euro 3 | 1150 | 5.0 | 3.8 |
| | | Euro 4 | 867 | 3.0 | 2.0 |

**Table 41: Nitric oxide emissions from diesel cars by COPERT engine capacity category: London 2008**

Sjodin and Jerksjo (2008) reported on a roadside remote sensing measurement campaign carried out in Gothenburg, Sweden in 2007 with the main aim to collect data to evaluate European emission models. The campaign was similar to the surveys carried out in Gothenburg in 2001/2, except that the instrumentation was developed to include nitrogen dioxide ($NO_2$), ammonia ($NH_3$), and sulphur dioxide ($SO_2$), in addition to CO, HC, and NO. Figure 67 presents a comparison for London and Gothenburg of the nitric oxide (NO) emissions for passenger cars, by fuel type and Euro class in the form of a bar chart. The London values are consistently lower than the Gothenburg measurements, although of similar magnitude. Values for petrol cars (Euro 2 – 4) are in particular similar. When interpreting such a comparison, the differences in sample size, vehicle operating speed and acceleration, distribution of engine capacities, and survey site characteristics should be taken into consideration. Nevertheless, the consistency in results, particularly for later Euro classes, is notable.

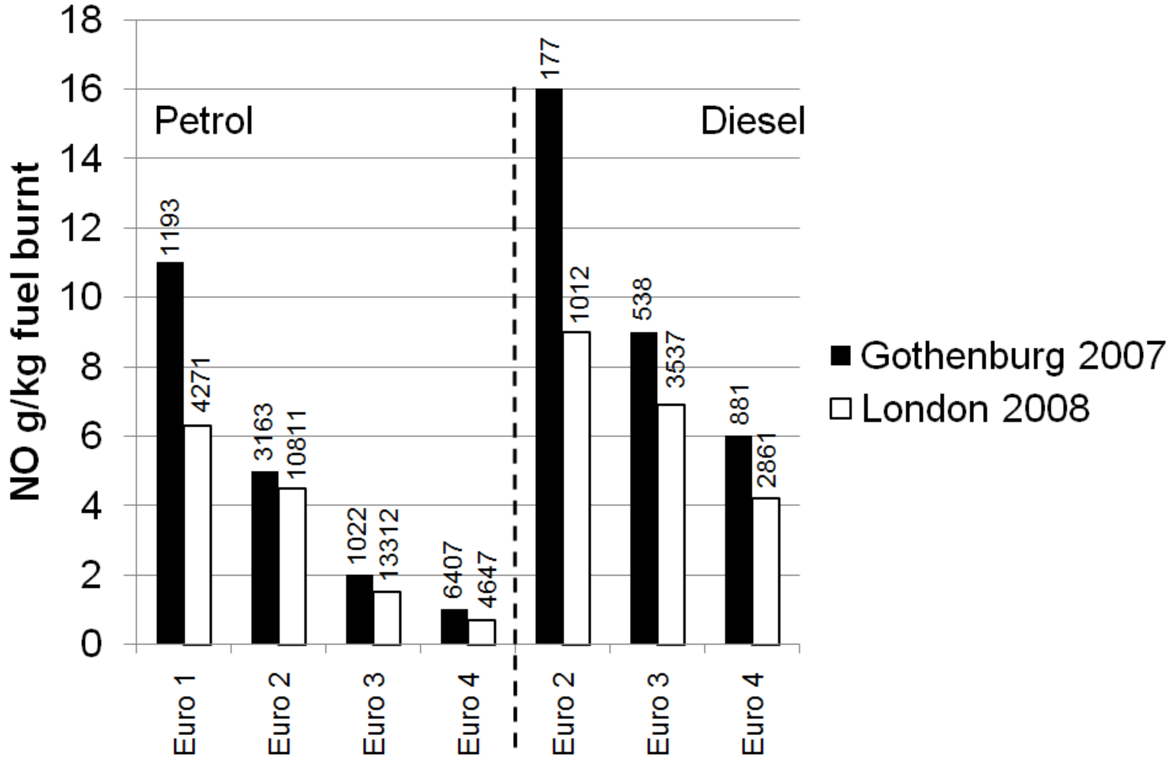



**Figure 67: Comparison of nitric oxide emissions for London 2008 and Gothenburg 2007**

*(Sjodin and Jerksjo, 2008) for passenger cars, by fuel type and Euro class. Sample size (n) is presented at the top of each bar.*

### 5.10 Comment on Instrument Accuracy and Sensitivity

The manufacturer of the RSD (Remote Sensing Device) 4600 instrumentation states that the equipment will meet or exceed the following accuracy specifications for $CO_2$ plumes greater than 20%-cm (ESP, 2005):

| | |
|---|---|
| Carbon monoxide (CO)%: | ±0.1 or ±10%, whichever is greater; |
| Hydrocarbons (HC)ppm: | ±100 or ±10%, whichever is greater; |
| Nitric oxide (NO)ppm: | ±150 or ±10%, whichever is greater; and, |
| Smoke number: | ±0.05 or ±10%, whichever is greater. |

With reference to Table 27, it can be seen that the rate of emissions varies significantly by fuel type and Euro class, and that certain fuel technologies tend to dominate certain pollutants. In terms of impact on local air quality, the primary policy focus will tend to be applied to higher emitting vehicles, weighted by vehicle kilometres driven.

CO and HC emissions from diesel vehicles tend in general to be very low, reflecting the excess air available to combustion for this fuel technology. For example, mean CO emissions from the observed diesel cars were 0.037%, and mean HC emissions from the observed diesel cars were consistently below 80ppm across all Euro classes.

On the other hand, mean NO emissions by Euro class from diesel passenger cars are consistently above 300ppm, with an observed fleet average of 435ppm. NO emissions from the observed petrol cars range from 955ppm (pre-Euro) to 49ppm (Euro 4).

In general, the relatively large sample size obtained for each combination of vehicle category, fuel type, and Euro class result in the calculated mean values being relatively stable and reliable, despite the expected distribution of data about the mean value inherent in the instrumentation specification. For the measurement of key pollutants such as nitric oxide and smoke (particulate matter) from diesel engine vehicles, the instrumentation is operating well within its design capabilities for the road vehicle fleet observed in 2008.

### 5.11 Summary

The objective of this chapter was to address the general research question “Are more stringent exhaust emissions standards, as applied to light vehicle type approval, resulting in reduced vehicle pollution in an urban area?”, in particular addressing the research objectives stated in section 1.12:

- Quantify the variability in observed road vehicle tailpipe exhaust emissions due to heterogeneity in vehicle technology, fuel type, and vehicle age, and;

- Assess the statistical significance of such variability in exhaust emissions with respect to vehicle technology, fuel type, and vehicle age.

The chapter explored the exhaust emissions characteristics of a large sample of light vehicles operating in London in 2008, based on data collected using roadside remote sensing techniques. Whilst remote sensing has some limitations in terms of the levels of absolute accuracy achievable, it has the advantage of being able to sample many thousands of vehicles as they drive past on the highway, internalising many factors which influence 'real-world' emissions. The chapter successfully quantified the variability in observed road vehicle tailpipe exhaust emissions due to heterogeneity in vehicle technology (Euro class), fuel type, and vehicle age.

It was found that evolving European emission standards, using vehicle age as a proxy for emissions standard, do have a statistically significant influence on light vehicle exhaust emissions. CO, HC, NO, and smoke (particulate) emissions from petrol cars are all seen to display statistically significant reductions with the introduction of each new emissions standard, from Pre-Euro through to Euro 4 emissions standard. It was found that NO emissions from Euro 2 diesel cars were statistically higher than either Euro 1 or Euro 3 diesel cars, but that smoke (particulates) from diesel cars reduce significantly in the transition from Euro 2 to Euro 3, and from Euro 3 to Euro 4. Perhaps of more concern for local air quality management areas is the fact that observed NO emissions from Euro 4 diesel cars were between 6 and 17 times higher than the equivalent Euro 4 petrol cars, depending on whether the comparison is based on the mean or median values. Given the continuing increase in the number of diesel cars in the UK fleet in recent years, combined with the concerns raised by some researchers regarding the increasing proportion of primary $NO_2$ in total $NO_x$ emissions from new diesel cars, this may have significant implications for future local air quality.

Interesting insights were gained into the exhaust emissions characteristics of the London taxi (black cab) fleet. Whilst the Euro 3 standard TX II and Euro 4 standard TX4 taxis were observed to have significantly lower NO emissions than older taxis retro-fitted with emissions control equipment, the Euro 3 standard TXII taxi was observed to produce significantly higher levels of smoke than either earlier TX1 or later TX4 model taxis, with the caveats identified in Section 5.3. Local air quality strategies should take this factor into account when considering the introduction of maximum age limits on the taxi fleet.

Median nitric oxide emissions from Euro IV diesel light commercial vehicles (<3.5 tonnes) were observed to be approximately 25% higher than emissions from Euro 4 diesel passenger cars. However, the transition from Euro III to Euro IV was observed to result in a statistically significant reduction in both NO and smoke emissions from diesel light commercial vehicles.

A general observation derived from the research reported in this Chapter is that it cannot be assumed that vehicle emissions decline monotonically with respect to time. Statistically significant instances have been noted where emission rates of some pollutants (whether specifically regulated or unregulated at type approval) can actually increase with the introduction of new emissions control regulations and technology. This highlights the value of monitoring the evolving emission characteristics of the UK road transport fleet systematically so that such instances can be identified and understood.

A key strategic policy issue highlighted by the data collection and analysis undertaken in this study was the dieselisation of the UK passenger car fleet. As noted previously in section 4.4, there are growing concerns about some of the environmental disbenefits associated with the 'dieselisation' of the passenger car fleet in the UK, in particular relating to production of $NO_x$, primary $NO_2$ and particulate matter. Approximately 10% of passenger cars manufactured in 1997 were diesel; By 2008, this figure had increased to approximately 43%, and it is still currently increasing. The growth in diesel fuelled passenger cars has been driven by explicit government policies to reduce fuel consumption and associated carbon dioxide emissions, through taxation and other instruments. It can be argued that local air quality policy has been seen by government as of secondary importance to the global climate change and $CO_2$ agenda, notwithstanding the economic cost calculations presented in Chapter 1. It remains to be seen whether government policy priorities will be rebalanced in future years to discourage the use of diesel fuelled vehicles in favour of more environmentally friendly alternatives, including high efficiency petrol engines, petrol hybrids, and in the longer term hydrogen fuel cells.

Chapter 6 goes on to investigate in more depth the relationship between vehicle dynamics, as characterised by vehicle specific power (VSP), and emission rates. These derived relationships are used to facilitate a reconciliation of essentially instantaneous roadside measurements of exhaust emissions from remote sensing, and published emission rates obtained from the statutory vehicle type approval process. A novel analytical technique is demonstrated to achieve this objective, and the results are used to highlight both the difference between 'in-use' vehicle emissions and results obtained from the type approval test procedure, and the degree to which 'in-use' emission rates are observed to deteriorate with respect to time as vehicles age.

# Chapter 6. Toward Reconciling Remote Sensing Data with Published Type Approval Data

## 6.1 Introduction

Exhaust emissions from road vehicles continue to be a significant source of atmospheric pollution. In European cities, emissions of particulate matter (PM) and oxides of nitrogen ($NO_x$) from road traffic are of particular concern in the context of their impact on public health (EEA 2011). The European Parliament has introduced legislation relating both to the emissions characteristics of new vehicles for type approval (also known as vehicle certification), and for ambient air quality (European Parliament 2007 & 2008). This legislation has been implemented in the domestic laws of member states of the European Community such as the United Kingdom (UK Parliament 2008 & 2010). The introduction of limit values (g/km) for polluting emissions (CO, HC, $NO_x$, and particulate matter) in exhaust gases (commonly referred to as 'Euro' standards) for new vehicle type approval in Europe has reduced emissions of some pollutants progressively since the adoption of the Euro 1 standard which implemented closed loop three-way catalytic converters for light vehicles in the early 1990's (Rhys-Tyler et al 2011). The Euro 5 standard came into force in January 2011, applicable to the registration and sale of new light vehicles, and Euro 6 is due to be implemented in January 2015 (European Parliament 2007).

Whilst the progressive tightening of exhaust emission standards for vehicle type approval over time has been successful in reducing the emissions of some pollutants, the reliance on legislated driving cycles (such as the New European Driving Cycle, or NEDC) to assess vehicle emissions has been criticized because of the differences between the specification of the laboratory based driving cycle, and the 'real-world' operation of vehicles which encompasses a range of confounding factors such as variability in highway design and operation, variation in ambient conditions, influence of other road users, and variability in driver behaviour (Pelkmans & Debal 2006, Samuel et al 2005, De Vlieger 1997). A better understanding of the 'in-use' exhaust emissions characteristics of the vehicle fleet has been achieved in recent years using remote sensing techniques (Rhys-Tyler et al 2011, Bishop & Stedman 2008). However, an analytical challenge has been to relate essentially instantaneous (typically circa 500 millisecond) roadside measurements of exhaust gases from remote sensing in terms of concentrations (ppm) or grams per kilogram (kg) of fuel burnt, to those observed over a type approval driving cycle in laboratory conditions quantified (for the purposes of the European statutory limit values) in units of grams per kilometer (g/km).

This chapter utilizes the London 2008 remote sensing dataset to determine the relationship between vehicle dynamics and exhaust emissions. The concept of vehicle specific power (VSP) is used, characterizing vehicle engine load, to facilitate this linkage (EPA 2004). The NEDC is synthesized from the remote sensing data using VSP (by Euro standard, engine capacity, and fuel type), and the emission results compared with data from vehicle type approval tests over the same driving cycle, with a view to moving towards a reconciliation of these measurement techniques. The development of such a reconciliation will help policy makers to arrive at a more coherent and holistic interpretation of the available data relating to road vehicle exhaust emissions, thereby helping to inform future policy interventions relating to both vehicle type approval and local air quality management. It will also assist in determining the rate and extent of changes in vehicle exhaust emissions with respect to vehicle age and fuel type, relative to original type approval performance, informing fleet inspection and maintenance programs, and the development of vehicle emissions models.

## 6.2 Processing of Remote Sensing Data

The AccuScan™ 4600 remote sensing device (RSD measured three exhaust gas ratios; $CO/CO_2$, $HC/CO_2$, and $NO/CO_2$. These measured ratios are utilized to produce estimates of grams of pollutant per kg of fuel burnt, following the form used by Pokharel et al (2002) and Burgard et al (2006).

$$\frac{gCO}{kgFuel} = \frac{28 \times Q \times 860}{(1+Q+(2\times 3Q'))\times 12} \qquad (1)$$

$$\frac{gHC}{kgFuel} = \frac{2\times44\times Q'\times860}{(1+Q+(2\times3Q'))\times12} \qquad (2)$$

$$\frac{gNO}{kgFuel} = \frac{30\times Q''\times860}{(1+Q+(2\times3Q'))\times12} \qquad (3)$$

where $Q = \frac{CO\%}{CO2\%}$, $Q' = \frac{HC\%}{CO2\%}$, and $Q'' = \frac{NO\%}{CO2\%}$

This assumes a fuel carbon fraction of 86%, 12g/mole for carbon, 28g/mole for carbon monoxide, 44g/mole for HC, 30g/mole for nitric oxide, and 3 carbon atoms per molecule of fuel (propane). A factor of 2 is applied to Q' because the non-dispersive infrared HC measurement calibrated with propane determines only around 50% of the HC mass compared to the flame ionization detector (FID) techniques used in the NEDC type approval test (Singer et al 1998). The RSD instrumentation also reports a 'smoke number', recorded in units of grams of diesel particulate matter per 100 grams of fuel, based on opacity measurements made at ultraviolet wavelengths in the 230 nm UV spectral range (ESP 2005, Stedman & ESP 2004).

In addition to exhaust emission data, the survey instrumentation measured vehicle speed and acceleration, and photographed each vehicle so that the license plate could be recorded. The vehicle license plates were cross referenced against the UK Driver and Vehicle Licencing Agency vehicle registration database in order to determine relevant technical information for each observed vehicle, including classification, age, and fuel technology. The date of manufacture of the vehicle was used to estimate the European emission standard for passenger cars consistent with Table 20.

## 6.3 Vehicle Specific Power

Vehicle Specific Power (VSP) is a commonly used metric of engine load, being a function of vehicle speed, acceleration, drag coefficient, tire rolling resistance, and highway gradient. The United States Environmental Protection Agency (EPA 2004) defines VSP in units of kilowatts (kW) per ton as:

$$VSP = 4.39\sin(slope)\,v + 0.22va + 0.0954v + 0.0000272v^3 \qquad (4)$$

where slope is the road grade in degrees, “v” is vehicle speed in mph, and “a” is vehicle acceleration in mph/s. VSP was calculated using Equation (4) for each remote sensing observation where data permitted.

## 6.4 New European Driving Cycle

The current European type approval driving cycle (NEDC), comprises (from a cold start) four repeated identical urban cycles of 195 seconds duration each, followed immediately by an extra-urban cycle of 400 seconds duration, resulting in a total cycle time of 1180 seconds. Each urban cycle has a theoretical distance of 1.013 km, and the extra-urban cycle has a theoretical distance of 6.955 km, resulting in a total test distance of 11.007 km. The average speeds of the urban and extra-urban cycles are 19 kilometers per hour (kph), and 62.6 kph respectively. Gear selection and change points are specified for manual transmissions. During application, a tolerance of ±2 kph is permitted between the indicated speed and the theoretical speed during acceleration, during steady speed, and during deceleration when the vehicle's brakes are used. The time tolerance is ±1.0 seconds, applicable equally at the beginning and at the end of each required gear change. The NEDC speed and acceleration profiles are illustrated in Figure 68 (a) and (b), and the calculated resultant VSP for the driving cycle from Equation (4) is presented in Figure 68 (c). During the urban cycle, the mean VSP is 1.39 (maximum 11.73, minimum -5.73); during the extra-urban cycle, the mean VSP is 6.54 (maximum 28.66, minimum -16.83); the mean VSP for the total NEDC is 3.14.

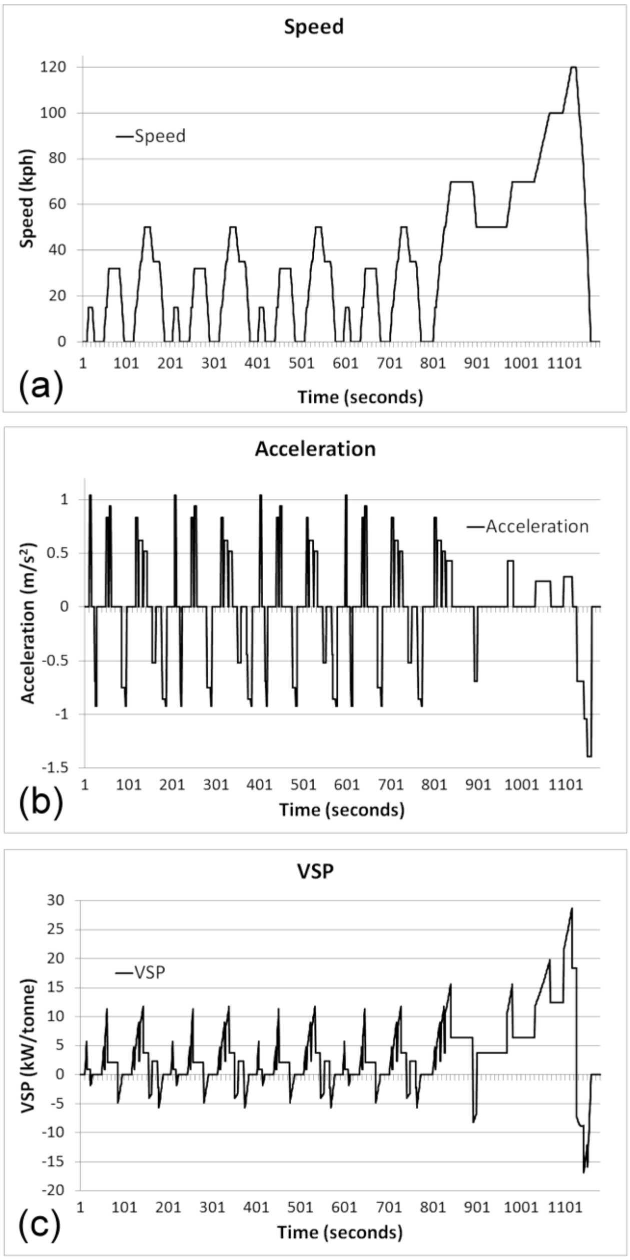



**Figure 68: New European Driving Cycle: Profiles with respect to time for (a) speed, (b) acceleration, and (c) Vehicle Specific Power**

## 6.5 Derivation of Emission Values over a Synthesized Driving Cycle

The frequency distribution of VSP over the NEDC is derived at a resolution of 2 (i.e. in VSP bins of 0<VSP≤2, 2<VSP≤4….18<VSP≤20, VSP>20). This could in principle be carried out at a higher or lower level of resolution depending on data availability. The mean emission rates derived from the remote sensing surveys for the respective VSP bins are then applied to the NEDC frequency distribution, and these are then summed (in this case at a frequency of 1Hz) to provide an estimate of the emission rate over the total driving cycle (Equation 5). In practice, the remote sensing data were classified not only by fuel type (petrol, diesel), and Euro standard (Euro 2, Euro 3, and Euro 4), but also by engine capacity.

$$Emis_{DC} = (F_{B1}.E_{B1} + F_{B2}.E_{B2} + ......F_{Bn}.E_{Bn}) / \sum_{B1}^{Bn} F \qquad (5)$$

where $Emis_{DC}$ = mean emissions rate over the synthesized driving cycle (grams/kg of fuel); F = frequency of occurrence of the VSP value in bins $_{B1..Bn}$ over the driving cycle; and E = mean emissions rate (grams/kg of fuel) associated with the VSP value in bins $_{B1..Bn}$ derived from the remote sensing data.

## 6.6 Reconciliation of Remote Sensing Emissions Data with Published Vehicle Type Approval (Certification) Data

The UK Vehicle Certification Agency (VCA) publish exhaust emission and fuel consumption test results for vehicles which have undergone the type approval test over the NEDC (VCA 2011). Data are available for tests from year 2000 onwards. The VCA data include the following variables: manufacturer; model and description; transmission; engine capacity; fuel type; Euro standard (Euro 2 onwards); fuel consumption over the test cycle (urban, extra-urban, and combined in liters/100km); and exhaust emissions (g/km) over the combined test cycle (CO, HC, HC+$NO_x$, $NO_x$, and PM, depending on the prevailing Euro standard). The VCA data were cleaned to remove any exact duplicate records in the data set, and were categorized according to fuel type, Euro standard, and engine capacity (using the commonly used European Environment Agency engine capacity classifications; petrol engines <1.4 liters, 1.4-2.0 liters, and >2.0 liters; diesel engines <2.0 liters, and > 2.0 liters) (EMEP/EEA 2012). Since both fuel consumption (liters/100km) and emissions (g/km) are available over a known driving cycle distance (11.007 km) for each vehicle tested, it is possible to calculate exhaust pollutant emissions in units of grams / liter of fuel consumed over the combined cycle.

$$\frac{grams\ of\ pollutant}{liter\ of\ fuel\ burnt} = \frac{B \times C}{\frac{A}{100} \times C}$$

where A = fuel consumption (liters/100km); B = emissions (grams/km); and C = driving cycle distance (km), in the case of the NEDC 11.007km.

Table 42 and Table 43 present summary descriptive statistics for the emission rates (grams per litre of fuel burnt), by Euro standard and engine capacity, for petrol cars and diesel cars respectively, derived as described above from the published VCA data.

| | **Euro standard** | **Engine capacity (liters)** | **n** | **Mean** | **Median** | **Max.** | **Min.** | **Std. dev.** |
|---|---|---|---|---|---|---|---|---|
| Carbon monoxide (CO) g/liter of fuel | Euro 4 | <1.4 | 956 | 6.30 | 5.31 | 17.23 | 0.37 | 3.31 |
| | | 1.4-2.0 | 2991 | 5.51 | 5.34 | 11.60 | 0.37 | 2.21 |
| | | >2.0 | 2544 | 3.65 | 3.26 | 12.15 | 0.17 | 1.83 |
| | Euro 3 | <1.4 | 455 | 8.65 | 7.91 | 28.90 | 1.51 | 4.02 |
| | | 1.4-2.0 | 1737 | 7.81 | 7.10 | 22.68 | 0.55 | 3.79 |
| | | >2.0 | 1306 | 5.33 | 4.70 | 18.06 | 0.01 | 3.25 |
| | Euro 2 | <1.4 | 221 | 9.19 | 9.09 | 22.75 | 0.33 | 4.58 |
| | | 1.4-2.0 | 732 | 7.40 | 6.89 | 21.97 | 0.53 | 4.15 |
| | | >2.0 | 348 | 4.46 | 4.10 | 14.80 | 0.00 | 3.48 |
| Oxides of nitrogen ($NO_x$) g/liter of fuel | Euro 4 | <1.4 | 956 | 0.51 | 0.48 | 2.35 | 0.02 | 0.27 |
| | | 1.4-2.0 | 2991 | 0.34 | 0.29 | 1.51 | 0.00 | 0.20 |
| | | >2.0 | 2544 | 0.26 | 0.23 | 1.87 | 0.00 | 0.16 |
| | Euro 3 | <1.4 | 455 | 0.56 | 0.47 | 8.97 | 0.00 | 0.53 |
| | | 1.4-2.0 | 1737 | 0.58 | 0.52 | 4.66 | 0.07 | 0.40 |
| | | >2.0 | 1306 | 0.40 | 0.33 | 5.58 | 0.00 | 0.30 |
| Hydrocarbons (HC) g/liter of fuel | Euro 4 | <1.4 | 956 | 0.91 | 0.88 | 1.66 | 0.18 | 0.26 |
| | | 1.4-2.0 | 2991 | 0.66 | 0.67 | 1.42 | 0.15 | 0.23 |
| | | >2.0 | 2544 | 0.49 | 0.48 | 1.17 | 0.00 | 0.20 |
| | Euro 3 | <1.4 | 455 | 1.29 | 1.23 | 2.83 | 0.12 | 0.57 |
| | | 1.4-2.0 | 1737 | 1.07 | 1.01 | 2.31 | 0.04 | 0.45 |
| | | >2.0 | 1306 | 0.73 | 0.68 | 2.20 | 0.00 | 0.35 |
| HC+$NO_x$ g/liter of fuel | Euro 2 | <1.4 | 221 | 2.82 | 2.71 | 6.23 | 0.45 | 1.26 |
| | | 1.4-2.0 | 732 | 2.44 | 2.39 | 7.28 | 0.33 | 1.12 |
| | | >2.0 | 348 | 1.58 | 1.30 | 11.54 | 0.11 | 1.26 |

**Table 42: Descriptive statistics of petrol car exhaust emissions (g/liter of fuel) from NEDC type approval tests (VCA).**

| | Euro standard | Engine capacity (liters) | n | Mean | Median | Max. | Min. | Std. dev. |
|---|---|---|---|---|---|---|---|---|
| Carbon monoxide (CO) g/liter of fuel | Euro 4 | <2.0 | 2062 | 2.76 | 2.34 | 10.45 | 0.00 | 1.93 |
| | | >2.0 | 998 | 1.91 | 1.69 | 6.96 | 0.01 | 1.29 |
| | Euro 3 | <2.0 | 1181 | 3.60 | 2.96 | 12.02 | 0.04 | 2.35 |
| | | >2.0 | 793 | 2.86 | 2.17 | 10.29 | 0.00 | 2.24 |
| | Euro 2 | <2.0 | 213 | 7.48 | 7.08 | 17.81 | 0.29 | 4.26 |
| | | >2.0 | 154 | 5.47 | 4.89 | 16.62 | 0.71 | 3.59 |
| Oxides of nitrogen ($NO_x$) g/liter of fuel | Euro 4 | <2.0 | 2062 | 3.67 | 3.62 | 5.97 | 0.35 | 0.63 |
| | | >2.0 | 998 | 2.97 | 2.93 | 4.90 | 1.40 | 0.46 |
| | Euro 3 | <2.0 | 1181 | 6.99 | 7.03 | 11.31 | 0.00 | 1.49 |
| | | >2.0 | 793 | 5.74 | 5.90 | 10.29 | 0.00 | 1.56 |
| $HC+NO_x$ g/liter of fuel | Euro 4 | <2.0 | 2062 | 4.06 | 4.04 | 6.83 | 2.07 | 0.71 |
| | | >2.0 | 998 | 3.31 | 3.31 | 5.50 | 1.95 | 0.48 |
| | Euro 3 | <2.0 | 1181 | 7.57 | 7.54 | 11.78 | 3.00 | 1.41 |
| | | >2.0 | 793 | 6.41 | 6.33 | 10.67 | 0.83 | 1.23 |
| | Euro 2 | <2.0 | 213 | 10.07 | 9.76 | 15.06 | 6.34 | 1.77 |
| | | >2.0 | 154 | 9.29 | 8.73 | 14.93 | 1.96 | 2.69 |
| Particulate matter (PM) g/liter of fuel | Euro 4 | <2.0 | 2062 | 0.23 | 0.30 | 0.79 | 0.00 | 0.18 |
| | | >2.0 | 998 | 0.16 | 0.06 | 0.74 | 0.00 | 0.16 |
| | Euro 3 | <2.0 | 1181 | 0.60 | 0.58 | 1.19 | 0.00 | 0.17 |
| | | >2.0 | 793 | 0.57 | 0.56 | 1.13 | 0.01 | 0.18 |
| | Euro 2 | <2.0 | 213 | 1.07 | 0.92 | 10.37 | 0.41 | 1.28 |
| | | >2.0 | 154 | 1.43 | 0.83 | 16.02 | 0.35 | 2.69 |

**Table 43: Descriptive statistics of diesel car exhaust emissions (g/liter of fuel) from NEDC type approval tests (VCA).**

The European type approval process specifies fuel density (diesel 833 – 837 kg/m$^3$ at 15°C; petrol 740 – 754 kg/m$^3$ at 15°C), and also stipulates that test vehicles must undergo preconditioning at between 20-30 degrees C prior to testing (European Parliament 2007). Therefore, assuming fuel density at 15°C of 747 kg/m$^3$ (petrol) and 835 kg/m$^3$ (diesel), a mean test temperature of 25°C, and estimates of coefficients of thermal expansion of fuel (petrol 0.00095 per degree C; diesel 0.00083 per degree C), it is possible to convert grams of pollutant per liter of fuel into units of grams of pollutant per kilogram of fuel for the VCA test results (Chevron 2007). This permits direct comparison with the exhaust pollutant emission rates calculated over the synthesized NEDC using the remote sensing data (based on emissions rate per VSP bin).

### 6.7 Relationship between Emissions Rate and VSP

Overall, 119,319 vehicles were observed passing through the remote sensing survey sites, of which 54,599 had valid emissions measurements and vehicle identification, across all vehicle types. The mean vehicle speed through the survey sites was 32.4 kilometers per hour (kph) (std. deviation 9.1kph), and the mean vehicle acceleration was +0.2 $m/s^2$ (std. deviation 0.6$m/s^2$).

Figure 69 to Figure 71 inclusive present the relationships between emissions rate (grams of pollutant per kilogram of fuel burnt) and VSP for diesel passenger cars by Euro class for nitric oxide, carbon monoxide, and smoke number respectively. Figure 72 to Figure 74 inclusive present the same relationships for petrol passenger cars by Euro class for nitric oxide, carbon monoxide, and hydrocarbons respectively. VSP has been aggregated into bins at intervals of two from -10 to +20. Most observations lie in the VSP range -4 to +14, as indicated by the increasing height of the confidence intervals at each tail (high and low) of the distribution.

In Figure 69 (a) and (b), nitric oxide emissions from diesel cars, it can be seen that whilst both Euro 4 and Euro 3 vehicles present a similar positive relationship between VSP and emissions when VSP is greater than 2, the absolute level of nitric oxide emissions from the Euro 4 vehicles is significantly lower according to a pair wise Mann Whitney test (Euro 4 un-weighted mean 4.2g/kg; Euro 3 un-weighted mean 6.9g/kg). See Figure 56 and Table 31 for previous discussion. The positive relationship between emissions and VSP is less well defined at Euro 2 (where mean NO emissions are at a maximum), and the relationship appears to become indeterminate or even negative at Euro 1.

In Figure 70, the relationships between carbon monoxide emissions from diesel cars and VSP are not clear. From Table 27 and Table 28, it is clear that carbon monoxide emissions decrease monotonically from Euro 1 through to Euro 4, but there is no clear relationship between CO emissions and engine load.

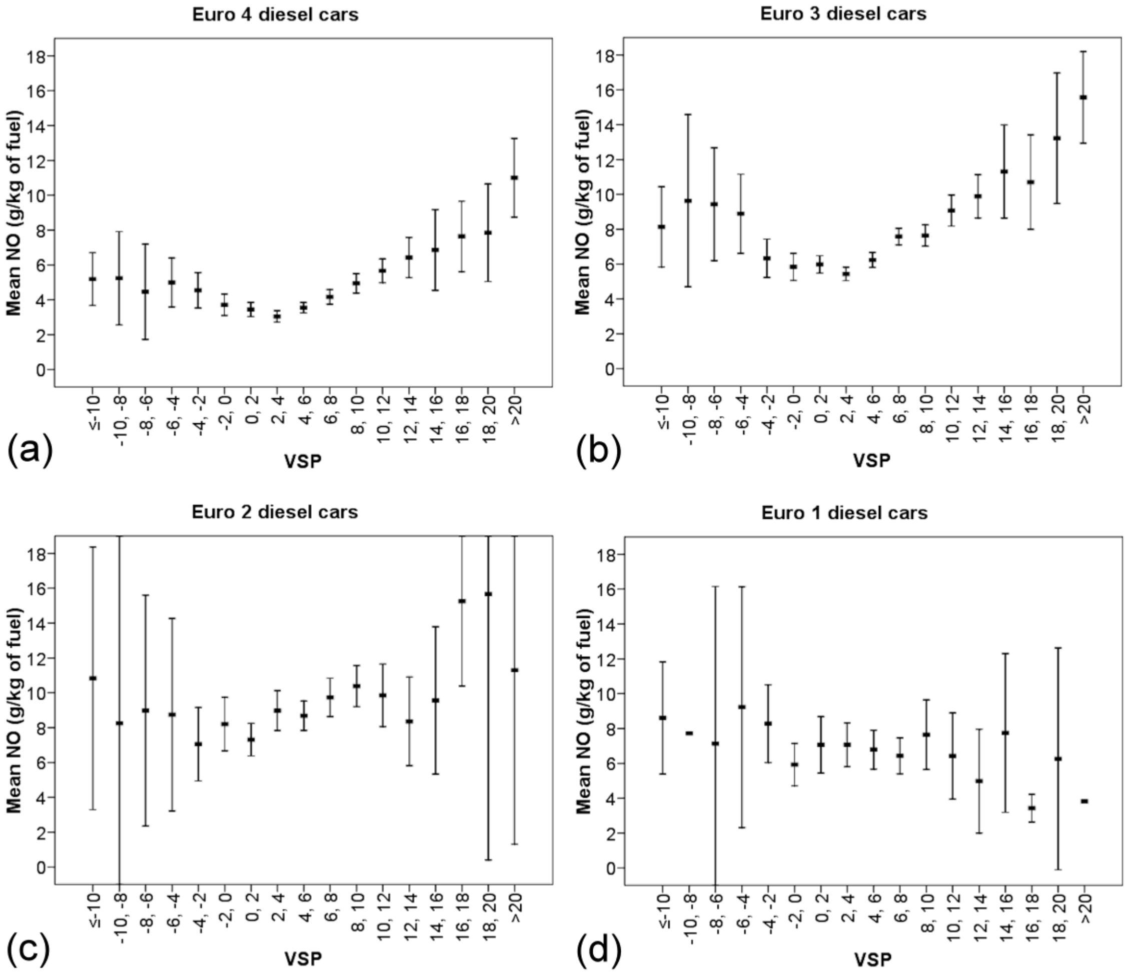



**Figure 69: Mean nitric oxide (NO) emissions (g/kg of fuel) by VSP bin for observed diesel powered passenger cars in remote sensing surveys**

(a) Euro 4 emissions standard; (b) Euro 3 emissions standard; (c) Euro 2 emissions standard; (d) Euro 1 emissions standard.

Error bars indicate 95% confidence level around the mean.

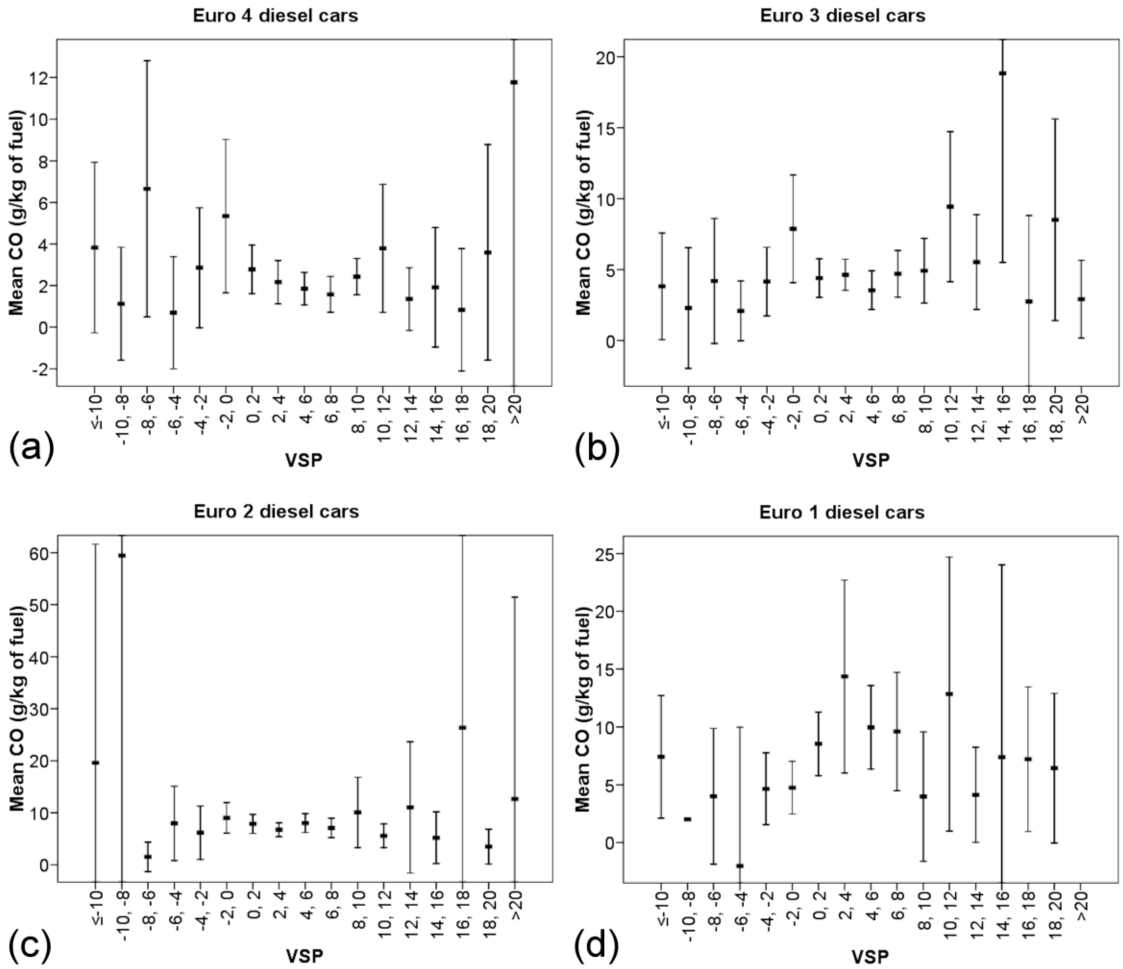



**Figure 70: Mean carbon monoxide (CO) emissions (g/kg of fuel) by VSP bin for observed diesel powered passenger cars in remote sensing surveys**

(a) Euro 4 emissions standard; (b) Euro 3 emissions standard; (c) Euro 2 emissions standard; (d) Euro 1 emissions standard.

Error bars indicate 95% confidence level around the mean.

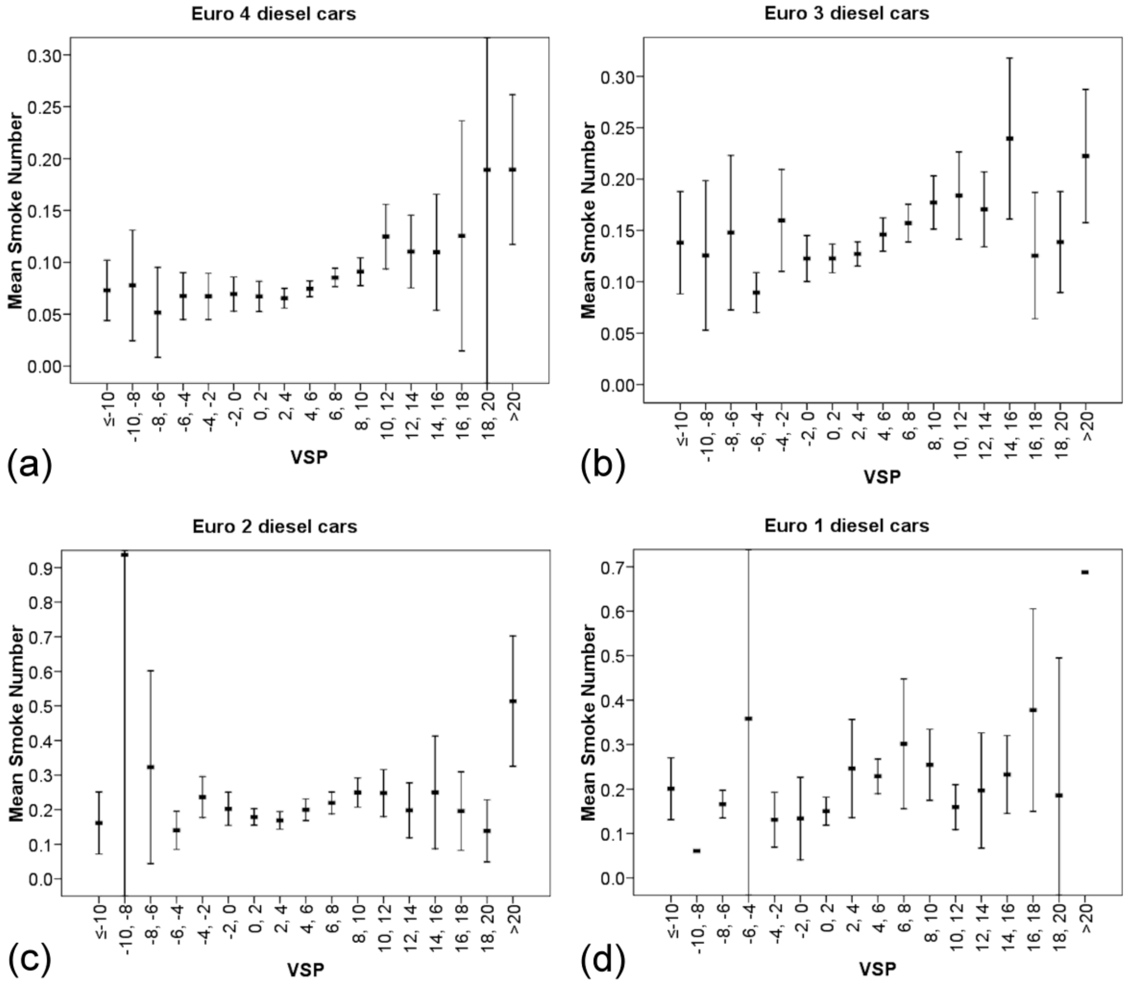



**Figure 71: Mean smoke number by VSP bin for observed diesel powered passenger cars in remote sensing surveys**

(a) Euro 4 emissions standard; (b) Euro 3 emissions standard; (c) Euro 2 emissions standard; (d) Euro 1 emissions standard.

Smoke number is reported in units of grams of diesel particles per 100 grams of fuel burnt, based on opacity measurements made at ultraviolet wavelengths in the 230 nm UV spectral range.

Error bars indicate 95% confidence level around the mean.

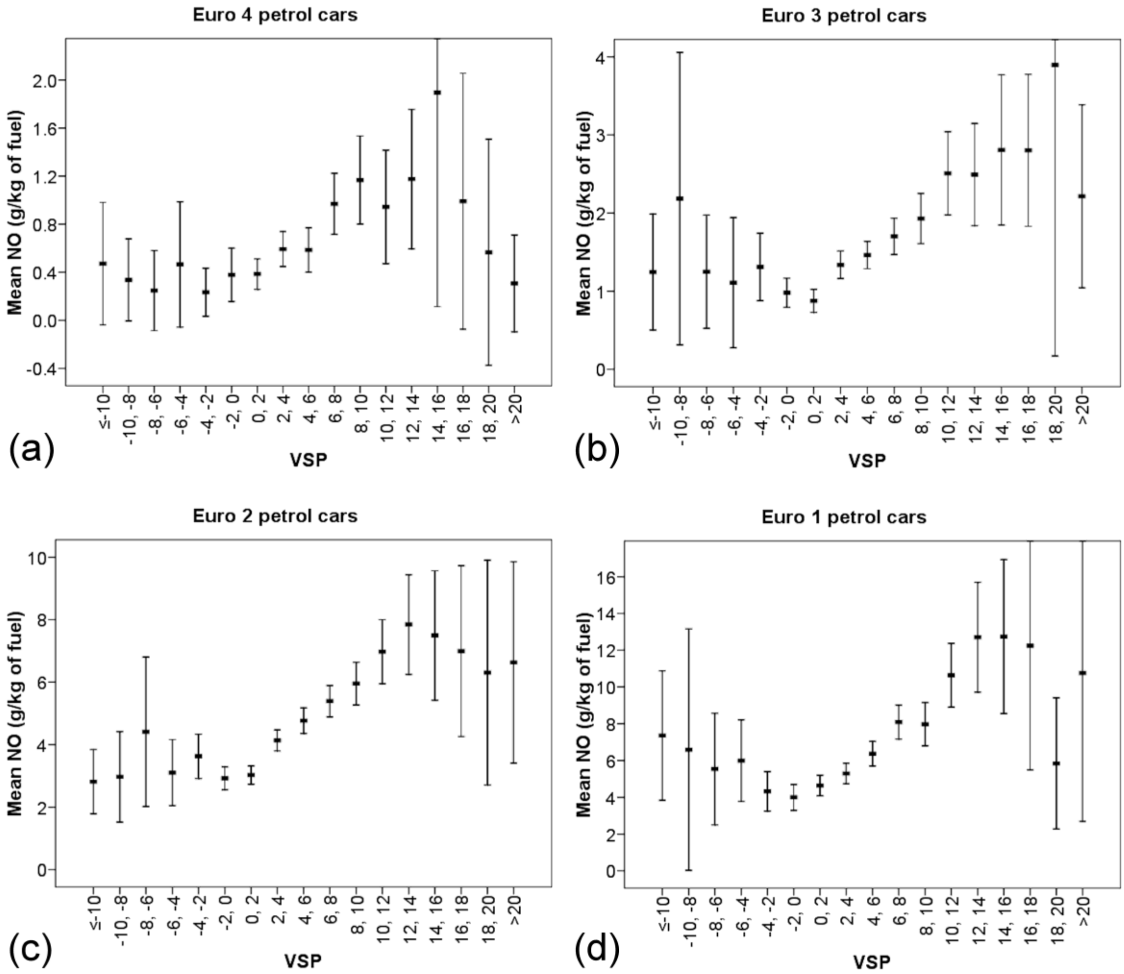



**Figure 72: Mean nitric oxide (NO) emissions (g/kg of fuel) by VSP bin for observed petrol powered passenger cars in remote sensing surveys**

(a) Euro 4 emissions standard; (b) Euro 3 emissions standard; (c) Euro 2 emissions standard; (d) Euro 1 emissions standard.

Error bars indicate 95% confidence level around the mean.

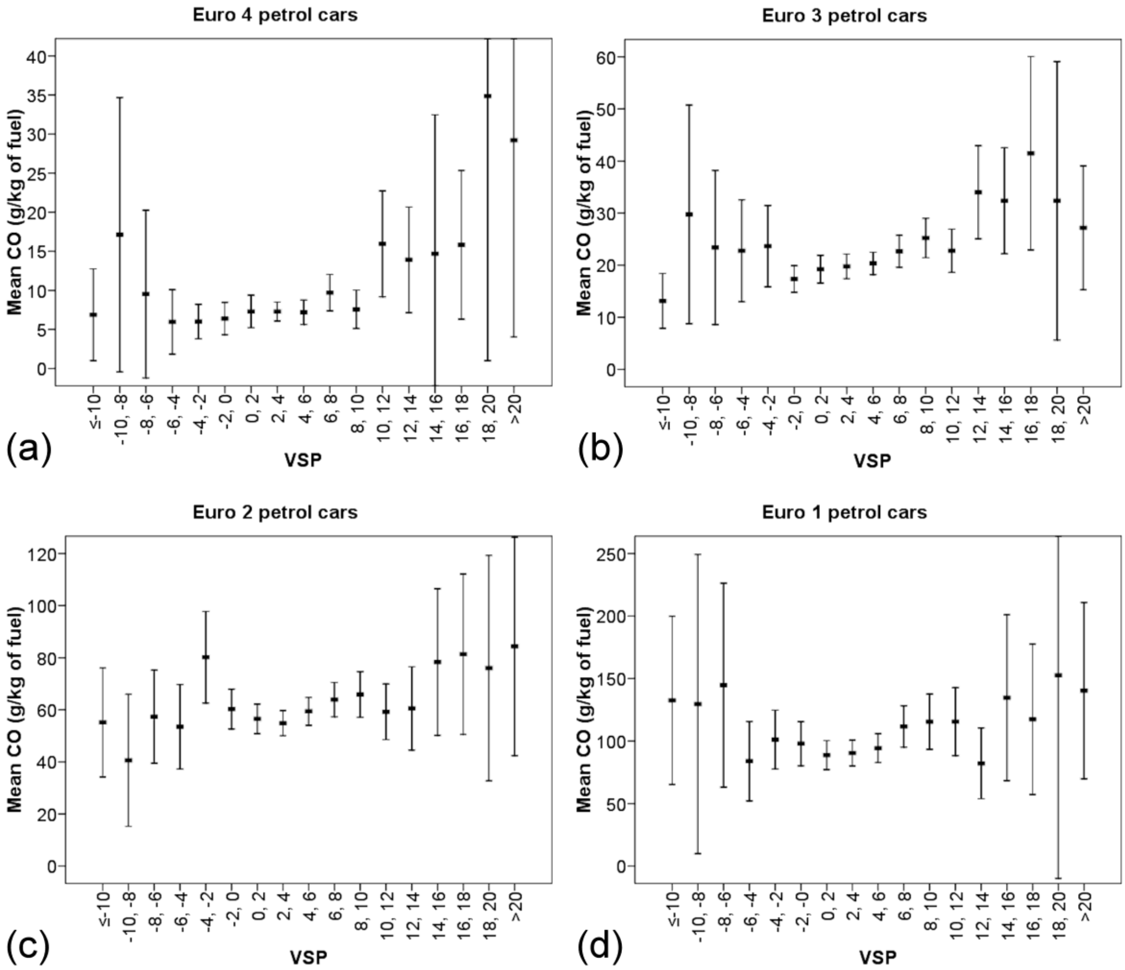



**Figure 73: Mean carbon monoxide (CO) emissions (g/kg of fuel) by VSP bin for observed petrol powered passenger cars in remote sensing surveys**

(a) Euro 4 emissions standard; (b) Euro 3 emissions standard; (c) Euro 2 emissions standard; (d) Euro 1 emissions standard.

Error bars indicate 95% confidence level around the mean.

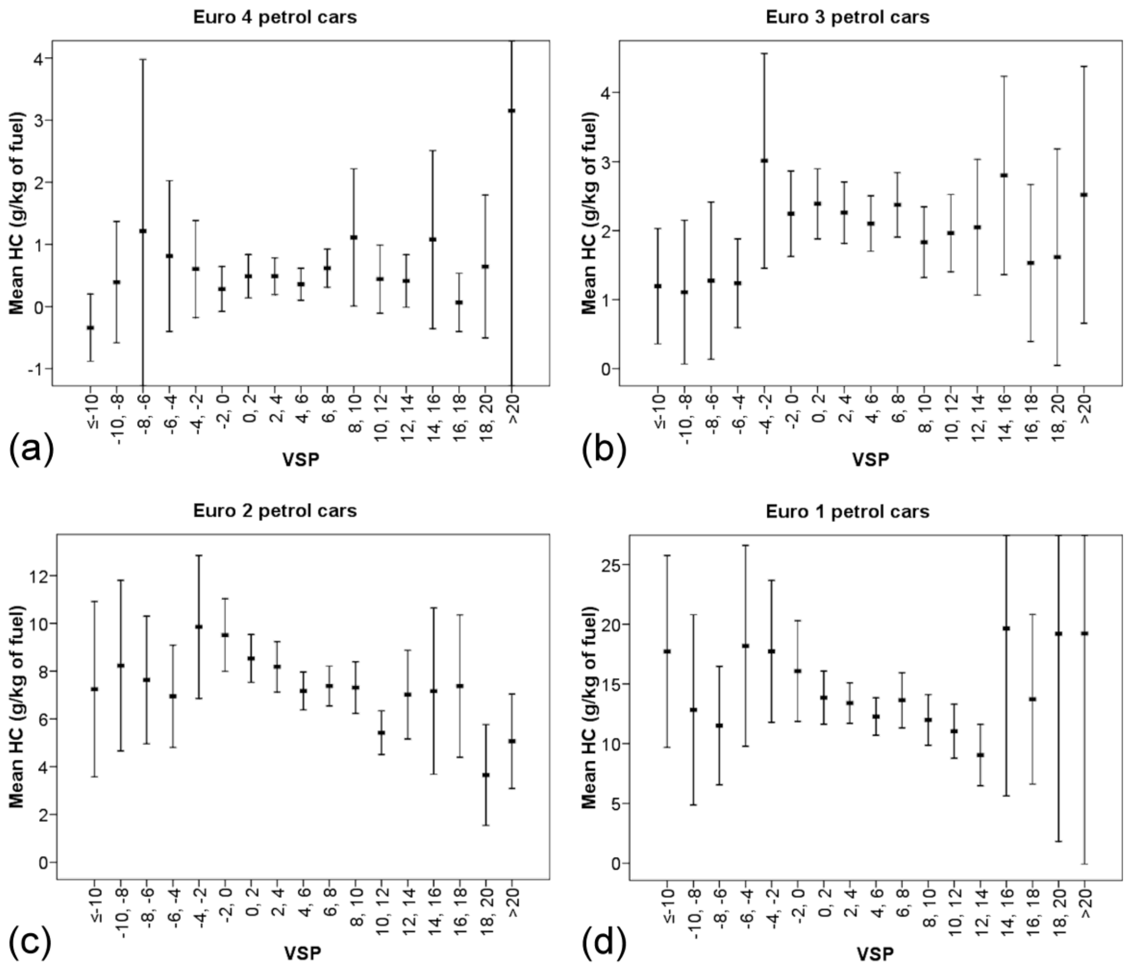



**Figure 74: Mean hydrocarbon (HC) emissions (g/kg of fuel) by VSP bin for observed petrol powered passenger cars in remote sensing surveys**

(a) Euro 4 emissions standard; (b) Euro 3 emissions standard; (c) Euro 2 emissions standard; (d) Euro 1 emissions standard.

Error bars indicate 95% confidence level around the mean.

In Figure 71 (a) Euro 4 and (b) Euro 3, there is a reasonably well defined positive relationship between smoke emissions from diesel cars and VSP when VSP > 0. The relationships are less clear at Euro 2 (Figure 71(c)) and Euro 1 (Figure 71(d)).

In Figure 72, there is a reasonably clear positive relationship between nitric oxide emissions from petrol cars and VSP, when VSP is greater than 0 but less than around 16. Higher emissions of oxides of nitrogen are generally produced by higher engine loads and combustion temperatures, so this is intuitive. The uncertainty for higher values of VSP will be influenced by low sample size. As noted in Table 27 and Table 30, there is a statistically significant reduction in nitric oxide emissions from petrol cars at each stage from Euro 1 to Euro 4.

In Figure 73 (carbon monoxide emissions from petrol cars), there appears to be a discontinuity or step change in the relationship between carbon monoxide emissions and VSP for Euro 4 and Euro 3 at VSP values of around 10 to 12. This may be due to the engine mapping providing fuel enrichment at higher engine loads to meet power demand, but it should be remembered that these data are fleet averages. Nevertheless, there does appear to be a step in the data. This is also noticeable at Euro 2, but to a lesser degree. From Table 27 and Table 30, there is a statistically significant reduction in carbon monoxide emissions from petrol cars at each stage from Euro 1 to Euro 4.

Figure 74 presents the relationship between VSP and hydrocarbon emissions from petrol cars for Euro 1 to 4. The relationship at Euro 4 and 3 appears rather indeterminate, whereas for Euro 2 and 1, the relationship appears negative for values of VSP between around -4 to +14. Again, sample size is a constraint on interpretation at the extremities of the distribution. From Table 27 and Table 30, there is a statistically significant reduction in hydrocarbon emissions from petrol cars at each stage from Euro 1 to Euro 4.

## 6.8 Comparison of VSP Frequency Distributions

Figure 75 presents (a) the frequency distribution of VSP observed from the light vehicles in the remote sensing surveys (mean VSP 4.28, standard deviation 5.04, n=45,855),), and (b) the frequency distribution of VSP in the total NEDC (mean VSP 3.14, standard deviation 6.02, n=1,180) respectively. The range of VSP values observed in the remote sensing surveys encompasses the range of VSP values generated by the driving cycle, although the different operating phases in the NEDC result in a distribution with more than one mode, whereas the VSP distribution from the remote sensing surveys has only one mode.

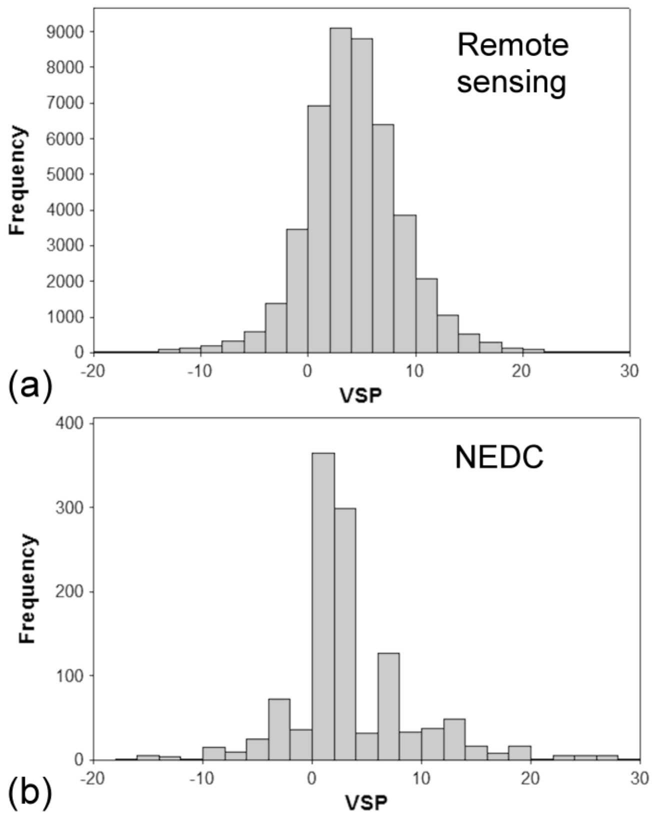



**Figure 75: Comparison of VSP frequency distributions.**

If one considers only the urban cycles within the NEDC (780 seconds), the resultant mean VSP is 1.39 (standard deviation 3.31, n=780) as noted previously. Therefore, notwithstanding the fact that the total NEDC includes an extra-urban element (with speeds up to 120 km/h), the frequency distribution of VSP over the total NEDC (1180 seconds), and in particular the mean, resembles more closely the observed urban RSD data than the urban element of the NEDC alone. This is not surprising given that the survey sites were located to observe moving traffic (ideally under load), whereas the urban element of the NEDC contains stops when the engine is idling.

## 6.9 Illustration of the Derivation of the Mean Emissions Rate over a Synthesised Drive Cycle

Table 44 presents an illustrative example of the application of Equation (5), calculating the mean emissions rate over the synthesized driving cycle ($Emis_{DC}$) in units of grams of pollutant per kg of fuel, using data for Euro 3 and Euro 4 diesel passenger cars.

| VSP Bin | Acceleration | *F* | *E* (Nitric oxide g/kg, Euro 3 diesel car) | *E* (Nitric oxide g/kg, Euro 4 diesel car) |
|---|---|---|---|---|
| <-10 | Negative | 12 | 8.14 | 5.19 |
| -10 to -8 | Negative | 16 | 9.64 | 5.24 |
| -8 to -6 | Negative | 10 | 9.44 | 4.46 |
| -6 to -4 | Negative | 25 | 8.89 | 5.00 |
| -4 to -2 | Negative | 73 | 6.34 | 4.55 |
| -2 to 0 | Negative<br>Zero | 50<br>280 | 5.84 | 3.71 |
| 0 to 2 | Zero<br>Positive | 50<br>22 | 5.72<br>6.80 | 3.42<br>3.50 |
| 2 to 4 | Zero<br>Positive | 277<br>22 | 4.27<br>5.61 | 2.89<br>3.06 |
| 4 to 6 | Positive | 32 | 6.24 | 3.55 |
| 6 to 8 | Zero<br>Positive | 100<br>28 | 7.58 | 4.17 |
| 8 to 10 | Positive | 34 | 7.64 | 4.95 |
| 10 to 12 | Positive | 38 | 9.07 | 5.67 |
| 12 to 14 | Zero<br>Positive | 30<br>19 | 9.89 | 6.43 |
| 14 to 16 | Positive | 17 | 11.31 | 6.86 |
| 16 to 18 | Positive | 8 | 10.70 | 7.64 |
| 18 to 20 | Zero<br>Positive | 10<br>7 | 13.22 | 7.85 |
| >20 | Positive | 20 | 15.56 | 11.01 |
| | | **$\Sigma F_{B1..Bn}$ =1180** | **$Emis_{DC}$ = 6.59g/kg** | **$Emis_{DC}$ = 4.12g/kg** |

**Table 44: Example derivation of mean emission rates of nitric oxide for a synthesized NEDC from the observed remote sensing observations.**

Where appropriate, VSP bins have been subdivided by acceleration state (negative, zero, positive), and the subdivisions populated with emission rates where the data permits, to reflect the potential differences in mean emissions rates which occur with differing acceleration rates within the same VSP bin.

Table 45 presents the comparison between petrol car mean emission rates obtained from VCA NEDC type approval tests, and emission rates derived from remote sensing data over a synthesized NEDC ($Emis_{DC}$). Table 46 presents a similar comparison for diesel cars. When interpreting these results, a number of important caveats should be noted. Firstly, the remote sensing device used in the surveys in London in 2008 measured nitric oxide (NO), whereas the type approval test measures total oxides of nitrogen ($NO_x$). Differences in NO and $NO_x$ emissions may be expected, particularly in newer diesel cars as the proportion of primary $NO_2$ in total $NO_x$ increases. Recent studies suggest that the proportion of primary $NO_2$ in total $NO_x$ in diesel car exhaust is in the range 11-14% at Euro 2, increasing to approximately 55% at Euro 4. In contrast, the proportion of primary $NO_2$ in total $NO_x$ in petrol car exhaust is estimated to be in the range 1-4%, with higher values for petrol cars with direct injection fuel systems (Grice et al 2009; Sjodin & Jerksjo 2008; Alvarez et al 2008). Secondly, European legislation stipulates that emissions of oxides of nitrogen ($NO_x$) are expressed in nitrogen dioxide ($NO_2$) equivalent values (European Parliament 1998). A conversion from NO to $NO_2$ equivalent values (assuming a factor of 46/30) for the remote sensing data is included in Table 45 and Table 46. Thirdly, the estimation of particulate matter based on opacity measurements in the remote sensing surveys differs fundamentally from the gravimetric approach used in the NEDC tests, so comparisons of trends within the two data sources may be more appropriate than direct comparisons between the two data sets. Fourthly, the calculated mean emission values in the VCA data set are measures of central tendency across the vehicles tested by VCA in the laboratory, whereas the mean calculated from the RSD measurements are based on the methodology described in Equation (5) and Table 44. Whilst aspects of driver behaviour such as gear changing and gear selection are controlled within known tolerances in the NEDC type approval test, there is no such control in the data obtained from remote sensing. Higher and more variable emission rates may be expected in the data obtained from remote sensing than from the VCA data, due to uncontrolled variability in driver behaviour. Finally, the VCA test results were obtained from the vehicles when they were new. In the RSD data collected in 2008, the observed Euro 4 vehicles were between 0 and 3 years old; the Euro 3 vehicles were between 4 and 8 years old; and the Euro 2 vehicles were between 9 and 12 years old. Mechanical deterioration of engines, failures in emission control systems, and variation in levels of maintenance over time may also be sources of variability in the emissions data obtained using remote sensing.

| Euro emission standard | Engine capacity (liters) | Mean emission rates (grams per kg of fuel burnt)[a] | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | VCA | | | | Remote sensing ($Emis_{DC}$) | | | |
| | | $NO_x$[b] | CO | HC | HC+$NO_x$ | NO | NO ( as $NO_2$ equivalent)[c] | CO | HC[d] |
| **Euro 4** | <1.4 | 0.69 ± 0.02 | 8.51 ± 0.28 | 1.22 ± 0.02 | - | 0.73 ± 0.18 | 1.12 ± 0.28 | 11.15 ± 2.39 | 0.98 ± 0.60 |
| | 1.4-2.0 | 0.46 ± 0.01 | 7.45 ± 0.11 | 0.90 ± 0.01 | - | 0.60 ± 0.13 | 0.92 ± 0.20 | 8.42 ± 1.36 | 0.30 ± 0.17 |
| | >2.0 | 0.35 ± 0.01 | 4.93 ± 0.10 | 0.66 ± 0.01 | - | 0.31 ± 0.34 | 0.48 ± 0.52 | 4.40 ± 1.55 | 0.38 ± 0.32 |
| | Total | 0.45 ± 0.01 | 6.62 ± 0.08 | 0.85 ± 0.01 | - | 0.62 ± 0.10 | 0.95 ± 0.15 | 8.88 ± 1.12 | 0.52 ± 0.20 |
| **Euro 3** | <1.4 | 0.76 ± 0.07 | 11.69 ± 0.50 | 1.75 ± 0.07 | - | 1.41 ± 0.19 | 2.16 ± 0.29 | 21.25 ± 2.17 | 2.44 ± 0.60 |
| | 1.4-2.0 | 0.79 ± 0.03 | 10.56 ± 0.24 | 1.44 ± 0.03 | - | 1.52 ± 0.15 | 2.33 ± 0.23 | 21.63 ± 2.03 | 1.86 ± 0.26 |
| | >2.0 | 0.54 ± 0.02 | 7.20 ± 0.24 | 0.98 ± 0.03 | - | 0.83 ± 0.19 | 1.27 ± 0.29 | 16.02 ± 2.98 | 1.62 ± 0.60 |
| | Total | 0.69 ± 0.02 | 9.45 ± 0.17 | 1.31 ± 0.02 | - | 1.37 ± 0.10 | 2.10 ± 0.15 | 20.70 ± 1.37 | 2.00 ± 0.24 |
| **Euro 2** | <1.4 | - | 12.42 ± 0.82 | - | 3.82 ± 0.22 | 3.33 ± 0.32 | 5.11 ± 0.49 | 64.78 ± 7.29 | 8.04 ± 1.11 |
| | 1.4-2.0 | - | 10.00 ± 0.41 | - | 3.30 ± 0.11 | 4.67 ± 0.31 | 7.16 ± 0.48 | 61.75 ± 5.02 | 8.53 ± 0.90 |
| | >2.0 | - | 6.03 ± 0.50 | - | 2.14 ± 0.18 | 3.61 ± 0.56 | 5.54 ± 0.86 | 47.94 ± 8.98 | 5.55 ± 1.00 |
| | Total | - | 9.36 ± 0.32 | - | 3.08 ± 0.09 | 4.19 ± 0.22 | 6.42 ± 0.34 | 60.21 ± 3.77 | 7.93 ± 0.63 |

**Table 45: Comparison between petrol car emission rates derived from VCA NEDC type approval tests, and emission rates derived from remote sensing data over a synthesized NEDC**

[a] Range (±) indicates bounds of 95% confidence interval for the mean.
[b] VCA $NO_x$ assumed as $NO_2$ equivalent values (European Parliament 1998).
[c] Conversion assumes (46/30)NO.
[d] A factor of 2 is applied to HC values derived from remote sensing because the non-dispersive infrared HC measurement determines only around 50% of the HC mass compared to the FID techniques used in the NEDC type approval test (Singer et al 1998).

| Euro emission standard | Engine capacity (liters) | Mean emissions (grams per kg of fuel burnt)[a] | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | VCA | | | | Remote sensing (*$Emis_{DC}$*) | | | |
| | | $NO_x$[b] | CO | PM | HC+$NO_x$ | NO | NO (as $NO_2$ equivalent)[c] | CO | PM[d] |
| **Euro 4** | <2.0 | 4.43 ± 0.03 | 3.33 ± 0.10 | 0.28 ± 0.01 | - | 4.44 ± 0.37 | 6.81 ± 0.57 | 3.64 ± 1.66 | 0.96 ± 0.10 |
| | >2.0 | 3.59 ± 0.03 | 2.31 ± 0.10 | 0.19 ± 0.01 | - | 3.54 ± 0.46 | 5.43 ± 0.71 | 2.90 ± 1.71 | 0.83 ± 0.12 |
| | Total | 4.15 ± 0.03 | 3.00 ± 0.08 | 0.25 ± 0.01 | - | 4.12 ± 0.29 | 6.32 ± 0.44 | 3.38 ± 1.23 | 0.94 ± 0.08 |
| **Euro 3** | <2.0 | 8.44 ± 0.10 | 4.35 ± 0.16 | 0.72 ± 0.01 | - | 6.77 ± 0.45 | 10.38 ± 0.69 | 6.32 ± 1.61 | 1.75 ± 0.16 |
| | >2.0 | 6.93 ± 0.13 | 3.46 ± 0.19 | 0.69 ± 0.02 | - | 6.33 ± 0.60 | 9.71 ± 0.92 | 4.29 ± 1.57 | 1.63 ± 0.18 |
| | Total | 7.83 ± 0.09 | 3.99 ± 0.12 | 0.71 ± 0.01 | - | 6.59 ± 0.36 | 10.10 ± 0.55 | 5.63 ± 1.19 | 1.72 ± 0.12 |
| **Euro 2** | <2.0 | - | 9.04 ± 0.69 | 1.30 ± 0.21 | 12.16 ± 0.29 | 9.47 ± 1.09 | 14.52 ± 1.67 | 11.20 ± 1.91 | 2.88 ± 0.34 |
| | >2.0 | - | 6.60 ± 0.69 | 1.73 ± 0.52 | 11.22 ± 0.52 | 7.05 ± 1.19 | 10.81 ± 1.82 | 6.02 ± 2.11 | 2.11 ± 0.43 |
| | Total | - | 8.01 ± 0.51 | 1.48 ± 0.25 | 11.76 ± 0.28 | 8.76 ± 0.85 | 13.43 ± 1.30 | 9.24 ± 1.42 | 2.60 ± 0.27 |

**Table 46: Comparison between diesel car emission rates derived from VCA NEDC type approval tests, and emission rates derived from remote sensing data over a synthesized NEDC**

[a] Range (±) indicates bounds of 95% confidence interval for the mean.
[b] VCA $NO_x$ assumed as $NO_2$ equivalent values (European Parliament 1998).
[c] Conversion assumes (46/30)NO.
[d] Remote sensing estimate of PM based on opacity measurements; VCA PM values based on gravimetric measurement.

## 6.10 Discussion

The mean emission rates of NO ($NO_2$ equivalent) derived from remote sensing for Euro 4 petrol cars are around double the $NO_x$ values reported by VCA. At Euro 3, the values derived from remote sensing are approximately three times the VCA values. Assuming a proportion of $NO_2$ in total $NO_x$ of 1 – 4%, there is clearly a large difference in the results for the two methods. A degree of consistency in the results for the Euro 4 petrol cars category might have been expected since the observed vehicles in the RSD surveys were relatively new (≤3 years old), and therefore any age / maintenance related deterioration would be expected to be low. However, ‘real-world’ NO emissions are seen to be higher than the values observed in the type approval tests. The larger difference observed at Euro 3 may reflect in part the fact that the observed Euro 3 vehicles in the RSD surveys were between 4 and 8 years old, with associated age / mileage related degradation. Guidance published by the European Environment Agency (EMEP/EEA 2012) suggests a linear mileage correction factor for urban $NO_x$ emissions up to a maximum of 2.2 for Euro 1 and Euro 2 petrol cars (from 45,000km up to 120,000km). At Euro 3 and Euro 4, the EEA suggest no urban $NO_x$ degradation for petrol cars with engine capacities ≤1.4 liters, but a linear mileage correction factor up to a maximum of 1.57 (assumed average mileage of 17,000km up to a maximum of 160,000km) for engine capacities greater than 1.4 liters. However, research in the United States, based on time series analysis of repeat annual observations, has indicated that fleet averaged emission deterioration is near zero for model years newer than 2001 (Bishop & Stedman 2008). Given that the remote sensing data set utilized in this study represents a single point in time, it is not possible to state definitively whether (a) the relatively larger differences in emission rates between RSD and VCA data for earlier Euro standards are due to age related deterioration, or (b) that the difference is due to a larger discrepancy between VCA and ‘on-road’ emission rates for earlier Euro standards independent of age effects.

The mean emission rates of NO ($NO_2$ equivalent) derived from remote sensing for Euro 4 diesel cars are around 50% higher than the $NO_x$ values reported by VCA. At Euro 3, the values derived from remote sensing are on average 30% higher than the VCA values. Assuming a proportion of $NO_2$ in total $NO_x$ of perhaps 30% at Euro 3, increasing to 55% at Euro 4, average NO emissions from remote sensing at Euro 3 are nearly twice the VCA values, and over three times higher at Euro 4. Of course, the actual $NO_2$/NO ratios in the fleet observed during remote sensing are not known. The EEA assume no additional mileage related emissions degradation for diesel cars beyond that assumed in baseline emission factors corresponding to fleet average mileage (30,000 – 60,000km). It should be noted in passing that the absolute levels of NO emitted from Euro 3 and Euro 4 diesel cars, observed in the remote sensing surveys, are statistically significantly higher than from comparable petrol cars, as noted in Table 27.

Mean CO emission rates for Euro 4 petrol cars with engine capacity equal to or greater than 1.4 liters are broadly comparable for the two data sources, within 15% depending on engine capacity category. Mean CO emissions from Euro 4 petrol cars with engine capacities less than 1.4 liters derived from remote sensing measurements are estimated to be 34% higher than the mean VCA value. Again, higher emission rates are observed in the remote sensing data for earlier (Euro 3 and Euro 2) vehicle categories, relative to the VCA data. This is particularly acute at Euro 2 (observed vehicles between 9 and 12 years old), where the mean CO emission rate derived from the RSD data is between 5 and 8 times the original Euro 2 type approval value. This result is despite the fact that CO is one of the exhaust gases measured in the UK Department for Transport compulsory annual exhaust emissions test, although such tests are carried out at engine idle, and not under load (VOSA 2012). The EEA suggest maximum mileage correction factors for CO emissions from Euro 1 and Euro 2 cars of between 1.67 and 2.39 in an urban context, depending on engine capacity. In contrast, mean CO emission rates for diesel cars from remote sensing data remain within 9% to 45% of the VCA values across all Euro categories and engine capacities.

Mean hydrocarbon (HC) emission rates for Euro 4 petrol cars derived from the RSD data are generally lower than the comparable VCA type approval values. This situation is reversed at Euro 3. Mean HC at Euro 3 in the VCA data is 1.5 times the equivalent Euro 4 value; mean HC at Euro 3 in the remote sensing data is 3.8 times the equivalent Euro 4 value. The EEA suggest maximum mileage correction factors for HC emissions from Euro 3 and Euro 4 petrol cars of between 1.00 and 1.44 in an urban context (mileage ≥160,000km), relative to emission rates at average mileage values (range 18,000 to 32,000km).

In the VCA data, mean PM emissions for diesel cars at Euro 4 are 17% of Euro 2 values and 35% of Euro 3 values. In the remote sensing data, the equivalent trend values are 36% and 55%. The PM emission rates reported from remote sensing (based on opacity measurements) are generally 1.8 to 3.7 times higher than the reported VCA (gravimetric) values, the wider divergence occurring with newer (Euro 4) vehicles.

When interpreting these comparisons, due cognizance should be paid to the differences in instrumentation and measurement techniques utilized. The form of remote sensing used in this study does not permit the accurate representation of the significant proportions of idling time in the (NEDC) type approval laboratory test, because idling whilst stationary is not included in the RSD measurements (emissions measurements from the RSD instrumentation are obtained when the vehicles are in motion). It is likely that the urban remote sensing data included an unknown proportion of cold start observations; future work could control this issue by careful site selection, and possibly thermal imaging (Monateri et al 2004). Other factors which are difficult to control, and which could make reconciliation more challenging, include the use of ancillary equipment such as air conditioning, vehicle loading, and other aspects of variability in driver behaviour such as gear changing. However, the significance of some of these issues will depend on the nature of the driving cycle under investigation. The future collection of time series data will permit the assessment of the significance of the relationships between emissions and vehicle age / mileage, which will be influenced by prevailing local inspection /

maintenance regimes. Further data collection is required to refine the technique to explicitly account for the fraction of $NO_2$ in total $NO_x$. Future research will also benefit from the inclusion of RSD data from higher speed (extra-urban) survey sites, to explicitly capture high VSP values generated by consistent higher speed cruising, rather than from lower speed acceleration events. It is considered likely that this will have a bearing on emissions rates of some pollutants.

This Chapter has successfully achieved the stated objective as set out in section 1.12 of:

- Reconciling observed ‘on-road’ vehicle exhaust emission rates with those observed in laboratory conditions at vehicle type approval.

In so doing, two key points for future policy and research have been highlighted. Firstly, the observed ‘in-use’ emission rates derived from remote sensing, when used to synthesise the New European Driving Cycle utilised for new vehicle type approval in Europe, are consistently higher that the emission rates reported from the laboratory based tests which are published by bodies such as the Vehicle Certification Agency. This may be due to a range of factors which have been well documented in the recent literature (Kadijk et al., 2012; Mock et al., 2012; Smokers et al., 2012):

a) The NEDC does not reflect ‘real-world’ driving (speed, acceleration, variability in gear selection, engine speed etc);
b) Use of allowable tolerances (±) or ‘flexibilities’ in the testing regulations (e.g. load, temperature, gear changing);
c) ‘Real-world’ use of vehicle ancillaries is not reflected in the laboratory test specification e.g. air conditioning;
d) Preparation of the test vehicle can influence the laboratory based results (e.g. laboratory ‘soak’ temperature, battery state of charge, running-in distance, wheel and tyre specification), and;
e) The laboratory measurement regime can be optimised, resulting in an optimised result which does not equate to ‘real-world’ driving conditions.

The inconsistency between published emission and fuel consumption rates, and those achieved by the general public in everyday driving, is currently being addressed by the UK Advertising Standards Agency which has recently required a manufacturer to add an appropriate caveat to advertising literature.

Secondly, the analysis highlights the deterioration in emissions performance (relative to the original published type approval values) with respect to vehicle age. This is also presumably related to vehicle mileage, but mileage data for the UK vehicle fleet was not available at the time this research was carried out. This apparent deterioration effect is particularly notable for petrol cars. However, research in the United States, based on time series analysis of repeat annual observations, has indicated that fleet averaged emission deterioration in the United States is near zero for model years newer than 2001 (Bishop & Stedman 2008). The difference in findings in a UK and US context requires further investigation and quantification. This will only be possible with continued systematic measurement campaigns at intervals in the UK to confirm and quantify this effect.

# Chapter 7. Conclusions and Recommendations

The analysis in Chapter 2 addressed the issue of variability in driver behaviour. An investigation was presented into the quantification of variability in behaviour within a small group of drivers in reasonably controlled conditions, and the influence of such variability on exhaust emission rates. Clearly, such a small sample of drivers is not necessarily representative of the whole driver population, but it is a subset of the UK driver population. Similarly, the highway network used for the experiment was not representative of all road types in the UK, or the vehicle kilometres driven on each road type. Later work in Chapter 3 suggested that the extent of variability in driver behaviour (and therefore potential benefits attainable from interventions) would probably differ by road type and speed. Nevertheless, the research provided an insight into the nature and potential scale of driver behaviour variability in the population, and the potential benefits which might be achieved if effective strategies can be identified to influence driver behaviour to realise particular operational, policy or environmental objectives.

The analysis highlighted a number of technical issues and constraints. Determination of the most appropriate sampling frequency to capture both system inputs (driver behaviour) and outputs (tail pipe emissions) is an important consideration in experimental design. The analysis suggested that a sampling frequency of 1Hz is generally too coarse to capture the detail of driver behaviour and associated exhaust emissions. A sampling rate of 10Hz  is likely to be more successful in capturing the relevant detail in driver behaviour which can potentially generate transient ‘spikes’ in exhaust emissions (such as sudden changes in throttle position at frequencies of 2Hz or 3Hz. However, sampling at a higher rate will have implications for the amount of data generated, and how it will be stored and processed.

The temporal synchronisation of driver inputs, vehicle dynamics, and exhaust emissions measurements would be facilitated by sampling at higher frequencies, but the choice of static or dynamic alignment techniques would have to be made on a case-by-case basis, depending on the characteristics of the vehicle, and variability in engine speed and load. Dynamic temporal synchronisation offers a more robust solution in the laboratory, but will be more challenging to implement for on-road emissions measurements, and more resource intensive.

It was demonstrated that de-convolution of the frequency distribution of emissions data by operating mode has benefits in terms of permitting association of operating modes with varying rates of emissions generation for a given context (recognising that these relationships can vary for different operating conditions, road types, and drivers).

The detail of variation in driver behaviour observed within this data set provided some useful insights into the factors relevant for the development of eco-driving techniques and guidance. Perhaps unsurprisingly, throttle application (as a precursor of both acceleration and engine speed), was seen to be a significant factor, although sampling at 1Hz precluded any detailed investigation into the significance of the rate of change of throttle position with respect to time for fuel consumption and emissions. It was seen that throttle application, if kept below 25% at the 95th percentile level was associated with much reduced levels of fuel consumption and emissions. However, a trade-off was also observed for some drivers between the rate of emissions per unit time and per unit distance, with hesitant driving resulting in potentially higher rates of emission per kilometre.

The results suggested that there may be a range of defining characteristics of ‘efficient’ and ‘inefficient’ driving which relate to the degree of alignment between vehicle operation as determined by the driver, and the ‘efficient’ operating regime for the vehicle. This raises an interesting question regarding the amount of ‘choice’ available to drivers. There appears to be a trade-off between the ‘drivability’ of the vehicle, and fuel consumption / emissions rates. Presumably, vehicle manufacturers have to design their products so that they can be operated reasonably effectively by all of the population (in principle), across a wide spectrum of behaviours, abilities, competencies, and choices. An interesting question would be whether strategies should be adopted to influence / change driver behaviour to achieve desirable objectives, or whether vehicle manufacturers should change the vehicle design to constrain vehicle operation to more ‘efficient’ operating regimes. This raises the question, ‘**To what extent should drivers be permitted to control aspects of the operation of the vehicle that influence exhaust emissions and fuel consumption?**’ Many developments in vehicle technology in recent years, mainly in the areas of safety and driver comfort, have increasingly taken aspects of control away from the driver, either by design or as optional driver choices. Examples include anti-lock braking systems, stability control systems, active cruise control, lane departure warning systems, and collision avoidance systems. There is a trend towards computer control of all of the major vehicle systems, with driver inputs (throttle, brakes, gear selection etc.) being moderated by the vehicle electronic control unit (ECU). Most recently, this has also included steering; systems are now in development where steering is controlled by the ECU, without direct mechanical linkage between the steering wheel and the road wheels during normal operation. Many cars now allow drivers to select from a range of driving modes (e.g. sport, comfort, eco) which place restrictions on the vehicle operation, including engine operation**. It would appear that scope exists in current vehicle design for further technological developments with the objective of optimising environmental performance.**

The degree to which driver behaviour can be influenced by information technology was explored in a case study in Chapter 3. The case study assessed the effectiveness of a mobile phone based application to provide drivers with feedback on their eco-driving performance using a normalised scoring system. The scale of the case study (only 7 drivers, assessing the efficacy of the system over a period of 4-6 weeks) makes it difficult to draw definitive conclusions. However, it was observed in the sample of trial participants that the users of the mobile phone application could improve their driving manner to increase their eco-driving score. The extent to which this was possible depended to some extent on the ‘normal’ driving behaviour of the individual, but there were examples within the sample where statistically significant improvements in eco-driving were possible and achievable within a very short period of time, utilising feedback from the application. The extent to which other drivers were able to improve depended to some extent on the road type and prevailing traffic conditions. Further refinement of the application would be required to internalise some of these factors. One possible development path would be to tailor the eco-scoring system to the make and model of vehicle being driven, so that the technical characteristics of the vehicle can be taken into consideration. This would be relatively easy to achieve by cross referencing against existing SMMT or VCA databases; it would only require the user to select his/her vehicle make and model. An adapted algorithm could then calculate bespoke eco-driving scores for that driver and vehicle. A second possible development path would be to utilise knowledge of the spatial and temporal location of the vehicle to inform the eco-scoring system, by explicitly considering road type, speed limits, historic journey times, and perhaps even real time congestion information. This would differentiate between endogenous driver behaviour and exogenous factors outside the control of the driver. This would arguably improve the confidence in the system. It also offers the potential for the vehicle to become a 'probe vehicle' and generate real time data for wider use in urban traffic management and control systems.

The analysis of the remote sensing data reported in Chapters 4, 5 and 6 is the first time that findings from such a large (>50,000 records) sample of the 'on-road' vehicle fleet have been reported in a UK context (and published in a peer reviewed academic journal). As such, the analysis is unique. The ongoing 'dieselisation' of the UK passenger car fleet was confirmed by the analysis. Other technology trends identified included the reducing trend over time in mean engine capacities of both petrol and diesel powered cars (reduced by approximately 6% and 3% respectively over the period 1997 to 2007). In contrast, mean car weight (maximum permitted) was observed to be increasing over the same time period (increasing by approximately 4% and 6% for petrol and diesel cars respectively).

Observed mean $CO_2$ emissions (type approval value recorded on the vehicle registration document for taxation purposes) for petrol and diesel cars manufactured in 1998 were 181g/km and 208g/km respectively; for cars manufactured in 2008, the corresponding figures are 165g/km and 161g/km, a reduction of 9% and 22% respectively. In contrast, mean engine power was observed to increase over the same period, presumably to continue to meet customer performance expectations with increases in vehicle mass.

Based on the analysis of the remote sensing data, it was found that evolving European emission standards, using vehicle age as a proxy for emissions standard, **do have a statistically significant influence on light vehicle exhaust emissions.** Carbon monoxide, hydrocarbons, nitric oxide and particulate matter emissions from petrol cars were all seen to display statistically significant reductions with the introduction of each new emissions standard, from Pre-Euro through to Euro 4 emissions standard. It was found that nitric oxide emissions from Euro 2 diesel cars were statistically higher than either Euro 1 or Euro 3 diesel cars, but that emissions of particulate matter from diesel cars reduced significantly in the transition from Euro 2 to Euro 3, and from Euro 3 to Euro 4.

Observed nitric oxide emissions from Euro 4 diesel cars were between 6 and 17 times higher than the equivalent Euro 4 petrol cars, depending on whether the comparison is based on the mean or median values. Given the continuing increase in the number of diesel cars in the UK fleet in recent years, combined with the concerns raised by some researchers regarding the increasing proportion of primary nitrogen dioxide in total oxides of nitrogen from new diesel cars, this may have significant implications for future local air quality. Further research and data collection is required to explicitly measure the primary nitrogen dioxide component in total oxides of nitrogen in the UK road vehicle fleet.

Surprising insights were gained into the exhaust emissions characteristics of the London taxi (black cab) fleet. Whilst the Euro 3 standard TX II and Euro 4 standard TX4 taxis were observed to have significantly lower nitric oxide emissions than older taxis retro-fitted with emissions control equipment, **the Euro 3 standard TXII taxi was observed to produce significantly higher levels of particulate matter than either earlier TX1 or later TX4 model taxis**, with certain caveats. Local air quality action plans need to take this factor into account when considering the introduction of maximum age limits for taxi fleets, and model the potential impact on emissions and local air quality of any such interventions.

A key general finding derived from the results reported in Chapter 5 is that **it cannot be assumed that road vehicle emissions necessarily decline monotonically with respect to time.** Statistically significant instances have been noted where emission rates of some pollutants (whether specifically regulated or unregulated at type approval) can actually increase with the introduction of new emissions control regulations and technology. This highlights the value of monitoring the evolving emission characteristics of the UK road transport fleet systematically so that such instances can be identified and understood.

A key strategic policy issue highlighted by the data collection and analysis undertaken in this study was the **dieselisation of the UK passenger car fleet**. The growth in diesel fuelled passenger cars has been driven by explicit government policies to reduce fuel consumption and associated carbon dioxide (greenhouse gas) emissions, influenced through taxation instruments such as vehicle excise duty. It can be argued that local air quality policy has been seen by government as of secondary importance to the global climate change and $CO_2$ agenda, notwithstanding the economic cost calculations presented in Chapter 1. The desirability for continued growth in diesel vehicles is being questioned, and there is anecdotal evidence that local authority fleet renewal and vehicle purchasing practices are increasingly being influenced by local air quality policies.

A novel approach (Rhys-Tyler and Bell, 2012) was adopted in Chapter 5 to move towards reconciling 'real-world' emissions measured using remote sensing, and emissions rates obtained from laboratory based type approval tests. The urban remote sensing dataset collected in 2008 was used to define the dynamic relationship between vehicle specific power and exhaust emissions, across a range of vehicle ages, engine capacities, and fuel types. The New European Driving Cycle was synthesised from the remote sensing data using vehicle specific power to characterize engine load, and the results compared with official published emissions data from vehicle type approval tests over the same driving cycle. Mean carbon monoxide emissions from petrol cars ≤3 years old measured using remote sensing were found to be 1.3 times higher than published original type approval test values; this factor increased to 2.2 for cars 4 – 8 years old, and 6.4 for cars 9 – 12 years old. The corresponding factors for diesel cars were 1.1, 1.4, and 1.2 respectively. **Generally, 'real-world' emission rates were found to be higher than the published type approval values** (due to the factors discussed in Section 6.10); **petrol engine cars tended to suffer particularly from age related deterioration in emissions rates** (relative to original type approval values). Diesel cars appeared to suffer from less deterioration, although it should be noted that this analysis is not based on a time series study. Generally, observed age related deterioration appears to be greater that assumed in current European Environment Agency emissions modelling advice. Additional repeat data collection is required to address this issue with greater confidence. The findings have potential implications for the design of traffic management interventions aimed at reducing emissions (such as the introduction of Low Emission Zones), fleet inspection and maintenance programs, and the specification of vehicle emission models.

This thesis has made an original contribution to the field in two main areas; firstly by quantifying the 'real-world' emission rates for an appreciable section of the UK light road vehicle fleet operating in an urban area, and demonstrating the statistically significant differences in emission rates between different groups of vehicles; and secondly, by proposing a feasible method to move towards reconciling essentially instantaneous road side measurements of exhaust emissions obtained from remote sensing, with laboratory based measurements taken over a legislated driving cycle as part of the new vehicle type approval process. In so doing, it has highlighted the discrepancy between published emission and fuel consumption rates obtained in the laboratory, and 'real-world' emission and fuel consumption rates. In addition, notable results have been obtained in the areas of influencing driver behaviour, and future experimental design.

**Recommendations**

a) Future instrumented vehicle experiments designed to monitor the relationship between driver behaviour and exhaust emissions should collect data at a minimum time resolution of 10Hz to capture relevant aspects of driver behaviour such as changes in throttle position;
b) Further research is required to characterise the nature and extent of variability in driving behaviour in the UK driver population. A useful potential source of data in this context is 'black box' data generated by company cars and insurance company schemes (recognising sampling issues);
c) A systematic programme of remote sensing surveys should be implemented to continue to monitor and characterise the exhaust emissions from the UK road vehicle fleet. Work to date has demonstrated that emission rates are highly dynamic, changing with vehicle and fuel technologies. A sample of 'census points', selected to be representative of fleet mix, vehicle speeds, and road type should be determined, and monitoring undertaken at least every three years, collecting sufficient sample size to obtain statistically significant results by vehicle type, fuel type, and Euro standard, to identify and monitor trends;
d) Future remote sensing surveys should explicitly include measurements of both nitric oxide (NO) and nitrogen dioxide ($NO_2$). This will facilitate research into the local relationships between primary $NO_2$ emissions, secondary $NO_2$ formation, and local air quality;

e) Comparative studies should be carried out of the smoke measurements obtained from remote sensing (at both infra red and ultra violet wavelengths), and traditional measurements of particulate matter such as gravimetric measurement and particle counters. This will inform the interpretation of smoke measurements from remote sensing in terms of particle composition, mass, and size;

f) Using data generated by (c) above, longitudinal studies should be undertaken of time trends in vehicle emissions, to gain an understanding of the relationships between vehicle age, vehicle mileage, and emission rates. Vehicle mileage data will generally be available from MoT test records for light vehicles;

g) A research project should be developed to address the problem of successfully collecting emissions data from heavy good vehicles in the UK using remote sensing techniques. This should consider the variability in position of exhaust plume, measurement triggering, and sampling strategies;

h) A research proposal should be developed to explicitly determine the relationships between road vehicle exhaust emissions and local air quality, taking into account the variability in emission rates by vehicle type, fuel type, Euro class, and vehicle dynamics (speed, acceleration) identified in this thesis. The project scope should also include environmental factors such as ambient temperature and humidity which have the potential to influence the efficiency of emissions control equipment, and driver behaviour with respect to operation of vehicle ancillary systems such as air conditioning;

i) European vehicle type approval regulations should be amended to include explicit limit values on $NO_x$ species, including both nitric oxide (NO) and nitrogen dioxide ($NO_2$). This would provide a mechanism for the control of primary $NO_2$ emissions from road transport;

j) UK Vehicle Excise Duty should be reviewed in the light of the apparent policy conflict between local air quality and climate change ($CO_2$). An economic analysis should be undertaken, considering current and future technology scenarios, to provide policy evidence to ministers;

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