Vehicle dynamics and personal exposure to black carbon in the vicinity of at-grade pedestrian infrastructure

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Declaration

Various measurement campaigns detailed within this thesis required practical assistance from other researchers. All experimental designs, data processing, analyses and interpretation are my own work.

I hereby certify that I have personally carried out all research detailed in this thesis, except where otherwise stated.

David Williams
October 2014

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Abstract

Urban areas are often subject to traffic-induced poor air quality. Variability in vehicle operating behaviours at traffic management infrastructure leads to increased emission rates of pollutant species harmful to health. Where these locations are also sites of pedestrian activity, exposure to pollution is increased. This thesis demonstrates this mechanism through measurement of vehicle dynamics and emissions modelling, with tailpipe emissions found to be at least 20% greater when the vehicle is delayed due to mid-link crossings.

As it has no non-combustion sources, black carbon (BC) is a useful proxy for traffic related emissions. Previous research into air quality at traffic management infrastructure has been of an insufficient scale to identify the variability in pollutant concentration and exposure. This thesis addresses this gap through an investigation into BC concentration and exposure at traffic management infrastructure, demonstrating that fixed monitors over coarse temporal and spatial scales are inadequate for assessing BC concentration and exposure, and finding that public health and transport professionals are ill-equipped to make recommendations for improvements on the basis of current data and understanding.

To provide data suitable for an assessment at the micro-scale, a measurement framework is specified for the use of micro-aethalometers in urban areas. This addresses problems of signal noise, aerosol loading and consistency where other studies have not, enabling measurement of BC concentration at higher temporal resolution (5-second) than previously. Micro-aethalometers are deployed at signalised intersections in London and Glasgow (UK). The variability in BC is identified, with median concentration up to 130% greater at pedestrian waiting locations across the intersection. In high traffic flow environments, the periodicity of peak concentration episodes is found to relate to traffic control cycles. High-resolution data are applied to pedestrian exposure studies, with in-transit exposure to BC varying by more than ten times as a result of activity patterns.
Dedication

This thesis is dedicated in loving memory to my mum, Margaret Williams.
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### Glossary

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<th>Term</th>
<th>Definition</th>
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</thead>
<tbody>
<tr>
<td>Acceleration noise</td>
<td>Defined as the standard deviation of acceleration</td>
</tr>
<tr>
<td>Aethalometer</td>
<td>Device for the optical measurement of black carbon</td>
</tr>
<tr>
<td>AIRE</td>
<td>Analysis of Instantaneous Road Emissions – an instantaneous emissions database derived from PHEM</td>
</tr>
<tr>
<td>Allotrope</td>
<td>A different structural form of the same chemical element</td>
</tr>
<tr>
<td>At-grade</td>
<td>Where the management of intersecting transport routes is at the same height or grade (as opposed to grade-separated)</td>
</tr>
<tr>
<td>ATN</td>
<td>Attenuation - the decreasing intensity of light as it passes through a medium</td>
</tr>
<tr>
<td>Attenuation coefficient</td>
<td>Parameter which describes the relationship between ATN and black carbon concentration</td>
</tr>
<tr>
<td>Black carbon (BC)</td>
<td>Carbonaceous component of atmospheric aerosol that absorbs visible radiation and is produced as a result of combustion</td>
</tr>
<tr>
<td>Carbon black</td>
<td>Carbonaceous aerosol, mainly consisting of elemental carbon and strongly associated with manufacturing</td>
</tr>
<tr>
<td>Char</td>
<td>Carbon aerosols and other solid matter generally formed as a residue from the partial burning of carbonaceous material</td>
</tr>
<tr>
<td>CMEM</td>
<td>An emissions database based on modal emission rates (Comprehensive Modal Emission Model)</td>
</tr>
<tr>
<td>CO</td>
<td>Carbon monoxide</td>
</tr>
<tr>
<td>CO₂</td>
<td>Carbon dioxide</td>
</tr>
<tr>
<td>Concentration (pollution)</td>
<td>The amount of a pollutant present, expressed as mass or fraction per unit volume of air</td>
</tr>
<tr>
<td>Defra</td>
<td>The UK Department for Environment, Food and Rural Affairs</td>
</tr>
<tr>
<td>DfT</td>
<td>The UK Department for Transport</td>
</tr>
<tr>
<td>DOP</td>
<td>Dilution of precision, a measure of confidence of GPS signals</td>
</tr>
<tr>
<td>Dose</td>
<td>The amount of pollution that enters the body (incorporating human exposure and breathing characteristics)</td>
</tr>
<tr>
<td>EC</td>
<td>Elemental carbon</td>
</tr>
<tr>
<td>GHG</td>
<td>Greenhouse gas</td>
</tr>
<tr>
<td>GNSS</td>
<td>Global navigation satellite system</td>
</tr>
<tr>
<td>GPS</td>
<td>Global Positioning System, a particular type of GNSS</td>
</tr>
<tr>
<td>Grade-separation</td>
<td>Where transport routes and the associated infrastructure intersect at different heights or grades</td>
</tr>
<tr>
<td>HC</td>
<td>Hydrocarbons</td>
</tr>
<tr>
<td>HGV</td>
<td>Heavy goods vehicles</td>
</tr>
<tr>
<td>Term</td>
<td>Definition</td>
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<tr>
<td>----------</td>
<td>------------</td>
</tr>
<tr>
<td>Human exposure</td>
<td>The amount of a pollutant humans are subject to (incorporating pollutant concentration and patterns of activity)</td>
</tr>
<tr>
<td>ICE</td>
<td>Internal combustion engine</td>
</tr>
<tr>
<td>MOVES</td>
<td>A mobile source emission model suitable for the US vehicle fleet (Motor Vehicle Emission Simulator)</td>
</tr>
<tr>
<td>NO₂</td>
<td>Nitrogen dioxide</td>
</tr>
<tr>
<td>NOₓ</td>
<td>Oxides of nitrogen, comprising of nitrogen dioxide (NO₂) and nitric oxide (NO)</td>
</tr>
<tr>
<td>O₃</td>
<td>Ozone</td>
</tr>
<tr>
<td>ONA</td>
<td>Algorithm designed to reduce noise and the occurrence of negative values in Aethalometer reporting (Hagler et al, 2011)</td>
</tr>
<tr>
<td>PDOP</td>
<td>Positional dilution of precision</td>
</tr>
<tr>
<td>PEMS</td>
<td>Portable emissions measurement system</td>
</tr>
<tr>
<td>PHEM</td>
<td>An instantaneous emissions database (Passenger Car and Heavy Duty Emission Model) on which AIRE is based</td>
</tr>
<tr>
<td>PM</td>
<td>Particulate matter – liquid or solid suspended matter</td>
</tr>
<tr>
<td>PM₁₀</td>
<td>Particulate matter with a diameter smaller than 10 micrometres</td>
</tr>
<tr>
<td>PM₂.₅</td>
<td>Particulate matter with a diameter smaller than 2.5 micrometres</td>
</tr>
<tr>
<td>RNP</td>
<td>Required navigation performance</td>
</tr>
<tr>
<td>SCOOT</td>
<td>An intelligent traffic control system that optimises for delay at one or more junctions (split cycle offset optimisation technique)</td>
</tr>
<tr>
<td>SO₂</td>
<td>Sulphur dioxide</td>
</tr>
<tr>
<td>Soot</td>
<td>Carbon particulates which form as a result of re-condensation of high temperature VOCs</td>
</tr>
<tr>
<td>TEC</td>
<td>Traffic engineering and control</td>
</tr>
<tr>
<td>UFP</td>
<td>Ultrafine particulates with a diameter smaller than 0.1 micrometres</td>
</tr>
<tr>
<td>VED</td>
<td>Vehicle Excise Duty – UK tax paid on motorised road vehicles, banded in accordance with the level of CO₂ emissions</td>
</tr>
<tr>
<td>VSP</td>
<td>Defined as the instantaneous power per unit mass of the vehicle</td>
</tr>
<tr>
<td>VOC</td>
<td>Volatile organic compounds</td>
</tr>
</tbody>
</table>
1 Introduction

Transport is an essential part of society, necessary for providing access to employment, education and services, and economic development.

“Transport is a crucial driver of development, bringing socio-economic opportunities within the reach of the poor and enabling economies to be more competitive. Transport infrastructure connects people to jobs, education, and health services; it enables the supply of goods and services around the world; and allows people to interact and generate the knowledge that creates long-term growth.”

World Bank (2014)

However, there are adverse effects of transport which are generally associated with the environment and human health. In some cases, these negative impacts may be indirect. An example of this is the increasing car dependence of children and the resultant health implications due to lack of exercise (Mackett, 2002). Other impacts are more direct. Cohen et al (2014) estimated that injuries and pollution from motorised road transport are responsible for the loss of 1.5 million lives and 79.6 million healthy years annually worldwide. Fatalities as a result of road transport are estimated at 1.3 million annually, with more than 78 million injuries which require medical care.

Pollution from road vehicles was identified as the cause of nearly 200,000 global annual deaths, including from heart disease, stroke, respiratory infections and cancer. The contribution of pollution to total attributed deaths is not consistent across the world. Cohen et al (2014) identified that in the poorest regions of the world, deaths from road transport are dominated by injuries. In more developed countries, road transport induced air pollution is a larger factor. The implication is that air pollution will also become a more substantial problem as the demand for motorised road transport increases across the world.

A recurrent theme is the impact of road transport on the environment, which extends beyond air pollution to problems of climate change and noise, which also have the potential to influence health, economy and society. This thesis details an investigation of the interaction between traffic management infrastructure and the environmental impacts of road transport. Whilst the case studies employed are specific to UK, results are transferrable and relevant to what is a global problem of increasing importance.
Specific reference is made to pedestrian facilities. The management of pedestrians in urban transport networks is a particularly interesting topic. The intention of managing the conflict between motorised traffic and pedestrians for safety reasons may have a detrimental impact on air pollution, and consequently human health. Black carbon is identified as a pollutant of interest, impacting not only local air quality but also global problems of climate change. This work contributes to the emerging body of research into black carbon, a pollutant species likely to become more important due to the increasing dieselisation of motor vehicle fleets.

The introductory chapter to this thesis discusses the background and context for the research investigations detailed in subsequent chapters. The research issues are summarised and objectives formulated. Finally, chapter contents are outlined.

### 1.1 Environmental impacts of road transport

Hensher and Button (2003) identify the main environmental issues associated with transport as air quality, greenhouse gas emissions, noise, and impacts on biodiversity and land use. The importance of transport to the society and economy is reflected in frequent debates on legislation and associated measures to control the negative impacts. This balance represents an enormous challenge.

Road is the dominant form of domestic transport in the UK (Table 1-1), accounting for 90% of all passenger travel (DfT, 2012a). Therefore, environmental problems associated with road transport are of particular interest.

*Table 1-1: Passenger transport by mode, 2011 (DfT, 2012a).*

<table>
<thead>
<tr>
<th>Mode</th>
<th>Billion passenger kilometres</th>
<th>Percentage of total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cars, vans, taxis</td>
<td>655.1</td>
<td>83.5%</td>
</tr>
<tr>
<td>Buses, coaches</td>
<td>43.4</td>
<td>5.5%</td>
</tr>
<tr>
<td>Motorcycles</td>
<td>4.9</td>
<td>0.6%</td>
</tr>
<tr>
<td>Pedal cycles</td>
<td>5.0</td>
<td>0.6%</td>
</tr>
<tr>
<td>Rail</td>
<td>68.2</td>
<td>8.7%</td>
</tr>
<tr>
<td>Air (UK)</td>
<td>8.2</td>
<td>1.0%</td>
</tr>
</tbody>
</table>
The impact of road transport on the environment can be broadly split into local (such as poor air quality from vehicle emissions and noise) and global (climate change, depletion of natural resources). This section briefly discusses the contribution of road transport to these and some of the regulatory measures which have been introduced to control vehicle emissions. Detailed discussions of particular pollutant species are presented in Section 2.1.

1.1.1 Greenhouse gas emissions

Carbon dioxide (CO\textsubscript{2}) is considered the most important greenhouse gas (GHG). The increasing production is thought to be responsible for global climate change (IPCC, 2013). The UK has several targets for reducing emissions of pollutant species considered responsible for climate change, including the legally binding Kyoto Protocol.

In 2011, transport was responsible for 27% of the total UK GHG emissions. Of this, road transport was the largest contributor, with 67% of the total (DfT, 2013a). In absolute terms, the estimated amount of GHG emissions from road transport has reduced from 117.4 million tonnes of carbon dioxide equivalent\textsuperscript{1} in 1999 to 108.9 million tonnes in 2011 (DfT, 2012b). European Union legislation has been a driving force in producing lower CO\textsubscript{2} emitting vehicles, with new cars emitting on average more than 26% less CO\textsubscript{2} (g/km) in 2010 than 2007 (SMMT, 2013).

Vehicles registered in the UK are subject to “Vehicle Excise Duty” (VED, commonly known as road tax) based on the estimated CO\textsubscript{2} emissions (g/km) of the vehicle. Previously based on engine size\textsuperscript{2}, VED was changed as an incentive to purchase lower-emitting vehicles. Currently, vehicles\textsuperscript{3} in the lowest emission category (up to 100g of CO\textsubscript{2} emitted per km) are not subject to a charge, with the highest emitting vehicles (over 255g/km) pay an annual tax of £490 (DVLA, 2013).

Reductions in vehicle emissions through technological advances are tempered by the growth in demand for motorised travel. For example, in the period 1997 to 2009, passenger kilometres travelled in cars, vans and taxis increased by 7% (DfT, 2012a). Reducing the demand for travel and other methodologies for managing the environmental impact of road transport are discussed in Section 2.4.

\textsuperscript{1} As CO\textsubscript{2} is not the only GHG, the carbon dioxide equivalent metric is used (equivalence is based on global warming potential).
\textsuperscript{2} For cars registered before March 2001, the level of VED remains dependent on engine size.
\textsuperscript{3} In this case, “vehicles” refers to petrol and diesel cars – different rates exist for other vehicle classes.
1.1.2 Local air quality

The subject of poor air quality has received increasing attention in recent years, with initiatives such as the European Commission’s “Clean Air for Europe” programme (European Union, 2006) providing a legislative framework to drive improvement. Whilst emissions of local pollutants (such as carbon monoxide, oxides of nitrogen and particulate matter) from road transport have fallen (DfT, 2012b) poor air quality is still considered to be responsible for as many as 50,000 premature deaths per year in the UK (Environmental Audit Committee, 2010). The economic cost of the impacts of air pollution in the UK is comparable to that of obesity, with estimates suggesting that life expectancy is reduced by an average of seven to eight months (Defra, 2007).

Much of the previous work in this area has been epidemiological, establishing statistical relationships between pollution levels and health parameters such as morbidity and hospital admissions (Katsouyanni and Samet, 2009). Aside from statistical significance, much of the pathology is also understood, and many of the pollutants from motor vehicles are known to lead to respiratory problems and to be carcinogenic.

The UK government cites road transport as one of the main sources of air pollution (Defra, 2010). In the US, transport related emissions are the dominant source of air pollutants (Yu et al, 2009) responsible for 82% of carbon monoxide (CO) and 56% of nitrogen dioxide (NO\textsubscript{2}). London in particular has been a cause for concern, with particulate matter (PM) and NO\textsubscript{2} levels failing to meet EU air quality standards (European Commission, 2010), leading to the imposition of fines and other punitive measures.

Air pollution control legislation has existed in the UK since the 1950s (Highways Agency, 2007), with the first “Clean Air Act” implemented partly in response to severe smog in London. Legislation passed in the 1990s granted powers to set limits for specific pollutants and later required a national strategy for improving air quality. Current air quality targets in the UK are provided by European Union Directives (Highways Agency, 2007) and cover a range of pollutant species. These are generally described as limit values with a certain number of allowed exceedances within a given time period (generally annual). These regulations are discussed in more detail in Section 4.2. Also in existence are limits for exhaust emissions, which are known as “Euro” standards (European Commission, 2012a). These set standards (in terms of g/km) for tailpipe emissions of carbon monoxide (CO), hydrocarbons (HC) nitrogen oxides (NO\textsubscript{x}) and particulate matter (PM). These regulations are discussed further in Section 2.2.
1.1.3 Black carbon

A major component (~75% by particle number, US EPA, 2012) of tailpipe particulate matter emissions is black carbon (BC). The term ‘black carbon’ is often used interchangeably with ‘elemental carbon’, ‘char’ and ‘soot’ (Han et al, 2010), but generally refers to ultrafine (<0.1 µm), light absorbing carbonaceous aerosols. Measurement-related definitions relevant to this research are discussed in Section 5.1. BC is a product of incomplete combustion of carbon fuels, and as such is associated with vehicle (especially diesel) emissions (Dodson et al, 2009). Invernizzi et al (2011) describe BC as “a unique primary tracer for combustion emissions, as it has no non-combustion sources, and is stable once released into the atmosphere”. BC is therefore a useful proxy for traffic emissions (Keuken et al, 2012).

BC is seen as a particularly important air pollutant due to the potential impacts on global climate change, local air quality and respiratory health (Highwood and Kinnersley, 2006). Currently vehicle emissions regulations do not make distinctions between the different fractions of particulate matter, and set limits based on mass. It is recognised that this is inadequate for finer fractions (European Union, 2007), and should be addressed on the basis of future research⁴. So, despite the lack of regulation, black carbon and other ultrafine particles are recognised as being important. The health effects of black carbon and other ultrafine fractions are also becoming more recognised (Janssen et al, 2012) further enforcing the need for particulates not to be considered as a single pollutant entity.

1.2 Human exposure to pollution in urban areas

Cocheo et al (2011) describe health risk assessment as a four-step process: hazard identification; human exposure assessment; dose-response assessment; and risk management. In the case of traffic induced local air pollution, the general hazard is that of vehicle emissions. However, the mere presence of a vehicle is an insufficient level of detail, as the emission and distribution of these pollutants is not homogenous.

1.2.1 Vehicle emission and air pollution hotspots

Urban areas are generally more likely to have higher pollutant concentrations due to high density traffic. In addition, the arrangement of buildings is such that the ventilation of emitted

Ambient air quality standards do make some distinction between the different fractions of particular matter. This is discussed further in Chapter 4.
pollutants can be restricted (Tomlin et al, 2009). Several studies have shown traffic management infrastructure such as signalised intersections, roundabouts and traffic calming measures to be “hotspots” of high, localised pollution in urban road networks (for example, Kaur et al, 2005). Pandian et al (2009) describe poor air quality at intersections as being due to variability of vehicle speed on approach and departure. The variability in vehicle behaviour leads to variation in demands for power and in the production of emissions by vehicles (Frey et al, 2003). The formation of pollutant emissions from road vehicles is discussed in more detail in Section 2.1.

1.2.2 Activity and exposure hotspots

Areas where emissions are highest, and air quality poorest, may also be characterised by high pedestrian activity. They may therefore be considered human exposure ‘hotspots’, with the potential to significantly impact health in urban areas. An example is a signalised intersection, where conflicting traffic and pedestrian movements are separated in time.

The management of traffic increases emissions by inducing accelerating behaviour which requires additional power. In addition, pedestrians use the facilities at the intersection to safely cross the road, often waiting to do so. A further example is a bus stop, where large, and high emitting, diesel vehicles decelerate, idle and accelerate. The vehicle operating behaviours that induce the greatest amount of pollutant emissions are concentrated in the vicinity of waiting travellers. Both of these examples are areas where pollutant sources (vehicles) and receptors (pedestrians) interact. Efforts to reduce the negative impacts of the former on the latter require a thorough understanding of all system components, enabling an integrated assessment.

1.3 Current research issues

This section briefly describes the current issues and limitations of research in this area. The summary is organised thematically, and reference is made to subsequent chapters of this thesis.

1.3.1 Traffic management and vehicle emissions

Reducing the environmental burden of road transport can be approached in several different ways. By decreasing the overall demand for travel, total emissions can be reduced. By
encouraging modal shift or technological change, the emissions produced by a single trip can also be reduced. A further pathway exists through influencing the operating environment of the vehicle, and consequently the operating behaviour. The mechanisms by which different vehicle operating behaviours increase the demand for power are understood. It is also accepted that, dependent on the specifics of the vehicle, changes to the operating behaviour increase pollutant emissions. Much research has therefore been conducted which investigates the impact of various elements of traffic management on vehicle operating behaviour, emissions and air quality. However, much of this work focuses only on the sources of emissions, without sufficient consideration of the receptors. In particular, the results of such studies often lack sufficient temporal and spatial granularity to be relevant to studies concerning exposure to pedestrians, who spend only a limited time at such locations. For example, the extent to which annual mean pollutant values are relevant to a 15-minute walking commute in the AM peak period are not properly addressed.

There is therefore a need to properly assess the potential of pedestrian infrastructure (representing a hotspot for pollution emissions, pedestrian activity and therefore exposure) to influence vehicle operating behaviours and emissions. This area is discussed further in chapters 2 and 3 of this thesis. As understanding of these effects on a high temporal and spatial scale is improved, assessments of pedestrian exposure can be better assessed and approaches to address these problems can be more thoroughly evaluated.

1.3.2 Local variability in air quality and personal exposure to pollution

The potential for vehicle operating behaviours and emissions to vary over space and time logically suggests that on-street levels of pollution will also vary at a similar scale. Despite this, air quality regulations, measurement and reporting metrics take place on much coarser spatial and temporal scales.

There is a lack of relevance of current air quality regulations to activity of pollutant receptors. For example, statistics such as daily averages do not indicate how pollution and exposure varies during pedestrian journeys. Furthermore, due to the practicalities of continuous monitoring, air quality over large areas is often represented by a single point. These issues are discussed further in Chapter 4. There is a need to understand the spatial and temporal variability of pollutant concentrations at a more relevant scale. In this case, relevance is determined by the activity of the pollution receptors, as the ultimate aim being to assess the exposure to pollution. These issues are discussed in chapters 4, 6 and 7 of this thesis.
1.3.3 Black carbon measurement techniques

Black carbon is identified as an emerging pollutant of interest, as a unique species for identifying combustion sources and with potential to impact human health and global climate change. Defined as the component of atmospheric aerosol that absorbs visible radiation (Highwood and Kinnersley, 2006), the species is therefore intrinsically linked to the optical measurement technique. The need to measure at a more granular level than common in air quality studies introduces challenges in the optical measurement of black carbon with aethalometers. Robust techniques are required to deal with known issues and deliver the high-resolution measurements required for assessment of air quality and human exposure to pollution. This research issue is discussed in Chapter 5 of this thesis.

1.4 Research aims and objectives

This thesis contributes towards improved understanding of the research issues detailed in Section 1.3. The overall aim of this work is to further understanding of the proliferation of emission and exposure hotspots in urban areas as a means to reduce their occurrence and impact on human health. Hotspots are defined as locations where, due to the management of transport and people, elevated vehicle emissions and poor air quality are observed. In addition, due to the presence of human activity, these locations are also considered hotspots for human exposure.

This is achieved by addressing the specific research objectives listed here:

1. Demonstrate the mechanism and evaluate the extent to which vehicle operating behaviour and emissions vary in the vicinity of traffic management infrastructure;

2. Specify, evaluate and refine techniques for the measurement of black carbon concentration around traffic management infrastructure, for the use in studies of personal exposure;

3. Identify the spatial and temporal variability in black carbon concentration and its relation to explanatory variables at traffic management infrastructure;

4. Assess the exposure of pedestrians using traffic management infrastructure to black carbon pollution and identify the relationship to traffic management.
At-grade pedestrian facilities provide a suitable series of traffic management infrastructure case studies for this work, and black carbon is considered a particular pollutant of interest.

1.5 Thesis structure

This thesis contains eight chapters. Each chapter includes an introduction and summary, and is further split into sections and subsections.

Chapter 1: Introduction

The introductory chapter describes the research area in general and gives an overview of the key elements of the thesis. The current research issues are summarised and, from this, research aims and objectives are specified.

Chapter 2: Traffic management and vehicle emissions

The second chapter describes the formation of vehicle emissions, identifies the key sources of variation and reviews the links to traffic management infrastructure. By means of a review of relevant literature, past work in this area is critiqued and gaps in understanding are identified. There is a particular focus on the interaction between pedestrians and road vehicles in urban areas, and of the production of black carbon and fine particulates.

Chapter 3: Traffic state, vehicle dynamics and emissions in the vicinity of at-grade pedestrian infrastructure

Chapter 3 presents a field campaign to characterise the variability of dynamic vehicle behaviour in the vicinity of traffic management infrastructure. Using repeated observations of a single instrumented vehicle and an instantaneous emission database, this work highlights the potential for increased vehicle emissions at locations where pedestrian activity is high. This chapter addresses the first research objective.

Chapter 4: Urban air quality, black carbon and pedestrian exposure to pollution

Personal exposure to pollution and the resulting health effects are discussed, with a particular focus on black carbon. Existing policies and legislative measures are critically reviewed alongside past epidemiological and environmental research. The factors that
influence pedestrian exposure are discussed, and the inadequacy of current means of assessing traffic-induced urban air pollution is highlighted. This chapter aids in specifying the measurement requirements needed for satisfying the second research objective.

Chapter 5: Measurement of black carbon

This chapter describes the aethalometer as a device for the optical measurement of black carbon and discusses the various challenges associated with high-resolution monitoring. The technique is utilised in different scenarios, and with multiple devices simultaneously, in order to characterise the associated errors. Measurement limitations are addressed and recommendations for the post-processing of raw data are made. This chapter addresses the second research objective.

Chapter 6: Black carbon concentration at urban intersections

Intensive experimental campaigns in two large UK cities are described. The resulting data allow for the identification of variability in the spatial and temporal distribution of black carbon concentration at urban intersections. The systematic variability of black carbon with explanatory factors such as traffic is investigated, with associated implications for urban traffic management. This chapter addresses the third research objective.

Chapter 7: Personal exposure to black carbon at an urban intersection

Personal exposure to black carbon is explored through a variety of techniques. A probabilistic model is estimated and applied as a tool for forecasting high-magnitude events. Links between pedestrian exposure and traffic control are determined, with associated implications for urban planning. High-resolution data on the spatial and temporal variability of black carbon concentration is used to estimate the exposure to black carbon of a pedestrian using a staggered crossing. This chapter addresses the fourth research objective.

Chapter 8: Conclusions and further work

The final chapter of this thesis compiles the conclusions of the preceding chapters and makes recommendations for further work in the field. Particular reference is made to the practical implications of this work, including for transport policy and best practice in local transport scheme design.
2 Traffic management and vehicle emissions

The problem of traffic-induced poor air quality is significant and covers many different subject areas. In order to address the research objectives identified in Section 1.4, it is important to have an understanding of the theoretical underpinnings, and of research previously conducted.

2.1 Formation of pollutant emissions

This section first deals with the formation of emissions and the factors that influence. Secondly, a detailed discussion of particulate matter and black carbon is presented.

2.1.1 Vehicle power requirements

For motion, a vehicle must generate power in order to overcome the resistive forces acting against it (Heywood, 1988). These resistive forces are collectively termed the “total running resistance” (Dietsche and Klingebiel, 2008), and are defined as:

\[ F_W = F_{Ro} + F_L + F_{St} \]

Where:

- \( F_{Ro} \) = rolling resistance (N)
- \( F_L \) = aerodynamic drag (N)
- \( F_{St} \) = climbing resistance / downgrade drag (N)

The first term, rolling resistance, refers to the resistive forces generated by the interaction of the vehicle tyres on the road surface. This differs according to the materials used in tyre and road construction, and to the operating conditions (Dietsche and Klingebiel, 2008). For standard pneumatic tyres, values of the coefficient of rolling resistance include 0.013 for asphalt surfaces and 0.05 for unpaved roads\(^5\).

\[ F_{Ro} = f \times m \times g \times \cos \alpha \]

\(^5\) When the vehicle is turning, a term for cornering resistance is also included.
Where:

- $f$ = coefficient of rolling resistance
- $m$ = mass of the vehicle (kg)
- $g$ = acceleration due to gravity (m/s$^2$)
- $\alpha$ = gradient angle

Aerodynamic drag refers to the forces opposing the motion of the vehicle through the air. Therefore, it is largely dependent on the vehicle body configuration and wind speed.

$$F_L = 0.5 \times \rho \alpha \times C_d \times A \times (v + v_0)^2$$  \hspace{1cm} \text{(Equation 2-3)}

Where:

- $\rho \alpha$ = density of air (kg/m$^3$)
- $C_d$ = drag coefficient of the vehicle
- $A$ = frontal area of the vehicle (m$^2$)
- $v$ = vehicle velocity (m/s)
- $v_0$ = headwind speed (m/s)

A vehicle that is more ‘streamlined’ allows air to pass more easily and therefore, has a lower drag coefficient, and lower aerodynamic drag (Dietsche and Klingebiel, 2008).

Climbing resistance accounts for the effects of gravity. This is negative when travelling downhill and is called downgrade force. This is determined by the angle ($\alpha$) of incline and mass of the vehicle.

$$F_{St} = m \times g \times \sin \alpha$$  \hspace{1cm} \text{(Equation 2-4)}

Jimenez-Palacios (1999) introduced the term vehicle specific power (VSP), defined as the “instantaneous power per unit mass of the vehicle”. This is the power generated by the engine to overcome the rolling resistance and aerodynamic drag, and to increase the kinetic and potential energies of the vehicle (Equation 2-5).
\[
VSP = \frac{d}{dt} \left( KE + PE \right) + F_{Ro} + F_L \cdot v
\]
\[
\frac{m}{\text{Equation 2-5}}
\]

Where, for a given point in time:

\[
KE = \text{the kinetic energy of the vehicle}
\]
\[
PE = \text{the potential energy of the vehicle}
\]

Jimenez-Palacios (1999) also provided a generic equation to evaluate VSP (Equation 2-6).

\[
VSP = v \cdot (a \cdot (1 + \epsilon_i) + g \cdot gr + g \cdot f + \frac{1}{2} \rho_a \frac{C_d \cdot A}{m} (v + v_0)^2) \cdot v
\]
\[
\text{Equation 2-6}
\]

Where:

\[
a = \text{vehicle acceleration (m/s}^2\text{)}
\]
\[
\epsilon_i = \text{the gear specific "mass factor"}\text{\textsuperscript{6}}
\]
\[
gr = \text{the road gradient}
\]

VSP has been utilised in several studies (Bapat and Gao, 2010; North, 2006; Zhai et al., 2008) as an explanatory variable when modelling vehicle emissions.

For simplicity, power requirements of the vehicle are considered in terms of Equation 2-1, and therefore, the power required to overcome total running resistance is termed \( P_W \). Power must also be sufficient to account for inefficiencies in transfer and supplementary systems (such as air conditioning). The total power demand \( P \) at time \( t \) by vehicle \( k \) is a function of the power required to provide motion, \( P_W \) and the power required for ancillary systems, \( P_A \), whilst acknowledging the efficiency \( (\eta) \) of the system is such that a proportion of power is lost.

\[
P_{t,k} = \eta(P_W + P_A)
\]
\[
\text{Equation 2-7}
\]

\textsuperscript{6}“Mass factor” is defined as the equivalent translational mass of the rotating components of the power train (Jimenez-Palacios, 1999).
The most common way of supplying motive power to a vehicle is through an internal combustion engine (ICE). The ICE operates by converting the chemical energy in hydrocarbon-rich fuel into thermal energy and mechanical work. More than 99% of the car fleet in Great Britain is powered by conventional combustion engines (DfT, 2013b), either compression-ignition (diesel) or spark-ignition (petrol). It is the process of combustion which leads to the formation of pollutant emissions. Significant research has been undertaken to demonstrate and characterise the relationship between vehicle power and pollutant emissions (for example Carslaw et al, 2013; Frey et al, 2003). In addition, the choice of fuel impacts the mix of emissions, making it an important aspect of research in the field of transport induced poor air quality. However, in both cases (diesel or petrol), a desirable outcome is to reduce the power requirements of the vehicle, hence reducing fuel consumption and pollutant emissions.

2.1.2 Formation of typical pollutant species

Petrol and diesel fuel consists of a complex mixture of aliphatic hydrocarbon chains. If a pure hydrocarbon reacts with oxygen, the only products are carbon dioxide and water. For example, octane is generally a major component of petrol fuel (Equation 2-8).

\[ 2C_8H_{18} + 25O_2 \rightarrow 16CO_2 + 18H_2O \]

Under high temperature and pressure (such as is found in an internal combustion engine), nitrogen and oxygen in air also react to form oxides of nitrogen (NO\textsubscript{X}). This is referred to as ‘complete’ combustion.

Although not generally of concern as a local air pollutant, carbon dioxide (CO\textsubscript{2}) is the main contributor to anthropogenic climate change (European Commission, 2012b). CO\textsubscript{2} is a greenhouse gas (GHG), meaning it absorbs infrared radiation, preventing it from leaving the atmosphere and consequently affecting the global energy balance. Although GHGs are essential for maintaining a suitable ambient temperature on Earth, increased emissions of GHGs from human activities are expected to cause global climate change (IPCC, 2013).

Nitrogen oxides refer to both nitric oxide (NO) and nitrogen dioxide (NO\textsubscript{2}). Whilst these are typically formed in small quantities, their environmental impact can be substantial. Depending on the design of the engine and operating conditions, emissions of NO\textsubscript{X} are typically of the order 500 – 1000ppm (or 20g per kg of fuel) (Heywood, 1988). On-road emissions of NO\textsubscript{X} have been shown to range between 0.2 and 1.2g/km for European diesel passenger cars.
(Lee et al, 2013). This is in excess of the specified regulatory limits, and discussed further in Section 2.2.3. During combustion, NO is the dominant NO\textsubscript{X} species formed. Further oxidation leads to the production of NO\textsubscript{2}. The formation of NO is by the following mechanism (Stone, 1999):

\begin{align*}
  O + N_2 &\rightleftharpoons NO + N & \text{Equation 2-9} \\
  N + O_2 &\rightleftharpoons NO + O & \text{Equation 2-10} \\
  N + OH &\rightleftharpoons NO + H & \text{Equation 2-11}
\end{align*}

Exposure to nitrogen dioxide has been linked to cardiovascular health problems, and nitrogen oxides are known to cause respiratory damage and to impair lung function (US EPA, 2013). For these reasons, NO\textsubscript{X} is regulated under vehicle emissions standards (see Section 2.2). NO\textsubscript{X} may also undergo further reaction to form nitric acid, which has multiple adverse effects, including contributing to acid rain.

The emissions discussed so far form during complete combustion of a pure hydrocarbon fuel in air, in an ICE. However, a more common occurrence is 'incomplete combustion'. This arises when the conditions are not ideal; for instance, if there is insufficient oxygen or the fuel contains impurities. Under conditions of incomplete combustion there are many more products, including carbon monoxide (CO), nitrogen oxides (NO\textsubscript{X}), unburned hydrocarbons (HC), soot and black carbon. Even in such circumstances, the major components of exhaust gas are as-designed (i.e. as in Equation 2-8), alongside un-reacted air. These make up the majority of exhaust emissions (Dietsche and Klingebiel, 2008).

2.1.3 Particulate matter and black carbon

Hydrocarbon and carbon emissions from motor vehicles are the result of unburned and partially burned hydrocarbon fuel components and other particulate waste from the combustion process. This may be considered a source of inefficiency in the system, as the chemical energy of the fuel has not been fully utilised. Particulates also form downstream of the engine and tailpipe as a result of secondary processes (see discussion surrounding definitions of black carbon in Section 4.1). Particulate matter (PM) forms when carbon containing molecules condense into solid form. PM is a broad term which refers to many different solid and liquid particles suspended in air. Commonly they are split according to particle size, with a subscript number indicating the upper level of particle diameter. For example, PM\textsubscript{10} refers to particles with an aerodynamic diameter of 10\textmu m or less. The use of physical size as a means of identification for particulate species (particularly for
environmental regulation and legislation) has been criticised, as the chemical composition is important when appraising the impacts (Maricq, 2007). Consideration by chemical composition (Heywood, 1988) includes elemental carbon (sometimes used synonymously with black carbon and soot and discussed further in Section 4.1), volatile organic compounds (VOC) and inorganic materials (nitrates, sulphates and other metallic compounds).

Production of particulates is most strongly associated with diesel fuelled vehicles with emissions from petrol engines being so low they are not generally measured\(^7\). Kittelson (1998) describes three modes of particle size. The smallest particles are contained within the *nuclei* mode, which whilst containing up to 20% of the particle mass, is responsible for more than 90% of the particle number. Figure 2-1 shows this for the *nuclei* (containing VOC and sulphur containing compounds), *accumulation* (consisting of solid material such as elemental carbon) and *coarse* (a mix of larger, agglomerated particles) modes.

*Figure 2-1: Typical engine exhaust size distribution (from Kittelson, 1998).*

![Typical engine exhaust size distribution](image)

Heterogeneity in vehicle emissions is illustrated, including the evident disparity when comparing particle count with mass. Image reproduced with permission of the rights holder, Elsevier.

Figure 2-1 represents a typical state, but serves to demonstrate the importance of not considering PM as a single species. This is particularly relevant in the study of health effects. Many of the health effects of particulate matter are intuitive; since they are not gaseous, particulate inhalation can be a direct cause of respiratory problems (WHO, 2013). Smaller

\(^7\) Prior to Euro 5, petrol engine passenger cars were not subject to PM limits. Current (Euro 5) and future (Euro 6) regulations legislate PM only for direct-injection petrol-engined passenger cars.
particles (for example PM$_{2.5}$) may also be absorbed through cell membranes and cause damage to internal organs.

The transport contribution to on-street levels of PM is not limited to tailpipe emissions, but also includes brake and tyre wear, road surface disturbance (wear and re-suspension of settled particles) and secondary atmospheric processes. The contribution of each of these to local concentration of PM is dependent on size. In a North American study, Abu-Allaban et al (2003) showed that tailpipe emissions were the largest contributor (by mass) to vehicle-induced PM$_{2.5}$, whilst PM$_{10}$ was made up mainly of re-suspended road dust. Similar studies have been conducted in Japan and Europe (Panko et al, 2013).

Black carbon (BC) is a major component of particulate matter at roadside (Quincey et al, 2009). However, the term is not universally defined. Highwood and Kinnersley (2006) state that black carbon is comprised of both elemental carbon (of various allotropes) and some organic carbon species. The shared characteristic of these components is that they absorb visible radiation. Invernizzi et al (2011) describe black carbon as "a unique primary tracer for combustion emissions, as it has no non-combustion sources, and is stable once released into the atmosphere". This makes it a useful component of particulate matter for direct measurement of the environmental impact of transport in urban areas. Black carbon is also interesting as the atmospheric effects are not confined to local pollution, but also to the impact on global climate. The importance of black carbon is discussed in detail in Chapter 4.

2.1.4 Summary: formation of pollutant emissions

The operation of motor vehicles is responsible for the production of several different pollutant emissions with associated local and global atmospheric effects. The formation of pollutant species can be linked back to the power demands upon a vehicle. Consequently, one course of action in reducing the pollutant emissions of a given vehicle is to reduce the demand for power. One important pollutant species is particulate matter, a result of unburned and partially burned hydrocarbon fuel components. A component of PM is black carbon, which has several mechanisms of impact on the environment and on respiratory health. The stability of black carbon emissions from motor vehicles makes it an attractive species for measurement and modelling.
2.2 Fleet composition

The composition of vehicle exhaust emissions is related to the amount of fuel burned (and so the power demands placed upon the vehicle), fuel type, vehicle age (reflecting technological advancement and general mechanical deterioration) and the operating state of repair of the vehicle. Understanding the composition of vehicle fleet is important in many aspects of transport modelling and traffic engineering. This is also true when considering the environmental impacts of traffic, as variability between and within sites is expected in part due to the fleet mix (Huo et al., 2011). This section details the different ways in which fleet characteristics influence the expected rate of vehicle pollutant emissions.

2.2.1 Fuel type

As stated in Section 2.1, more than 99% of the vehicle fleet in the UK is powered by conventional internal combustion engine technology, commonly referred to as petrol (gasoline) and diesel. Whilst the exact chemical makeup of these fuels is different, both are hydrocarbon fuels, generally refined from petroleum crude oil. Whilst the generic pollutant species produced from their combustion (as detailed in Section 2.1) are the same, the proportion of each component in vehicle exhaust is not. Diesel fuelled vehicles are generally lauded as being more efficient than petrol. As diesel fuel contains more energy by volume, diesel vehicles generally produce better volumetric fuel economy. This does not necessarily mean an overall lower environmental impact. This is illustrated by the different UK fleet-average emission factors (mass of pollutant per unit distance) for these fuel types, shown in Table 2-1.

Table 2-1: Hot exhaust emission factors for the UK vehicle fleet (Defra, 2013).

<table>
<thead>
<tr>
<th>Fuel type</th>
<th>Hot exhaust emission factor (g/km)</th>
<th>NO\textsubscript{X}</th>
<th>PM\textsubscript{10}</th>
<th>PM\textsubscript{2.5}</th>
<th>CO</th>
<th>CO\textsubscript{2}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Petrol car</td>
<td>Urban</td>
<td>0.181</td>
<td>0.001</td>
<td>0.001</td>
<td>1.085</td>
<td>215.4</td>
</tr>
<tr>
<td></td>
<td>Rural</td>
<td>0.173</td>
<td>0.001</td>
<td>0.001</td>
<td>1.083</td>
<td>187.6</td>
</tr>
<tr>
<td></td>
<td>Motorway</td>
<td>0.181</td>
<td>0.001</td>
<td>0.001</td>
<td>1.544</td>
<td>201.0</td>
</tr>
<tr>
<td>Diesel car</td>
<td>Urban</td>
<td>0.612</td>
<td>0.020</td>
<td>0.019</td>
<td>0.127</td>
<td>203.5</td>
</tr>
<tr>
<td></td>
<td>Rural</td>
<td>0.521</td>
<td>0.018</td>
<td>0.017</td>
<td>0.054</td>
<td>170.8</td>
</tr>
<tr>
<td></td>
<td>Motorway</td>
<td>0.638</td>
<td>0.020</td>
<td>0.019</td>
<td>0.034</td>
<td>183.4</td>
</tr>
</tbody>
</table>

National Atmospheric Emissions Inventory emissions factors (mass of pollutant per unit distance) are average values derived from empirical measurements.
Whilst diesel vehicles are more fuel efficient (as exemplified by CO₂ emission rate) than petrol vehicles, emissions of particulates such as PM₁₀ can be in the order of 20 times higher. Due to these differences, the proliferation of diesel vehicles in the UK fleet can have significant consequences for vehicle emissions, and by extension local air quality and human health. Since 1990, the proportion of new car sales accounted for by diesel vehicles has risen greatly in the UK and Europe. In the UK, 6.4% of new passenger car registrations in 1990 were diesel powered. By 2012 this had risen to around 50% (ACEA, 2013).

The potential impact of UK fleet dieselisation can be illustrated through a simple worked example. In this hypothetical scenario, data relating to the increasing number of diesel vehicles (ACEA, 2013) is used alongside existing exhaust emission factors (Table 2-1) to produce estimates of total emissions for various pollutants.

The emissions ($V_{ehE}$) of pollutant $p$ by vehicle $i$ in a given time period are equal to the fuel and road type specific emission factor, $E_f$, multiplied by the distance travelled on that road type, $Dist$, summed over all $k$ fuel and road types.

$$V_{ehE_{p,i}} = \sum_{k} E_{f_k} * Dist_{k} \quad \text{Equation 2-12}$$

In this example, annual vehicle distance travelled is taken to be 15,000km, split evenly between urban, rural and motorway driving. Fuel and road type emission factors are used as per Table 2-1 (Defra, 2013).

Fleet emissions ($FleetE$) of pollutant $p$ for year $t$ are subsequently the sum of the total emissions from all $i$ vehicles.

$$FleetE_{p,t} = \sum_{i} V_{ehE_{i}} \quad \text{Equation 2-13}$$

It is assumed that the passenger car fleet size in year 1 is 10 million vehicles, of which 6.4% are diesel. Annual growth is assumed to be 2%, with 3% uniform replacement of the existing fleet. Diesel fleet share is then progressed in the model as per UK figures from 1990 onwards (ACEA, 2013), and are used to project the proportion of diesel vehicles of the total fleet. As the proportion of diesel vehicles that make up the fleet increases over the 25 year
period, annual average per vehicle emissions of NO\textsubscript{X} and PM\textsubscript{10} are seen to rise significantly, against a relatively small decrease in CO\textsubscript{2} emissions (Figure 2-2).

*Figure 2-2: Evolution of diesel fleet share and annual average per vehicle emissions.*

As the share of the diesel fleet grows (secondary y-axis), annual average pollutant emissions per vehicle of PM\textsubscript{10} and NO\textsubscript{X} are seen to rise, offset against a relatively small reduction in average CO\textsubscript{2} emissions.

This scenario is simple, and does not take into account potential improvements in vehicle technology or the impact of vehicle deterioration on emissions and efficiency. However, it serves to illustrate the prospect of increased emissions of certain pollutants, and the potential trade-offs, as the makeup of the vehicle fleet changes.

### 2.2.2 Vehicle type

In addition to fuel, vehicle type is also an important determinant of emissions. Considerable research effort has been directed at estimating emission rates of various pollutants from different classes of vehicles (for example Frey et al, 2003; North, 2006; Zhai et al, 2008). Figure 2-3 shows UK NAEI emission factors for vehicle classes over a range of different pollutants (Defra, 2013). Emission rates for heavier vehicle classes (bus, HGV) are between
five and ten times greater than those for the lighter vehicles. This is expected when considering the likely different demands for power.

*Figure 2-3: National Atmospheric Emissions Inventory (NAEI) UK hot exhaust emission factors for diesel vehicles (Defra, 2013).*

![Graphs showing emission factors for different vehicle types](image)

*Higher emissions rates are shown for heavier vehicles, such as buses and heavy goods vehicles. In this instance, 'LGV' refers to light goods vehicles; 'HGV' refers to articulated heavy goods vehicles.*

For vehicle classes with higher pollutant emission rates, it would not necessarily be correct to assert that they are more ‘damaging’ to the environment than others. For example, a passenger bus may carry many more passengers than a single car, and so emissions per capita could be lower. However, this demonstrates the importance of understanding the makeup of a vehicle fleet.

### 2.2.3 Vehicle age and technology

The importance of vehicle age is two-fold. Firstly, vehicle and fuel technologies have improved over recent years, leading to a reduction in the emission of most harmful pollutants. For pollutants such as lead and benzene, emission has been largely eliminated (DfT, 2012b). Improvements in vehicle technology can be attributed several factors, such as consumer demand for greater fuel efficiency, and national and international legislation enforcing more rigorous vehicle emissions standards.
Secondly, research has demonstrated that over the life of a vehicle, the emissions control systems deteriorate, increasing emission rates of harmful pollutants (Samaras et al., 1998). Although vehicle mileage generally decreases with age (Zachariadis et al., 2001), vehicle age remains an important factor that influences emissions and air quality at a given location. Furthermore, the expectation is that the mechanical efficiency of a vehicle decreases with age, necessitating a greater fuel burn to achieve the same level of travel. Whilst it is a general expectation that older vehicles, with inferior emissions control technology and more wear to mechanical components, will produce greater levels of harmful pollutant emissions (Beydoun and Guldmann, 2006), this is not a simple linear relation between emission rates and vehicle age.

In Europe (including the UK), vehicle emissions have been regulated since 1970 for light-duty vehicles\(^8\) and 1987 for heavy-duty vehicles\(^9\) (European Commission, 2012a). Current emissions legislation (imposing the generally referred to “Euro Standards”) has been in force for passenger cars and larger vehicles since 1992\(^{10}\). This legislation sets out the acceptable limits of various exhaust emissions for new vehicles sold in the European Union. Since inception, these have become more stringent with time. As an example, Table 2-2 shows diesel emissions standards for selected pollutants (determined over the New European Driving Cycle). It should be noted that no distinction is made between the difference fractions of PM, and that black carbon is not subject to any specific standard.

<table>
<thead>
<tr>
<th>Euro standard</th>
<th>Date of implementation</th>
<th>CO (g/km)</th>
<th>NO(_X) (g/km)</th>
<th>PM (g/km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Euro 1</td>
<td>07/1993</td>
<td>2.72</td>
<td>-</td>
<td>0.140</td>
</tr>
<tr>
<td>Euro 2</td>
<td>01/1997</td>
<td>1.00</td>
<td>-</td>
<td>0.080</td>
</tr>
<tr>
<td>Euro 3</td>
<td>01/2001</td>
<td>0.64</td>
<td>0.50</td>
<td>0.050</td>
</tr>
<tr>
<td>Euro 4</td>
<td>01/2006</td>
<td>0.50</td>
<td>0.25</td>
<td>0.025</td>
</tr>
<tr>
<td>Euro 5</td>
<td>09/2010</td>
<td>0.50</td>
<td>0.18</td>
<td>0.005</td>
</tr>
<tr>
<td>Euro 6</td>
<td>09/2014</td>
<td>0.50</td>
<td>0.08</td>
<td>0.005</td>
</tr>
</tbody>
</table>

---

\(^8\) Directive 70/220/EEC  
\(^9\) Directive 88/77/EEC  
\(^{10}\) Direction 91/441/EEC
The latest emissions standards, Euro 6, come into force from September 2014 and will be applied to the registration and sale of new cars from January 2015. For diesel vehicles, there is a reduction in the permissible level of NO\textsubscript{X} emissions.

The real-world impacts of emissions standards in Europe have come under scrutiny, with some research indicating that the seemingly progressive improvements are not demonstrated in the real-world. Rhys-Tyler et al (2011) showed through observations in London that emissions of nitric oxide (NO) from Euro 2 and Euro 3 diesel passenger cars were actually higher than Euro 1. Furthermore, some research has shown that when driven in real-world conditions (as opposed to the laboratory drive cycles used in vehicle certification) emissions from Euro-standard vehicles may exceed the limits set (Mamakos et al, 2013; Tzamkiozis et al, 2010). Franco et al (2014) compared on-road emissions from a series of diesel vehicles to Euro 6 standards. Empirical data was measured using PEMS equipment, and is therefore representative of the real-world, rather than the off-road chassis dynamometer testing that is used to check compliance with standards. On average, it was found that NO\textsubscript{X} emissions from diesel vehicles were seven times greater than stipulated by Euro 6 regulatory limits. However, the level of exceedance seen over the 15 test vehicles was not consistent. At the upper end, there were two instances of test vehicles reporting greater than 1.5g/km of NO\textsubscript{X} emissions, which is more than 20 times the specified Euro 6 limit. However, as Franco et al point out, instances of vehicles meeting the regulations over the course of on-road testing, and it can therefore be concluded that the limits are achievable within the confines of existing technology. These results are in keeping with those of other studies, such as Lee et al (2013) and Weiss et al (2012).

Some of the regulatory measures on vehicle emissions have been discussed, and in particular, reducing the amount of pollution emitted by a vehicle (mass per unit distance) has been encouraged. One potential means of improvement is through technological advancement. Whilst the role of technological change in reducing vehicle emissions should not be ignored, it is inadequate, particularly for short-term targets. As of 31 March 2011, there were 34.5 million registered vehicles in Great Britain (DfT, 2013b). The majority of these (28.7 million) are classed as cars\textsuperscript{11}, accounting for over 83% of the road vehicle fleet. Over the preceding year, there were approximately 2 million new car registrations. Even assuming zero total fleet growth and the homogenous replacement of vehicles, it would take more than 14 years to replace all registered vehicles.

\textsuperscript{11} Cars are classed as four-wheel vehicles, including people carriers and all passenger carrying vehicles which can carry no more than eight passengers. This includes private hire taxis which are car-based, but not “Hackney Carriages” (DfT, 2013b).
Therefore, even if zero-emissions technology became readily available and affordable (compared to conventional ICE vehicles), a substantial reduction in vehicle emissions would take several years to become apparent. In addition, zero-emissions technology at point of use may incur significant emissions or other environmental costs at other locations. Therefore, an appropriate evaluation of the trade-offs concerned should be conducted.

2.2.4 Summary: fleet composition

A vehicle fleet is not homogenous, with vehicle class, fuel type, vehicle age, state of repair and stage of technological advancement all being influencing factors on the rate of pollutant emissions. Therefore these factors are also important to research into vehicle-induced poor air quality. When considering air quality at a local level, an understanding of the makeup of the vehicle fleet is likely to be a significant influencing factor. For example, poor local air quality near a coach station may be readily explained by the presence of heavy diesel vehicles, and not by a general increase in diesel passenger cars in the UK.

Policies aimed at influencing the make-up of the vehicle fleet should be mindful of several different factors. Firstly, trade-offs exist on fuel type. Consumers may be encouraged to purchase diesel vehicles due to their greater fuel efficiency reducing operating costs. This has some environmental benefits in reducing CO\textsubscript{2} emissions, but has far greater rates of emissions of other pollutants when compared to an equivalent petrol vehicle. As such, the proliferation of diesel vehicles in the UK fleet makes emissions of NO\textsubscript{x} and PM (and as a consequence BC) a particularly important issue. Secondly, the rate at which large-scale technological change can influence vehicle emissions is related to the turnover of the vehicle fleet, and as such may take many years to have a significant effect.

2.3 Traffic engineering and control (TEC)

Section 2.1 discussed the link between the demand for power and the production of vehicle emissions. The power demands placed upon a vehicle are linked to the operating environment, on which traffic engineering and control (TEC) have a significant effect. TEC can be considered as the management of different road users, with often conflicting demands, in space and time. Slinn et al (2005) describe the biggest challenge for traffic engineers as addressing the imbalance between the amount of traffic and route capacity.
This section will provide a background to the key concepts of TEC and explain the mechanism through which elevated levels of vehicle emissions occur.

### 2.3.1 Urban intersections

Intersections are potential points of conflict on the traffic network, where a vehicle transfers from one route to another, and in doing so crosses other traffic streams between it and its destination. In doing so, the vehicle may merge with, diverge from, or cross paths with pedestrians and other road users (Salter and Hounsell, 1996).

Management of this conflict is achieved in different ways, with the choice of intersection impacting how vehicles utilise it, the demand for power and ultimately emissions. Although such decisions are ideally made with safety, economic and environmental considerations, in urban areas practicalities of space often weigh heavily. Slinn et al (2005) discuss five general types of intersection, as summarised in Table 2-3.

**Table 2-3: Types of traffic intersection (from Slinn et al, 2005).**

<table>
<thead>
<tr>
<th>Intersection type</th>
<th>General characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uncontrolled non-priority</td>
<td>Used in area with low levels of traffic flow</td>
</tr>
<tr>
<td>Priority</td>
<td>Common form of junction control with traffic on a minor road giving way to that on a major road</td>
</tr>
<tr>
<td>Roundabouts</td>
<td>Vehicles give way to off-side traffic thus removing crossing conflicts</td>
</tr>
<tr>
<td>Traffic signals</td>
<td>Widely used in urban areas to control conflicting high-flow traffic streams and pedestrians</td>
</tr>
<tr>
<td>Grade separated</td>
<td>At-grade conflicts are avoided by connecting major road access routes</td>
</tr>
</tbody>
</table>

In urban areas it is likely that pedestrians and cyclists will also compete for space on the network. Due to space constraints and large traffic flows, it is often preferable to separate conflicting movements of different road users in time, rather than space, by the use of traffic signals.
2.3.2 Traffic signals

The basic principle of traffic control is to maximise safety and efficiency by separating conflicting traffic movements in time (Salter and Hounsell, 1996). In recent years there has been some debate about the predominant use of traffic signals in urban areas, with some concern that they impede smooth running of the network and induce unnecessary delay (in London for example, GLA, 2009). Despite this, they remain a common traffic management solution in urban areas. At the start of 2009, there were over 2,500 signalised intersections in London, with many more existing as stand-alone pedestrian crossings. As part of a "smoothing traffic flow" programme in London (Transport for London, 2013), traffic signal sites are reviewed to see if they can be removed to provide economic and environmental benefits without compromising safety. Traffic signals are still necessary in many cases, such as where a major road traffic flow is too heavy to allow access from a minor road, or where there is no other means of safe crossing for pedestrians.

In the design of signalised intersections, traffic streams are separated into "phases". Each phase represents a series of movements that can occur at a given time. Traffic movements which do not conflict can be included in the same phase. The portion of time in which a phase is allowed to move (given a green light) is called a "stage"; a complete set of stages is a "cycle" (Salter and Hounsell, 1996). A simple example is that of a signalised crossroads where no right-turns are permitted and no pedestrian facilities, as shown in Figure 2-4.

Figure 2-4: Simple signalised crossroads.
The arms of the junction are labelled clockwise from A to D. There are eight possible traffic movements: A-B; A-C; B-D; B-C; C-A; C-D; D-B; D-A. Since not all of these movements conflict, they can be achieved (for example) in two stages, as shown in Figure 2-5. A staging diagram can be thought as a set of instructions – a signal plan – for traffic control at a junction. In addition to permissible traffic movements, the amount of time allocated to each stage and the total length of a cycle is a key characteristic of a signal plan.

Figure 2-5: Example staging diagram for a simple crossroads with banned right turns.

As there are conflicting movements, at any given time certain traffic movements are not allowed. Vehicle delay, and delay for other road users, is therefore, a common occurrence at traffic signals.

More complex junctions with greater opposing movements, facilities for pedestrians and capability for vehicle priority require more complex staging sequences and control. For greater efficiency, traffic control often occurs on a larger scale than one junction, so that the parameter of interest (often vehicle delay) can be optimised across a network. Rogers (2008) discuss the advantages and disadvantages of traffic control, as summarised in Table 2-4.

Table 2-4: Advantages and disadvantages of traffic control (from Rogers, 2008).

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reduces delay to motorists and pedestrians</td>
<td>Frequent maintenance and monitoring required</td>
</tr>
<tr>
<td>Reduces accidents</td>
<td>Can increase rear-end collisions</td>
</tr>
<tr>
<td>Minimises journey times, particularly in busy periods</td>
<td>Can be inefficient during off-peak times, when unnecessary delay is induced</td>
</tr>
<tr>
<td>Facilitates certain traffic management policies (such as bus priority)</td>
<td>Infrastructure failure can cause serious disruption to the traffic network</td>
</tr>
</tbody>
</table>
The advantages of traffic control are only relevant if the signals are implemented correctly and in appropriate locations.

### 2.3.3 Pedestrian facilities

A source of conflict in urban areas (both mid-link and at intersections) is between pedestrians and road vehicles. There are several ways of accommodating pedestrians in these situations. Grade-separation is possible through the use of subways and bridges. Although these can be useful in areas of high pedestrian and traffic flow, subways in particular have been a cause for concern in terms of personal safety for pedestrians.

The same space constraints relevant to road traffic management also impact the range of options available for pedestrian facilities. At intersections, at-grade solutions are often favoured when they can be integrated with the existing approach to traffic management (DfT, 1995a).

An example of incorporating pedestrians into a traffic intersection is shown in Figure 2-6. In this case, the dominant traffic stream is east to west. In order to accommodate pedestrians without disrupting the major flow of vehicles, certain movements are banned. This allows pedestrians to cross whilst vehicles are traversing the north-south route (Stage 2), allowing a higher proportion of the cycle time to be devoted to vehicular traffic.

*Figure 2-6: Pedestrian crossing incorporated into a signalised crossroads.*

In Stage 2, north-south traffic is allowed to move, but turning movements are not permitted, and as such pedestrians may cross safely on the eastern arm of the junction.
Decisions regarding the type and location of pedestrian facilities in urban areas influences the position of vehicles, the power requirements (and therefore emissions) of a vehicle and the position of pedestrians as receptors of pollution. For example, increasing the power demand of vehicles in a local area may result in increased vehicle emissions, and degradation in air quality. However, a system that reduces emissions from vehicles may also have the effect of delaying pedestrians, increasing the time that they are exposed to pollution.

The optimisation of these factors in order to minimise the emission of, and exposure to, harmful pollutants is a challenge. A more detailed discussion of pedestrian facilities in contained in Section 3.2, and on human exposure to pollution in Section 4.3.

2.3.4 Environmental impacts of interrupting traffic flow

This section discusses the environmental importance of interrupting the flow of traffic through TEC measures. When managing competing demands for road space in time, it is likely that delay is induced for roads users at some point. This interrupts the general flow of traffic, with vehicles decelerating, idling and accelerating in the course of using the intersection. Pandian et al (2009) describe poor air quality at junctions as due to variation in vehicle speed as they approach and depart. As well as increased vehicle emissions, junctions are areas where there is significant mixing of air flows. Therefore, emissions at an intersection may influence air quality in adjoining links (Soulhac et al, 2009), with the relationships expected to be complex and time-varying.

Interrupting traffic flow and the subsequent delay causes vehicles to spend a greater amount of time decelerating, idling (stopped) and accelerating. Frey et al (2001) conceptualise these states as the “vehicle operating mode”, as defined in Table 2-5.

Table 2-5: Definitions of vehicle operating mode (from Frey et al, 2001).

<table>
<thead>
<tr>
<th>Mode</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Idle</td>
<td>Zero speed, zero acceleration</td>
</tr>
<tr>
<td>Acceleration</td>
<td>Speed greater than zero; acceleration at least 2 mph/sec or averaging at least 1 mph/sec for 3 sec</td>
</tr>
<tr>
<td>Deceleration</td>
<td>As before, but negative acceleration</td>
</tr>
<tr>
<td>Cruising</td>
<td>All other states</td>
</tr>
</tbody>
</table>
Whilst these states are described as “somewhat arbitrary” (Frey et al, 2001), experimental work conducted yielded average emission rates that were shown to be statistically significant (Frey et al, 2003). In this work, a portable emissions measurement system (PEMS) was fitted to a vehicle conducting repeated trips. Modal emission rates were developed based on assigning the vehicle state, and emissions produced, to one of the modes described in Table 2-5. Average modal emissions for a range of pollutants for a single passenger car are shown in Figure 2-7.

Figure 2-7: Average modal emission rates (from Frey et al, 2003).

For all pollutants, emission rates (mass per unit time) were highest when the vehicle was accelerating. The idle rate produced the lowest rate. However, since a vehicle is not moving when idling, emissions in this mode do not contribute to the vehicle traversing the intersection.

2.3.5 Summary: traffic engineering and control

The competing demands for space lead to congestion, delays and increased environmental impacts of road transport. In addition, general road characteristics such as design speed, horizontal curvature and vertical alignment impact the resistive forces acting upon a vehicle and consequently the energy required for movement. These factors influence the power required by the vehicle, and therefore, the pollutant emissions.
Any aspect of traffic management that increases the likelihood of time spent in the acceleration, idle and deceleration modes of operation increases the emission rate of a given vehicle. In particular, acceleration from a stop line, such as those associated with pedestrian crossings, is likely to produce more emissions than a vehicle operating a consistent cruise speed through the intersection. Since emission rates are per second, and speed during acceleration is generally lower, more time is spent in the vicinity of a pedestrian crossing and hence, pollutant emissions are higher. The mechanism by which pedestrian infrastructure can cause increased vehicle emissions is investigated further in Chapter 3.

2.4 Approaches to reducing vehicle emissions

In order to improve air quality and minimise the health effects of air pollution, there is a general requirement to reduce emissions from the vehicle fleet. There are several possible approaches through which this can be achieved, which are detailed below.

1) Reducing the demand for travel

The sum total of emissions produced could be reduced by lowering the overall demand for travel. This approach could be enhanced by targeting the particular vehicles which are responsible for a relatively large proportion of the emissions (i.e. heavy diesel vehicles).

2) Modal shift

Transport is an essential part of the economy, and therefore any effort to reduce the demand for travel may have detrimental impacts on other parts of society. Encouraging modal shift (for example, from private car to public transport, or from public transport to walking and cycling) can be seen as a means of reducing the environmental burden without a negative impact on the economy.

3) Encouraging technological change

A further means by which existing patterns of travel could be maintained whilst reducing the environmental cost of transport is by adopting new technologies. Technological change, such as introducing vehicles with lower emissions at the point of use, could be encouraging to reduce the unit cost to the environment of each vehicle. However, the trade-offs of such an approach would need to be fully understood before the impact of such an approach could be
properly evaluated. Furthermore, the benefits would not be realised immediately, as it would take time for the technology to penetrate the existing fleet (discussed in greater detail in Section 2.2).

4) Altering the operating environment

A fourth approach involves influencing the operating environment of the vehicle so that the transient demands for vehicle power are lowered, thus reducing the production of emissions. This would lead to a more efficient system as the same amount of useful work (travel) is obtained at a lower cost.

All approaches are viable, potentially complementary and the subject of much research and discussion. However, the final approach offers significant advantages in targeting particular areas of poor air quality. It is argued in this thesis that the first, second and third approaches are necessary for long-term and lasting changes to traffic-induced poor air quality. However, the fourth approach offers much in terms of the potential for short-term gains in areas where traffic-induced poor air quality hotspots exist, and the risk to human health is greatest.

2.5 Existing research on the influence of TEC

The previous sections established a theoretical basis for the influence of traffic engineering and control on vehicle emissions and urban air quality, and a rationale for further research in this area. A review of relevant literature is required to establish current understanding and identify gaps in existing knowledge.

2.5.1 General influence of traffic engineering

Brundell-Freij and Ericsson (2005) showed that some general qualitative characteristics of a street affect driver behaviour. The investigation was based upon the analysis of real-world driving patterns and utilised a data set of almost 19,000km of vehicle traces. However, the variables used to describe the street environment (for example, street function described as local, main or arterial) are rudimentary, lacking the level of detail required for local pedestrian infrastructure. Using a qualitative classification system is necessarily subjective and as such, only suitable for establishing general principles. However, the authors did acknowledge the broad range of parameters required to address the research problem, by also including vehicle properties (such as power-to-mass ratio). The largest effect found was that of the
density of junctions controlled by traffic lights, and the lower average travel speeds and
greater amount of vehicle acceleration events caused by this. This result is significant in
justifying the need for research to address the impact of traffic management infrastructure.

This research, in addition to Jensen (1995) and Owen (2005), does not acknowledge the
physical principles and mechanisms by which pollutant emissions are formed. Owen (2005)
investigated the air quality impacts of speed-restriction zones. The sites investigated did not
show significant change when speed was restricted. Whilst this was on a larger scale than
suitable for this research (0.5km by 0.5km), the study aim was to understand the impacts of
an area-wide scheme on ambient air quality. However, there was no discussion regarding
the change to vehicle dynamics that may be caused by a reduction of top speed in a given
zone, and the implication for pollution hotspots. For instance, in the context of vehicle
operating mode, it is of interest to investigate the influence of large-scale policy measures,
such as speed restrictions, on periodic episodes of acceleration and deceleration.

Litman (1999) concluded that methods to smooth traffic flow (i.e. increase propensity for
vehicles to cruise) generally reduce air pollution, whereas increasing the number of stops
(and starts) is likely to worsen the problem. This is sensible given the work of Frey et al
(2003) (discussed in Section 2.1) that demonstrated vehicle emissions increase under the
same circumstances. Ahn and Rakha (2009) also showed through a combination of
modelling and measurement that speed-calming methods that interrupt the steady-flow of
traffic (speed humps) tend to increase emissions. Similarly, Várhelyi (2002) showed that in
the case of a signalised junction being replaced by a roundabout, there was a significant
(28%) decrease in fuel consumption (and an associated decrease in emissions) without a
significant change in traffic volumes. This was attributed to a decrease in vehicle acceleration
events.

2.5.2 Research specific to traffic control

As discussed in Section 2.3, traffic signals are a common traffic management solution in
dense urban areas, and therefore research in this area is particularly relevant. The initial
sections of this chapter discussed the process by which delay is incurred by road users at a
signal-controlled intersection. Research has been undertaken to understand how traffic
control parameters impact emissions, and how they might be optimised for environmental
benefits.
Zhang et al (2009) estimated vehicle emissions for a series of different traffic control strategies. Although this research was concerned with a larger scale than relevant here, the use of micro-simulation techniques means that the analysis was based on microscopic driving cycles. For example, signal coordination was expected to result in lower emissions of NO$_x$, HC, CO and CO$_2$. For non-environmental parameters, travel time was shown to decrease, and there was an increase in average speed.

Li et al (2011) investigated the impacts of signal timing on vehicle emissions at a single intersection. Traffic control parameters, such as cycle time, were related to vehicle delay and the number of stops. A modelling approach (using VSP as an explanatory variable, see Section 2.1) was used to estimate the emissions of several pollutant species. It was shown that decreasing the number of stops resulted in increasing delay and a general increase in pollutant emissions. In general, minimising delay was found to be environmentally preferable. Although an interesting result, this fails to acknowledge other road users and the exposure to pollution.

Chen and Yu (2007) developed an integrated platform in order to assess different traffic control strategies on microscopic vehicle emissions. They showed the environmental benefits (in terms of emissions reductions for different vehicle classes) of operating an “optimised” signal plan, as shown in Figure 2-8.

*Figure 2-8: Benefits of an emission-optimised signal plan (from Chen and Yu, 2007).*

Reductions are between 2.5 and 15%, dependent upon pollutant and vehicle. Image reproduced with permission of the rights holder, China Association for Science and Technology.
De Coensel et al. (2012) showed through a simulation study that through a coordinated traffic signal green wave, emissions of some air pollutants could be reduced by between 10 and 40%. Coelho et al. (2005) discussed the trade-offs concerned with some of the primary aims of traffic control (in this case, controlling speed) and vehicle emissions. This research found that such aims were often conflicting with methods to reduce speed (to the expected benefit of safety) leading to increased vehicle emissions. The implication of this is to ensure that all aspects of the system are considered, not just environmental parameters.

2.5.3 Critical review of relevant literature

The research discussed in this section demonstrates that infrastructure designed to maintain the steady-flow of traffic may be beneficial to vehicle emissions and air quality when compared to that which encourages stop-start traffic conditions. In general these studies have all taken place on a large spatial scale and have been primarily concerned with only vehicle emissions. A common recurrence in research of this type is the failure to incorporate the position, and exposure to pollution, of receptors.

Whilst there is an acknowledgement of the detrimental impact of vehicle-induced poor air quality on human health, the research discussed so far does not pay particular attention to pedestrians and elements of pedestrian infrastructure. The presence of pedestrians in these locations makes the management of traffic in urban areas an area of interest to both transport and public health professionals. However, research to date on the influence of traffic management on vehicle emissions generally fails to acknowledge the importance of pedestrians and other receptors (such as cyclists and vehicle passengers).

Jayaratne et al. (2009) undertook a theoretical modelling study which sought to understand the impact of a mid-link pedestrian crossing on particle number. In this case, rather than being the focus of research, a signalized pedestrian crossing simply served as a convenient and simple case study. Nonetheless, it was demonstrated that particulate emissions (measured as particle number) increased significantly when delay was induced. Studies of this sort lack empirical data and therefore do not capture the range of traffic situations that may be encountered in urban areas.

It is telling that the majority of the literature that has specific reference to pedestrian infrastructure has been conducted from a human exposure to pollution perspective. This is discussed further in Chapter 4, with particular reference to studies of the exposure to black carbon and other fine particulates contained within Section 4.3.
In order to take make an integrated assessment of air quality and exposure at pedestrian infrastructure sites, neither vehicles nor pedestrian can be addressed in isolation, with the concentration of dispersed pollutants and relative positions of sources and receptors very important.

2.6 Summary: traffic management and vehicle emissions

The levels of emissions from motorised vehicles and resultant poor air quality can be related to the number of trips and overall demand for travel, the mode of transport and technology employed, and the operating environment of a vehicle. All of these factors represent levers which can be used to reduce the environmental burden of transport. However, manipulating the operating environment through traffic engineering and control is an approach that may potentially yield short-term benefits.

The role of traffic engineering in managing the safe operation of the road network has been discussed, and several key concepts of control introduced. It is demonstrated from previous literature that traffic management interventions such as signalised urban intersections and pedestrian crossings increase the likelihood of poor air quality due to the delay and subsequent acceleration of vehicles.

Much of the existing research lacks focus on pedestrian infrastructure in particular. Given then presence of pedestrians and the resultant exposure to harmful pollution, this is inadequate. Chapter 3 seeks to address this gap, presenting a field study designed to assess the potential for increased emissions from a single vehicle at different types of pedestrian infrastructure.
3 Traffic state, vehicle dynamics and emissions in the vicinity of at-grade pedestrian infrastructure

This chapter examines the management of the conflict between pedestrians and general road traffic in urban areas and, following on from Chapter 2, the potential for such facilities to induce additional vehicle emissions. This chapter details an investigation and subsequent analyses to address the first research objective:

*Demonstrate the mechanism and evaluate the extent to which vehicle operating behaviour and emissions vary in the vicinity of traffic management infrastructure.*

A field campaign is presented to characterise the variability in dynamic vehicle behaviour and the potential for increased pollutant emission rates in the vicinity of pedestrian infrastructure. The chapter contains the background to the research area, data collection methods and experimental design, analysis and results, and implications for transport planning and traffic engineering.

3.1 Background

As stated in Chapter 2, one of the greatest challenges faced by transport professionals today is managing the competing, and often conflicting, demands for road space in busy urban areas. One such conflict is between pedestrians and road users, made up predominantly of motor vehicles. Whilst the basic principles of this work may be applied to all urban areas, the focus of this research is on the UK.

Speed and acceleration are important for describing the operating state of the vehicle, and are related directly to the demand for power (Section 2.1). Therefore, they have particular relevance to the formation of pollutant emissions (see Section 2.1, Section 2.3.4 and, for example, the works of Frey et al (2003) and Jimenez-Palacios (1999). Section 2.5 discusses the research conducted to date to quantify the impact of various traffic engineering and control decisions on the environmental impacts of traffic management, engineering and control, including vehicle dynamics, emissions and local air quality. From a vehicle-centred perspective, the literature is in agreement that traffic management interventions that have the impact of interrupting the flow of traffic will most likely increase the demand for power and as
such, tailpipe emissions. This argument is also constructed from first-principles in Section 2.1.

Given the established basic mechanism for elevated vehicle emissions in the vicinity of pedestrian infrastructure, a natural extension is to quantify the effects. This thesis adds to the body of work in this area by seeking to understand the variability in vehicle dynamics and vehicle emissions. This complements other work done in this area, such as that by Jayaratne et al (2009), by collecting empirical data and capturing the range of traffic situations present in urban areas.

### 3.2  Pedestrian infrastructure in urban areas

When the desired path of a pedestrian intersects that of a motor vehicle, it may be necessary to provide dedicated crossing facilities. The decision is based predominantly on safety concerns. In the UK, government guidance states that at sites with high levels of traffic flow “…pedestrians may require a crossing facility before they feel secure enough to cross” (DfT, 1995b). Government guidance also states:

“The purpose of a crossing is to provide pedestrians with a passage across a carriageway. Each type of crossing has advantages and disadvantages; the type chosen should be appropriate to the circumstances of the site and the demands and behaviour of road users”

DfT (1995a)

It is not the aim of this thesis to provide a critique of the appropriateness of different types of pedestrian crossing. However, given the suitability of different infrastructure for different situations, it is important to understand the distinguishing features. The work presented here describes the main characteristics of the dominant pedestrian crossing options available to planners in the UK (but not unique to the UK). The main source of best practice in the UK is central government, currently in the guise of the Department for Transport (DfT)\(^\text{12}\). Whilst implementation of transport schemes is generally the remit of other authorities (which in the case of pedestrian facilities, is usually local government), the DfT provides guidance to ensure compliance with appropriate standards.

\(^{12}\) Over the past 100 years, the government department responsible for the transport network in the UK has been known as the Department for Transport, the Department for Transport, Local Government and the Regions, the Department for the Environment, Transport and the Regions, the Ministry of Transport and the Department for the Environment.
3.2.1 Crossing grade and position

In certain situations it may be preferable to separate pedestrians and general traffic by grade through the use of bridges and subways. This approach has been criticised by interest groups such as Living Streets (2007), who recommend that the aspiration should be to cross at street level. The reasons for opposing subways and bridges include pedestrian inconvenience, concerns about personal safety and cost of implementation. As part of a general desire to increase travel by non-motorised modes (see Section 2.4), UK guidance recognised the need to improve the attractiveness of walking:

“Streets should not be designed just to accommodate the movement of motor vehicles. It is important that designers place a high priority on meeting the needs of pedestrians, cyclists and public transport users, so that growth in these modes of travel is encouraged”

DfT (2007)

In the UK the use of pedestrian subways and bridges remains an option, although DfT guidance is that they should only be considered in exceptional circumstances, when other options have been exhausted (DfT, 2005). Whilst an assessment of pedestrian exposure to pollution at subways and foot-bridges is an area of possible investigation, attributing any change in vehicle behaviour to the presence of such infrastructure is beyond the scope of this research.

The position of at-grade facilities is a key design factor. In general, a crossing may be directly associated with a junction (at-junction) or be a standalone facility (mid-link). Whilst a mid-link crossing usually consists of isolated physical infrastructure, the method of traffic control may still be part of a wider intelligent system (such as SCOOT) and therefore, coordinated with nearby junctions.

3.2.2 At-junction facilities

In choosing the appropriate type of crossing at a signalised junction, it is necessary to consider the pedestrian flow patterns, degree of saturation (ratio of junction use to overall capacity in respect to motor vehicles) and topographical layout (DfT, 2005). However, at-

\[13\] SCOOT (split cycle offset optimisation technique) is a traffic control system that adjust signal timings at one or more junctions in order to optimise for delay. SCOOT is one example of adaptive traffic control, where signal timings respond to changes in the network, characterised by data collected from on-street sensors (www.scoot-utc.com).
grade pedestrian infrastructure at signalised junctions always make some use of the existing form of traffic control, augmented with a “green man” to demonstrate to pedestrians when it is safe to cross.

The different ways that pedestrians can be accommodated is summarised in Table 3-1. In some cases, the facilities may be a regular part of the traffic light cycle. This is particularly the case in parallel type crossings where the impact on traffic is minimised. Alternatively, they may be activated at pedestrian request, by means of a push button. This type of system is more common in the case of a full pedestrian phase. An example of pedestrian crossing infrastructure was previously discussed in Section 2.3.3.

Table 3-1: Different options for accommodating pedestrians at signalised intersections.

<table>
<thead>
<tr>
<th>Option</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>No pedestrian phase / stage</td>
<td>Pedestrians are expected to cross during gaps in traffic / inter-green periods of the cycle. Crossing may be assisted with the use of pedestrian refuges (small islands in the middle of the carriageway) or crossing studs to mark a preferred path.</td>
</tr>
<tr>
<td>Full pedestrian stage</td>
<td>All traffic streams are stopped to allow pedestrians to cross.</td>
</tr>
<tr>
<td>Parallel pedestrian crossing</td>
<td>Non-conflicting pedestrian and vehicle movements are allowed passage at the same time; conflicting streams are stopped.</td>
</tr>
<tr>
<td>Staggered pedestrian crossing</td>
<td>A large central island is provided in-between lanes allowing the pedestrian crossing movement to be split; the mode of operation is similar to that provided in parallel pedestrian facilities.</td>
</tr>
</tbody>
</table>

It can be argued that the presence of pedestrians is no different to any other traffic stream. From a motor vehicle perspective, all of these methods have similar modes of operation with delay being induced to allow a conflicting stream to proceed. Therefore, when considering pedestrian exposure, the relative position of sources (vehicles) and receptors (pedestrians), and the time spent at these positions, are important.

3.2.3 Mid-link facilities

Unlike those at signalised intersections, the presence of a pedestrian crossing in the middle of a link has the potential to stop traffic where it may previously have been free-flowing. The exact type and layout of a crossing incorporates many different features, including size, presence of guard rails, road markings and signage. There are several general categories of mid-link crossing, summarised in Table 3-2.
Table 3-2: Mid-link options for accommodating pedestrians.

<table>
<thead>
<tr>
<th>Option</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>None</td>
<td>Pedestrians cross when traffic conditions allow.</td>
</tr>
<tr>
<td>Pedestrian refuge / island</td>
<td>A waiting area (“refuge”) situated in the middle of the carriageway allows pedestrians to cross the road one traffic lane at a time (again, when conditions allow).</td>
</tr>
<tr>
<td>Zebra</td>
<td>Right of way is giving to the waiting pedestrian, with all traffic stopping.</td>
</tr>
<tr>
<td>Signal controlled</td>
<td>Various types of crossing are operated by pedestrians (and others requiring to cross the road) by pushing a request button – these include pelican, puffin and toucan crossings. Whilst operational differences exist, all utilise traffic signals to halt oncoming traffic, allowing pedestrians to cross safely.</td>
</tr>
</tbody>
</table>

Given the different mechanisms of operation of these facilities, each has advantages and disadvantages from the point of view of pedestrians. For example, in the case of zebra crossings, pedestrians gain right of way of the carriageway and therefore, less time is spent waiting. It is of interest to investigate the impact of this infrastructure on vehicle dynamics, and therefore, the potential to induce higher vehicle emissions and cause poor air quality.

Mid-link pedestrian facilities are primarily aimed at managing the conflict between pedestrians and road traffic. However, in complex urban traffic networks, pedestrian crossings may aid access to a link, particularly for a major/minor priority junction with no other traffic management. A simple example (Figure 3-1) illustrates this.

Figure 3-1: Example pedestrian crossing assisting downstream vehicle movements.
In some cases, careful placement of a crossing may result in a signalised junction being unnecessary. In the example of Figure 3-1, traffic on the main link (left to right) is stopped by operation of the pedestrian crossing. This allows traffic on the minor link to join the main carriageway where may otherwise require a signalised junction. In this case it is inappropriate to attribute higher vehicle emissions or poor air quality solely to the presence of such a crossing.

### 3.2.4 Summary: pedestrian infrastructure

When considering the needs of pedestrians, planners have essentially two choices in at-grade facilities:

- To integrate the management of pedestrians with other road traffic by designing junctions with pedestrian facilities included (at-junction);
- To provide stand-alone (in so far as they are spatially distinct) facilities which halt the flow of traffic to allow pedestrians to cross (mid-link).

Whilst the former is likely to induce more overall delay than at a junction without pedestrian facilities\(^\text{14}\), the negative impacts (including additional delay and increased vehicle emissions) are localised. From the literature presented in Section 2.5, there is a need to better understand the behaviour of road traffic in the vicinity of pedestrian infrastructure as it is the major cause of poor air quality. Since mid-link crossings are, unlike junctions, generally dedicated to managing the conflict between pedestrians and road traffic, they provide an interesting and practical case study. Mid-link crossings have a high potential to influence traffic dynamics, as when the crossing is not in use it may be argued that the link is as if the infrastructure were not present. In addition, there is also variability in the type of crossing, and so there is an opportunity to explore categorical variability.

### 3.3 Experimental design

This section details the scope of the experiment, the measurement requirements and the solution. Finally, the selection of suitable data collection sites is discussed and the data collection procedure is specified.

\(^{14}\) For certain junction configurations, it may be possible to manage pedestrians through conflict points to avoid additional delay to road traffic.
3.3.1 Aims

As discussed in Section 3.2, mid-link pedestrian crossings have the potential to increase vehicle emissions and contribute to poor air quality. When a crossing is in-use, the vehicle traversing the link has to decelerate, stop and then accelerate back to cruise speed. Section 2.3 described the environmental impacts of interrupting traffic flow in this manner, causing an increased demand for power and additional pollutant emissions. In addition, capacity on the link is decreased, which may cause congestion and further environmental impacts.

If not in use, the vehicle may traverse the area of the crossing as the rest of the link. The difference in vehicle dynamics and emissions between these two operating behaviours provides a means of isolating the environmental impacts of the pedestrian crossing.

The research detailed in the remainder of this chapter investigates the variability in vehicle operating behaviour at mid-link crossings, and the potential for elevated emissions due to this. Where previous research has demonstrated the mechanism for theoretical cases (Jayaratne et al, 2009), this investigation will account for the variability provided by real-world driving conditions, and the influence of other traffic.

Section 1.4 specified the first research objective:

*Demonstrate the mechanism and evaluate the extent to which vehicle operating behaviour and emissions vary in the vicinity of traffic management infrastructure.*

To achieve this objective, this chapter addresses the following research questions:

- How does vehicle operating behaviour vary in the vicinity of mid-link, at-grade pedestrian infrastructure?
- What is the potential for increased pollutant emissions at mid-link infrastructure due to variability in vehicle dynamics?
- How are emissions linked to the operation of the crossing and the subsequent state of traffic?
- What are the implications for vehicle emissions and air quality due to the presence of mid-link pedestrian crossings?

By conducting repeated observations at a range of infrastructure types, this research aims to assess inter- and intra-site variability in a manner which a theoretical study is unable.
3.3.2 General methodology

Particular variables have been identified as having the potential to impact vehicle dynamics, and as such vehicle power requirements and emissions. These variables were controlled where possible, as detailed in Table 3-3.

Table 3-3: Variables controlled, or mitigated for, through experimental design.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Method of control / mitigation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Road infrastructure</td>
<td>Independent variable – control not necessary</td>
</tr>
<tr>
<td>Vehicle</td>
<td>The same model of vehicle was used throughout</td>
</tr>
<tr>
<td>Driver</td>
<td>The same driver was used throughout</td>
</tr>
<tr>
<td>Other traffic</td>
<td>Range required; multiple observations collected to reduce the impact of particular incidents</td>
</tr>
<tr>
<td>Weather conditions</td>
<td>All data collected in a short time period; observations made</td>
</tr>
</tbody>
</table>

The scope of the experiment does not extend to investigating different classes of vehicle or different driver behaviour. Both of these factors (amongst others) have the potential to impact vehicle emissions and therefore local air quality. However, in order to isolate the influence of infrastructure, variables of this type are controlled.

Data regarding vehicle behaviour in the vicinity of pedestrian facilities is required for a range of situations in urban areas, Chapter 2 discussed that vehicle speed and acceleration are related to the demand for power and therefore to vehicle emissions. As a vector, velocity \( v \) is described as the rate of change of position \( s \) with respect to time \( t \). Acceleration \( a \) is the rate of change of velocity with respect to time, or alternatively the second derivative of position:

\[
a = \frac{dv}{dt} = \frac{d^2 s}{dt^2}
\]

Equation 3-1

Therefore, measurement of position over time may be used to derive these other quantities. Evaluation of position may be achieved by use of a GNSS\(^{15}\), such as GPS\(^{16}\). Measurement of 3D position through GNSS has an associated error. Space-based positioning and navigation systems were designed to be ideally used in open spaces (Ordóñez Galán et al, 2013),

\(^{15}\) Global Navigation Satellite System
\(^{16}\) Global Positioning System (GPS)
where an unobstructed line of sight to four (or more) satellites allows position and time to be determined. However, these systems are frequently used in areas where, due to topographical features, there are concerns over the availability of GPS measurements. This is particularly the case in urban areas, where the presence of tall buildings can obstruct and reflect satellite signals, requiring augmentation to achieve the desired level of accuracy. This is discussed further in Section 3.3.3.

The use of GPS technology is well established in transport research (for example: Herrera et al, 2010; Houston et al, 2011; Iqbal et al, 2014; Jiménez-Meza et al, 2013; Taylor et al, 2000) and has proved a useful means of passive sensing, especially with the proliferation of GPS-enabled mobile phones (Gao and Liu, 2013; Herrera et al, 2010). However, some studies fail to acknowledge the potential for error. For example, Li et al (2012) used 1Hz GPS data to estimate emissions from buses using different types of bus stops, in a study that is analogous to the one presented here. Confidence of measurement is clearly of importance, and especially so when studying a relatively small geographical area, and yet a post-processing method to characterise the accuracy is not presented. Whilst this research is not a contribution to the field of positioning and navigation, it is important that the data meet the measurement requirements so that results can be interpreted with confidence. A further concern is that GPS is an on-board data collection technique, and is limited to GPS-enabled vehicles in an area of interest. Video capture and associated image processing could be used, as has been demonstrated for applications such as detecting lane position and obstacles (Kastrinaki et al, 2003). Alternative means of measuring vehicle behaviour include static sensors such as video, inductive loop detectors and microwave sensing. These can provide estimated speed and limited positional data (i.e. occupancy of a given point). How well a location can be surveyed using these techniques depends upon the density of sensing equipment. The requirements are therefore facilitated best by the use of on-board monitoring such as GPS. In addition, this makes control of the variables listed in Table 3-3 possible.

3.3.3 Measurement requirements

Measurement requirements must be sufficient to assess the dynamic behaviour (derivatives of position) of the vehicle and its position on the traffic network. Pedestrian infrastructure covers a relatively small area of the road network. The minimum width of a pedestrian crossing in the UK is 2.4m (DfT, 1995a), with an preferred specification stated to be 4m. However, the sphere of influence of the crossing extends beyond that, as an approaching vehicle must decelerate, stop and accelerate when the crossing is in use. Setting a boundary around the pedestrian infrastructure is a difficult proposition, as it is necessary to sufficiently
capture the influence of the crossing whilst at the same time isolating it from other traffic management infrastructure. The UK Highway Code 17 provides guidance on stopping distances, and will be used as a starting point. At 30mph, the standard speed limit in urban areas, stopping distances for a passenger vehicle are around 23m (or six car lengths). This gives an idea of the order of magnitude of the influence of a pedestrian crossing, extending far beyond the actual infrastructure and road markings.

The vehicle itself occupies a space on the lane, consisting of its physical length and a further gap between it and any following vehicles. This gap (the separation distance) is dependent upon the speed of the traffic and the fleet mix present (Brooks, 2010). Due to congestion, average day time traffic speeds in London have been reported at between 9mph (central London major roads) and 19mph (London-wide). Assuming a vehicle length of 5m and a separation distance of 6m, at any given time a single vehicle could be said to occupy a bounded area 11m in length and the full width of a link. A vehicle travelling at 19mph will cover a distance of 11m in approximately 1.3 seconds. A sampling frequency of 1.3 seconds is therefore required as a minimum. Furthermore, the position of the vehicle must be established to be within this bounded area.

The performance of a positioning and navigation system is usually specified in relation to four specific parameters (Ochieng et al, 1999). These four, accuracy, integrity, continuity and availability, make up the required navigation performance (RNP). These parameters are summarised in Table 3-4.

\[\text{Table 3-4: RNP (required navigation performance) parameters (from Ochieng et al, 1999).}\]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accuracy</td>
<td>The degree of conformance of a measured position to the truth</td>
</tr>
<tr>
<td>Integrity</td>
<td>The degree of trust which can be placed in the correctness of the information supplied by the system</td>
</tr>
<tr>
<td>Continuity</td>
<td>The ability of the system to perform its function without interruption</td>
</tr>
<tr>
<td>Availability</td>
<td>The percentage of the time the service is available (i.e. meeting the requirements of accuracy, integrity, continuity and availability)</td>
</tr>
</tbody>
</table>

Section 3.3.2 discussed the calculation of velocity and acceleration as derivatives of position. However, since there is an error associated with estimating the 3D position of a vehicle, there is potential for these errors to propagate when calculating speed from successive data

17 https://www.gov.uk/highway-code
points. For example, a positional error of 2m compounded over successive data points of a 1Hz measurement regime could lead to an erroneous velocity of 4m/s for a stationary vehicle. This method of calculating velocity is therefore only suitable if positional errors are relatively small compared to the measurement (or calculation) frequency, and that velocity is uniform over the time period (Kaplan and Hegarty, 2005). In practice, velocity is estimated through Doppler shift (a thorough explanation of Doppler shift techniques is available in Kaplan and Hegarty, 2005); from which acceleration may be derived as previously stated. As with position, the accuracy of this measure is determined by the quality of the GPS signal. This is discussed further in Section 3.4.

3.3.4 Site selection

A range of different examples, described in Table 3-5, of mid-link pedestrian infrastructure was sought. Sites were chosen to cover a range of different urban driving situations and to allow for multiple observations of the same infrastructure within the collection period. All routes were in central London, contained within an area of 50km². Figure 3-2 shows the distribution of data collection sites in the context of Greater London.

*Figure 3-2: Location of routes for data collection.*

![Location of routes for data collection](image)

*All routes were in a 50m² area of central London (shaded grey).*

Each route provided examples of different types (broadly categorised as zebra or signal-controlled) of mid-link pedestrian infrastructure in a range of road types. The sites for analysis, consisting of 12 zebra crossing and 6 signal-controlled crossings, are described in Table 3-5.
Table 3-5: Type, location and description of pedestrian crossings included in the study.

<table>
<thead>
<tr>
<th>ID</th>
<th>Type</th>
<th>Street name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Zebra</td>
<td>Upper Street</td>
<td>Important through route (A1) with mainly commercial frontage</td>
</tr>
<tr>
<td>2</td>
<td>Zebra</td>
<td>Cross Street</td>
<td>Residential street with significant on-street parking, 20mph speed limit but no other traffic calming measures</td>
</tr>
<tr>
<td>3</td>
<td>Signal-controlled</td>
<td>Essex Road</td>
<td>Busy high street with frequent buses</td>
</tr>
<tr>
<td>4</td>
<td>Zebra</td>
<td>Liverpool Road</td>
<td>One-way residential street with wide carriageway and traffic calming measures, 20mph speed limit</td>
</tr>
<tr>
<td>5</td>
<td>Zebra</td>
<td>St Pancras Way</td>
<td>Mainly residential one-way street with larger commercial property access, 20mph speed limit</td>
</tr>
<tr>
<td>6</td>
<td>Zebra</td>
<td>St Pancras Way</td>
<td>Mainly residential one-way street with larger commercial property access, 20mph speed limit</td>
</tr>
<tr>
<td>7</td>
<td>Zebra</td>
<td>Royal College Street</td>
<td>One-way residential street with wide carriageway and traffic calming measures, 20mph speed limit</td>
</tr>
<tr>
<td>8</td>
<td>Zebra</td>
<td>Royal College Street</td>
<td>One-way residential street with wide carriageway and traffic calming measures, 20mph speed limit</td>
</tr>
<tr>
<td>9</td>
<td>Signal-controlled</td>
<td>Camden Street</td>
<td>Wide-multi lane one-way street, mainly residential but important through route</td>
</tr>
<tr>
<td>10</td>
<td>Signal-controlled</td>
<td>Kensington Road</td>
<td>Major east-west route with access to Hyde Park and tourist attractions</td>
</tr>
<tr>
<td>11</td>
<td>Zebra</td>
<td>Queen's Gate</td>
<td>Wide, residential street that forms important north-south connecting route, significant on-street parking</td>
</tr>
<tr>
<td>12</td>
<td>Signal-controlled</td>
<td>Vauxhall Bridge Road</td>
<td>Major route, commercial frontage and residential access, boundary of London Congestion Charge zone</td>
</tr>
<tr>
<td>13</td>
<td>Signal-controlled</td>
<td>Vauxhall Bridge Road</td>
<td>Major route, commercial frontage and residential access, boundary of London Congestion Charge zone</td>
</tr>
<tr>
<td>14</td>
<td>Signal-controlled</td>
<td>Marshalsea Road</td>
<td>Through route with mix of residential and commercial properties, 20mph speed limit. no other traffic calming</td>
</tr>
<tr>
<td>15</td>
<td>Zebra</td>
<td>The Cut</td>
<td>High street with commercial frontage and residential access</td>
</tr>
<tr>
<td>16</td>
<td>Zebra</td>
<td>The Cut</td>
<td>High street with commercial frontage and residential access</td>
</tr>
<tr>
<td>17</td>
<td>Zebra</td>
<td>Baylis Road</td>
<td>Residential street with cycle provision</td>
</tr>
<tr>
<td>18</td>
<td>Zebra</td>
<td>Borough Road</td>
<td>Mixed use road with commercial, residential and education</td>
</tr>
</tbody>
</table>
The routes were chosen with consideration to the ideas of ‘link’ and ‘place’ (Jones et al, 2007). Urban streets may be classified as having varying degrees of function as both a link and a place. Links provide “a conduit for through movement” and are a key part of the road and transport network in urban areas. In contrast, a place is “a destination in its own right” (Jones and Boujenko, 2009), where activities such as shopping and eating take place. Jones et al (2007) advocate a system whereby streets are classified as per their importance for link and place functions. Although ultimately subjective, such a system can be useful for identifying planning requirements and as an aid to performance management. Classification was not required for this exercise, but streets were identified to cover a range of link and place functions, as described in Table 3-5. Section 3.3.1 discussed an interest in the variability in vehicle behaviour and emissions at, and between, traffic management infrastructure sites. Due to their fundamental difference in operation, zebra and signal-controlled crossings offer a categorical difference that will be explored in the remainder of this chapter.

3.3.5 Data collection procedure

Section 3.3.3 determined the requirements of surveying a range of different infrastructure types whilst controlling other explanatory variables (such as vehicle and driver). On-board measurement through a GPS device offers a suitable and practical solution. The equipment used is an uBlox Antaris 4 GPS receiver. This provides information regarding position and velocity, associated with UTC (coordinated universal time) time stamp, recording at a resolution of 1Hz. Positional accuracy is listed as 2.5m, whilst velocity is accurate to within 0.17m/s. In addition, data are provided regarding transient GPS performance. This is discussed further in Section 3.4.2.

The same driver, who had knowledge of the research and was familiar with driving in central London, was used throughout. An additional person (again, the same for all data collection) monitored the GPS equipment and made notes regarding the traffic situation. For consistency, the antenna was placed in the approximate centre of the roof of the vehicle. The logging setup is shown in Figure 3-3. Data was collected over eight days during a three week period in January and February 2013. This was carried out over a range of times of day (approximately between 10am and 8pm) and on different days of the week (Monday, Tuesday, Wednesday, Thursday, Saturday). This allowed enough time for each route to be surveyed on at least two separate occasions, with multiple observations of the pedestrian infrastructure. Care was taken to ensure all routes were surveyed for both peak and off-peak traffic situations to account for different levels of general traffic and pedestrian presence. Due
to equipment availability, and for ease of data collection, only the PM peak was observed. Each data collection resulted in a GPS log file, field note log file and, on some occasions, photographic evidence of sites and traffic situations.

Figure 3-3: Logging setup and antenna position.

Logging setup consisted of a GPS receiver and laptop for real-time GPS logging, and recording of general observations. Antenna position was kept constant and placed in the approximate centre of the roof of the vehicle for each data collection period.

3.4 Data processing

This section describes the processing required in order to produce suitable observations for further analysis. As an initial processing step, a geographic bounding box was defined to allow the log file to be split into individual ‘laps’, as shown in Figure 3-4. Areas of particular poor data quality (discussed in Section 3.4.2) were identified and removed in conjunction with lap splitting when appropriate.

3.4.1 Geographical definition

The geographical boundary of the pedestrian crossing must be defined in order to filter the relevant observation from the data. Ideally this would represent the entire “zone of influence” of the infrastructure, and would include (when the crossing is active) the vehicle slowing from cruise speed, stopping, traversing the crossing and accelerating back to cruise speed. To illustrate this, simple example where a vehicle travelling at 10m/s decelerates at a rate of -1m/s$^2$ to a stop line and then accelerates at a rate of 1m/s$^2$ back to cruise speed is considered in Figure 3-5.
Figure 3-4: Initial post-processing showing full dataset (L) and a single filtered lap (R).


Figure 3-5: Simple, hypothetical trajectory.

The trajectory a vehicle decelerating to a stop line and accelerating back to cruise speed.
Real-world traffic situations are likely to be more complex than this situation. It is expected that vehicles travel at a lower speed, and that acceleration and deceleration events (such as these) takes place at a greater, and heterogeneous, rate. This would have the effect of reducing the zone of influence of the crossing. However, local features would also impact operation, with parked cars, side roads and other elements having a direct impact on driver behaviour and vehicle dynamics. Where possible, these factors are excluded (based on field notes) and the geographic area defined on a site-by-site basis.

Using geographic information systems (GIS) software, a geographical bounding box is defined giving upper and lower limits for latitude and longitude. An example is shown in Figure 3-6.

*Figure 3-6: Defining conditions for inclusion.*

![Vehicle trajectory](image)

Defined on a site-by-site basis with the aim of capturing the periods of vehicle behaviour directly under the influence of the crossing.

In order to satisfy the criteria for inclusion, the data point $i$, characterised in two dimensions by the coordinates $Lat_i$ and $Lon_i$, must lie within this area.

\[
Lat_1 > Lat_i > Lat_2 \\
Lon_1 > Lon_i > Lon_2
\]

*Equation 3-2*  
*Equation 3-3*
Reflecting the different conditions at each location, the distance of the link observed for each crossing varies from 70m to 120m. Each instance of the vehicle traversing this portion of a link is classed as an observation.

### 3.4.2 Data availability

The principles of RNP (required navigation performance) discussed in Section 3.3.3 and comprised of accuracy, integrity, continuity and availability are applied to the dataset in order to assess quality. If the conditions of continuity, accuracy and integrity are not met, the system is not deemed to be available and the observation is therefore discarded.

Continuity is a factor for GPS in urban areas due to problems associated with line-of-sight and satellite availability. When an appropriate ‘fix’ cannot be obtained, the receiver is unable to report position, and a data point is missing. As the GPS signal is time stamped and sequential, these are easily identified.

For the purposes of this work, integrity of accuracy is assessed by a single performance metric. The *Dilution of Precision* (DOP) is a dimensionless measure of the quality of the GPS estimation (Kaplan and Hegarty, 2005). There are different types of DOP, dependent upon the position dimension and/or time. PDOP (positional DOP) is a single metric which can be used to describe the accuracy of 3D position, based on the geometry of the available satellites. Accuracy is the product of PDOP and the measurement precision. Based on the manufacturer’s advice, measurements with an associated PDOP greater than eight are considered poor and should be discarded. The precision of the device is 2.5m\(^{18}\), and so a PDOP of 8 would result in an accuracy of 20m, which based on Section 3.3.3 is inadequate. Therefore, in order to ensure sufficient confidence in the accuracy (i.e. integrity), data points with associated PDOP values of less than 4.4 are discarded. This relates to 11m, the distance determined to be the link length occupied by the vehicle.

SDOP (speed DOP) is not available for this device, and as such there is no direct way of evaluating the integrity of this measurement. Kaplan and Hegarty (2005) state that the estimation of velocity through Doppler shift is related on positional accuracy, due to the importance of relative satellite position for each. As such, PDOP is used as a proxy for the integrity of the entire GPS signal. However, since acceleration is derived from velocity, there is the potential for errors to propagate in the analysis. This would potentially lead to spurious reporting of acceleration. For example, if successive data points reported 0.17m/s below and

\(^{18}\) ANTARIS 4 Data Sheet
0.17m/s above actual speed, the calculated acceleration would be +0.34m/s (0.76mph). Given the established link between speed, acceleration and emissions, potential errors of this type influence the validity of conclusions that can be drawn from these data. However, for the purposes of this work, it is assumed the filtering regime based on PDOP is adequate. These limitations are discussed further in Section 8.2.

The result of this filtering step is missing data points in the vehicle trajectory. Missing data points effectively reduce the measurement frequency below the requirements set out in Section 3.3.3. As such, it was decided not to interpolate the remaining data, and that these observations would not be considered.

The potential cumulative effect of the errors discussed here has not been investigated in detail. Whilst this thesis does not represent a contribution to the field of positioning and navigation, it is recognised that researchers should better qualify the confidence in measurement techniques when drawing conclusions.

### 3.4.3 Identifying delay

Mid-link crossings have been selected as a case study for several reasons. First of all, there are several different types, presenting an opportunity to identify categorical variability in vehicle behaviour and emissions. Secondly, they are dedicated to managing the conflict between pedestrians and motorised traffic, and as such the impact of the infrastructure can be more easily isolated. Thirdly, there is great potential to present variation in vehicle dynamics, from vehicles continuing at cruise speed (when the crossing is not in use), to vehicles forced to stop, idle and accelerate (when the crossing is in use).

Given this, it is necessary to be able to identify when a particular crossing is being used, and the immediate impacts on vehicle dynamics. As such infrastructure has previously described as interrupting the flow of traffic, an obvious starting point is in assessing changes in travel time. Excess travel time (delay) is also interesting to evaluate as it is often used as a desired minimum in the optimisation of traffic networks. It is therefore important to establish a systematic method for assessing how much excess travel time, or delay, has been incurred for a given observation at a particular crossing.

Statistical methods of outlier detection are not suitable as they require knowledge and assumptions of the underlying distribution. However, the operation and conditions of
crossings are sufficiently different that this cannot be applied in a systematic way. For example, Figure 3-7 shows histograms for travel times at two crossings.

In this case, crossing 12 (signal-controlled) appears to show a highly skewed distribution with the majority of observations complete in less than 10-seconds. Crossing 11 (zebra) displays a flatter distribution. This example is not intended to characterise the distribution of travel time at either site or infrastructure type, but rather serves to illustrate the difficulty in assuming certain statistical distributions for outlier detection.

Figure 3-7: Travel time histogram for selected observations, crossing 11 and crossing 12.

![Histograms for travel times at two crossings](image)

A further issue is in the fundamental differences in mechanism of operation of the different types of crossing. Since a zebra crossing essentially gives right of way to pedestrians, it would be most appropriate to model their arrival, most commonly through application of a Poisson process (such as Hamed, 2001). This cannot be separated from the probability of
vehicle arrival at the infrastructure. There are also likely to be issues with sample size in determining a suitable distribution. Instead, assessment of the delay incurred by the vehicle is considered from first principles.

A hypothetical minimum travel time for each site can be determined as a function of the observed link length (in metres) and the maximum speed. Since the speed limit (30mph or 20mph) is not necessarily attainable, this is defined as the maximum observed speed at a given site (Table 3-6).

Table 3-6: Observed distance and speed by site.

<table>
<thead>
<tr>
<th>ID</th>
<th>Type</th>
<th>Observed length of link (m)</th>
<th>Maximum observed speed (m/s)</th>
<th>Number of observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Zebra</td>
<td>90</td>
<td>12.6</td>
<td>18</td>
</tr>
<tr>
<td>2</td>
<td>Zebra</td>
<td>100</td>
<td>9.1</td>
<td>18</td>
</tr>
<tr>
<td>3</td>
<td>Signal-controlled</td>
<td>110</td>
<td>12.1</td>
<td>18</td>
</tr>
<tr>
<td>4</td>
<td>Zebra</td>
<td>120</td>
<td>8.6</td>
<td>18</td>
</tr>
<tr>
<td>5</td>
<td>Zebra</td>
<td>120</td>
<td>12.5</td>
<td>15</td>
</tr>
<tr>
<td>6</td>
<td>Zebra</td>
<td>100</td>
<td>11.7</td>
<td>15</td>
</tr>
<tr>
<td>7</td>
<td>Zebra</td>
<td>80</td>
<td>9.3</td>
<td>15</td>
</tr>
<tr>
<td>8</td>
<td>Zebra</td>
<td>90</td>
<td>9.4</td>
<td>14</td>
</tr>
<tr>
<td>9</td>
<td>Signal-controlled</td>
<td>90</td>
<td>12.7</td>
<td>14</td>
</tr>
<tr>
<td>10</td>
<td>Signal-controlled</td>
<td>110</td>
<td>12.7</td>
<td>12</td>
</tr>
<tr>
<td>11</td>
<td>Zebra</td>
<td>90</td>
<td>11.7</td>
<td>12</td>
</tr>
<tr>
<td>12</td>
<td>Signal-controlled</td>
<td>90</td>
<td>12.4</td>
<td>27</td>
</tr>
<tr>
<td>13</td>
<td>Signal-controlled</td>
<td>90</td>
<td>13.0</td>
<td>27</td>
</tr>
<tr>
<td>14</td>
<td>Signal-controlled</td>
<td>80</td>
<td>9.2</td>
<td>14</td>
</tr>
<tr>
<td>15</td>
<td>Zebra</td>
<td>70</td>
<td>10.7</td>
<td>14</td>
</tr>
<tr>
<td>16</td>
<td>Zebra</td>
<td>80</td>
<td>7.7</td>
<td>14</td>
</tr>
<tr>
<td>17</td>
<td>Zebra</td>
<td>90</td>
<td>10.8</td>
<td>14</td>
</tr>
<tr>
<td>18</td>
<td>Zebra</td>
<td>100</td>
<td>12.1</td>
<td>14</td>
</tr>
</tbody>
</table>
As a simple, linear transformation, calculating delay in this manner does not result in different distributions to those of the underlying data relating to travel time (such as those displayed in Figure 3-7). However, the data are effectively normalised to allow comparison between sites to be made more easily.

3.5 Traffic characteristics

This section describes the results as related to differences in traffic characteristics and network performance indicators at pedestrian infrastructure. Two main indicators are used; vehicle delay, often used a measure of performance in traffic networks, and acceleration noise. Vehicle delay, derived from travel time, was discussed in Section 3.4.3. Acceleration noise is introduced in Section 3.5.2.

3.5.1 Vehicle delay

Actual travel time is compared to a hypothetical minimum to give delay as described in Section 3.4.3. This is shown in Figure 3-8, with a colour coding used to show the amount of delay incurred by each observation: green banded observations are those with travel time within 25% of the hypothetical minimum; yellow within 50%; red within 100%; black more than 100%. Due to the 1Hz measurement frequency and small geographical area, travel time is a coarse measure. Each bar indicates the ID of the crossing and the type (referred from Table 3-6). As the number of observations is not equal across sites (Table 3-6), the data has been normalised for ease of viewing.

Based on the simple, four-group categorisation, it is clear that the vehicle is more likely to incur significant delay at certain sites than at others. However, there does not appear to be any systematic variation. At crossings 3 and 18, the majority of observations have a travel time of more than twice the hypothetical minimum. It is not possible to deduce from this data alone if the delay is incurred due to either operation of the pedestrian crossing or general traffic conditions. Consideration of data collection notes indicates that congestion at these sites rendered the pedestrian crossings inert (delay was such that traffic was frequently stopped on the network) for the majority of observations. Therefore, these are excluded from further analysis.
Figure 3-8: Delay incurred per observation, by site.

The colour coding system shows the proportion of observations by delay band. These bands are arbitrary, but show a progression in delay.

Crossing 12 is a signal-controlled pedestrian crossing on Vauxhall Bridge Road, a busy street in the Westminster area of London. A total of 27 observations of this crossing were made on three separate days. Figure 3-9 shows some example speed traces where the vehicle has not incurred any significant delay. Although there is some variability, the speed profile of the vehicle is largely equivalent across the observations.
As Figure 3-10 shows, when delay is incurred it is not necessarily in a homogenous fashion. Observation 17 (O17) shows an observation where the vehicle has stopped upstream of the crossing and is accelerating to cruise speed through the zone of influence (and has no episodes of deceleration). Conversely, observation 10 (O10) demonstrates a more expected trajectory of deceleration due to a signal-controlled pedestrian crossing and then accelerating from the stop line. The implication of this is that travel time alone cannot be taken as the sole indication of the influence of the pedestrian crossing on vehicle dynamics.
Overlaying both with- and without-delay observations onto the same axes demonstrates the difference in delay and vehicle speed (Figure 3-11).

*Figure 3-11: Vehicle speed trace with and without delay (crossing 12).*

Figure 3-12 shows vehicle speeds for all 27 observations at crossing 12 as a function of distance.

*Figure 3-12: Vehicle speeds for all observations at crossing 12 as a function of distance.*
Multiple observations are present in the upper portion of the y-axis, showing a traverse of the crossing without delay. Observations occupying the lower portion of the y-axis show that delay has been incurred, although the variability of relative vehicle speeds is such to demonstrate variability in stopping location\textsuperscript{19}. Consultation of observation field notes indicates this to be caused in some cases by queue position from the pedestrian crossing stop line, but is sometimes not related to operation of the crossing.

3.5.2 Acceleration noise

Herman et al (1959) first proposed acceleration noise as a method for assessing the traffic situation. This was further developed by Jones and Potts (1962) who described acceleration noise as “a measure of the smoothness of the speed-time graph”. Boonsiripant (2009) notes that acceleration noise is best derived from speed data of an individual vehicle on a link rather than from multiple vehicles at a single point. Therefore, it is an appropriate measure to describe the behaviour of a GPS-enabled vehicle in a single metric, as further evidenced by use in studies such as Boonsiripant (2009) and Ko et al (2010).

Acceleration noise is usefully defined\textsuperscript{20} as the standard deviation of the acceleration (Ko et al, 2010), retaining the same units. In this case, acceleration noise is calculated for each observation (i.e. traverse of a pedestrian crossing). Whilst overall speed is an important factor when considering emissions, fluctuations in changes to instantaneous speed (acceleration) are considered to have a greater influence (Int Panis et al, 2006). Acceleration noise is therefore an interesting metric through which to characterise the individual observations.

Figure 3-13 shows the different distributions for acceleration noise and delay across the site observations\textsuperscript{21}. Although both distributions are skewed, the skewness of acceleration is less pronounced. Also shown in Figure 3-13 are distributions of average speed and variability in speed (shown as the standard deviation). In each case, the metric is calculated for each observation separately. The standard deviation of speed shows a similarly skewed distribution to acceleration noise and delay. However, average speed shows a more normal distribution, potentially indicating it is a poor explanator of the other variables.

\textsuperscript{19} Due to the coarse measurement resolution, some normalisation of distance travelled is required.
\textsuperscript{20} A more detailed discussion of acceleration noise is available in Highway Research Board (1964).
\textsuperscript{21} Excluding sites 3 and 18, as discussed in Section 3.5.1.
Figure 3-13: Histograms showing distribution of acceleration noise and delay.

Both distributions indicate skew, although this is less evident for acceleration noise than delay.

A scatter plot of two variables, acceleration noise and delay, is shown in Figure 3-14. There is a general linear relationship, with many observations with higher delay associated with higher acceleration noise. However, delay is shown to be a generally poor predictor of acceleration noise. This is illustrated by observations of high delay associated with low acceleration noise. This is potentially due to prolonged periods of vehicle idling; heavy congestion leads to vehicles stopped in a queue, with increased delay. As vehicle speed is low and relatively static in this situation, a high value of acceleration noise is not necessarily associated with delay.

\[^{22} r^2 \text{ for a linear trend line } = 0.33\]
Figure 3-14: Acceleration noise and delay.

*Delay is shown to be a poor predictor variable, with high delay observations sometimes exhibiting low acceleration noise.*

Figure 3-15 displays acceleration noise data for crossing 12. Four observations where the vehicle was not delayed (also shown in Figure 3-9) all display low variation in vehicle acceleration. However, for observations where the vehicle was delayed (also shown in Figure 3-10), acceleration noise is both greater and more variable between observations.

Figure 3-15: Acceleration noise of selected observations of crossing 12.

The greater variation suggests that acceleration noise provides a better description of the traffic conditions than delay. Comparison of distributions of acceleration noise at zebra and signal-controlled, shown in Figure 3-16, suggest that there may be a categorical difference.
Since the data are not normally distributed, a non-parametric test is required to test for differences in the data. The Mann-Whitney-Wilcoxon test can be used to test whether the two samples (different types of pedestrian crossing characterised by acceleration noise) are drawn from the same population (Daly, 1995). The median (M) is used to characterise the two samples (Z and SC) as they are not normally distributed. In assuming the two samples are drawn from the same population and that $M_Z - M_{SC} = \delta$, the null and alternate hypotheses are:

$$H_0: \delta = 0$$
$$H_1: \delta \neq 0$$

The results are summarised in Table 3-7. The null hypothesis is rejected at the 1% level, meaning it cannot be assumed that the two samples are drawn from the same population.

**Table 3-7: Mann-Whitney-Wilcoxon test statistics.**

<table>
<thead>
<tr>
<th></th>
<th>Zebra</th>
<th>Signal-controlled</th>
</tr>
</thead>
<tbody>
<tr>
<td>n</td>
<td>167</td>
<td>94</td>
</tr>
<tr>
<td>M</td>
<td>0.4424</td>
<td>0.2554</td>
</tr>
<tr>
<td>p-value</td>
<td></td>
<td>3.3970 x 10^{-6}</td>
</tr>
<tr>
<td>z statistic</td>
<td></td>
<td>-4.6452</td>
</tr>
</tbody>
</table>

*Conducted for evaluation of the null hypothesis that two samples are drawn from the same population.*
Sites and traffic conditions are sufficiently different to make an assertion that zebra crossings result in a greater amount of accelerating behaviour in a vehicle due to the greater acceleration noise exhibited by these sites. The impact of these infrastructure types on vehicle dynamics and emissions are discussed in Section 3.6 and Section 3.7 respectively.

### 3.6 Vehicle dynamics

Chapter 2 discussed the link between the demand for power and vehicle emissions. Furthermore, vehicle specific power (VSP) was introduced as an estimate for transient engine power. This is calculated from a series of parameters, including vehicle speed and acceleration.

Various works have demonstrated the link between these measures of vehicle dynamics and production of pollutant emissions. These relationships have also been exploited in the construction of emission models, which are discussed further in Section 3.7 (for example Frey et al, 2003; Rakha et al, 2004).

Since these variables are important in the determinant of pollutant emissions, and therefore air quality and human exposure to pollution, this section will explore the observed distribution in the vicinity of at-grade pedestrian infrastructure.

#### 3.6.1 Candidate parameters

Data collection requirements, procedures and processing methodologies are discussed in sections 3.3 and 3.4. Speed is measured directly through Doppler shift and has an associated accuracy. Acceleration is then derived from this measurement, and so there is the potential for errors to propagate in the dataset. Steps were taken to ensure confidence (detailed in Section 3.4), and it is assumed that the data are valid. Further research questions posed by these data collection techniques are discussed in Section 8.2.

VSP was introduced in Section 2.1 as the instantaneous power per unit mass of the vehicle (Jimenez-Palacios, 1999). The generic equation for estimating VSP is:

\[
VSP = v \ast (a \ast (1 + \varepsilon_i) + g \ast gr + g \ast f + \frac{1}{2} \rho a \frac{C_d \ast A}{m} (v + v_0)^2 \ast v
\]  

Equation 3-4
Where:

\[ \begin{align*}
    v &= \text{vehicle speed (m/s)} \\
    a &= \text{vehicle acceleration (m/s}^2) \\
    e_i &= \text{the gear specific “mass factor”}^{23} \\
    m &= \text{mass of the vehicle (kg)} \\
    C_d &= \text{drag coefficient of the vehicle} \\
    f &= \text{coefficient of rolling resistance} \\
    A &= \text{frontal area of the vehicle (m}^2) \\
    v_0 &= \text{headwind speed (m/s)} \\
    \rho_a &= \text{density of air (kg/m}^3) \\
    gr &= \text{road grade} \\
    g &= \text{acceleration due to gravity (m/s}^2)
\end{align*} \]

Dynamic vehicle characteristics

Static features of the vehicle

Operating environment

Estimating VSP requires information on the dynamic characteristics of the vehicle (speed, acceleration and gear), the static characteristics of the vehicle (such as vehicle mass) and regarding the operating environment (including road grade and headwind speed). For some of these variables, such as the density of air or force of gravity, reasonable assumptions can be made from reference literature. However, detailed information regarding the operating environment (the resistive forces acting on the vehicle) is not available.

Therefore, there is little value in evaluating VSP. Instead, the product of speed and acceleration can be used as a proxy for power. This measure does not account for the additional power required to overcome the resistive forces acting on the vehicle, such as that caused by road grade or a headwind. It is, however, dimensionally equivalent to power (units of m\(^2\)/s\(^3\)) and has been utilised in emissions modelling (Joumard et al, 1995; Zhai et al, 2011).

---

\(^{23}\) “Mass factor” is defined as the equivalent translational mass of the rotating components of the power train (Jimenez-Palacios, 1999).
3.6.2 Observed distributions

Observations were pooled\textsuperscript{24} into categories of zebra and signal-controlled. Histograms of acceleration and speed are shown in Figure 3-17 and Figure 3-18 respectively. The distributions for acceleration are focused around a peak at 0m/s\textsuperscript{2}, corresponding to either vehicle cruising or delay. The shape of the distributions is similar, and a range of approximately ±3m/s\textsuperscript{2} is exhibited in both datasets.

\textit{Figure 3-17: Histogram of vehicle accelerations for zebra and signal-controlled datasets.}

\begin{figure}
\centering
\includegraphics[width=\textwidth]{histogram}
\caption{Histogram of vehicle accelerations for zebra and signal-controlled datasets.}
\end{figure}

Observed speeds at zebra crossings appear more normally distributed, with a peak between 7 and 9m/s (approximately 18mph). The peak occurs at a marginally higher speed over observations of signalised crossings. The data collected has been categorised according to the type of pedestrian crossing present. Any conclusions drawn consequently assume that it is the type of crossing which dominates vehicle dynamics at the site.

\textsuperscript{24} Excluding sites 3 and 18
Table 3-5 summarised the other characteristics of the sites, including the speed limit. Half of the zebra crossing sites have 20mph speed limits, compared to only 1/6th of signal-controlled crossings. This is particularly interesting in the context of Figure 3-18, as the presence of higher speeds may be a feature of the underlying speed limit rather than the type of crossing.

Figure 3-18: Histogram of vehicle speeds for zebra and signal-controlled datasets.

To further explore this, observations for zebra crossings were further split between 30mph and 20mph sites. Histograms of vehicle speed at these sites are shown in Figure 3-19. This confirms the higher speeds seen at signal-controlled crossing sites observed as part of this work.
Figure 3-19: Histogram of vehicle speeds for zebra (30mph), zebra (20mph) and signal-controlled crossing datasets.

Scatter plots of acceleration against speed (Figure 3-20) and the product of speed and acceleration against speed (Figure 3-21) offer a further means of characterising the data.
Figure 3-20: Scatter plot of acceleration against speed.

Figure 3-21: Scatter plot of the product of speed and acceleration against vehicle speed.
A similar range of vehicle behaviours is seen at both types of infrastructure, with the exception of cruise speeds over approximately 10m/s. By definition these observations illicit low acceleration (as low variation in speed). Again this indicates the different driving conditions at these sites. The product of speed and acceleration, used as a proxy for vehicle power requirements, shows a larger range for zebra crossing sites than signal-controlled. This can also be seen in Figure 3-20, where there are several higher-speed, high acceleration events.

As discussed in Section 2.3, interruption to traffic induces acceleration events which increase the demand for power of the vehicle, leading to the production of vehicle emissions. This is investigated further in Section 3.7 through the application of emissions modelling.

### 3.7 Emission modelling

Whilst the metrics used in Section 3.5 are of interest for describing the traffic state, the ultimate aim is to assess the variability in emissions from a vehicle using a pedestrian crossing. This section continues the investigation of Section 3.6 by estimating vehicle emissions from the vehicle trajectories recorded around at-grade pedestrian infrastructure.

#### 3.7.1 Background

Assessment of emissions from a single vehicle can be carried out by two general methods; measurement and modelling. Whilst their availability is becoming more widespread and their use in research more common (for example Frey et al, 2003), on-board portable emissions measurement systems (PEMS) are costly and sometimes impractical due to size, weight and difficulty in fitting. However, by making use of emissions inventories that are based on empirical data, it is possible to estimate emissions from the general characteristics and dynamic behaviour of the vehicle.

Chassis dynamometer and drive cycle testing is widely used to establish emissions inventories used in many models. Barlow and Boulter (2009) discuss the various types of models for estimating exhaust emissions, input data and typical applications, which are summarised in Table 3-8.
Table 3-8: Models for estimating tailpipe emissions (from Barlow and Boulter, 2009).

<table>
<thead>
<tr>
<th>Model type</th>
<th>Input data</th>
<th>Typical application</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aggregate emission factors</td>
<td>Area or road type</td>
<td>Inventories</td>
</tr>
<tr>
<td>Average speed</td>
<td>Average trip speed</td>
<td>Inventories</td>
</tr>
<tr>
<td>Adjusted average speed</td>
<td>Average speed and congestion level</td>
<td>Urban traffic management (UTM) scheme assessment</td>
</tr>
<tr>
<td>Traffic situation</td>
<td>Road type, speed limit, congestion level</td>
<td>Inventories and UTM assessment</td>
</tr>
<tr>
<td>Microscopic</td>
<td>Driving mode (vehicle operating mode) / vehicle trajectory</td>
<td>Detailed temporal and spatial emissions analysis</td>
</tr>
</tbody>
</table>

In order to assess the impact of differing vehicle dynamics in a small geographical area, only microscopic models are suitable. These models are sensitive to changes in the operating pattern of vehicles, and can therefore be used to assess variation in emissions on a microscopic level.

Microscopic models may be further classified as “modal” and “instantaneous”. In the case of modal models, vehicle operation is classified into a finite number of modes (such as Frey et al, 2001, discussed in Section 2.3.4) with empirically derived average emission factors for each operating state. The benefits of this are that it requires a lower level of detail of vehicle dynamics (a range rather than a single value) and is generally less data and computationally intensive. However, binning of vehicle dynamics in this way is less precise than using a continuous dataset, and in particular is susceptible to boundary effects. Instantaneous emission models relate directly to particular vehicle parameters, such as speed and acceleration. Emissions may then be quantified through a statistically derived polynomial equation, such as VT Micro (Rakha et al, 2004) or by means of a simple look-up table, such as MODEM (Barlow and Boulter, 2009). In each case, the inputs required represent the operating pattern of the vehicle, usually on a second-by-second basis.

Emission modelling enables studies of vehicle dynamics to be extended for consideration of pollution and air quality; however, for confidence in absolute modelled emission rates, greater scrutiny of measurement or estimation methods is required. This is discussed further in Section 8.2.
3.7.2 Analysis of Instantaneous Road Emissions (AIRE)

Analysis of Instantaneous Road Emissions (AIRE) is an instantaneous emissions database for estimating particulate matter, total carbon and oxides of nitrogen. The model calculates emissions per time-step, and therefore captures the dynamic behaviour of the vehicle. AIRE is derived from the Passenger Car and Heavy Duty Emission Model (PHEM), developed by the Technical University of Graz (Transport Scotland, 2013). PHEM uses information on vehicle behaviour to calculate transient power requirements. Engine power demand is calculated on the basis of the principles described in Chapter 2, and incorporates the power required to overcome the resistive forces acting on the vehicle.

Engine speed is then simulated using the base vehicle characteristics and a driver gear change model25 (Hausberger et al, 2009). Vehicle emissions maps in PHEM are populated with data from chassis dynamometer measurements, engine load testing and PEMS. Boulter et al (2007) discuss the performance of PHEM and detail some validation studies, concluding that accuracy was generally good, with some concern regarding overestimation of NO\textsubscript{x} in petrol vehicles. PHEM has been refined to provide better estimates, by for example simulating selective catalytic reduction, which has the effect of reducing oxides of nitrogen (Hausberger et al, 2009). It has been used in several academic studies to estimate real-world tailpipe emissions (Oettl et al, 2006; Tielert et al, 2010; Zamboni et al, 2013).

PHEM is particularly useful due to the large database of European passenger cars and the capability of simulating any drive cycle (Zamboni et al, 2013). This is in contrast to models such as CMEM and MOVES, which are suitable for the North America vehicle fleet which has different characteristics.

As stated, AIRE is derived from PHEM and offers a practical solution for emissions modelling. AIRE was developed with application to the UK in mind, and is freely available. AIRE consists of more than 3000 look-up tables (termed “Instantaneous Emissions Modelling” tables). These tables, which relate the dynamic behaviour of the vehicle to emissions were generated from PHEM, include a range of data sources (such as PEMS and chassis dynamometer tests) and a range of engine loading scenarios. Each table relates to a particular type of vehicle, incorporating body type, EURO emissions standard, loading and age.

\[\text{\scriptsize 25 It is also possible to input engine speed directly into PHEM.}\]
AIRE is primarily designed to be used with the outputs of microsimulation models. Users are allowed to change the make-up of the vehicle fleet being simulated (for example, EURO type, age and body type) to allow for geographical differences. The emissions from each simulated vehicle are then estimated, given link and network level pollution estimates. As mentioned previously, AIRE is usually applied to the outputs of microsimulation models (Transport Scotland, 2011), a conversion script was written using MATLAB to allow a single drive cycle to be analysed for emissions. In order to assure repeatability of results, emissions for a single vehicle type were estimated in AIRE. Body type, load, age and emissions standard were kept constant, with only fuel type varied amongst the static vehicle parameters.

The use of emissions modelling in this way is limited as it is based on fleet average data, and not on the exact characteristics of the vehicle that generated the trajectory. Whilst the dynamic character of the vehicle (change in speed) is captured, the specifics of engine loading are not. Modelling of this type cannot be considered a substitute for empirical measurement of pollution, but are useful in comparing different types of infrastructure in a consistent fashion.

The drive cycle is first interpolated to a frequency of 2Hz, before being converted to the correct file type. AIRE may then be configured for a range of vehicle and fuel types. Tailpipe emissions for a given drive cycle are estimated for oxides of nitrogen (NO\(_X\)), particulate matter (PM) and total carbon (TC).

### 3.7.3 Modelled emissions results

In this section, emission rate (mass per unit distance) estimates of tailpipe emissions for oxides of nitrogen (NO\(_X\)), particulate matter (PM) and total carbon (TC) are shown. Emission rates are normalised by route length to calculate an emission factor (g/km). This accounts for the slightly different length of observation, as detailed in Table 3-6. Euro IV is used as this is the most recent vehicle class contained within the AIRE database and the dominant passenger car class currently in use in the UK.

High level results for each pollutant and fuel type are shown in Figure 3-22 and Figure 3-23. The shape of the distribution is broadly similar between fuel types, but the order of magnitude increase\(^{26}\) of emissions of NO\(_X\) and PM\(_{10}\) for diesel emissions is important in the

\(^{26}\) NO\(_X\) and PM\(_{10}\) emissions are around 10 times higher for diesel vehicles.
context of the changing vehicle fleet, as discussed in Section 2.2. All distributions are non-symmetric, and demonstrate a positive skew.

*Figure 3-22: Petrol emission rates for NO\textsubscript{X}, PM\textsubscript{10} and total carbon.*

![Histograms showing emission rates for NO\textsubscript{X}, PM\textsubscript{10} and total carbon for petrol vehicles.]

*Figure 3-23: Diesel emission rates for NO\textsubscript{X}, PM\textsubscript{10} and total carbon.*

![Histograms showing emission rates for NO\textsubscript{X}, PM\textsubscript{10} and total carbon for diesel vehicles.]

High level statistics can be used to indicate whether there is a difference in emission rates between the two broad types of infrastructure. These results are shown in Table 3-9. As these variables are not normally distributed (Figure 3-22 and Figure 3-23), the mean is not an appropriate measure of central tendency. Instead, the median is reported.
Table 3-9: Descriptive statistics for the entire sample, zebra and signal-controlled portions.

<table>
<thead>
<tr>
<th></th>
<th>Entire sample</th>
<th>Zebra</th>
<th>Signal-controlled</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>N</strong></td>
<td>261</td>
<td>167</td>
<td>94</td>
</tr>
</tbody>
</table>

**Petrol**

<table>
<thead>
<tr>
<th></th>
<th>Entire sample</th>
<th>Zebra</th>
<th>Signal-controlled</th>
</tr>
</thead>
<tbody>
<tr>
<td>Median NO$_X$ emission rate (g/km)</td>
<td>0.0541</td>
<td>0.0561</td>
<td>0.0477</td>
</tr>
<tr>
<td>Median PM$_{10}$ emission rate (g/km)</td>
<td>0.00182</td>
<td>0.00189</td>
<td>0.00164</td>
</tr>
<tr>
<td>Median TC emission rate (g/km)</td>
<td>48.85</td>
<td>51.55</td>
<td>43.51</td>
</tr>
</tbody>
</table>

**Diesel**

<table>
<thead>
<tr>
<th></th>
<th>Entire sample</th>
<th>Zebra</th>
<th>Signal-controlled</th>
</tr>
</thead>
<tbody>
<tr>
<td>Median NO$_X$ emission rate (g/km)</td>
<td>0.201</td>
<td>0.245</td>
<td>0.139</td>
</tr>
<tr>
<td>Median PM$_{10}$ emission rate (g/km)</td>
<td>0.0147</td>
<td>0.0151</td>
<td>0.0132</td>
</tr>
<tr>
<td>Median TC emission rate (g/km)</td>
<td>35.95</td>
<td>38.16</td>
<td>30.52</td>
</tr>
</tbody>
</table>

Zebra-type crossings are shown to induce higher median rates of emissions for all pollutants and both fuel types and signal-controlled crossings.

Across all pollutants and both diesel and petrol fuel, zebra crossings are shown to produce higher estimated median emission rates than signal-controlled crossings. In the case of diesel NO$_X$ emissions, rates are around 76% higher at zebra crossings than signal-controlled sites. The difference was also shown to be significant at the 1% level for all pollutants\(^{27}\).

Given that zebra crossings were shown to have greater variability in levels of speed (Section 3.5, Table 3-7), this is an expected result. It is of interest to compare modelled emission rates (and by association, vehicle dynamics as discussed in Section 3.6) with the traffic characterisation statistics discussed in Section 3.5. Figure 3-24 and Figure 3-25 displays scatter plots of various emission rates and acceleration noise per observation, by fuel type. The trend is broadly linear, within increasing emissions with greater variability in acceleration.

\(^{27}\) Using the Mann-Whitney-Wilcoxon test as per Section 3.5.
Figure 3-24: Acceleration noise as an explanator of petrol emission rates.

Acceleration noise is shown to account for more of the variability of emission rates for observations at signal-controlled crossings than observations at zebra crossings. Correlation coefficient (r sq) for linear fit also shown.

For both diesel and petrol emission rates, acceleration noise is shown to account for a greater amount of variation in the dependent dataset for signal-controlled crossing observations compared to zebra crossing observations. This is consistent across all pollutant types. In the case of emission rate of NO\(_X\), acceleration noise accounts for 66% and 73% of the variability (demonstrated by the r-squared statistic) for petrol and diesel emissions respectively. An important distinction is in the disparity of sample size. There are 11 zebra crossing sites providing a total of 167 observations, compared to 5 signal-controlled crossing sites providing a total of 94 observations. Given this, it would generally be expected that the zebra crossing sample exhibit greater variability, and as such the error term greater.
Figure 3-25: Acceleration noise as an explanator of diesel emission rates.

Acceleration noise is shown to account for more of the variability of emission rates for observations at signal-controlled crossings than observations at zebra crossings. Correlation coefficient (r sq) for linear fit also shown.

In the case of zebra crossings in particular, there are several examples of apparent outliers, with high emission rates associated with low acceleration noise. This may be a facet of a larger dataset, but may also be a reflection of the zebra crossing sites demonstrating a wider range of vehicle behaviour. Whilst a simple linear relationship between these two variables is not appropriate, the mechanism for an increased variability in vehicle speed (as illustrated by acceleration noise) to cause an increase in vehicle emissions is demonstrated. The examples that follow further qualify the particular impact of a pedestrian crossing on the production of vehicle emissions, and relate these estimates to the traffic characteristic statistics explored in Section 3.5.
Crossing 12 is a signalised crossing on a busy main road in the Victoria area of Westminster, central London. Table 3-10 shows emission results for 12 observations of this crossing – four of each where no delay was incurred, where the delay could be largely attributed to traffic conditions and where delay could be attributed to operation of the pedestrian crossing.

Table 3-10: Crossing 12 modelled emission results for selected observations of traffic, pedestrian crossing and no delay.

<table>
<thead>
<tr>
<th>Observation</th>
<th>Acceleration noise (m/s²)</th>
<th>Petrol emission rates (g/km)</th>
<th>Diesel emission rates (g/km)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>NOX</td>
<td>PM₁₀</td>
<td>TC</td>
</tr>
<tr>
<td><strong>No delay</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>O2</td>
<td>0.164</td>
<td>0.0411</td>
<td>0.00166</td>
</tr>
<tr>
<td>O9</td>
<td>0.110</td>
<td>0.0377</td>
<td>0.00139</td>
</tr>
<tr>
<td>O13</td>
<td>0.156</td>
<td>0.0374</td>
<td>0.00146</td>
</tr>
<tr>
<td>O21</td>
<td>0.168</td>
<td>0.0427</td>
<td>0.00169</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td>0.150</td>
<td>0.0397</td>
<td>0.00155</td>
</tr>
<tr>
<td><strong>Traffic delay</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>O6</td>
<td>1.041</td>
<td>0.0674</td>
<td>0.00201</td>
</tr>
<tr>
<td>O10</td>
<td>1.009</td>
<td>0.0854</td>
<td>0.00294</td>
</tr>
<tr>
<td>O16</td>
<td>0.575</td>
<td>0.0770</td>
<td>0.00248</td>
</tr>
<tr>
<td>O17</td>
<td>0.328</td>
<td>0.0796</td>
<td>0.00281</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td>0.738</td>
<td>0.0774</td>
<td>0.00256</td>
</tr>
<tr>
<td><strong>Pedestrian crossing delay</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>O11</td>
<td>1.275</td>
<td>0.0889</td>
<td>0.00284</td>
</tr>
<tr>
<td>O19</td>
<td>0.930</td>
<td>0.0755</td>
<td>0.00231</td>
</tr>
<tr>
<td>O24</td>
<td>1.185</td>
<td>0.0873</td>
<td>0.00285</td>
</tr>
<tr>
<td>O27</td>
<td>0.827</td>
<td>0.0948</td>
<td>0.00340</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td>1.054</td>
<td>0.0866</td>
<td>0.00285</td>
</tr>
</tbody>
</table>

It is not possibly to completely separate the phenomena of general traffic delay and pedestrian crossing induced delay. The influence of the pedestrian crossing is particularly evident on diesel emissions of NO₅. These are on average eight times greater (0.799g/km vs 0.097g/km) when the vehicle incurs pedestrian crossing delay and nearly five times greater
(0.478g/km vs 0.097g/km) in the case of traffic delay as opposed to the vehicle incurring no delay. In all cases, emissions rates are at least 50% greater in instances where the vehicle has been subject to delay caused directly by the pedestrian crossing.

As there are a relatively high number of observations (27), Figure 3-26 has been generated to show the relationship between acceleration noise and emission rates at crossing 12. Due to the superior explanatory power of acceleration noise for diesel emissions, this is the example used.

*Figure 3-26: Acceleration noise and emission rates for crossing 12 (signal-controlled).*

A general linear trend has been shown, with particularly high r-squared values for emission rates of NO\textsubscript{X}. This suggests that acceleration noise can be a useful explanator of emission rates. The results of the previous section suggest that this is too simplistic an explanator to
be applied to the population at large, but for specific examples, such as crossing 12, it appears valid. The variability between observations at a single crossing shows the potential for increased pollutant emissions due to the presence of the pedestrian crossing, with emissions of TC shown to double, PM$_{10}$ to triple and NO$_X$ emissions to increase by five times when comparing the lowest observation to the highest.

Consideration of a different signal-controlled crossing yields similar results, as shown in Table 3-11. Crossing 9 is located on a wide, mainly residential street in the Camden area of London. Once again the higher emission rates are related to more variable vehicle operating behaviour and the operation of pedestrian crossings.

Table 3-11: Crossing 9 emission results for selected observations of traffic, pedestrian crossing and no delay.

<table>
<thead>
<tr>
<th>Observation</th>
<th>Acceleration noise (m/s$^2$)</th>
<th>Petrol emission rates (g/km)</th>
<th>Diesel emission rates (g/km)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>NO$_X$</td>
<td>PM$_{10}$</td>
</tr>
<tr>
<td>No delay</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>O3</td>
<td>0.256</td>
<td>0.0404</td>
<td>0.00161</td>
</tr>
<tr>
<td>O8</td>
<td>0.268</td>
<td>0.0379</td>
<td>0.00152</td>
</tr>
<tr>
<td>Average</td>
<td>0.262</td>
<td>0.0392</td>
<td>0.00156</td>
</tr>
<tr>
<td>Traffic delay</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>O5</td>
<td>0.919</td>
<td>0.0614</td>
<td>0.00195</td>
</tr>
<tr>
<td>O13</td>
<td>0.825</td>
<td>0.0602</td>
<td>0.00192</td>
</tr>
<tr>
<td>Average</td>
<td>0.872</td>
<td>0.0608</td>
<td>0.00194</td>
</tr>
<tr>
<td>Pedestrian crossing delay</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>O6</td>
<td>1.285</td>
<td>0.0858</td>
<td>0.00300</td>
</tr>
<tr>
<td>O9</td>
<td>1.487</td>
<td>0.0822</td>
<td>0.00282</td>
</tr>
<tr>
<td>Average</td>
<td>1.386</td>
<td>0.0840</td>
<td>0.00291</td>
</tr>
</tbody>
</table>

This pattern can also be seen in the case of zebra crossings, with crossing 17 used as an example (Table 3-12). Crossing 17 is a zebra crossing on a mainly residential street in the Southwark area of central London. Despite the results Section 3.5, which suggested that vehicle acceleration measures in the whole were more variable in the vicinity of zebra when compared to signal-controlled crossing, emission rates are in line with the previous examples.
Table 3-12: Crossing 17 emission results for selected observations of traffic, pedestrian crossing and no delay.

<table>
<thead>
<tr>
<th>Observation</th>
<th>Acceleration noise (m/s²)</th>
<th>Petrol emission rates (g/km)</th>
<th>Diesel emission rates (g/km)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>NOₓ</td>
<td>PM₁₀</td>
</tr>
<tr>
<td><strong>No delay</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>O4</td>
<td>0.366</td>
<td>0.0468</td>
<td>0.00166</td>
</tr>
<tr>
<td>O7</td>
<td>0.254</td>
<td>0.0453</td>
<td>0.00164</td>
</tr>
<tr>
<td>O8</td>
<td>0.359</td>
<td>0.0440</td>
<td>0.00149</td>
</tr>
<tr>
<td>O11</td>
<td>0.637</td>
<td>0.0544</td>
<td>0.00185</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td></td>
<td>0.404</td>
<td>0.0476</td>
</tr>
<tr>
<td><strong>Pedestrian crossing delay</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>O1</td>
<td>1.392</td>
<td>0.0872</td>
<td>0.00309</td>
</tr>
<tr>
<td>O3</td>
<td>1.346</td>
<td>0.0859</td>
<td>0.00284</td>
</tr>
<tr>
<td>O5</td>
<td>1.149</td>
<td>0.0804</td>
<td>0.00259</td>
</tr>
<tr>
<td>O12</td>
<td>1.205</td>
<td>0.0826</td>
<td>0.00276</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td></td>
<td>1.273</td>
<td>0.0840</td>
</tr>
</tbody>
</table>

In this case, emission rates are, for example, twice as high for total carbon emissions and when the vehicle incurs delay as a result of the pedestrian crossing. It is clear that, regardless of the type of infrastructure, the interruption of traffic flow results in not only delay, but also increased vehicle emission rates of various pollutant species. This type of difference can be analysed in detail by comparing the potential for difference in emission rates at a given piece of infrastructure, as is examined in the following section.

### 3.8 Implications for air quality and exposure

The previous sections (3.5, 3.6 and 3.7) have investigated the potential for pedestrian infrastructure to induce variability in metrics related to traffic conditions, vehicle dynamics and consequently emissions. Mid-link pedestrian crossings were selected as they offer a simple example within a complex system. If the crossing is not in use, it may be treated as if was not there, and so the infrastructure will induce a range of vehicle behaviour. This is a simplification, as it can be argued that the mere presence of a crossing impacts driver
behaviour. However, by considering the infrastructure in this way it is possible to look at the range of vehicle behaviour that can be induced by a crossing, and attempt to quantify the impact.

Observations at a given site are separated in time. Therefore, they give an indication of the potential for mobile source emissions to influence variation in air quality and human exposure at pedestrian infrastructure. Figure 3-27 shows the ratio of maximum to minimum observation for acceleration noise, by crossing. The most extreme example, crossing 10, displays more than 15 times the acceleration noise at the maximum observation when compared to the minimum. This is demonstrable of how variable driving conditions at a single locale can be. The crossing with the lowest ratio (crossing 18) still exhibits more than twice the acceleration noise at the highest observation compared to the lowest.

*Figure 3-27: Ratio of max to min, observation of acceleration noise, by crossing.*

Section 3.7 discussed the variability of vehicle emission rates, modelled from measured vehicle dynamics, at different pedestrian infrastructure sites, and the association with acceleration noise. Figure 3-28 and Figure 3-29 show how the increased acceleration noise translates to higher emission rates\(^{28}\).

\(^{28}\) It is not necessarily the case that the observation with lowest/highest acceleration noise is also the observation with the lowest/highest emission rate.
Figure 3-28: Ratio of max to min, estimation of emission rates (petrol), by crossing.

Figure 3-29: Ratio of max to min, estimation of emission rates (diesel), by crossing.
The ratio between maximum and minimum estimations is not (generally) as large as those seen for observations of acceleration noise. Across all sites, the maximum observation is at least 20% greater for all pollutants and both fuel types. Diesel emission rates of NO\textsubscript{X} are particularly interesting, with six sites exhibiting a ratio greater than 10 (ratio of maximum to minimum)\textsuperscript{29}.

In the case of acceleration noise, there is an indication of a categorical relationship between the reported ratio and the type of infrastructure (signal-controlled or zebra). Signal-controlled crossings generally exhibit a higher ratio between the maximum and minimum observed acceleration noise. The relationship is less apparent for modelled emission rates. Whilst the sample size is too small to draw a firm conclusion, it is possible that this can be attributed to the different mechanism of operation.

3.9 Summary: traffic state, vehicle dynamics and emissions

Research objective (1), specified in Chapter 1 concerns the impact of traffic management infrastructure on vehicle operating behaviour and emissions.

*Demonstrate the mechanism and evaluate the extent to which vehicle operating behaviour and emissions vary in the vicinity of traffic management infrastructure.*

This objective was devolved to a series of research questions, which will be addressed here.

- How does vehicle operating behaviour vary in the vicinity of mid-link, at-grade pedestrian infrastructure?

Mid-link pedestrian crossings were chosen as they represent a simple example in a complex system, and are likely to invoke the widest range of possible vehicle operating behaviours. Consideration of traffic state and measures of vehicle dynamics has yielded acceleration noise as a single metric by which the dynamic behaviour of the vehicle can be described for an observation. Comparison of acceleration noise across the broad categories of zebra and signal-controlled crossings suggest that vehicle behaviour is more variable at the former. This is not surprising, considering the operation of these crossings. In giving the pedestrian

\textsuperscript{29} It is worth noting that crossing 3, which displays extremely high ratios of maximum : minimum, had been excluded from earlier analysis as an outlier.
right-of-way, the vehicle is likely to be subject to more frequent interruption given the same level of pedestrian demand.

- What is the potential for increased pollutant emissions at mid-link infrastructure due to variability in vehicle dynamics?
- How are emissions linked to the operation of the crossing and the subsequent state of traffic?

Sections 3.7 and 3.8 discussed the range of delay, acceleration noise and emissions rates observed at particular infrastructure sites. It is argues that the difference in emission rates at observations with no delay compared to those with delay caused by the pedestrian crossing indicates the potential for elevated emissions due to the infrastructure. The ratio of maximum to minimum observations was shown to be at least 20% greater for all pollutants over both fuel types. Diesel NO\(_X\) emission rates have been identified as displaying a particularly large variation, with multiple sites exhibiting a ratio of maximum to minimum greater than 10.

Whilst categorically, delay and no delay were shown to explain increasing emission rates at an observation, the continuous variable did not serve as a good explanator. Acceleration noise proved to be a better explanator, displaying a generally linear relationship. It was also shown that acceleration noise is able to explain a greater amount of the variation in emission rates at signal-controlled crossings when compared to zebra crossings. In the case of diesel emissions of NO\(_X\), acceleration noise accounts for 73% of the observed variation. It is hypothesised that zebra crossings induce a greater variation in conditions for the vehicle to traverse, and as such acceleration noise alone is insufficient as an explanator. When selecting specific examples, there does not appear to be any greater propensity for a vehicle to emit pollutants at a higher rate at a zebra over a signal-controlled crossing.

- What are the implications for vehicle emissions and air quality due to the presence of mid-link pedestrian crossings?

It can be concluded that if a vehicle incurs delay due to operation of a crossing, emission rates will be higher. Therefore, the presence of a pedestrian at a crossing will induce increased vehicle emissions that could lead to a degradation of local air quality.

In addressing the research objective, the mechanism for increased pollution at the places where pedestrians wait has been demonstrated through the simple example of the mid-link crossing. By considering different observations of the same crossing, the ratio of the
maximum to minimum emission rates indicates the potential for increased emissions, poor air quality and elevated human exposure at a given locale.

The logical next step is to consider from point-of-view of the pedestrian and to explore the variability in vehicle induced air pollution at the locations where exposure is most pertinent. The difference in pollutant emission rates, both over multiple observations at the same site, and between sites in the same locale, are such that the traffic network can clearly not be treated as a homogenous entity when considering emissions and air quality. In contrast to the vehicle-centric review (Chapter 2) and analysis (Chapter 3) carried out so far, Chapter 4 adopts a pedestrian-centric view, discussing the importance of black carbon, the implications for health and reviewing methodologies for assessing human exposure to pollution.
4 Urban air quality, black carbon and pedestrian exposure to pollution

The importance of vehicle emission ‘hotspots’ in urban areas is elevated by the presence of pedestrians and other road users, leading to ‘pollutant exposure hotspots’. This chapter introduces black carbon as a pollutant of interest when considering personal exposure and discusses the body of knowledge surrounding its assessment, including health effects and the existing legislation.

This chapter also discusses current methodologies for assessing pedestrian exposure to pollution and identifies the limitations of the existing body of research.

The second research objective, specified in Section 1.4, is to:

*Specify, evaluate and refine techniques for the measurement of black carbon concentration around traffic management infrastructure, for the use in studies of personal exposure.*

This chapter aids in specifying the spatial and temporal resolution of measurement required to assess black carbon concentration and personal exposure to pollution. The other elements of this research objective (to evaluate and refine measurement techniques) are addressed in Chapter 5.

4.1 Introduction to black carbon

Black carbon is not universally defined, further complicated by the erroneous and interchangeable use of several terms. This section provides a working definition of black carbon (BC) for use in this research.

Highwood and Kinnersley (2006) define BC as “the component of atmospheric aerosol that absorbs visible radiation”. However, unlike most defined pollutant species, it is not chemically homogenous, consisting of various allotropes of elemental carbon (EC) and organic carbon (OC). The difficulties of characterising BC in this way are raised by Buseck et al (2012), who object to the definition being so closely related to the means of measurement\(^\text{30}\). However,

\(^{30}\) The authors make direct reference to the definition adopted by the IPCC and referenced to Charlson and Heintzenberg (1995)
since BC is named due to its optical absorption properties (Hansen et al, 1984), defining it in this manner is logical. Concerns over nomenclature are clearly important when conducting research, particularly when considering cause and effect relationships of drivers, and the impacts of pollution. This thesis takes approach of the report on the health effects of black carbon which refers to BC as an “operationally defined term” (Janssen et al, 2012). Despite concerns, the operational definition is vital as it ensures a consistent approach, especially for empirical data collection.

Other terms sometimes used interchangeably with black carbon are carbon black, soot and char. Carbon black, despite the similar name and also being a product of incomplete combustion, differs from black carbon in being nearly completely made of elemental carbon in a characteristic aggregation (Long et al, 2013). Like black carbon, carbon black also has recognised health effects, but these are more strongly associated with the manufacturing industry (Gardiner et al, 2001). Soot is limited to carbonaceous aerosols that form as a result of volatile organic compounds which re-condense in the high-temperature gas phase (Han et al, 2009). Char, conversely, is formed from the solid residues of combustion.

The different chemical and physical properties of these species impact upon, amongst other things, reactivity, detection and transport. However, these definitions should not be considered mutually exclusive, and equivalence is sometimes assumed between species. Table 4-1 references definitions included in Janssen et al (2012).

Table 4-1: Commonly used definitions for ultrafine carbonaceous aerosols (from Janssen et al, 2012).

<table>
<thead>
<tr>
<th>Substance</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Black carbon (BC)</td>
<td>Black carbon (BC) refers to the dark, light-absorbing components of aerosols that contain two forms of elemental carbon</td>
</tr>
<tr>
<td>Elemental carbon (EC)</td>
<td>Elemental carbon (EC) in atmospheric PM derived from a variety of combustion sources contains the two forms “char-EC” (the original graphite-like structure of natural carbon partly preserved, brownish colour) and “soot-EC” (the original structure of natural carbon not preserved, black colour) with different chemical and physical properties and different optical light-absorbing properties</td>
</tr>
<tr>
<td>Soot</td>
<td>Soot is defined as only those carbon particles that form at high temperature via gas-phase processes (typical of diesel engines)</td>
</tr>
<tr>
<td>Char</td>
<td>Char is defined as carbonaceous material obtained by heating organic substances and formed directly from pyrolysis, or as an impure form of graphitic carbon obtained as a residue when carbonaceous material is partially burned or heated with limited access to air (typical of burning vegetation and wood in small residential heaters)</td>
</tr>
</tbody>
</table>
This operational definition for black carbon has been used extensively in traffic and transport related research (Begum et al, 2012; Dodson et al, 2009; Dons et al, 2013a; Invernizzi et al, 2011). Definition of BC in this way is analogous with that of other particulate matter fractions, which are also not defined as a result of the chemical composition, but by another physical property.

4.1.1 Sources

As stated in Section 2.1, BC is a product of incomplete combustion of carbon fuels, and is therefore, associated with vehicle (especially diesel) emissions (Dodson et al, 2009). Invernizzi et al (2011) describe BC as “a unique primary tracer for combustion emissions, as it has no non-combustion sources, and is stable once released into the atmosphere”.

BC is seen as a useful proxy for determining the presence of traffic related emissions (Keuken et al, 2012) although is not necessarily representative of the magnitude of each species (production of pollutant emissions is discussed in more detail in Section 2.1).

Whilst much research cites BC as being strongly associated with mobile sources, this is location dependent. Other means of combustion which contribute towards global levels of BC are open biomass burning (i.e. wood fires) and power generation (for example, coal fuelled power stations). Whereas a global emissions inventory cannot ignore the multiple sources of BC emissions, levels in cities such as London are dominated by contributions from mobile sources, and in particular diesel fuelled vehicles.

4.1.2 Environmental impacts

Black carbon is of particular interest as the atmospheric effects are not confined to local air pollution, but also include contributions to anthropogenic climate change. The various climatic effects are discussed by Highwood and Kinnersley (2006) and are summarised in Table 4-2.

31 While Dodson et al. (2009) use an operational definition of black carbon consistent with other studies, the paper also defined elemental carbon in this way – this is symptomatic of a wider problem regarding consistency of definition. As Jeong et al. (2004) discuss, although the two are well correlated, they have different characteristics.
Table 4-2: Atmospheric effects of black carbon (summarised from Highwood and Kinnersley, 2006).

<table>
<thead>
<tr>
<th>Effect</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct</td>
<td>BC scatters and absorbs solar radiation, decreasing planetary albedo and reducing solar radiation that reaches the ground, contributing to global dimming.</td>
</tr>
<tr>
<td>Indirect</td>
<td>BC (and other aerosols) alter the micro-physics of clouds with various impacts (including changing droplet size).</td>
</tr>
<tr>
<td>Semi-direct</td>
<td>BC increases rate of atmospheric heating, alters humidity profiles and affects cloud formation.</td>
</tr>
<tr>
<td>Indirect surface albedo</td>
<td>Deposition onto snow and ice leads to melting and rising sea levels.</td>
</tr>
</tbody>
</table>

These effects are reflected in estimated radiative forcing$^{32}$ of up to $0.55\text{W/m}^2$. Studies have also demonstrated that, when compared to other aerosols, the contribution of BC to radiative forcing is disproportionately high (Panicker et al, 2010).

4.1.3 Health impacts

Chapter 2 discussed the significance of poor air quality (not confined to black carbon) due to the impacts on human health, and by extension the economy. Estimates of the annual number of premature deaths$^{33}$ caused by air pollution include around 4,000 in London (GLA, 2008), 50,000 in the UK (Environmental Audit Committee, 2010) and 370,000 in the EU (European Commission, 2005). These are not attributed solely to BC, but demonstrate the magnitude of the issue.

The impacts of pollutant species on human health are well understood. For example:

- Long-term exposure to ozone may reduce lung-function growth in children and an increased prevalence of asthma (WHO, 2003);

- There is some evidence that long-term exposure to NO$_2$ may decrease lung function and increase the prevalence of respiratory disease (WHO, 2003);

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$^{32}$ The impact of a species in altering the balance of incoming and outgoing energy in the atmosphere

$^{33}$ As a result of respiratory and other diseases strongly associated with long-term exposure to fine particulates, NO$_X$ and ground level ozone
- Long-term exposure to ambient particulate matter can lead to reduced life expectancy as a result of increased mortality due to cardio-pulmonary disease, respiratory disease and lung cancer (WHO, 2013).

The pollutants mentioned here do not exist in isolation, and there is significant scope for interaction. The effects of this cannot be easily estimated (WHO, 2003), and the health impacts cannot be easily isolated. Considering health effects, it has been recognised also that it is important to differentiate between the constituent components of particulate matter (US EPA, 2012).

The impacts of BC on health are generally consistent with that of other fine particles. Due to its small size, BC may be inhaled into the lungs, penetrate the bloodstream (Highwood and Kinnersley, 2006), damage the immune system and act as a transport mechanism for toxic metal combustion products (Janssen et al, 2012).

A recent study by the WHO European Centre for Environment and Health (Janssen et al, 2012) summarises current understanding in relation to the health impacts of black carbon and particulate matter. For short-term health effects, it was concluded that whilst the impacts of PM$_{2.5}$ and PM$_{10}$ were also associated with BC, associations are “more robust” for BC. Therefore, BC is considered a more useful indicator of harmful particulates from combustion than particulate matter differentiated by size alone. This is consistent with earlier discussion of the sources of black carbon and its position as a primary tracer for vehicle exhaust. Despite this, it was recommended that PM$_{2.5}$ should remain as the primary pollutant in assessing human exposure to particulate matter. BC concentration was recognised as providing a good additional metric for evaluating proposals and actions aimed at reducing exposure to traffic induced particulate matter. This further reflects the properties of BC as a proxy for vehicle emissions.

### 4.2 Black carbon management issues

Black carbon, particulate matter and urban air pollution in general are recognised as being detrimental to health and therefore, quality of life. There is a recognised need to reduce the negative impacts of BC. Some of the legislative and technological methods of reducing the production of pollutant emissions from motor vehicles were considered in Chapter 2. This section discusses and critiques the regulations relating to air quality in Europe and the UK.
4.2.1 Legislative approaches

UK air quality standards are driven by European legislation. The Ambient Air Quality Directives\(^{34}\) impose legal limits on the concentration of various pollutants in outdoor air. The National Emissions Ceilings Directive\(^{35}\) imposes legal limits on annual totals for each member state. Table 4-3 summarises the air quality standards imposed by these directives (and assumed by the UK) for selected pollutants\(^{36}\). Black carbon is not included amongst these pollutants, and as such ambient concentrations of BC are not directly regulated.

Table 4-3: EU air quality legislation, transposed into UK air quality standards.

<table>
<thead>
<tr>
<th>Pollutant</th>
<th>Concentration limit</th>
<th>Averaging period</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particulates (PM(_{10}))</td>
<td>50 µg/m(^3)</td>
<td>24 hours</td>
</tr>
<tr>
<td></td>
<td>40 µg/m(^3)</td>
<td>1 year</td>
</tr>
<tr>
<td>Fine particulates (PM(_{2.5}))</td>
<td>25 µg/m(^3)</td>
<td>1 year</td>
</tr>
<tr>
<td>Nitrogen dioxide (NO(_2))</td>
<td>200 µg/m(^3)</td>
<td>1 hour</td>
</tr>
<tr>
<td></td>
<td>40 µg/m(^3)</td>
<td>1 year</td>
</tr>
<tr>
<td>Sulphur dioxide (SO(_2))</td>
<td>350 µg/m(^3)</td>
<td>1 hour</td>
</tr>
<tr>
<td></td>
<td>125 µg/m(^3)</td>
<td>24 hours</td>
</tr>
<tr>
<td>Carbon monoxide (CO)</td>
<td>10 mg/m(^3)</td>
<td>Eight hour daily mean</td>
</tr>
<tr>
<td>Ozone (O(_3))</td>
<td>120 µg/m(^3)</td>
<td>Eight hour daily mean</td>
</tr>
</tbody>
</table>

European legislation refers to the ‘limit value’ (referred to in Table 4-3 as the concentration limit) as:

“…a level fixed on the basis of scientific knowledge, with the aim of avoiding, preventing or reducing harmful effects on human health and/or the environment as a whole…”


\(^{34}\) European Directive 2008/50/EC and 2004/107/EC

\(^{35}\) European Directive 2004/107/EC

\(^{36}\) Other regulated pollutants include PAH, arsenic, lead, cadmium and nickel
Pollutant concentrations must meet the imposed standard at the level of the averaging period specified. For some pollutants, a number of exceedances are permitted. Failure to meet EU air quality standards can result in punitive measures such as fines.\(^{37}\)

### 4.2.2 Limitations

Much like vehicle emissions regulations (discussed in Section 2.2), air quality standards do not distinguish between the different components of particulate matter beyond PM\(_{2.5}\) and PM\(_{10}\). Measured concentrations of PM\(_{10}\) and PM\(_{2.5}\) (Namdeo and Bell, 2005), and BC and PM\(_{10}\) have been shown to be generally linearly correlated (Muir and Laxen, 1995; Ruellan and Cachier, 2001) and black carbon is recognised as a major component of PM\(_{2.5}\) associated with road traffic (Air Quality Expert Group, 2012).

A range of values from literature for the ratio of atmospheric BC to legislated fractions of particulate matter are displayed in Table 4-4.

**Table 4-4: Ambient black carbon\(^{38}\) relation to particulate matter fractions.**

<table>
<thead>
<tr>
<th>Study</th>
<th>Location</th>
<th>Averaging period</th>
<th>BC/PM(_{2.5}) (%)</th>
<th>BC/PM(_{10}) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Patel et al (2009)</td>
<td>Urban, 50m from highway New York, USA</td>
<td>Daytime average over multiple days</td>
<td>10%</td>
<td>-</td>
</tr>
<tr>
<td>Ruellan and Cachier (2001)</td>
<td>Urban, 5m from an eight-lane highway Paris, France</td>
<td>Daily means calculated from hourly measurements</td>
<td>37%</td>
<td>23%</td>
</tr>
<tr>
<td>Viidanoja et al (2002)</td>
<td>Urban, 14m from busy road Helsinki, Finland</td>
<td>Monthly means for 1 year</td>
<td>7-22%</td>
<td>4-12%</td>
</tr>
<tr>
<td>Richmond-Bryant et al (2009)</td>
<td>Urban street canyon New York, USA</td>
<td>105min averages over multiple days</td>
<td>4-22%</td>
<td>-</td>
</tr>
<tr>
<td>Begum et al (2012)</td>
<td>Urban, traffic-influenced site Dhaka, Bangladesh</td>
<td>Monthly means for 1 year</td>
<td>23-42%</td>
<td>-</td>
</tr>
</tbody>
</table>

---

\(^{37}\) Such as legal action by the European Commission against the UK in 2014 (http://europa.eu/rapid/press-release_IP-14-154_en.htm)

\(^{38}\) In relation to the discussion in Section 4.1, all of these studies made use of optical techniques for measurement of black carbon.
Over the course of six studies at a range of urban areas and averaging periods, ratios of BC to PM$_{2.5}$ range from 7 to 42%. Whilst it may be possible to explain the variation between the studies (for example, due to differences in source composition), the key conclusion is that ambient levels of PM$_{10}$ and PM$_{2.5}$ cannot necessarily be used as a proxy for BC.

As a pollutant that is not only harmful to human health but also a particularly good marker for vehicle exhaust, the lack of appropriate legislation to reduce ambient concentrations of black carbon can be considered a failing. For example, the success of transport schemes to reduce the environmental impact of road vehicles could be better assessed through standards relating to black carbon.

4.2.3 Reporting of black carbon

Assembling the necessary data to meet legislative requirements is the motivation for much of the ambient air quality monitoring that occurs. However, despite the current lack of dedicated legislation, there is a history of black carbon measurement in the UK.

The earliest air quality network in the UK was the “UK Black Smoke Network”, established in the 1960s in response to the poor air quality and resulting Clean Air Act of 1956 (NPL, 2013). From 2006, a network has been in place to monitor black carbon, currently consisting of 20 sites across the UK (Fuller and Connolly, 2012). The network has been designed to gather data on particulate matter sources from a range of areas, for epidemiological studies and to assess the impact of air quality management interventions. The usefulness of such a network depends on the spatial and temporal variability of the pollutant, and will be considered in greater detail in Chapter 6.

4.3 Assessing exposure to black carbon pollution

The US Environmental Protection Agency (EPA) advocates a four-stage process (Figure 4-1) for human health risk assessment. This is applied not only to air pollution, but also to water and other areas of environmental risk (US EPA, 2014).

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39 It could be argued that legislation relating to fine particulates is also aimed at reducing ambient concentrations of BC. In addition, UK local authorities are able to designate “smoke control areas”, which again may reduce ambient concentrations of BC – however, these do not cover mobile source emissions.
In conjunction with understanding the health effects of an air pollutant, exposure assessment is necessary to properly characterise the risk.

Zou et al (2009) reviewed various exposure assessment methods and defined several key terms. Much as in the case of differing definitions of black carbon, a consistent use of terminology is important.

- **Concentration** refers to the amount of a pollutant present, generally expressed in terms of mass or fraction per unit volume of air (for example, micrograms per metre cubed or parts per million).

- **Human exposure** acknowledges the interaction of humans (receptors) and pollution – concentration does not recognise if humans are subject to the pollution present in the air. Therefore, exposure requires knowledge of human activity patterns alongside pollution concentration measurements.

- **Dose** relates to the actual pollution that enters the body, and so requires more detailed information regarding the subject (for example, breathing rate).

The extent to which each of these types of metric is relevant to transport planning applications is dependent on the system element. By managing the flow of road traffic, planners can influence where and how much pollution is emitted. In addition, but to a lesser extent, planners can seek to manage where pedestrians and other road users are subject to pollution.

However, the prospect of influencing personal characteristics, such as breathing rate, is out of scope of this thesis, and is discussed in Section 8.2.
4.3.1 Framework for analysis

Section 2.4 detailed the potential ways in which emissions from vehicles could be reduced, broadly categorising these methods as reducing the demand for travel, modal shift, technological change and influencing the operating environment. In the same manner, there are several different ways of reducing human exposure to traffic-induced pollution.

In order to estimate the impact of traffic management interventions on air pollution and health, North et al (2009) suggested a modelling workflow Figure 4-2. This represents the necessary inputs and processes required to evaluate the impact of a given traffic management scenario. This provides a suitable starting point for discussion of the various parameters of importance.

*Figure 4-2: Pollutant exposure modelling work flow (adapted from North et al, 2009).*

Chapters 2 and 3 discussed the importance of understanding the road network (in terms of the propensity to induce emissions), vehicle fleet data and emissions profiles for influencing air quality and human exposure to pollution. This section details the scientific basis for the other components of this analytical framework.
4.3.2 Assessing concentration

An assessment of the traffic state and subsequent measurement or modelling of the tailpipe emissions is an important component of evaluating human exposure to pollution. However, in order to relate tailpipe emissions (i.e. mobile sources of pollution) with concentration (and subsequently exposure), more information is required. In understanding the processes that occur after the pollutant species has exited the tailpipe there are two elements to consider. Firstly, there may be additional reactions that alter the composition of the vehicle exhaust (for example, changes in the equilibrium of NO$_X$, as discussed in Section 2.1). Secondly, it is important to understand how vehicle emissions disperse in the local atmosphere.

An assessment of pollutant concentration for a given location can be achieved through empirical measurement, modelled estimation, or a combination of the two. Whilst they differ in approach, modelled estimations generally rely on the use of explanatory variables which may themselves be estimated from more coarse parameters. This section describes the broad categories of models that exist for this purpose.

Proximity models use information regarding the position of the receptor and pollution sources to explain epidemiology. For example, McConnell et al (2006) found an association between the proximity of a home to the road and incidence of childhood asthma. This type of statistical modelling may prove useful for establishing cause-effect relationships, but is less useful in understanding actual variation in pollution concentration and human exposure.

Land-use regression (LUR) models are a further method, where land use and traffic characteristics are used to predict concentration and human exposure. Measured values of pollution (the dependent variable) from mobile or fixed sensors are regressed against the assumed important explanators, such as traffic intensity and industrial sources, with demographic factors (such as housing and population) factored in (Johnson et al, 2010). The accuracy of these types of model depends on the input data. Whilst LUR (and other interpolative methods) makes use of empirical data, the resolution of the assessment is determined largely by the density of the sensor network. In addition, LUR models do not account for factors such as meteorology and any short term variation in explanatory variables (such as traffic intensity). The regression models can be applied to large spatial scales (e.g. city wide), with a reduced applicability to the micro-scale.

Much of the understanding associated with urban air pollution is based on continuous automated monitoring stations. Although these sites have provided a wealth of information.
that was not previously available, their ability to identify small scale spatial and temporal (second-by-second) variations in air quality is questionable. Mobile source emissions (Chapter 2) and other determinants of pollutant concentration (i.e. dispersion parameters, Tomlin et al, 2009) can vary in the order of several metres (for example Weijers et al, 2004). This naturally impacts upon concentration and exposure. In recent years, there have been many studies aimed at better understanding the temporal and spatial distribution of air pollution.

A review of the literature by Kaur et al (2007) concluded that fixed monitoring stations are poor indicators of pollutant concentration levels relevant for human exposure. An example of a fixed monitoring network is the London Air Quality Network, which comprises more than 100 monitoring stations for various pollutants (King’s College London, 2014). This is an example of a dense network, although it represents the equivalent of one monitoring station for every 15km². Therefore, as Johnson et al (2010) recognise, “these methods do not adequately capture the smaller-scale spatial and temporal variations in pollutant concentrations such as occurs near roadways”.

4.3.3 Studies of pollution variability

Morawska et al (2008) reviewed the influencing factors of the temporal distribution of particles in urban environments. Temporal variability was characterised in the hierarchy of diurnal, seasonal and long-term. Diurnal variability, as exhibited in studies such as Ruuskanen et al (2001), is attributed to changes in traffic intensity throughout the day. Conversely, seasonal variability in particle concentration is more closely associated with changing patterns of dispersion due to atmospheric conditions. Meteorology has been cited as a factor which influences pollutant concentration (Figure 4-2). The extent to which local variations in meteorology influence pollutant concentrations has been the subject of much research. As part of a wider study, Namdeo et al (1999) found a poor correlation between wind speed (based on a 15 minute average) and PM₁₀ and PM₂.₅. However, as this study took place in a street canyon, it was also shown that wind speed was a better predictor of pollutant concentration when normal to the site. It was also determined that the correlation was stronger for the coarser fraction. Another key output of this research was the lack of periodicity with passing traffic. It was concluded that tailpipe-emitted particulates “remain suspended in air for a sufficient time that their concentrations are not correlated with traffic volume”. This effect was also greater for the coarse fraction of particulate matter (i.e., coarse particles settle more quickly than fine particles). Pateraki et al
(2012) also demonstrated a weaker correlation with meteorology for fine particulates, utilising daily average values of $\text{PM}_{2.5}$ and $\text{PM}_{10}$. Through analysis of a long term trend, the authors were able to show the poor relation between particulate matter and meteorological factors. Hagler et al (2008) investigated the relationship between ultrafine particles and the explanatory factors of traffic and meteorology. A 500% difference was observed between the (upwind) background and the (downwind) traffic-influence site. Furthermore, with no change in local weather conditions, the highest levels of UFP were observed during commuting hours, whereas low levels observed on weekends.

Several studies at urban sites have demonstrated an inverse correlation between black carbon (BC) concentration and wind speed (Cao et al, 2009; Ramachandran and Rajesh, 2007). Richmond-Bryant et al (2009) demonstrated that background concentration is the most significant factor in concentration of on-street black carbon. Contrary to other research, it was found that BC concentration increased with cross-street wind (as opposed on along-street wind), which is contrary to other research. It was also found that mobile sources are a more important explanator of black carbon than $\text{PM}_{2.5}$. This is a significant result in the context of this thesis, as it further highlights the need for consideration of BC independently of other particulates, and also strengthens the case in using BC as a proxy for all traffic-related emissions.

Some studies have shown meteorology to be a significant factor in determining the levels of BC concentration in urban areas. A common way of incorporating wind speed and direction into the assessment of pollutant concentrations is through atmospheric dispersion modelling. These models help to explain current patterns of dispersion and forecast future levels. Dispersion models utilise information on sources of pollution (fixed and mobile source), physical topography (buildings heights, road layout) and metrological conditions (wind speed, direction) to estimate concentration. Clearly, the quality of the estimate is related to the input data. More complex models allow estimation at a fine spatial resolution, but are more data and computationally intensive.

In the context of this research, meteorology is considered outside of the (direct) influence of transport planners. As such, an understanding of the exact mechanism of pollutant dispersion at a site is outside the scope of this thesis. However, the potential for local weather conditions to impact on-street levels of pollution must be acknowledged for any meaningful conclusions to be drawn.
There is currently no substitute for empirical measurement for a full understanding of the spatial variability present in. Where sophisticated monitoring has been deployed such as in the MESSAGE project (Cohen et al, 2009), the potential for use has been demonstrated. Although the technology to enable the use of dense networks of pollution sensors is improving (Galatioto et al, 2011; Mead et al, 2013), long term deployment is currently unlikely to be a practical or affordable solution at all locations. The use of mobile monitoring has also been advocated for use in air quality research (Gulliver and Briggs, 2004; Van Poppel et al, 2013; Yu et al, 2013). Whilst such techniques enable a greater geographical area to be surveyed, data availability problems still persist.

Investigation into smaller-scale spatial distribution of particles is generally conducted with distance acknowledgement of mobile sources. The explanatory parameter of 'distance from roadway' is often utilised (Morawska et al, 2008). The findings for such studies may form a basis for the proximity models discussed in Section 4.3.2. Boogaard et al (2011) suggested that average roadside concentrations are up to twice that of background levels. These measurements consisted of one-week averages, and do not give any indication as to whether this relationship changes in time. Pirjola et al (2012) investigated spatial distribution of traffic pollutants (NO\textsubscript{x}, PM\textsubscript{2.5}, BC) in several urban micro-environments in Helsinki, Finland. It was shown that concentrations decreased sharply at around 8m from the carriageway, and continued to decrease with distance. In some environments variation in concentration was explained by the different street characteristics (for example, open or street canyon) influencing pollutant dispersion. This is in keeping with those of other studies, such as Zhu et al (2009).

Multiple studies have highlighted the importance of proximity to traffic and meteorological factors (wind speed and direction) as influencing pollutant dispersion and concentration. However, often such studies do not acknowledge activity patterns of human receptors and therefore do not evaluate exposure to pollution.

4.3.4 Studies of exposure to black carbon and fine particulates

Kaur et al (2007) stated that there are few studies which examine pedestrian exposure to particulate matter and ultrafine particle counts. Since this time there has been considerable effort to better understand this subject area. However, specific reference to black carbon is still lacking in the available literature. Kaur et al (2005) found significance between exposure to PM\textsubscript{2.5} and walking position. Walking position was characterised by position on the pavement (adjacent to traffic or the building) and direction of travel in relation to the direction
of traffic flow. The relative position of sources (vehicles) and receptors (pedestrians) is a key outcome of this research, and something that is a recurring theme.

Kaur et al (2006) demonstrated (reporting data from the DAPPLE project) that exposure to ultrafine particles was linked to both proximity to mobile sources (traffic) and the density of traffic. In addition, it was shown that concentration of these particles decreased rapidly with an increasing distance from the pollutant source. It was submitted that the urban environment could be considered as two types of microenvironment: those with low magnitude concentrations and low variability; those with high magnitude events and greater variability in concentration.

Buonanno et al (2011) conducted experimental work in order to determine the parameters of influence on pedestrian exposure. It was shown that there is a large variation between pollutant concentrations in seemingly close locations. This was attributed to variations in traffic density causing high, short-term exposures. Street geometry and meteorological conditions were also found to be influential, and it was acknowledged that these are not independent. Even though classification of street geometry was coarse, based on a qualitative description of separate locations, this is a significant result. This is insufficient, particularly for understanding variation and assessing the impact of interventions.

The previous section highlighted the need for assessment techniques to adequately capture spatial variability, i.e., how the concentrations of pollutants vary over short distances. Exposure to short-term, high-magnitude pollution events has been shown to be particularly important in the assessment of human exposure (Brugge et al, 2007; Strak et al, 2010). It has also been shown that, in urban areas such as London, modes of transport account for a disproportionately high proportion of personal exposure (Buonanno et al, 2011; Dons et al, 2011; Gulliver and Briggs, 2004; Wang et al, 2011). It is widely recognised that human exposure to pollution must be considered in terms of not only the changing concentration of pollutants, but also the position of the population.

Dons et al (2012) ascertained through means of an experimental campaign in Flanders, Belgium, that the highest average contributions to black carbon dose are encountered whilst using transport (Table 4-5). Transport in general contributed to more than one fifth of exposure and nearly one third of BC dose, despite the time spent in transport being only 6.3%. This is in agreement with the results of previous studies (including Dons et al, 2011). The difference between exposure and dose can be explained by disparity in breathing rate – more physically active travel modes, such as walking and cycling have a higher contribution.
to dose. As the authors point out, this is consistent with research from Adams et al (2002) and Kaur et al (2007). The outcome is that concentrations of fine particulates (in this case BC, EC or PM$_{2.5}$) are lower outside vehicles than within. However, it can be argued that the data presented is not of a sufficient resolution to make that distinction.

Table 4-5: Contribution to BC exposure and dose by activity (from Dons et al, 2012).

<table>
<thead>
<tr>
<th>Activity type</th>
<th>Proportion of time spent</th>
<th>Contribution to exposure</th>
<th>Contribution to dose</th>
</tr>
</thead>
<tbody>
<tr>
<td>Home</td>
<td>29.9%</td>
<td>26.7%</td>
<td>21.8%</td>
</tr>
<tr>
<td>Sleep</td>
<td>35.5%</td>
<td>25.0%</td>
<td>13.9%</td>
</tr>
<tr>
<td>Work</td>
<td>17.0%</td>
<td>12.2%</td>
<td>12.8%</td>
</tr>
<tr>
<td>Social and leisure</td>
<td>6.3%</td>
<td>8.9%</td>
<td>12.8%</td>
</tr>
<tr>
<td>Shopping</td>
<td>1.1%</td>
<td>2.0%</td>
<td>3.2%</td>
</tr>
<tr>
<td>Other</td>
<td>3.9%</td>
<td>4.3%</td>
<td>5.6%</td>
</tr>
<tr>
<td>Transport</td>
<td>6.3% (100%)</td>
<td>21.0% (100%)</td>
<td>29.8% (100%)</td>
</tr>
<tr>
<td>Car driver</td>
<td>2.9% (45.3%)</td>
<td>12.3% (58.6%)</td>
<td>10.5% (35.2%)</td>
</tr>
<tr>
<td>Car passenger</td>
<td>0.7% (11.4%)</td>
<td>2.2% (10.3%)</td>
<td>1.7% (5.8%)</td>
</tr>
<tr>
<td>Bike</td>
<td>1.0% (15.7%)</td>
<td>2.5% (11.8%)</td>
<td>9.1% (30.5%)</td>
</tr>
<tr>
<td>On foot</td>
<td>1.0% (16.4%)</td>
<td>2.2% (10.5%)</td>
<td>6.6% (22.3%)</td>
</tr>
<tr>
<td>Train</td>
<td>0.5% (7.9%)</td>
<td>0.9% (4.2%)</td>
<td>0.9% (3.0%)</td>
</tr>
<tr>
<td>Light rail / metro</td>
<td>0.1% (0.8%)</td>
<td>0.2% (1.0%)</td>
<td>0.2% (0.7%)</td>
</tr>
<tr>
<td>Bus</td>
<td>0.2% (2.4%)</td>
<td>0.7% (3.6%)</td>
<td>0.7% (2.5%)</td>
</tr>
</tbody>
</table>

In their review of exposure research, Kaur et al (2007) compare the (limited number of) studies around fine particulates and black carbon. However, limited reference is made to the temporal resolution of such studies. Adams et al (2001) measured aggregate PM$_{2.5}$ for an entire journey on different transport modes (ranging from approximately 15 minutes to 1 hour). Data of this sort can provide information on exposure, and will inform assessment of pollutant dose for different modes of travel. As it does not capture any in-transit variation, techniques such as these do not yield information regarding variation in rates of exposure. Consequently, opportunities for reduction are not available.

The study by Dons et al (2012) collected black carbon data at a resolution of five minutes (averaging period). Compared to many studies of ambient air quality and personal exposure,
this offers a relatively high temporal resolution. However, no explicit rational is provided for a seemingly arbitrary time window. This leads to two questions:

- Is five minutes a sufficient window to capture the variation?
- Is the arithmetic mean representative of the variation experience in the window?

Both of these questions must be answered to satisfaction prior to an experimental campaign. Whilst the first is dependent on data, the second can be considered from secondary sources. The London Travel Demand Survey (Transport for London, 2011) indicates that people in London spend no more than 20 minutes walking each day. Assuming this consists of two, 10 minute journey stages, characterising these journeys with two data points appears wholly inadequate. For example, SCOOT-enabled signalised intersections in London have a cycle time (see Section 2.3.2) of between 32 and 120-seconds (Transport for London, 2010). It would therefore not be expected for a pedestrian to occupy a waiting position for more than 120-seconds. Furthermore, the change in traffic control state and the consequent change in vehicle operating behaviour would also be in the order of seconds rather than minutes.

Chapter 3 showed this, demonstrating in the case of a mid-link crossing that there is potential for vehicle dynamics and emissions to change in the order of seconds. It is reasonable to suppose that kerbside air quality may also be subject to the same level of temporal change. Wang et al (2011) stated that “…peak exposure events may be the reason for the high pedestrian exposure”. This suggests the need for capturing these high magnitude events. This is in line with the findings of Kaur et al (2007), who concluded that high-resolution time measurements in urban micro-environments are essential to inform understanding. The prospect of a network of monitoring stations (such as the previously mentioned black carbon network) providing a suitable data resolution to recognise this variation is unlikely.

4.4 Summary: urban air quality, black carbon and pedestrian exposure to pollution

Black carbon (BC) is important due to its impacts on global climate change and human health. This together with the fact that it is a primary tracer for combustion makes it important to understand BC’s variability in concentration and exposure. Estimates of concentration through modelling studies are neither able to provide the necessary spatial resolution nor account for the variability such as that associated with meteorology on a high temporal scale.
Therefore, empirical measurement provides the best approach to understand the variation present and determine routes to minimise the impacts on human health.

Significant research has been undertaken in recent years to consider poor air quality in conjunction with time-activity patterns that inform the assessment of human exposure (for example Dons et al, 2014).

The second research objective is to:

*Specify, evaluate and refine techniques for the measurement of black carbon concentration around traffic management infrastructure, for the use in studies of personal exposure.*

This chapter addressed the first element of this objective. Changes in vehicle operating behaviour and in the mechanism of traffic and pedestrian control vary in the order of seconds and metres. Current research does not achieve this resolution, and therefore cannot properly assess exposure. It is the conclusion of the review in this chapter that in failing to survey air quality at a sufficient resolution, these studies cannot make adequate assessment of human exposure. It is not possible to target, specify and evaluate interventions to reduce the incidence of vehicle-induced pollution hotspots if the problem is not sufficiently understood.

The following chapters of this thesis (5 and 6) will address this gap in current understanding. It has been a failing of previous research to not capture the variability the pollutant concentrations for use in assessing personal exposure. Chapter 5 discusses various methodologies and specifies a suitable measurement regime for assessing temporal and spatial variability of pollution in urban areas. Chapter 6 details an experimental deployment to characterise the spatial and temporal variability in pollution, and the subsequent results. Black carbon, the importance of which was established in Section 4.1 and 4.2, is selected as the pollutant of interest.
5 Measurement of black carbon

This chapter describes the measurement of black carbon through the use of aethalometers and the interpretation and use of the data. The function and operation of the device is detailed with particular reference to its use for high time resolution measurement. The relevant research to date is reviewed and gaps identified.

The second research objective, specified in Section 1.4, is to:

Specify, evaluate and refine techniques for the measurement of black carbon concentration around traffic management infrastructure, for the use in studies of personal exposure.

It was argued in Chapter 4 that investigations into pedestrian exposure cannot be conducted without measurement resolution sufficient to capture the variability in air quality. The time period of this variability is expected to be in the order of seconds and metres due to the changing vehicle operating behaviours and consequent rates of mobile source emissions. This chapter addresses the remaining elements of this objective, namely to evaluate and refine measurement techniques.

In order to produce a dataset suitable for application to assess black carbon concentration and personal exposure, the errors associated with the measurement device are classified and characterised for urban environments. The techniques for mitigating such errors are reviewed and a recommendation made for the need for simultaneous monitoring employing networked multiple micro-aethalometers for high-resolution measurement in urban areas.

Subsequent deployments of multiple-aethalometers for measurement of black carbon concentration are described in Chapter 6. Application of these data to assessments of personal exposure to pollution is described in Chapter 7.

5.1 Introduction to optical measurement of black carbon

Section 4.1 described black carbon, using the operational definition, as “the component of atmospheric aerosol that absorbs visible radiation” (Highwood and Kinnersley, 2006). This definition is linked intrinsically to the measurement methodology, which is optical in nature.
Optical measurements for black carbon were first introduced by Gundel et al (1984). The motivation for this method was based on the drawbacks of others such as chemical or gravimetric, which were time consuming (Gundel et al, 1984) and did not offer sufficient resolution or real-time detection (Hansen et al, 1984).

Gundel et al (1984) introduced the laser transmission method (using a single wavelength), which measures the attenuation of visible light as it passes through a sample of particulates. This methodology offered an advantage over existing techniques in that it is fast, relying on only the optical absorption properties of the material.

Attenuation (ATN) is used to describe how light decreases in intensity as it passes through a medium (Rosen et al, 1978). As black carbon absorbs and scatters visible light, the deposition of black carbon particles on a filter reduces the transmittance of light through the filter.

Figure 5-1: Transmittance of light through a filter.

The filter reduces transmittance by absorption and scattering (attenuation), reducing the intensity of $I_0$ to $I$.

The transmittance ($T$) can be described as the ratio of the intensity of light exiting the medium ($I$) to the initial intensity of light ($I_0$).

$$ T = \frac{I}{I_0} $$ \hspace{1cm} \textit{Equation 5-1}

The difference in intensity can be used also to derive the attenuation of the medium, ATN.

$$ \text{ATN} = -100 \times \ln \frac{I}{I_0} $$ \hspace{1cm} \textit{Equation 5-2}
The Beer-Lambert law defines the linear relationship between absorbance and concentration of an absorber of visible light (or other electromagnetic radiation).

\[ A = \varepsilon \times c \times l \]

*Equation 5-3*

Where:

- \( A \) = absorbance
- \( \varepsilon \) = molar absorption coefficient
- \( c \) = concentration of the absorbing species
- \( l \) = sample path length

From equation 5-3, absorbance is proportional to the concentration of the absorbing species in situations where the molar absorption coefficient (how strongly a given species absorbs a given wavelength of light) and the path length are constant.

Aerosols such as black carbon scatter light as well as absorb it. Therefore the idealised situation described in Equation 5-3 does not describe the process fully. The principle of the Beer-Lambert law may be expanded to include these effects, for example, by considering an extinction coefficient (\( \beta_e \)), which incorporates both light absorption (\( \beta_a \)) and light scattering (\( \beta_s \)).

Gundel et al (1984) empirically derived a linear relationship between attenuation of light and concentration of black carbon. The relationship was populated using samples from different sources in a range of environments (Figure 5-2). However, the linear relationship was observed to breakdown at high black carbon concentration (Figure 5-3), with attenuation of light no longer increasing linearly.

The definition of this relationship allows black carbon concentration to be estimated from changes in light attenuation. However, it was also recognised that the linear relation is not valid for all concentrations of black carbon.
Figure 5-2: Relationship between light attenuation and concentration of black carbon (from Gundel et al, 1984).

Fig. 2. The relationship between attenuation and black carbon concentration for ATN ≤ 200 and [BC] ≤ 8 µg cm⁻². Particles from a) sources and b) urban air.

Panel (a) shows different sources (propane soot, diesel vehicles etc.) whilst panel (b) shows different measurement locations in the United States and Europe. Image reproduced with permission of the rights holder, Elsevier.

Figure 5-3: Loss of linear relationship between black carbon concentration and attenuation of light at high cumulative deposition of black carbon (taken from Gundel et al, 1984).

Image reproduced with permission of the rights holder, Elsevier.
5.2 Aethalometer principles of operation

Hansen et al (1984) exploited the empirical relationship between light and black carbon concentration to design an “aethalometer” - a device that can measure “the concentration of optically absorbing aerosol particles in real time”. Air is drawn into the device at a constant rate and passed through a filter. Particles within the air stream are deposited on the filter, which changes the attenuation of light passing through the filter ticket. This attenuation is compared to that of a portion of the filter ticket through which air is not passed (the reference).

Figure 5-4 shows an example filter ticket with a characteristic black spot (approximately 3mm in diameter) where particulates have been deposited, alongside a blank filter ticket.

Figure 5-4: Used (top) and blank (bottom) aethalometers (AE51) filter tickets⁴⁰.

The used filter strip shows the characteristic dark spot (3mm in diameter) created by the sample measurement.

Over the desired sampling period \((t_0 \rightarrow t_1)\), the increase in the attenuation of light is caused by the deposition of particles on the sampling ticket. By utilising the empirical relationship derived by Gundel et al (1984), and the device specific parameters (static characteristics such as path length), BC concentration can be determined (Hansen et al, 1984).

The surface concentration of black carbon on the filter \((\mu g/m^2)\) is proportional to concentration and is related to the increase in attenuation (Hansen et al, 1984). In Kirchstetter and Novakov (2007) this is presented as:

\[ \mu g/m^2 = \text{constant} \times \text{attenuation increase} \]

⁴⁰ Note that the measurement reference is (generally) a part of the same filter media that has not had particles deposited on it, rather than a separate filter.
\[ BC = \frac{ATN}{\sigma} \]

Where:

\[
\begin{align*}
BC & = \text{concentration of black carbon (mass per unit volume)} \\
ATN & = \text{attenuation of light} \\
\sigma & = \text{attenuation coefficient}
\end{align*}
\]

The attenuation coefficient (\(\sigma\)) is a proportionality constant, analogous to the extinction coefficient discussed in Section 5.1. This was initially determined based on the work of Gundel et al (1984). Since its inception and development in the early 1980’s, the aethalometer has been further developed and is now available in a range of different models. One advance has been in producing a hand-held version that allows for mobile BC monitoring, generally referred to as a micro-aethalometer.

The AethLabs AE51 micro-aethalometer is the model used in this thesis (Table 5-1). This device is suitable due to being lightweight, compact and easily transported. In addition, the AE51 has on-board power and storage.

**Table 5-1: Micro-aethalometer (AE51) black carbon monitor specification.**

<table>
<thead>
<tr>
<th>Light source</th>
<th>880nm (IR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Range</td>
<td>0 – 1000 µg/m³</td>
</tr>
<tr>
<td>Resolution</td>
<td>0.001 µg/m³</td>
</tr>
<tr>
<td>Precision (approx.)</td>
<td>± 0.1 µg/m³</td>
</tr>
<tr>
<td>Time-base (variable)</td>
<td>1-second, 1-minute, 5-minutes</td>
</tr>
<tr>
<td>Flow rate (variable)</td>
<td>50, 100, 150 mL/min</td>
</tr>
<tr>
<td>Dimensions</td>
<td>117mm x 66mm x 38mm</td>
</tr>
<tr>
<td>Weight</td>
<td>280g</td>
</tr>
</tbody>
</table>

*As shown in the microAeth Model AE51 Operating Manual (AethLabs, 2011).*
Flow rate and time-base (1-second, 1-minute or 5-minutes) are user defined settings. Each of the nine possible combinations is recommended by the manufacturer for a particular purpose. The highest data reporting resolution of 1-second is referred to as “Data Acquisition Mode” (AethLabs, 2011). The manufacturer advises that this time resolution should only be used in cases where the data are post-processed (“smoothed or averaged over longer periods”). This is due to the signal-to-noise ratio, and is discussed in subsequent sections.

The AE51 reports BC concentration (ng/m$^3$, integer values) and the attenuation of light value (to 2 decimal places). The AE51 has no real-time reporting of black carbon or attenuation of light. Status of operation is indicated by sounds and coloured lights. The device has an internal clock which can be synchronised with a PC prior to use. Output data files also include a timestamp, battery and pump status. The resulting product is a time-series of black carbon concentration and light attenuation data.
5.3 Micro-aethalometer use and issues

The requirement of post-processing means that the micro-aethalometer does not directly measure at the instrument specified resolution of 1Hz. As discussed in Chapter 4, a measurement resolution of 1-minute is not sufficient in order to understand pollutant concentrations in urban areas. This section reviews the use of micro-aethalometers in urban pollution research and discusses the factors that influence their operation and measurement capabilities.

5.3.1 Operational issues and post-processing techniques

As introduced at the end of Section 5.2, there are known issues associated with the use of micro-aethalometers that may cause error in measurement and impact the available temporal resolution. This section discusses some current error mitigation techniques and efforts to maximise the available data.

Alongside the empirically determined linear relationship used by Hansen et al (1984), Gundel et al (1984) demonstrated that attenuation does not increase linearly at high levels of black carbon (Figure 5-3). Hansen et al (2007) describe this as a second-order effect. The first-order process is where the increase in light attenuation (or decrease in transmission) is proportional to the rate of accumulation of particles. In the second-order effect, already collected particles may “shadow” those being freshly deposited. The consequence is that these freshly deposited particles do not have the same impact in increasing ATN. As such, the linear relationship between black carbon concentration and light attenuation is no longer valid.

Accounting for the shadowing effect, also known as the filter loading effect (Kirchstetter and Novakov, 2007), has been the subject of much research (Hansen et al, 2007; Jimenez et al, 2007; Park et al, 2010; Virkkula et al, 2007). Since the effect is second-order, a practical method of avoidance is to not allow deposition of particles on a filter ticket to the extent that shadowing occurs; i.e., to change the filter ticket regularly. This led to the definition of a maximum filter loading of $Q_{\text{max}}$ (Hansen et al, 1984). Virkkula et al (2007) explored the impact of filter loading on accuracy of black carbon measurement. Figure 5-6 shows the correlation between black carbon concentration and a reference aerosol volume concentration (measured with a differential mobility particle sizer). The agreement between the two datasets is much greater at low concentrations of black carbon, as illustrated by the
clustering of data points around the linear trend line. However, at increasing BC concentration (above 6µg m\(^{-3}\)) the deviation of measured BC against the reference is larger.

*Figure 5-6: Measured BC and reference data (from Virkkula et al, 2007).*

The linear relationship between measurements is shown to be poorer at higher concentrations, illustrated by the larger spread of data. Image reproduced with permission of the rights holder, Taylor & Francis.

The correction algorithm proposed by Virkkula et al (2007) takes the form:

\[
BC_{\text{corrected}} = (1 + k \times \text{ATN}) \times BC_{\text{aethalometer}}
\]

*Equation 5-5*

The value of the correction parameter, \(k\), would vary dependent on location and season (Virkkula et al, 2007, Hansen et al, 2007). The impact of correction is shown in Figure 5-7,

*Figure 5-7: Application of linear correction in Virkkula et al (2007).*

Success of the algorithm in improving model fit (R\(^2\)) is shown. Image reproduced with permission of the rights holder, Taylor & Francis.
There is much greater agreement with the reference data after application (illustrated by the value of $R^2$ in Figure 5-6 and Figure 5-7).

Filter loading effects are related to the assumption that the attenuation coefficient ($\sigma$, see Equation 5-4) is constant for all concentrations of BC. In addition to changes in absorption, the light scattering effects of particles are also a factor in the estimation of the attenuation coefficient. Grundel et al (1984) argued that the relationship between black carbon and attenuation is consistent across all combustion sources (see Figure 5-2). This is essentially an assumption that the attenuation coefficient $\sigma$ is constant for all BC emission sources, and as such is homogenous. Lioussse et al (1993) demonstrated a variability in $\sigma$ related to combustion source and atmospheric processing (such as particle aggregation), contrary to the earlier findings of Grundel et al (1984). Crucially, however, it was determined that values of $\sigma$ were found to be constant in a given type of atmospheric environment.

Values of $\sigma$ are vital to aethalometer instrument calibration. Many of the algorithms developed for filter loading are also aimed at correcting other issues that relate to inadequate assumptions regarding the value of $\sigma$, including multiple scattering by filter fibres which serves to increase the optical path length (Collaud Coen et al, 2010). In this thesis, changing filter strips serves to reduce the impact of filter loading, and the constrained area of interest (vehicle-induced pollution hotspots in urban areas) facilitates the mitigation of the other concerns about the assumed value of $\sigma$. This is explored further in Section 5.6.

Hagler et al (2011) describe the process by which negative and other erroneous values can occur during operation of a filter-based optical measurement device. Where the attenuation of light (ATN) should always increase between successive measurements (or remain static), instrument optical, electronic or mechanical “noise” may lead to a reported decrease in ATN for a short period. The operation of the device requires that ATN is either static or increasing. As such, the change in ATN ($\Delta$ATN) cannot be negative. A decrease in ATN initially results in impossible negative values of BC concentration. As the measurement recovers, the change in ATN is high (coming from a lower base of ATN in the preceding time-step), and a high value is reported. By using knowledge of the measurement process of the device and the reported ATN values, an algorithm (the Optimized Noise Reduction Algorithm, or ONA) was developed to correct such data (Hagler et al, 2011). For small changes in BC concentration (and small changes in ATN) the averaging period is increased, whereas in highly variable conditions (large changes in ATN), a small average period is retained. This approach is based on the logical assertion that, unless there is a significant change in ATN, there is no BC event that is of a sufficiently different level to the underlying trend. The change
in ATN that is considered significant is user-defined on application, but was experimentally determined by Hagler et al (2011) as being 0.05\textsuperscript{41}. This leads to variable averaging periods for a given time-series. This construction and performance of this method is further investigated in Section 5.5.

The authors also quantified the noise component (retaining the same units as concentration) of the black carbon measurement, allowing for data quality to be assessed.

\[
\text{Noise} = \frac{1}{n} \sum_{i=0}^{n} |BC_{i+1} - BC_i|
\]

\textbf{Equation 5-6}

Noise (units of concentration) is defined as equal to the average absolute value of the instantaneous change in measured black carbon concentration for the entire data set\textsuperscript{42}. A higher number of large changes between successive data points result in a higher value for noise. Given this, it is not necessarily appropriate to compare the noise of data recorded in different environments; rather, the metric was defined to assess performance of ONA in improving a given time-series.

Hagler et al (2011) used several sets of data to test the performance of ONA in terms of reducing noise, eliminating negative values and maintaining a suitable time resolution. Results relating to the highest resolution measurements from this study are shown in Table 5-2.

\textit{Table 5-2: ONA performance (from Hagler et al, 2011).}

<table>
<thead>
<tr>
<th>Case</th>
<th>Time-base</th>
<th>Median averaging window</th>
<th>Average BC (ng/m\textsuperscript{3})</th>
<th>Noise original (ng/m\textsuperscript{3})</th>
<th>Noise ONA (ng/m\textsuperscript{3})</th>
<th>% -ve original</th>
<th>% -ve ONA</th>
</tr>
</thead>
<tbody>
<tr>
<td>AE51(a)</td>
<td>1s</td>
<td>15s</td>
<td>27,500</td>
<td>12,500</td>
<td>63</td>
<td>0.2</td>
<td>0.0</td>
</tr>
<tr>
<td>AE51(b)</td>
<td>1s</td>
<td>8.4 min</td>
<td>14,500</td>
<td>10,100</td>
<td>109</td>
<td>32.4</td>
<td>0.0</td>
</tr>
<tr>
<td>AE42(c)</td>
<td>1s</td>
<td>10s</td>
<td>3960</td>
<td>3,200</td>
<td>386</td>
<td>13.3</td>
<td>0.1</td>
</tr>
</tbody>
</table>

A reduction of noise and the proportion negative values is seen across all relevant test cases.

In case AE51(a), the device was measuring BC emitted at a constant rate and a high level of BC by a diffusion flame. Therefore it may be argued that the noise is related to the

\textsuperscript{41} As the micro-aethalometer reports ATN to two decimal places, this is greatest level of accuracy that ATN can practically be defined to

\textsuperscript{42} Due to the need for successive values, the number of total records is equal to n+1.
instrument rather than a low concentration of BC, and the rate of BC emitted was constantly high. This is shown by the high average concentration, high noise value and low occurrence of negative values. Although using a portable aethalometer AE42 (rather than the micro-aethalometer, AE51), the third case (c) was conducted as an on-road mobile monitoring study of traffic-induced emissions. Compared to the other two cases, the AE42 study exhibits an initial low value of noise. In this case, application of the algorithm has reduced noise and occurrence of negative values whilst reporting at a median 10-second averaging period. The relative improvement on application of ONA is also lowest. However, there is success in reducing noise and the occurrence of negative values in all cases.

Cheng and Lin (2013) investigated the performance of the algorithm, incorporating a focus on the impacts of loading on measured BC concentration. They concluded that at high loadings (ATN approximately greater than 40), whilst negative values were eliminated, BC concentration was underestimated by as much as 15%. This was conducted on 5-minute average data, and therefore, does not provide a useful indicator of performance at a higher time resolution. This is especially important considering the problems associated with continuous measurement at the 1-second level.

The conclusions of Chapter 3 and Chapter 4 demand high-resolution measurement to account for variability in mobile source emissions and pedestrian activity in urban areas. To this end, performance of this algorithm and other post-processing techniques must be evaluated more fully to ascertain their suitability. This is described in sections 5.4 – 5.6 of this chapter.

5.3.2 Micro-aethalometer use in urban pollution studies

Whilst the measurement of ATN, and the resulting estimated BC concentration can be conducted at a 1Hz resolution (i.e. the acquisition of data), it is recommended that longer averaging periods are used to mitigate the errors caused by instrument noise. This section describes the use of micro-aethalometers in urban pollution studies and documents the time resolution and post-processing methods employed.

Dons et al (2013b) made use of micro-aethalometers at a 5-minute temporal resolution at 63 fixed rural and urban locations in Flanders, Belgium. These time-series were aggregated to hourly averages, but no mention was made of any other post-processing or of problems experienced with data acquisition. Invernizzi et al (2011) used micro-aethalometers in various urban scenarios to understand the different impacts of traffic management policies.
Data was recorded as 5-minute averages, with no further processing detailed. Similarly, Vette et al (2013) and Galaviz et al (2014) used 5-minute averages, with no information on further processing. Amongst the datasets used by Hagler et al (2011) in the development of a post-processing methodology, was a 5-minute resolution near-road sample. In this case, negative values made up 2.6% of the data. It is not clear how such occurrences (if any) were treated by the studies reviewed here, but since negative values of BC concentration are physically impossible, some action is clearly required. Dons et al (2011) utilised the device for a study of personal exposure. Although a 5-minute average was used, reference was made to negative values. This was attributed to instrument noise, caused by a small change in the position of the light beam or filter ticket resulting in a decrease in attenuation, and missing data caused by operating procedure. However, no treatment was sought other than removing the erroneous values. The proportion of the datasets with negative values was between 1.5% and 2%, with missing values accounting for 10.9% in one instance.

Liang et al (2013) incorporated micro-aethalometers into a wider study of black, organic and elemental carbon. In this instance a 1-minute resolution was used, although no reference is made to errors of measurement. Wang et al (2012) describe a measurement campaign in which data were initially recorded at the 1-second time-base before being averaged to 10-seconds. The averaging was conducted to align the BC dataset with that of other pollutants. However, no reference to other data processing requirements is made. Van Poppel et al (2013) discussed the use of micro-aethalometers at a high time resolution (1-second). They state that this level of temporal resolution is difficult to obtain due to problems of signal noise. In this study, the noise reduction algorithm (ONA) developed by Hagler et al (2011) was utilised to good effect, with negative values eliminated and a high time resolution maintained (~ 5 seconds). Table 5-3 summarises these studies.

Table 5-3: Summary of micro-aethalometer use in urban pollution studies and the associated post-processing methodology.

<table>
<thead>
<tr>
<th>Study</th>
<th>Time-base</th>
<th>Post-processing method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dons et al (2011)</td>
<td>5-minute</td>
<td>Negative values removed</td>
</tr>
<tr>
<td>Dons et al (2013)</td>
<td>5-minute</td>
<td>None detailed</td>
</tr>
<tr>
<td>Galaviz et al (2014)</td>
<td>5-minute</td>
<td>None detailed</td>
</tr>
<tr>
<td>Invernizzi et al (2011)</td>
<td>5-minute</td>
<td>None detailed</td>
</tr>
<tr>
<td>Vette et al (2013)</td>
<td>5-minute</td>
<td>None detailed</td>
</tr>
<tr>
<td>Liang et al (2013)</td>
<td>1-minute</td>
<td>None detailed</td>
</tr>
<tr>
<td>Van Poppel et al (2013)</td>
<td>1-second</td>
<td>ONA</td>
</tr>
<tr>
<td>Wang et al (2012)</td>
<td>1-second</td>
<td>10-second average</td>
</tr>
</tbody>
</table>
5.3.3 Summary

There are several known issues regarding the use of micro-aethalometers to measure black carbon. These can be split into two categories. The first, filter loading, is related to the attenuation coefficient, $\sigma$, which is essential in defining the relationship between ATN and BC. This can result in underestimation of BC, as second-order shadowing effects take place.

The second is related to instrument noise, and results in erroneous (and sometimes impossible) values. Whilst both are important, it is argued that the second category is more relevant in understanding pollution dynamics as it is an obstacle in producing high-resolution measurements. This is evidenced by the review of the literature, where a 5-minute resolution was generally preferred, and instrument noise problems rarely even acknowledged. Where signal-processing techniques have been implemented, it has often been limited to simple averaging (such as Wang et al 2012) or removal of impossible values (such as Dons et al 2011). It is a failing of these studies not to properly acknowledge the potential for instrument error, with only Van Poppel et al (2013) implementing a detailed and specific post-processing methodology (ONA).

This section has recognised the potential for errors caused by instrument noise. The technique proposed by Hagler et al (2011) has been identified as addressing the cause of some erroneous problems, namely those caused by negative $\Delta$ATN. As such, this algorithm offers a suitable starting point. The performance and suitability of this algorithm (the ONA) is explored in Section 5.5.

Further errors are caused by variation in $\sigma$, described here as filter-loading effects. These will in part be mitigated by frequent changing of the filter in line with the recommendations of the manufacturer (AethLabs, 2011). It is also assumed that manufacturers' calibration is appropriate, and that recording only in environments dominated by traffic-induced pollution will render relative levels of BC concentration viable (Lioussse et al, 1993). However, in order to have confidence in the measurement device, filter loading effects will be further investigated for relevance to this study. This is detailed in Section 5.6.

As an initial step, the exact nature of the data (including errors) should be detailed for urban areas identified as important in Chapter 2 and Chapter 3 of this thesis. This work is described in the following section, 5.4.
5.4 Data characterisation and error identification

This section describes the characterisation of micro-aethalometer performance in situations relevant to pedestrians in urban areas subject to vehicle-induced pollution. The errors are identified and techniques for producing a suitable time-series considered.

5.4.1 Equipment

Multiple micro-aethalometers were used for the work in this thesis. They were obtained from a variety of collaborators and were all in good working order, with procedures regarding pump changes and annual maintenance previously adhered to. Each aethalometer has a unit specific serial number, a portion of which is used in this research as a unique identifier for the device (Table 5-4).

Table 5-4: Micro-aethalometers (AE51) used in this work.

<table>
<thead>
<tr>
<th>Device ID</th>
<th>Equipment owner</th>
<th>Availability of use</th>
</tr>
</thead>
<tbody>
<tr>
<td>193</td>
<td>Air Monitors Ltd</td>
<td>February – July 2012</td>
</tr>
<tr>
<td>364</td>
<td>School of Public Health, Imperial College London</td>
<td>March – June 2012</td>
</tr>
<tr>
<td>574</td>
<td>Centre for Transport Studies, Imperial College London</td>
<td>February – October 2013</td>
</tr>
<tr>
<td>670</td>
<td>Centre for Transport Studies, Imperial College London</td>
<td>May – October 2013</td>
</tr>
<tr>
<td>347</td>
<td>VITO (Flemish Institute for Technological Research)</td>
<td>May – July 2013</td>
</tr>
<tr>
<td>351</td>
<td>VITO (Flemish Institute for Technological Research)</td>
<td>May – July 2013</td>
</tr>
<tr>
<td>432</td>
<td>VITO (Flemish Institute for Technological Research)</td>
<td>May – July 2013</td>
</tr>
<tr>
<td>571</td>
<td>VITO (Flemish Institute for Technological Research)</td>
<td>May – July 2013</td>
</tr>
<tr>
<td>577</td>
<td>VITO (Flemish Institute for Technological Research)</td>
<td>May – July 2013</td>
</tr>
<tr>
<td>581</td>
<td>VITO (Flemish Institute for Technological Research)</td>
<td>May – July 2013</td>
</tr>
</tbody>
</table>
The micro-aethalometers were available for use at different times, as detailed in Table 5-4. For the purposes of the work detailed in this section, the devices were not used simultaneously. However, issues of measurement consistency between devices are discussed in Section 5.7.

5.4.2 Initial data collection

A data collection campaign was undertaken to provide time-series micro-aethalometer data. The objectives were three-fold: firstly, to gain an initial overview of the type of data expected in environments relevant to this research; secondly, to classify errors and seek a systematic reason for their occurrence; and finally, to inform an assessment of techniques for providing a suitable dataset.

Three sites were selected to provide a range of urban situations relevant to investigations of a human exposure. They each represented three broad categories of environments: an urban intersection, a narrow urban street canyon and a main road bus stop. The sites are described in Table 5-5 and displayed in Figure 5-8.

Table 5-5: Initial data collection locations and aethalometers used for measurement.

<table>
<thead>
<tr>
<th>Site</th>
<th>Description</th>
<th>Micro-aethalometer used</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Praed Street urban street canyon</td>
<td>364</td>
</tr>
<tr>
<td>B</td>
<td>Eastbound bus stop on Cromwell Road (A4)</td>
<td>193</td>
</tr>
<tr>
<td>C</td>
<td>Intersection of Queen's Gate and Cromwell Road</td>
<td>364</td>
</tr>
</tbody>
</table>

Location A is Praed Street, an urban street canyon UK with annual average daily flows\(^{43}\) of approximately 5,500 vehicles. Due to the close proximity of London Paddington Station, a high proportion of the traffic on this link is made up of public transport buses and taxis. On-street surveys determined the proportion of buses to be around 30% and taxis of between 15% and 20%. Data collection took place on the north (eastbound) side of the road, at several locations extending 50m along the link from the westerly entry to the street canyon.

Location B is a bus stop on Cromwell Road, a major road in central London. The bus stop is located on the north (eastbound) side of the road, directly in front of the Victoria and Albert

\(^{43}\) DfT count point data for 2012, counter ID 37775
Museum, a popular tourist attraction. As such, there are substantial numbers of public transport buses, coaches and taxis in the vicinity. The road is four lanes at this point, with two lanes in either direction. Annual average daily flows are approximately 45,000 vehicles, with approximately 8% consisting of buses, coaches and heavy goods vehicles. There are several large deciduous trees nearby, which at the time of data collection were in full leaf.

Figure 5-8: Data collection locations (clockwise) A, B and C.

Location C is the intersection between Queen’s Gate and Cromwell Road, around 1km to the west of location A. The site is approximately 350m from Gloucester Road London

44 DfT count point data for 2012, counter ID 58164
Underground Station, forming part of a pedestrian route to the Natural History Museum, Royal Albert Hall and various other tourist attractions associated with the area. The intersection comprises four arms arranged approximately north-south and east-west. Each arm has a staggered, signalised pedestrian crossing with a pedestrian refuge mid-carriageway. The north east of the junction consists of a wildlife garden, with all other quadrants bordered by four and five story buildings.

It is not the intention of this analysis to examine the specific features of each location and their potential to impact levels of urban pollution and human exposure to pollution. However, there are broad characteristics of each that represent common situations in dense urban environments.

Location A is a narrow street canyon, with tall buildings on both sides restricting ventilation. As such, particulate pollutant levels may be higher than surrounding areas (Namdeo et al., 1999; Zhou and Levy, 2008). Location B is a bus stop, where the presence of large diesel buses decelerating, idling and accelerating would be expected to produce elevated emissions of particulates and NOX (Li et al., 2012). Location C is an urban intersection. Urban intersections, whilst well-ventilated, have been described as important for urban air quality due to the change in vehicle speed inducing higher emissions, and the mixing of air flows from adjacent links (see Section 2.3.4).

It is recognised that these sites do not provide an exhaustive account of all relevant situations to traffic induced pedestrian exposure.

5.4.3 Procedure

Data collection was carried out during May 2012. In addition to black carbon, observations were made regarding weather conditions and the general traffic situation. Regarding micro-aethalometer use, the inlet of the sample tube was kept at a height of around 1.5m, in line with practice seen in similar studies (Gulliver and Briggs, 2004; Hess et al., 2010; Kaur et al., 2005; Moore et al., 2012). Care was taken to ensure that the inlet was not obstructed, and orientation (towards the carriageway) was kept consistent.

Before each measurement campaign, the internal clock was synchronised with a PC through use of the manufacturer provided software.
Table 5-6: Data collection procedure for each site.

<table>
<thead>
<tr>
<th>Site</th>
<th>Timing</th>
<th>Procedure</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>7:30am – 10:00am Weekday</td>
<td>Continuous time-series consisting of 15-minute monitoring at four locations along a 50m stretch of road (extending from the entry point for traffic along the street canyon). Each location was 0.5m from the carriageway, with measurement sequence repeated. Background measurements in a nearby mews street were conducted before data collection.</td>
</tr>
<tr>
<td>B</td>
<td>10:00am – 12:00pm Weekday</td>
<td>Continuous time-series at a location approximately 3m away from the carriageway alongside the bus stop. Two aethalometers were used for a portion of the study. Background measurements were taken in a nearby mews street before data collection.</td>
</tr>
<tr>
<td>C</td>
<td>10:30am – 1:00pm Weekday</td>
<td>Continuous time-series consisting of 10-minute monitoring at 12 locations around the intersection at waiting points of each pedestrian crossing (four per crossing). Background measurements taken from nearby wildlife garden.</td>
</tr>
</tbody>
</table>

All data collection was carried out in May 2012.

5.4.4 Descriptive statistics

This section describes statistics computed for complete time-series data. The only post-processing carried out at this stage was concerned with limiting the data to the appropriate time period of the data collection.

Box plots of the data collected at each site are shown in Figure 5-9. Each site displays a different range of data, with maximum and minimum values more extreme at site A when compared to sites C and B respectively. In all cases it appears that there are a large number of outliers\(^45\), which may be a result of the potential for errors described in Section 5.3. Summary statistics are shown in Table 5-7.

\(^{45}\) Plots have been created using the MATLAB function boxplot. Outliers are defined as being more than 1.5 IQRs above the 75\(^{th}\) percentile or below the 25\(^{th}\) percentile. This equates to ±2.7\(\sigma\) and 99.3% coverage if the data follows a normal distribution.
Figure 5-9: Box plots of raw BC concentration measurements by site.

Table 5-7: Summary statistics for all sites.

<table>
<thead>
<tr>
<th></th>
<th>Site A</th>
<th>Site B</th>
<th>Site C</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>n</strong></td>
<td>7200</td>
<td>3300</td>
<td>7800</td>
</tr>
<tr>
<td><strong>Mean</strong></td>
<td>17.3</td>
<td>12.2</td>
<td>12.7</td>
</tr>
<tr>
<td><strong>Median</strong></td>
<td>13.2</td>
<td>11.0</td>
<td>9.4</td>
</tr>
<tr>
<td><strong>Standard deviation</strong></td>
<td>27.3</td>
<td>9.1</td>
<td>25.5</td>
</tr>
<tr>
<td><strong>Maximum</strong></td>
<td>1069.1</td>
<td>100.2</td>
<td>483.4</td>
</tr>
<tr>
<td><strong>Minimum</strong></td>
<td>-172.1</td>
<td>-41.5</td>
<td>-417.2</td>
</tr>
<tr>
<td><strong>Inter-quartile range</strong></td>
<td>18.9</td>
<td>9.7</td>
<td>16.5</td>
</tr>
<tr>
<td><strong>% negative values</strong></td>
<td>13.9%</td>
<td>3.3%</td>
<td>18.6%</td>
</tr>
<tr>
<td><strong>% outliers</strong></td>
<td>6.3%</td>
<td>3.9%</td>
<td>6.9%</td>
</tr>
</tbody>
</table>

Uncorrected data recorded at 1Hz, BC concentration measured in $\mu$g m$^{-3}$.

Negative values make up a significant portion of the data, ranging from 3.9% at site B to 18.6% at site C. A smaller proportion of data are considered outliers than are negative values. In addition, the median values are smaller than the mean in all cases, suggesting that the data are not normally distributed. However, conclusions regarding the nature of the statistical distribution cannot be made until data has been adequately treated to ensure confidence. Similarities between sites can be better seen by constraining the range of data, as shown in Figure 5-10.
From the summary statistics in Table 5-7, sites A and C exhibit greater variation than B. Whilst it is not the aim here to investigate the reasons for differences between sites, it should be noted that the data collection at site B was conducted approximately 3m away from the kerbside, whereas at sites A and C this was 0.5m, and in some cases, on mid-carriageway islands. This was chosen as the most likely waiting place for pedestrians, and as such provided the most relevant place for future concentration and exposure studies. As such, the measurement at site B was further away from the mobile sources expected to contribute to ambient levels of BC, potentially resulting in a lower measured concentration and less variability (as demonstrated by a lower IQR).

Background data were collected prior to each roadside data collection series. Background sites were chosen for the purposes of understanding a baseline away from (more) traffic-induced pollution. At sites A and B, background locations were nearby mews streets which are bordered by two-storey buildings and are not generally used by motorised traffic. At site C, the background site was a shielded part of the wildlife garden around 7m away from the kerbside. Table 5-8 compares summary statistics of the background sites with the main data collection episode.
Table 5-8: Site comparison showing roadside and background data.

<table>
<thead>
<tr>
<th>Location</th>
<th>Median</th>
<th>Mean</th>
<th>Standard deviation</th>
<th>% -ve</th>
<th>Noise</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site A</td>
<td>Background</td>
<td>2.6</td>
<td>2.4</td>
<td>8.4</td>
<td>37.9%</td>
</tr>
<tr>
<td></td>
<td>Roadside</td>
<td>13.2</td>
<td>17.3</td>
<td>27.3</td>
<td>13.9%</td>
</tr>
<tr>
<td>Site B</td>
<td>Background</td>
<td>3.3</td>
<td>3.3</td>
<td>11.0</td>
<td>23.0%</td>
</tr>
<tr>
<td></td>
<td>Roadside</td>
<td>11.0</td>
<td>12.2</td>
<td>9.1</td>
<td>3.3%</td>
</tr>
<tr>
<td>Site C</td>
<td>Background</td>
<td>3.0</td>
<td>3.1</td>
<td>15.2</td>
<td>42%</td>
</tr>
<tr>
<td></td>
<td>Roadside</td>
<td>9.4</td>
<td>12.7</td>
<td>25.5</td>
<td>18.6%</td>
</tr>
</tbody>
</table>

The background data displays a higher proportion of negative data, lower concentration (mean and median) and variability (standard deviation) in all cases. This is consistent with knowledge of aethalometer operation and expected due to the proximity of mobile sources. All units are in $\mu gm^{-3}$.

As expected, mean and median values are lower at background sites. In addition the standard deviation is lower. Median and mean values are also closer in value at the background sites. This suggests that these data more closely approximates to a normal distribution than those at the main data collection site. Negative values are much more common at background sites, making up as much as 42% of the data. This is consistent with work by Hagler et al (2011) the lower change in the attenuation of light results in ATN signal noise at low concentrations of BC (discussed in Section 5.3.1). However, there does not appear to be any systematic variation in the value of BC concentration noise at any of the locations.

Figure 5-11 shows a normal probability plot for the observed data against corresponding normal scores. A normal distribution will approximate to a straight line. The assumption of normality appears more credible for background data when compared to the main site. Positively skewed data are largely expected for air pollution measurements. This results from the low-occurrence of high-magnitude pollution events. This is also expected when considered with knowledge of the transient power demands (and resulting emissions profiles) of mobile sources (for example, as in Chapter 3) and with studies into personal exposure (such as Wang et al, 2011).

These data demonstrate the problem of using arithmetic mean average values that are not representative. This is true for both emissions produced by mobile sources and poor air quality as experienced by receptors.
Data for the background site more closely approximates a normal distribution, with the roadside data collection showing an “S” shape, indicating the distribution is skewed.

A test for normality is completed using the one-sample Kolmogorov-Smirnov test\textsuperscript{46}. The procedure tests the null hypothesis ($H_0$) that the data are drawn from a normal distribution, against the alternate hypothesis ($H_1$) that they are not. The null hypothesis is rejected for all sites, at both roadside and background locations. Once again, the underlying distribution should be further assessed after treatment of erroneous values.

5.4.5 Time-series data

The time-series of data at each site is also of interest. Figure 5-12 shows a time-series of BC concentration at all three sites. The time-series presents the range of data seen at each site including the occurrence of negative values and extreme positive values. Some of these values extend beyond the specified measurement range of the instrument (Table 5-1) and so may be immediately considered erroneous.

\textsuperscript{46} Computed using the MATLAB function \texttt{kstest}
Figure 5-12: Time-series of BC concentration at all sites.

Measured at 1Hz. Data are presented without any smoothing or error correction applied. Peaks, extreme values and impossible negative concentrations are evident.

Also apparent are the occurrence of extreme positive values that exist within the instrument measurement range, and negative values as previously discussed. All sites appear to show periodic peak episodes – aside from the extreme positive values – alongside the base level of black carbon.

The time-series of background data (Figure 5-13) exhibits oscillation in a smaller range, with a high proportion of values being negative. Unlike the roadside time-series (Figure 5-12) periodic peak events are less apparent. This is expected in background locations due to the lack of proximity to mobile source emissions.
Figure 5-13: Time-series of BC concentration at all background sites.

Measured at 1Hz. Data are presented without any smoothing or error correction. Negative values associated with low concentration are clearly present, as is apparent noise due to the low signal-to-noise ratio.

The data presented in Figure 5-12 were captured for the periods of 7200, 3200 and 7800 seconds respectively. Given that the objective is to understand performance of a much higher time resolution, Figure 5-14 shows a subset of these data for each. A period of 5-minutes (300 data points) is chosen at random. This time frame is in keeping with the time-base used in many of the aethalometer studies referenced in Section 5.3, and so provides further scrutiny of preceding work in this area.

As expected, background data has more frequent negative values due to the low levels of BC concentration and the small change in ATN (the signal to noise ratio is lower). The main data collection sites exhibit peak events contained within the time period, further demonstrating that a 5-minute time-base is not a sufficient measurement resolution.
Examples of this are apparent at locations A and B (t ~ 150 in both) in Figure 5-14. A five-minute average would not capture the significance of this event for pedestrian exposure.

*Figure 5-14: 5-minutes of data at each location, roadside and background.*

Measurements at the background sites appear much noisier (lower signal-to-noise ratio), with more frequent instances of negative values but a smaller data range overall. Note the different subplot y-axis scales used to enhance visibility of key features.

Site C shows a high magnitude peak event following a negative value. This is consistent with knowledge of aethalometer operation; an erroneous measurement of decreasing ATN leads to an incorrectly high ΔATN in subsequent time-steps, and a high value of BC concentration.
is reported. The time-series data demonstrates that whilst it is the case that some of these peaks may be due to instrument error, it is also likely that by taking an average value, some of the dynamic variability at the site is not recognised.

In order to better understand the frequency of errors and instrument noise, multiple continuous, random 5-minute samples were generated for each site from the time-series data. In generating 100 samples for each time-series, there is overlap between the data. Therefore, the data cannot be presented as a time-series. For each 5-minute sample, the mean, median and standard deviation (SD) were computed. In addition, the numbers of negative values were counted and noise was calculated as described in Section 5.3.1. Figure 5-15 shows the relationship between the potential explanators of BC mean, median and standard deviation, and the count of negative values and noise. From a visual inspection, there is little evidence of a linear relationship between these metrics.

*Figure 5-15: Plots showing the relationship between hypothesised dependent and explanatory variables.*
5.4.6 Time-base comparison

Inspection of the data in the previous section indicated that a 5-minute resolution is insufficient in understanding BC concentration at a site. This is further explored through comparison of different averaging periods. Figure 5-16 shows that whilst longer averaging periods reduce the occurrence of negative and extreme values, some variation inherent to the concentration trend may be lost.

Figure 5-16: Demonstration of different averaging periods for black carbon data, site A.

Although smoothing in this fashion removes negative values and reduces noise, there also appears to be a loss of granularity when considering the inherent variability present in pollution data.

Table 5-9 shows the reduction in noise and the occurrence of negative values on application of different averaging periods to the (raw) 1Hz data. In all cases noise is reduced and negative values are eliminated.

Working towards optimising metrics such as noise and the percentage of negative values is potentially contrary to the aims of urban pollution measurement. The improvements show in Table 5-9 at the expense of misrepresenting the dynamic variability in BC concentration, as demonstrated in Figure 5-16.
Table 5-9: Reduction of noise and occurrence of negative values by averaging period.

<table>
<thead>
<tr>
<th>Location, averaging period</th>
<th>Noise (µg m(^{-3}))</th>
<th>% -ve</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Original (1s)</td>
<td>13.60</td>
<td>13.9%</td>
</tr>
<tr>
<td>1-minute</td>
<td>9.65</td>
<td>0%</td>
</tr>
<tr>
<td>5-minute</td>
<td>5.30</td>
<td>0%</td>
</tr>
<tr>
<td>Site B</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Original (1s)</td>
<td>5.46</td>
<td>3.3%</td>
</tr>
<tr>
<td>1-minute</td>
<td>4.27</td>
<td>0%</td>
</tr>
<tr>
<td>5-minute</td>
<td>3.65</td>
<td>0%</td>
</tr>
<tr>
<td>Site C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Original (1s)</td>
<td>15.88</td>
<td>18.6%</td>
</tr>
<tr>
<td>1-minute</td>
<td>7.03</td>
<td>0%</td>
</tr>
<tr>
<td>5-minute</td>
<td>5.67</td>
<td>0%</td>
</tr>
</tbody>
</table>

5.4.7 BC data summary

Initial data collection at three urban sites relevant to the research questions in this thesis has demonstrated the occurrence of problems previously discussed in the literature and summarised in Section 5.3.

Negative values, noise and outliers are all identified by descriptive statistics and time-series analysis. The use of averaging periods is disputed for two reasons. Firstly, averaging over longer periods does not sufficiently capture the dynamic variability of black carbon concentration. Secondly, it is expected the data are not normally distributed, and therefore, the arithmetic mean is not an appropriate metric for the time periods often used. Whilst the problems of instrument noise and negative values have been demonstrated, less clear are the effects of aerosol loading in underestimating BC concentration.

In order to retain the variation and mitigate measurement errors, instrument noise (Section 5.5) and aerosol loading (Section 5.6) are investigated further in this chapter.
5.5 ONA performance

Section 5.3.1 discussed the ONA method of variable time-averaging, as described in Hagler et al (2011). The algorithm creates varying time-averaging windows based upon a minimum change in ATN (ΔATN_{min}). The default setting for this is positive 0.05, determined empirically as the optimum trade-off between maintaining a high time resolution and reducing noise (Hagler et al, 2011).

The time period for averaging, t₀ → t₁, must be sufficient so that the change in the attenuation of light (ΔATN) exceeds the minimum specified in the algorithm (ΔATN_{min}), ignoring erroneous negative values of ΔATN.

\[ \text{ATN}_{t_1} - \text{ATN}_{t_0} \geq \Delta \text{ATN}_{\text{min}} \]  

*Equation 5-7*

Once this criterion is satisfied, BC is averaged over the time period. The relative value of ATN is then reset, and the next value that satisfies the criteria in Equation 5-7 is sought.

The previous section demonstrated that straightforward processing techniques, such as time-averaging, correct errors at the expense of losing the peak events present. By using the value of ATN, the ONA method is tailored to specifically address the cause of aethalometer measurement error. However, before this technique can be properly employed, the performance against relevant data should be assessed.

5.5.1 High-level performance

The performance of this algorithm is assessed against the different time-series data collected at the three urban sites. Data were processed using the ONA at the default ΔATN_{min} = 0.05. Table 5-10 shows the results for application of the ONA at all three sites. Noise and negative values are reduced in all cases, consistent with the results of Hagler et al (2011).

The noise statistic reported here is potentially misleading. As the data output is still in the form of 1Hz data, many of the successive time-steps are identical numbers (as many as 97 consecutively). In this case, noise is zero. Figure 5-17 shows histograms of the resulting averaging periods from ONA application to all three sites. Whilst there is a wide range, median values are around a resolution of 20s. This is evidence of the similar conditions, and therefore, similar underlying trends in BC concentration experienced at all three sites.
Table 5-10: Performance of the ONA technique on the three datasets.

<table>
<thead>
<tr>
<th>Location</th>
<th>Time-base</th>
<th>Averaging window range</th>
<th>Noise original ($\mu$g m$^{-3}$)</th>
<th>Noise ONA ($\mu$g m$^{-3}$)</th>
<th>% -ve original</th>
<th>% -ve ONA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site A street canyon</td>
<td>1s</td>
<td>1s – 67s</td>
<td>13.60</td>
<td>0.14</td>
<td>13.9%</td>
<td>0%</td>
</tr>
<tr>
<td>Site B bus stop</td>
<td>1s</td>
<td>3s – 46s</td>
<td>5.46</td>
<td>0.29</td>
<td>3.3%</td>
<td>0%</td>
</tr>
<tr>
<td>Site C intersection</td>
<td>1s</td>
<td>1s – 97s</td>
<td>15.88</td>
<td>0.80</td>
<td>18.6%</td>
<td>0%</td>
</tr>
</tbody>
</table>

Noise and negative values reduce substantially ($\Delta ATNmin = 0.05$).

Figure 5-17: Histogram of averaging periods on application of the ONA, by site.

Despite a sometimes wide range of averaging periods utilised, median values are around 20 in each case.
5.5.2 ATN reporting

The ONA algorithm works on the principle that the attenuation of light must change by a minimum amount. If the ATN does not change sufficiently, there is insufficient evidence to conclude that there is a deviation from the underlying trend of black carbon concentration. Scrutiny of the measured ATN can help explain the methodology applied and the results. Figure 5-18 shows the BC concentration (raw, untreated) and ATN (from a base of zero) for a random 30-second period at site A.

*Figure 5-18: Example of BC concentration and ATN change in a highly variable setting.*

ATN is set to zero at the start of the period to give ΔATN from a common base.
The BC trace (top panel) appears dynamic, with rising BC and a peak between 5 and 10-seconds, followed by a return to ~60μg m⁻³. The second panel shows change in ATN from a base of zero. The gradient is highest as BC increase the greatest, and the resulting change in ATN over the entire 30-second period is around 0.5. This would result in a maximum of 10 distinct data points if using the ONA procedure with ΔATN_min equal to +0.05. This is contrasted against changing BC concentration in a less variable setting in Figure 5-19.

*Figure 5-19: Example of BC concentration and ATN change in a less variable setting.*

ATN is set to zero at the start of the 30-second period to give ΔATN from a common base.

---

Maximum is referred to as the reported resolution cannot exceed the 1Hz input resolution, even if the change in ATN between successive time-steps is equal to double (or more) ΔATN_min.
Again this shows a 30-second sample from site A. In this case the measured ATN does not change greatly, only just reaching the minimum change for averaging (0.05) over the entire time period. At around 14-seconds, there is an instance of measured ATN decreasing. This is implausible, and so is an example of instrument noise at low BC concentration. The presence of noise in measuring ATN further demonstrates the need to choose an appropriate smoothing technique for the data. A further example is around extreme positive values, as illustrated by a 30-second sample of data at site C (Figure 5-20). In this case the extreme positive values are also associated with extreme negative values.

*Figure 5-20: Example of BC concentration and ATN change (site C).*

*ATN is set to zero at the start of the 30-second period to give ΔATN from a common base.*
Consideration of the ATN time-series shows a relatively large decrease in ATN, which causes a large negative value of BC concentration. As this decrease in ATN is implausible, it's considered an error. As the device recovers, there is an apparent large increase in ATN, leading to a high value of BC concentration. This can also be considered erroneous, as the true change in ATN is not being reflected. These examples justify the use of ONA. The impact of running the algorithm, with $\Delta ATN_{\text{min}}$ equal to 0.05, can be seen in Figure 5-21.

Figure 5-21: Treatment of highly and less variable samples with the ONA procedure.
The top panel shows that the peak event has been captured, including the magnitude and position in the time-series. The bottom panel shows the less variable example, with a constant, low concentration reported due to the lack of change in ATN. Apparent noise is reduced and there are no negative values present.

Figure 5-22 displays the impact of applying the algorithm on the raw BC measurement. The true change in ATN is captured through use of an averaging period, in this case removing the extreme negative and positive values reported in error.

*Figure 5-22: Application of ONA to deal with errors.*

![Graph showing BC concentration over time comparing BC ONA and BC original]  
*Extreme positive and negative values are removed, reflecting a more realistic increase in ATN.*

Reporting of ATN to two decimal places has the effect of quantizing the time-series. Due to the change between successive time-steps, it is clear from Figure 5-18, Figure 5-19, and Figure 5-20 that BC concentration is initially estimated from a time-series of ATN with greater precision. This is limiting in that any attempt to use reported ATN to estimate BC (rather than simply define an averaging period) results in a loss of measurement precision.

### 5.5.3 Summary of ONA performance

Application of the ONA method with the default (empirically defined) $\Delta ATN_{\text{min}}$ was initially shown to be successful in reducing noise and the occurrence of negative values. Subsequent scrutiny of particular error types has demonstrated the robustness of the ONA in reproducing the dynamic variability of the data. In some cases, the averaging period was shown to be longer that that required for work in the area of pedestrian exposure (Chapter 4).
However, scrutiny of the time-series indicates that peak events are properly captured. When the minimum change in ATN threshold is not met, the underlying trend is continued. The assumption that the change in ATN is sufficiently low that there is no BC event to record means that reporting the underlying trend is a suitable approach, and that the resulting data can be treated as high time resolution. In all cases, the success of this algorithm is predicated on $\Delta$ATN relating to a real event only when it exceeds $\Delta$ATN$_{\text{min}}$. Whilst the value of $\Delta$ATN$_{\text{min}}$ is empirically defined and shown to be appropriate, it has not been determined to be optimum. This and other potential investigations into the use of aethalometers are discussed in Section 8.2.

## 5.6 Aerosol loading

Section 5.3 introduced the impact of aerosol loading on BC measurement with micro-aethalometers. The aethalometer is based on the empirical, linear relationship between increasing black carbon concentration and increasing attenuation of light (ATN). Gundel et al (1984) showed that for high levels of BC, this relationship was no longer linear. This has been described as a second-order effect (Hansen et al 2007), as freshly deposited particles are shadowed by those already on the filter. As this does not result in an increase in ATN, estimated levels of BC may be lower than actual.

### 5.6.1 Magnitude of loading effects

It has been shown that BC concentration is underestimated with increasing ATN value (Cheng and Lin, 2013; Weingartner et al, 2003), with various correction algorithms having been developed (some of which are discussed in Section 5.3.1).

Park et al (2010) demonstrated the application of loading correction factors for different urban sites. Figure 5-23 shows some of the results from Park et al (2010), where average black carbon is calculated for each 2-ATN bin$^{48}$. This study did not conduct roadside measurements$^{49}$ but is relevant due to the application in urban areas. They showed a decrease in reported BC for successive ATN bins.

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$^{48}$ Black carbon concentration is binned by ATN – 0-2, 2-4 etc and bin-average BC is calculated.

$^{49}$ This study used an urban site on the rooftop of a three-story building around 100m from a busy road; a different model of aethalometer was used, although of the same measurement wavelength.
Figure 5-23: Variability in deviation between measured BC concentrations with increasing ATN value (from Park et al, 2010).

The data demonstrates that aethalometer performance worsens with increasing ATN. Image reproduced with permission of the rights holder, Elsevier.

Cheng and Lin (2013) stated that the deviation from true BC concentration could be as much as 15% when ATN reached around 40. The extent to which filter loading can be considered a problem for the data collection in Section 5.4 can be seen from Table 5-11.

Table 5-11: ATN values achieved during data collection at each urban site.

<table>
<thead>
<tr>
<th>Location</th>
<th>n (at 1Hz)</th>
<th>ATN-ATN₀</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site A – street canyon</td>
<td>7200</td>
<td>36.1</td>
</tr>
<tr>
<td>Site B – bus stop</td>
<td>3300</td>
<td>11.6</td>
</tr>
<tr>
<td>Site C – intersection</td>
<td>7800</td>
<td>28.8</td>
</tr>
</tbody>
</table>

A maximum was achieved at the street canyon location (2-hours monitoring).

ATN levels reached 36 during data collection at the street canyon. Comparing this to the results of Park et al, (2010) in Figure 5-23, this would represent a reduction of between 10

\[ \text{ΔATN} = \text{ATN} - \text{ATN₀} \]

50 Described as the difference between current and starting ATN, ATN-ATN₀; ΔATN is the change between successive time-steps
and 15% in BC reporting. Therefore, there is at least potential for filter loading to affect BC measurement when using aethalometers in urban areas.

5.6.2 Determining the impact of aerosol loading

A common way of demonstrating the impact of filter loading is to compare aethalometer-measured BC to a reference source (such as in Gundel et al, 1984, and Virkkula et al, 2007). For the purposes of this experiment, the reference used is ultrafine particles (PM$_{0.1}$ or UFP). Ultrafine particles are the fraction of particulate matter less than 100 nanometres in diameter. Like BC, UFPs are strongly associated with diesel exhaust emissions in urban environments, and therefore, a linear correlation between the two is expected.

Measurement of UFPs and BC was conducted concurrently at site A, the street canyon at Praed Street, London. UFPs were measured through the use of a Philips Aerasense Nanotracer. This device detects particles of between 10 and 300nm in diameter at a 5-second resolution, reporting a particle concentration (np/cm$^3$). Of importance is that this device does not rely on optical measurement$^{51}$, and is therefore, not subject to the same second-order effects as the aethalometer.

Data was averaged over a 5-minute period prior to comparison. This was done to minimise instrument noise which may impact both devices, without resorting to a variable time-window that may make comparison difficult. Whilst a 5-minute average has been criticised in this thesis, the purpose of these measurements is to understand the potential for loading effects. Therefore, it is important to establish a resolution that provides an initial good degree of association with the reference measurement. It is recognised that this would not be appropriate for assessing the variability of BC concentration in relation to pedestrian activity.

Figure 5-24 shows the agreement between UFP and BC. The two instruments show a high degree of association, with a correlation coefficient of 0.88. Also shown in Figure 5-24 is a plot of model residuals (measured BC minus predicted BC) against the predictor variable (UFP). The dispersal of the model residuals suggests that UFP is a suitable linear predictor of BC concentration.

$^{51}$ The Nanotracer measures particle number through diffusion charging. This involves mixing the aerosol particles with unipolar ions, which attach to the particles by diffusion. After removal of excess ions, the resulting charge is measured and related to particle number and particle diameter.
The two variables show a high degree of association, with a correlation coefficient \((r^2)\) of 0.88. A plot of model residuals against the predictor variable of UFP does not show any systematic bias.

The effects of loading are assessed through consideration of how well UFP predicts aethalometer-measured BC with increasing ATN. Filter loading effects result in underestimation of the concentration of BC. Therefore, the expectation is that the predicted value, as determined by UFP measurement, should be greater, with model residuals being negative. Figure 5-25 shows a plot of model residuals against increasing values of ATN.
Figure 5-25: Plot of model residuals against increasing ATN.

Residuals seem to be randomly distributed up to approximately 30 ATN, after which there may be a systematic variation.

In the first portion of Figure 5-25 (ATN between 0 and 20), the deviation between predicted and observed BC concentration does not appear to be systematically related to ATN. However, after this point (ATN greater than 20) residuals are concentrated in the negative portion of the x-axis.

Assuming the UFP is an unbiased linear predictor of BC, this is evidence that the micro-aethalometer is systematically underestimating black carbon concentration at high ATN. This is consistent with other research, such as that by Park et al (2010).

This evidence is limited, as there is no reason to conclude that increasing ATN beyond this point causes a proportional underestimation of BC. In addition, filter loading effects do not occur until a certain level of ATN has been reached. Given this, a linear correction (such as that proposed by Virkkula et al, 2007) may not be appropriate.
5.6.3 Instrument specific loading effects

A further measurement campaign was conducted to determine the practical effects of loading on the measurements of specific aethalometers when deployed in an urban environment. The investigation was conducted in three phases. Firstly, the instruments were co-located in an urban setting. Secondly, the devices were subject to differing levels of black carbon to induce different levels of filter loading. Finally, the devices were co-located.

Table 5-12 summarises the change in ATN for each investigatory phase. The change in ATN (ΔATN) is largely equivalent for the first co-location, with a difference of only 0.3%. However, during the second co-location there is a difference of around 3% (compared to the lower bound). The device that had been subject to higher levels of BC (unit 432) reported lower levels of concentration during the second co-location.

This result is expected due to the mechanism of filter loading already discussed. However, the extent to which this negatively impacts the assessment of BC concentration at a specific location is still to be established.

Table 5-12: Change in ATN by experimental phase.

<table>
<thead>
<tr>
<th>Phase</th>
<th>Unit</th>
<th>Starting ATN</th>
<th>Finishing ATN</th>
<th>ΔATN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase 1</td>
<td>Unit 432</td>
<td>0</td>
<td>6.91</td>
<td>6.91</td>
</tr>
<tr>
<td>Co-location</td>
<td>Unit 571</td>
<td>0</td>
<td>6.93</td>
<td>6.93</td>
</tr>
<tr>
<td>Phase 2</td>
<td>Unit 432</td>
<td>6.91</td>
<td>26.89</td>
<td>19.98</td>
</tr>
<tr>
<td>Separation</td>
<td>Unit 571</td>
<td>6.93</td>
<td>20.10</td>
<td>13.17</td>
</tr>
<tr>
<td>Phase 3</td>
<td>Unit 432</td>
<td>26.89</td>
<td>30.21</td>
<td>3.32</td>
</tr>
<tr>
<td>Co-location</td>
<td>Unit 571</td>
<td>20.10</td>
<td>23.51</td>
<td>3.41</td>
</tr>
</tbody>
</table>

Figure 5-26 shows 1-minute averages for black carbon concentration from each device. The figure is also split by investigatory stage. It should be noted that the data have not been treated with the ONA or any smoothing algorithm. Instead, 1-minute averages have been used in an effort to reduce measurement noise.

The time-series trend does not show degradation in the association between the two devices as a result of the additional filter loading on unit 432.
Figure 5-26: Time-series of 1-minute average black carbon data for phase 1 and phase 3 co-location periods.

Figure 5-27 shows the linear association between the two devices for both co-location phases. Whilst correlation is not perfect (especially considering the data are also affected by noise not related to filter loading, as discussed earlier in this chapter), an $R^2$ of 0.99 is computed for both.

Having determined a linear fit is appropriate a comparison of the estimated parameter associated with the x variable should indicate whether there is degradation in the agreement between the units as a result of filter loading. A value of 1.0 (with a constant of 0) would indicate a perfect association. This is seen to increase from 1.04 to 1.06, suggesting that black carbon may be underestimated by as much as 2% as a result of filter loading.
There is insufficient evidence to conclude that there is significant degradation in agreement between the units as a result of filter loading for this experiment.

5.6.4 Summary of aerosol loading effects

Comparison against a reference data source suggests that, above a certain level of ATN (~20), the micro-aethalometer underestimates concentration of black carbon. However, whilst there is evidence that this underestimation is proportional to increasing ATN, it cannot be concluded that this will impact the results of this experiment. This, along with a limited dataset, does not allow for the estimation of a linear (or other) correction. Comparison of two units exposed to different levels of BC does provide sufficient evidence that filter loading could introduce bias into experiments of spatial variability.

Based on the results presented in Section 5.6.2, the risks of loading effects can be negated by avoiding higher levels of ATN. As such, best-practice of changing filter tickets regularly should be implemented. In general, it is important to assess the potential for filter loading effects in all aethalometer data by considering the maximum ATN value obtained. The potential for underestimation of BC can then be assessed on a site-by-site basis.

It has also been shown that there is a lack of evidence for a linear correction to be applied. Due to a lack of data, no alternate correction has been presented. Further efforts to address this are discussed in Section 8.2.
5.7 Measurement consistency

The analysis detailed so far addresses problems of instrument noise and filter loading effects for a single instrument. The focus has been on obtaining a sufficient temporal resolution to understand the variability in pollution and exposure as discussed in Chapter 4.

Previous work in this thesis also discussed the potential for pollution to vary in space. As such, any effort to properly characterise spatial variability in black carbon pollution would require deployment of multiple monitoring devices. Prior to such an experiment, the performance of multiple micro-aethalometers must be evaluated to ensure consistency between measurement nodes.

5.7.1 Sensor co-location

A short experiment was undertaken to determine the agreement between different measurement nodes. All micro-aethalometers available were co-located at a roadside site in the South Kensington area of London, UK (referred to as site C in Section 5.4). The devices were arranged such that inlet pipes were as close as practicable, and then placed on a telecommunications cabinet, approximately 1m high and 3m from traffic (Figure 5-28).

*Figure 5-28: Co-location of micro-aethalometers at a roadside site.*

*Co-location was at a telecommunications cabinet, approximately 1m high and 3m from the roadside.*
Prior to detailed analysis, all data were treated with the post-processing algorithm (ONA) described in Section 5.5.

5.7.2 Initial results

The time-series for each sensor consists of 3114 data points, equivalent to more than 50 minutes of continuous monitoring. As discussed in Section 5.5, the data are reported and treated as 1Hz after processing. This is justified as longer averaging periods are a reflection of the lack of change in ATN, and as such the underlying trend of BC concentration.

Table 5-13 shows descriptive statistics for each sensor. The mean, standard deviation, median and interquartile range are computed with the last two considered better measures of central tendency and variability as the data has been shown to be skewed in Section 5.4.

Table 5-13: Descriptive statistics for sensor co-location (BC concentration, µgm$^{-3}$).

<table>
<thead>
<tr>
<th>Unit</th>
<th>Mean</th>
<th>Median</th>
<th>SD</th>
<th>IQR</th>
</tr>
</thead>
<tbody>
<tr>
<td>U347</td>
<td>15.60</td>
<td>11.11</td>
<td>14.71</td>
<td>11.28</td>
</tr>
<tr>
<td>U351</td>
<td>15.90</td>
<td>11.52</td>
<td>14.13</td>
<td>10.26</td>
</tr>
<tr>
<td>U432</td>
<td>15.54</td>
<td>11.19</td>
<td>14.04</td>
<td>9.62</td>
</tr>
<tr>
<td>U571</td>
<td>16.30</td>
<td>12.12</td>
<td>14.61</td>
<td>9.84</td>
</tr>
<tr>
<td>U574</td>
<td>14.94</td>
<td>10.84</td>
<td>13.36</td>
<td>10.11</td>
</tr>
<tr>
<td>U577</td>
<td>16.02</td>
<td>11.37</td>
<td>14.62</td>
<td>10.46</td>
</tr>
<tr>
<td>U581</td>
<td>14.80</td>
<td>10.76</td>
<td>13.23</td>
<td>9.29</td>
</tr>
<tr>
<td>U670</td>
<td>15.53</td>
<td>11.45</td>
<td>13.99</td>
<td>9.14</td>
</tr>
</tbody>
</table>

An immediate result is that the devices do not report the same values of black carbon concentration. The median values are approximately 13% greater in the highest-reporting micro-aethalometer when compared to the lowest-reporting. The highest IQR is more than 20% greater than the lowest, although there does not appear to be a systematic relationship between these two variables.

Inconsistency in measurement can also be seen when considering box plots, of both the full data (Figure 5-29) and a constrained range (Figure 5-30). The data are distributed in a similar manner across all devices, with a low occurrence of high magnitude values indicating a positive skew.
Whilst some signal noise is still expected, if a unit is consistently under- or over-representing black carbon concentration (relative to the ‘truth’), it suggests a static offset. This offset could occur in two dimensions. First of all, a device may continually over or underestimate concentration. In the case of measured pollution concentration over time, this is an offset in the y-dimension, as shown in Figure 5-31. Secondly, there may be a time-lag in
measurement (caused by differences in instrument response time or a lack of synchronisation), causing an x-dimension offset (Figure 5-32).

*Figure 5-31: Example of an offset in the y-dimension.*

These examples of inconsistency in measurement do not vary in time. It is also possible that either of these offsets is not static. It is also possibly that any differences between devices changes over time (i.e. drift).

*Figure 5-32: Example of an offset in the x-dimension.*
As no reference data are available, a hypothetical truth is established by taking the average measurement for a given point in time. This provides a basis for the determination of the quality of a given device. The difference between the average value (assumed truth) and reported concentration of each unit was calculated for the entire time-series. Figure 5-33 displays this for unit 571 and unit 581. These units are shown as examples as they have the highest and lowest median reported values respectively.

There is no evidence for a consistent concentration offset (i.e. on the y-axis). The presence of a large under-reporting of one unit, followed by a large over-reporting of another unit (such as at time is approximately 300s) may be evidence of an offset in the x-dimension (i.e., where one sensor lags the other). It should be re-iterated that a negative value in Figure 5-33 merely indicates the unit is reporting less than the average of all units, as negative values of BC are eliminated upon use of ONA.

*Figure 5-33: Time-series of the difference between unit reported BC concentration and the average across all devices.*

Plotting a portion of the BC time-series, such as is shown in Figure 5-34, yields evidence of both a time and concentration offset between devices. Unit 581 reaches a peak earlier (~t=312) and has a higher maximum value than unit 571. However, this y-dimension offset is not shown to be consistent, as shown in Figure 5-35.
Figure 5-34: Time-series BC concentration for unit 571, unit 581 and the 8-unit average.

Figure 5-35: Time-series BC concentration (unit 571, unit 581 and the 8-unit average).
Consideration of all data shows that while all units detect the peak event, the exact magnitude and time of occurrence (according to the on-board time stamp) differs. Although a limited sample of the time-series, the data displayed in Figure 5-36 shows that the inconsistency in concentration is smaller (in absolute terms) at lower levels of BC.

*Figure 5-36: Time-series BC concentration of individual devices and the 8-unit average.*

5.7.3 Correlation between units

Pearson’s product-moment correlation coefficient (denoted by $r$) is a useful estimator of the linear association between two variables. Computing $r$ for the linear relationship between all units\[52\] yields a matrix of values. The correlation coefficient is a measure of the strength of the linear association, and therefore, does not account for the absolute magnitude of each variable. In addition, there is no distinction between dependent and independent variables. Table 5-14 displays the matrix of $r$ across all devices.

---

\[52\] Pearson’s product-moment correlation coefficient was estimated using the MATLAB function `corr`. 
Table 5-14: Matrix of unit correlation (Pearson’s product-moment correlation coefficient).

<table>
<thead>
<tr>
<th>Unit</th>
<th>347</th>
<th>351</th>
<th>432</th>
<th>571</th>
<th>574</th>
<th>577</th>
<th>581</th>
<th>670</th>
</tr>
</thead>
<tbody>
<tr>
<td>347</td>
<td>1.00</td>
<td>0.79</td>
<td>0.83</td>
<td>0.84</td>
<td>0.80</td>
<td>0.83</td>
<td>0.81</td>
<td>0.81</td>
</tr>
<tr>
<td>351</td>
<td>0.79</td>
<td>1.00</td>
<td>0.89</td>
<td>0.89</td>
<td>0.90</td>
<td>0.84</td>
<td>0.87</td>
<td>0.89</td>
</tr>
<tr>
<td>432</td>
<td>0.83</td>
<td>0.89</td>
<td>1.00</td>
<td>0.91</td>
<td>0.87</td>
<td>0.88</td>
<td>0.89</td>
<td>0.89</td>
</tr>
<tr>
<td>571</td>
<td>0.84</td>
<td>0.89</td>
<td>0.91</td>
<td>1.00</td>
<td>0.88</td>
<td>0.92</td>
<td>0.88</td>
<td>0.88</td>
</tr>
<tr>
<td>574</td>
<td>0.80</td>
<td>0.90</td>
<td>0.87</td>
<td>0.88</td>
<td>1.00</td>
<td>0.83</td>
<td>0.90</td>
<td>0.92</td>
</tr>
<tr>
<td>577</td>
<td>0.83</td>
<td>0.84</td>
<td>0.88</td>
<td>0.92</td>
<td>0.83</td>
<td>1.00</td>
<td>0.85</td>
<td>0.85</td>
</tr>
<tr>
<td>581</td>
<td>0.81</td>
<td>0.87</td>
<td>0.89</td>
<td>0.88</td>
<td>0.90</td>
<td>0.85</td>
<td>1.00</td>
<td>0.91</td>
</tr>
<tr>
<td>670</td>
<td>0.81</td>
<td>0.89</td>
<td>0.89</td>
<td>0.88</td>
<td>0.92</td>
<td>0.85</td>
<td>0.91</td>
<td>1.00</td>
</tr>
</tbody>
</table>

The smallest value of $r$ reported is between units 347 and 351. A portion of the time-series (for consistency, the same portion used in Figure 5-34 and Figure 5-36) is shown in Figure 5-37. In terms of time-offset, unit 351 appears to report peak events several seconds earlier than unit 347.

Figure 5-37: Time-series of BC concentration data for unit 347 and unit 351.
From Figure 5-37, there is no evidence of a constant inconsistency in measured BC. This is evidenced from the underlying BC trend; at around $t \sim 305$, unit 351 reports a higher level of BC, whereas at $t \sim 325$, unit 347 reports higher.

5.7.4 Data smoothing

Figure 5-36 suggests that all devices recognise and report peak events. Since the occurrence of these has been determined to be essential for the assessment of pedestrian exposure, this is a welcome and necessary result. However, the magnitude and location of these events in the time-series is not consistent between devices. No evidence of a simple offset between devices has been identified. In order to make an accurate assessment of spatial variability in BC concentration, ensuring all devices are measuring the same physical phenomena is essential.

A possibly course of action in addressing the inconsistency between devices is to report BC as a discrete measurement value. This would be according to a nominal or ordinal scale, for example peak event or no peak event. This is an alternative to the current presentation as a continuous variable. An assessment of this kind would result in a loss of precision, as the relative magnitudes between peak events is an important potential result.

In order to deal with inconsistencies between measurement devices, a moving average filter can be applied to the data. In some ways this is analogous to the ONA method previously described. However, the algorithm was related directly to instrument operation, meaning that the data returned could still be treated as being of 1Hz resolution. In this case, the smoothing is related only to time, and so the returned value is of a more coarse time resolution than the input data.

In the context of urban pollution measurement, the process assumes that the actual BC concentration at time $t$ is a function of both BC concentration reported at time $t$, and of those data points for a given range before and after. For a 3-second range, this consists of the data point at time $t$, the data point at $t-1$ and the data point at $t+1$. In this case, no weighting has been applied, and the result is the arithmetic mean of all data points.

Figure 5-38 shows the time-series data for three types of smoothed data. The time-series of the smoothed unit data appears more similar with a larger smoothing time window. However, there is also an apparent loss of detail regarding the occurrence of peak events.
Figure 5-38: Average data (true value) compared to smoothed data of various ranges.

Determining an optimum smoothing time span is linked to the measurement of interest (BC concentration), the potential explanators (for example, traffic state) and other inputs to dependents (for example, pedestrian waiting times for the purposes of assessing exposure). Figure 5-39 shows the improvement in correlation (Pearson’s correlation, averaged over all time-series relationships as per Table 5-14) with increasing smoothing window. The largest improvements are seen in the initial increases in smoothing window size, with less improvement as the average correlation coefficient approaches unity.
Based on Figure 5-38 and Figure 5-39, a smoothing window of 5-seconds is selected for further use. This provides a balance between an improved correlation between units, and retaining the dynamic character of the BC concentration time-series. The marginal benefit of increasing the size of the smoothing window is at the expense of not capturing peak events, as shown in Figure 5-38.

5.8 Summary: measurement of black carbon

This chapter has described the way in which black carbon can be measured through the use of aethalometers. Much research has made use of aethalometers for the measurement of black carbon in urban areas. This has taken place for both air quality and personal exposure studies. However, it has been a general failing of research to properly acknowledge the operational issues surrounding black carbon concentration acquired through optical filter based techniques (Section 5.3).
The second research objective, specified in Section 1.4, is to:

*Specify, evaluate and refine techniques for the measurement of black carbon concentration around traffic management infrastructure, for the use in studies of personal exposure.*

Continuing on from the spatial and temporal scale requirements specified in Chapter 4, this research objective has been addressed. This research (in sections 5.4 – 5.6) identified and quantitatively assessed the potential for both instrument noise and aerosol loading effects to impact BC measurement. In treating these effects, conclusions were drawn and recommendations made for future measurement campaigns. Firstly, the application of the Optimized Noise Reduction Algorithm (ONA) reduces noise and eliminates negative values from a BC time-series without the loss of important detail on the variability of concentration (Section 5.5).

Secondly, there is evidence that filter loading effects are apparent above a certain attenuation of light (~ATN = 20). As such, operation of the device needs to be managed to avoid underestimation of BC. Two experiments were conducted to investigate the potential of this phenomenon to influence measurement of BC in an urban environment (Section 5.6). Evidence was presented that indicates regular changing of the filter strip, and thus maintaining a low level of ATN, would mitigate these effects. In particular, it is recommended that the total ΔATN of a filter ticket be less than 20 (Section 5.6.2). Due to a lack of data, a correction procedure was not presented, and is discussed further in Section 8.2.

In order to facilitate deployment of multiple measurement devices in a local environment, the agreement between individual sensors was investigated. No constant offset between devices was found. Therefore, a smoothing window of 5-seconds was shown to be effective in providing a consistent time-series between devices whilst still capturing the dynamic variability inherent in the data.

Chapter 3 and 4 discussed the potential for emissions, air quality and exposure to pollution to vary in the order of several metres. Existing monitoring networks were described as inadequate, and not being of the required resolution to sufficiently characterise spatial variability. Chapter 6 details an measurement campaign designed to assess the spatial and temporal variability in black carbon concentration at urban intersections with at-grade pedestrian facilities. The work carried out in Chapter 5 allows for multiple measurement devices to be deployed in order to address this research problem.
6 Black carbon concentration at urban intersections

Chapter 2 discussed the importance of traffic and pedestrian management infrastructure in elevating vehicle emissions through an increased demand for power. This mechanism was demonstrated with a simple example (a mid-link pedestrian crossing) in Chapter 3. A further example of infrastructure that manages the interaction between pedestrians and general road traffic is a signalised intersection. Subsequent to establishing a suitable measurement regime, the third research objective is to:

Identify the spatial and temporal variability in black carbon concentration and its relation to explanatory variables at traffic management infrastructure.

This chapter describes an investigation to determine the spatial and temporal variability of vehicle-induced pollution at a signalised intersection. This consists of two case studies, in London and Glasgow (UK). The pollutant of interest is black carbon (BC), discussed in Chapter 4 as an important component of vehicle emissions due to the impact on local air quality, human health and contribution to global environmental problems. The optical technique for measurement of black carbon was assessed in Chapter 5; the knowledge gained is applied to the experiments described in this chapter.

6.1 Experimental aims and methods

This section describes the general approach and methodology employed. The black carbon measurement device (AE51 micro-aethalometer) was discussed in detail in Chapter 5, and the units available for the experiment are listed in Table 5-4.

6.1.1 Aims

This chapter details an investigation to characterise the variation in black carbon concentration at signalised intersections in urban areas. The aim of this chapter is to identify how black carbon varies in space and time. Implications for pedestrian exposure are then discussed in Chapter 7. In order to achieve this objective, several questions are posed:

- How does black concentration vary in space at traffic-controlled urban intersections?
- How do black carbon concentrations at two locations relate to each other?
- Can spatial variation be explained by the micro-scale traffic characteristics of a site?
Signalised intersections control the movement of traffic and pedestrians through separation in time. The management of the infrastructure causes delay for all categories of users. In the case of motor vehicles, some are forced to decelerate, idle and accelerate, rather than maintain a constant speed. Consequently, the power demand, and consequently emission rate, of different vehicles varies in the order of metres. It is hypothesised that this results in variability in pollutant concentration over a similar distance.

A general understanding of the mechanism of pollutant formation (Section 2.1), coupled with the collection of pilot data (Section 5.4) demonstrates that black carbon concentration at a given location follows a positively skewed distribution. This indicates the low-occurrence of high-magnitude events, also known as peak events. Given the underlying distribution of the data and the occurrence of these peak events, further questions are formed:

- How does black carbon concentration vary in time?
- Is there a fixed periodic structure to the occurrence of peak events?
- Can the occurrence of peak events be linked to individual vehicles?
- To what extent do peak events dominate BC concentration at a location?

Chapter 4 cited literature stating that peak exposure events may be responsible for high pedestrian exposure (Kaur et al, 2007; Wang et al, 2011). It was also asserted in Chapter 4 that the current level of monitoring, consisting of fixed sensor networks with longer (15min, 1 hour and daily) averaging periods, is inadequate to assess pedestrian exposure to pollution. Therefore, the outputs of this chapter will be applied to pedestrian exposure in Chapter 7.

To ensure usefulness and transferability of results, two independent urban sites were selected. Whilst acknowledging the role of meteorology (Section 4.3), this thesis has focused on explanatory factors of traffic. The validity of this approach, and the potential for local meteorology (outside of seasonality) to impact the results is also discussed (Section 6.5).

6.1.2 General approach

Fixed monitoring stations are limited in their ability to assess urban air quality, including an inability to provide sufficient spatial resolution. Given the importance of vehicle-induced poor air quality for human health, this study adopts a receptor-based approach. Rather than attempting to achieve a detailed spatial resolution with a sensor network (which is impractical) or through atmospheric dispersion modelling (complex and subject to the accuracy of the input data), monitoring is conducted at natural, managed points of pedestrian
delay. It has been a criticism of previous work into the impact of traffic infrastructure on pollution that it often fails to properly acknowledge the relative position of receptors. This is despite the impact on human health of vehicle-induced pollution frequently being used as a motivation for the research. This investigation seeks to address this limitation.

Figure 6-1 shows a simple, signalised traffic intersection with pedestrian crossing facilities. Pedestrians are able to cross at all four arms through the use of traffic signals. The conflict between road traffic and pedestrians means that opposing movements are separated in time. When pedestrians have priority, vehicles incur delay, waiting in queues extending back from the marked stop line of each approach lane. When vehicles have priority, pedestrians also incur delay. However, the waiting positions of pedestrians are harder to predict, as pedestrian traffic is not managed to the same extent as general vehicular road traffic.

**Figure 6-1: Simple signalised crossroads (left hand drive traffic) with pedestrian facilities.**

Managed pedestrian waiting locations are marked, related to the presence of pedestrian crossing facilities.

However, for the purposes of this experiment, there is an initial assumption that pedestrians wait at the locations marked on Figure 6-1. These locations correspond to the position of the push button box. Mid-link, operation of a signalised pedestrian crossing is usually achieved by request, activated by use of a push button box (such as that shown in Figure 6-2). At signalised junctions, this is more complicated.
At many locations (especially at busy times), operation of the push button does not serve to expedite pedestrian priority, as demand is such that a pedestrian phase is a component of the traffic light cycle. It has been suggested that, at these locations, the button acts as a ‘placebo’, encouraging both walking and crossing of the carriageway at a safe time and location (Tolley, 2003). Pedestrian crossing at these locations is also encouraged by road markings and crossing marking studs. Furthermore, the green man that indicates the pedestrian has right of way is usually situated directly opposite (Figure 6-2). Despite this, pedestrian compliance at signalised crossings is not absolute.

Figure 6-2: Pedestrian facilities at an intersection.

Clockwise from top left): Signal mounted push button box; push button box; far-side green man indicator; crossing marking studs and instructions.
Section 3.2 discussed the occurrence of staggered pedestrian crossing facilities. In order to increase capacity for general traffic, pedestrian crossing movements are split, with mid-carriageway refuges providing additional waiting areas. In the example shown in Figure 6-3, the number of pedestrian waiting areas around the intersection is doubled.

*Figure 6-3: Signalised crossroads (left hand drive) with staggered pedestrian facilities.*

In order to increase capacity for road traffic, pedestrians crossing movements are staggered, with waiting locations at mid-carriageway refuges.

Whilst scrutiny of pedestrian crossing behaviour is beyond the scope of this research, it is acknowledged that, despite the efforts of planners to encourage crossing at these locations, pedestrian behaviour does not always respond. There is substantial research on pedestrian behaviour in crossing systems, with Yang et al (2006) categorising pedestrians as either ‘law-abiding’ or ‘opportunistic’. This thesis focuses on the former. Investigations into the latter are out of scope of this research, but are discussed further in Section 8.2.
6.1.3 Micro-aethalometer deployment

Sensor networks may be used for monitoring and control. A simple example in wireless sensor networks is the star arrangement, where a series of nodes each relay information to a base station. By surveying multiple locations simultaneously, the temporal and spatial distribution of the quantity of interest can be understood.

The aethalometers used in this study have no in-built wireless communication function. However, by deploying a series of sensors simultaneously, each is treated as a node in a network. Whilst there is no real-time reporting of information, by synchronising the internal clock of each device with a single PC (analogous to a base station in this example), and assembling all records post-deployment, the same data ensues.

During deployment around an intersection, each micro-aethalometer was temporarily affixed to traffic signal posts, immediately above push button pedestrian call boxes. Each signal post is used as a proxy for the pedestrian waiting location, as described in Section 6.1.2. Using existing infrastructure in this fashion also has the advantage of providing a repeatable location for any future experiments. Prior to fixing, the micro-aethalometers were placed inside a weatherproof enclosure. Each enclosure has two apertures, allowing for the sample pipe to extrude from the bottom, unit operation and inspection of status lights.

*Figure 6-4: Weatherproof enclosure and lid.*

Two apertures allow for extrusion of the sample tube and instrument operation.

---

53 Enclosures were not aethalometer specific, but designed for outdoor operation.
Attachment to the signal post can then be achieved in a variety of ways, including with stainless steel banding or through the use of ratchet straps (Figure 6-5). The attachment is temporary, easy to remove and does not cause any damage to the instrument or the signal post. In all cases, permission from the relevant authority was sought before deployment.

Figure 6-5: Temporary instrument fixing with steel banding (L) and ratchet straps (R).

Enclosures were also marked with the unique identifier of the micro-aethalometer contained within. As discussed in Chapter 5, orientation was towards the carriageway at all times and the height of the inlet tube was about 1.70m, suitable for human exposure to pollution.

In addition to a deployment in this way providing stable, repeatable measurements, there is an added advantage of not subjecting a researcher to high levels of pollution for the duration of an experimental campaign. In all cases, a risk assessment was carried out in line with guidance from the Department of Civil and Environmental Engineering, Imperial College London.

Throughout this chapter, the urban setting (i.e. the junction) where monitoring is taking place is termed the ‘site’. The particular black carbon monitor is deployed at a ‘location’. This chapter details measurement campaigns at two sites, each of which has multiple data collection locations.
6.2 Byres Road

This section describes a measurement campaign at Byres Road, Glasgow, UK. Glasgow is the largest city in Scotland and the third largest in the UK, with a population of approximately 600,000. The measurements described were carried out on Thursday 13th June 2013, covering the AM peak period (07:30am – 10:30am).

6.2.1 Site description

The location for this study is the intersection of Byres Road and University Avenue (Figure 6-6), in the city's West End. Byres Road is a key north-south route and high street in the city, providing access to Greater Western Road (A82) in the north and Dumbarton Road to the south. There is a two-lane approach and one-lane exit on each arm, with no banned movements. Due to on-street parking, it was observed that the inside lane is not heavily trafficked, and the junction essentially operates with a one-lane approach.

Pedestrians are served by crossings on each arm of the junction. The crossings are approximately straight, and there are no central islands, as can be seen in Figure 6-6. The intersection operates as a simple crossroads, with each arm assigned to a separate stage of the light cycle, and a further stage for pedestrians. This leads to a cycle time of 144-seconds in the AM peak. A stage diagram for the junction is shown in Figure 6-7.

Figure 6-6: Layout (L) and aerial view (R) of intersection of Byres Road, Highburgh Road and University Avenue (map data © Google 2014)
A classified count (incorporating vehicle flows and fleet mix) was conducted for the relevant period. Although conducted on a different day, this was validated against a less comprehensive count carried out at the same time as the main data collection. Entry and exit flows for Highburgh Road were compared to video data and found to be within 5% of the classified count. Figure 6-8 shows the view of Byres Road (south) and Highburgh Road, provided by a camera mounted on a signal post. A summary of the vehicle flows for the peak hour (8am – 9am) is shown in Figure 6-9. The data from the classified count are used as they cover all vehicle movements at the junction.
A classified survey was carried out on a different day to the main data collection, and then validated against video data for Highburgh Road.

The data can also be summarised as inbound and outbound flows by link, as shown in Figure 6-10. The highest flows were observed on the eastbound exit of the junction (University Avenue), and the lowest flows on the westbound exit (Highburgh Road). This is likely to be due to the position of the junction to the west of Glasgow's central business district, and would therefore be expected for the AM peak period.
Passenger cars and light goods vehicles make up 89% – 93% of vehicle flows per link, with heavy goods vehicles and buses making up between 4% and 7%\(^{54}\). The highest proportions of heavy vehicles were observed on the northbound exit of the junction (Byres Road). However, there is no particular imbalance in the distribution of heavy vehicles and fleet mix across the junction.

The traffic signal timings (Figure 6-11) of the junction reflect the dominance of east-west flows, with a larger proportion of the cycle time reserved for stage 2 (Highburgh Road).

*Figure 6-11: Signal timings at Byres Road junction.*

<table>
<thead>
<tr>
<th>Stage 1</th>
<th>Stage 2</th>
<th>Stage 3</th>
<th>Stage 4</th>
<th>Stage 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>27s</td>
<td>73s</td>
<td>97s</td>
<td>118s</td>
<td>144s</td>
</tr>
</tbody>
</table>

*Diagram shows stage lengths and intergreen times (top) and the fixed time stage appearance (bottom) in seconds.*

The junction operates in a fixed time manner, with separate signal plans for different portions of the day. The AM peak plan was in place for the duration of the data collection, and so these signal timings were consistent throughout.

6.2.2 Instrument deployment

According to the procedure described in Section 6.1, seven instruments were temporarily affixed to signal posts around the junction (denoted A – G in Figure 6-12). The signal posts were between 0.7m and 0.9m away from the kerbside, with the inlet of the sample tube at a height of between 1.65m and 1.70m. As described previously in Section 5.4, care was taken to ensure that the inlet was not obstructed and that the orientation (towards the carriageway) was kept consistent.

\(^{54}\) A small number of motorcycles and pedal cycles were also observed.
Figure 6-12: Deployment of micro-aethalometers at Byres Road, Glasgow.

Section 6.1 described a general approach whereby the location of a monitoring device was a proxy for pedestrian waiting locations. At an intersection with four distinct crossings, such as that at Byres Road shown in Figure 6-12, this is conceivably made up of eight locations. In the case of Byres Road, the layout of the crossings on the northern and eastern arm is such that a single monitor (G) is used as a location for one side of each. As such, the intersection is surveyed with seven monitors in total. A further aethalometer was placed at location H, co-located at an air quality monitoring site. Details of all locations are shown in Table 6-1.

Table 6-1: Measurement location characteristics.

<table>
<thead>
<tr>
<th>Location</th>
<th>Unit</th>
<th>Height of inlet</th>
<th>Distance from kerb</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>571</td>
<td>1.65m</td>
<td>0.70m</td>
</tr>
<tr>
<td>B</td>
<td>577</td>
<td>1.70m</td>
<td>0.90m</td>
</tr>
<tr>
<td>C</td>
<td>347</td>
<td>1.65m</td>
<td>0.80m</td>
</tr>
<tr>
<td>D</td>
<td>670</td>
<td>1.68m</td>
<td>0.70m</td>
</tr>
<tr>
<td>E</td>
<td>581</td>
<td>1.70m</td>
<td>0.70m</td>
</tr>
<tr>
<td>F</td>
<td>574</td>
<td>1.65m</td>
<td>0.70m</td>
</tr>
<tr>
<td>G</td>
<td>351</td>
<td>1.65m</td>
<td>0.90m</td>
</tr>
<tr>
<td>H</td>
<td>432</td>
<td>2.35m</td>
<td>7.00m</td>
</tr>
</tbody>
</table>
Black carbon concentration was collected continuously at all locations between 07:30am and 10:30am. Raw data were then treated with the noise reducing algorithm (ONA, as described in Section 5.5) and smoothed with a 5-second window (as described in Section 5.7).

### 6.2.3 Background data

Unit 432 was situated at location H, the site of an air quality monitoring station\(^{55}\). Due to an equipment fault, air quality data are not available for the collection day. However, data from the same week can be used as context. Figure 6-13 shows hourly PM\(_{10}\) concentration for three roadside sites in Glasgow. The magnitude is comparable at all sites, with maximum values observed during the PM peak period (5pm – 6pm). A local maximum is also apparent around the AM peak period (8am – 9am), although levels appear to build throughout the day.

*Figure 6-13: Comparison of Byres Road and other roadside sites in Glasgow, UK (hourly averages).*

![Graph showing PM\(_{10}\) concentrations for three sites in Glasgow](image)

*Data shown is for 12\(^{th}\) June 2013, the day before data collection.*

Figure 6-14 shows this trend at Byres Road for the day before (12\(^{th}\)) and the day after (14\(^{th}\)) the data collection. The mean PM\(_{10}\) concentration is 50% higher on the 14\(^{th}\), demonstrating the potential for variation. Elevated levels associated with peak traffic movements (AM and PM) are also apparent.

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\(^{55}\) Glasgow Byres Road (GLA6) - http://www.scottishairquality.co.uk/latest/site-info?site_id=GLA6
Figure 6-14: PM$_{10}$ trend at Byres Road for the day preceding (12$^{th}$) and following (14$^{th}$) data collection.

6.2.4 Initial results

Table 6-2 shows descriptive statistics by site. The lowest median values are seen at site C and E. The highest median values are observed at sites A and B.

Table 6-2: Descriptive statistics by location (BC concentration, µgm$^{-3}$).

<table>
<thead>
<tr>
<th>Location</th>
<th>Maximum</th>
<th>Minimum</th>
<th>Median</th>
<th>IQR</th>
<th>ΔATN</th>
<th>Time-series integral*</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>102.13</td>
<td>0.64</td>
<td>4.04</td>
<td>2.76</td>
<td>15.10</td>
<td>51,941</td>
</tr>
<tr>
<td>B</td>
<td>155.56</td>
<td>0.57</td>
<td>4.04</td>
<td>2.75</td>
<td>15.21</td>
<td>55,139</td>
</tr>
<tr>
<td>C</td>
<td>398.39</td>
<td>0.75</td>
<td>1.87</td>
<td>1.57</td>
<td>10.15</td>
<td>34,194</td>
</tr>
<tr>
<td>D</td>
<td>230.49</td>
<td>1.17</td>
<td>3.21</td>
<td>3.04</td>
<td>17.62</td>
<td>59,935</td>
</tr>
<tr>
<td>E</td>
<td>170.56</td>
<td>0.40</td>
<td>1.64</td>
<td>1.20</td>
<td>7.23</td>
<td>23,882</td>
</tr>
<tr>
<td>F</td>
<td>64.31</td>
<td>1.15</td>
<td>2.51</td>
<td>1.50</td>
<td>11.01</td>
<td>36,220</td>
</tr>
<tr>
<td>G</td>
<td>167.41</td>
<td>1.29</td>
<td>3.81</td>
<td>2.99</td>
<td>18.97</td>
<td>64,600</td>
</tr>
<tr>
<td>H</td>
<td>210.37</td>
<td>1.23</td>
<td>3.22</td>
<td>2.52</td>
<td>14.80</td>
<td>48,790</td>
</tr>
</tbody>
</table>

*As BC rate is not measured, it would be incorrect to refer to the integral of the time-series as ‘total BC concentration’

Sites C and E are also among the least variable (alongside site F), as exemplified by low values of IQR. Figure 6-15 shows box plots of time-series data for each location, both for the
entire range and a constrained set of data. All locations demonstrate positively skewed time-
series data, with the majority of measured values of low BC concentration. Table 6-2 also 
shows the total ΔATN on each device filter ticket at the end of the monitoring period 
(10:30am). None of the devices exceed the value of 20 identified as being important in 
Chapter 5.

Figure 6-15: Box plots of the entire time-series by location, and a constrained range.

The data for each device is a three-hour time-series at 1Hz, consisting of 10,800 data points. 
The total measurements are therefore 86,400 data points over eight devices. Despite the 
large range exhibited, greater than 99% of the data points are of BC concentration below
50µgm\(^3\), 98% of the data points are of BC concentration below 20µgm\(^3\) and 95% of the data points are of BC concentration below 10µgm\(^3\). The constrained data range of Figure 6-15 shows this more clearly, with the 3\(^{rd}\) quartile (upper boundary of the ‘box’) of the data at less than 10µgm\(^3\) at all locations. Figure 6-16 shows the integral of time-series BC concentration by location. In this case the time-series has been split into 30-minute segments. Location E is appears low throughout the data collection period.

*Figure 6-16: Integral of BC concentration by location, time-series split into 30-minute segments.*
The trend can be viewed in Figure 6-17. Locations E and F appear consistently low throughout, whereas A, B and D remain high. In general there is less variability between locations in the latter stages of the data collection (for this metric). Explanations for the variation shown here will be investigated in subsequent sections.

Figure 6-17: Trend of BC concentration integral by location (30-minute segments).

Given the skewed nature of the data, it is of interest to understand whether this is due to a lower trend in BC, or due to the lack of peak concentration episodes measured at this location. The contribution of large values to the total (time-series integral) at a location can be viewed as the cumulative distribution function of the data. This describes the probability that a random variable \(X\), in this case, concentration of black carbon) takes on a value less than or equal to a number \(x\).

\[
F(x) = P(X \leq x) \quad \text{Equation 6-1}
\]

And similarly:

\[
1 - F(x) = P(X > x) \quad \text{Equation 6-2}
\]
An example cumulative distribution function plot for location A is shown in Figure 6-18. The skew is evident, with more than 90% of values occurring below 10µgm$^{-3}$. This is in spite of a large data range, with a maximum observed value of greater than 100µgm$^{-3}$.

*Figure 6-18: Example empirical cumulative distribution function for location A.*

The distribution is skewed, with more than 90% of values occurring below 10µgm$^{-3}$.

As previously stated, there is a high probability of a given value of $x$ (BC concentration) being under 10µgm$^{-3}$. Figure 6-19 shows this function at all sites. For ease of viewing, the graph has been constrained to show only the upper left quadrant. Whilst the shape (and evidence of positively skewed data) is consistent, there are clear differences in the distribution of the data at each location.

The extreme left (location E) and extreme right (location D) are marked. The position at which $F(x) = 0.9$ (i.e. the 90th percentile) is markedly different for these locations (3.7 and 9.5µgm$^{-3}$) respectively. Conversely, the probability of a measured value exceeding, for example, 10µgm$^{-3}$ is higher at location D.
The practical implications of this are two-fold. Firstly, the pollution characteristics at sites as close as opposite sides of the street are distinct. Secondly, that probability of air pollution at these locations being of elevated levels is greater. It follows that the probability of pedestrian exposure to these elevated levels is also higher.

Median values at locations A, B and G are more than twice of those at locations C and E. The reasons for this will be investigated further in subsequent sections.

6.2.5 Explanatory variables

In chapters 2, 3 and 4, multiple explanatory factors were identified as relevant to the magnitude and distribution of pollutants at an intersection. Alongside pollution data, observations were made of weather and traffic, and notes were made on building topography. Wind speed was measured periodically through the use of a handheld anemometer (Figure 6-20), and observations were made of wind direction (by general compass point). The prevailing wind direction was south-westerly, with speeds generally under 3m/s (light breeze) and occasional gusts.
Carriageway widths (across three lanes) were approximately 15m, with a further 5m pavement width. All arms of the junctions are lined with buildings, with the exception of the north-east side. This is also the location of the background air quality monitoring station, with which monitor G was co-located. Several large trees (in leaf) are also present around this location, although the presence of a car park directly behind the monitoring station may dissipate any air quality benefits. Despite the surrounding buildings, the measurement devices were not directly shielded and were well ventilated.

Consideration of data for location G and H (Figure 6-15 and Figure 6-16) demonstrates that they are amongst the most polluted locations in terms of magnitude of BC concentration. This is conceivably due to their position at the north-eastern side of the junction. However, since these locations are also well ventilated, there is insufficient evidence to conclude that meteorological factors, and particularly low wind speed such as that observed, are influential.

A large difference in measured BC concentration is also seen between locations D and E. This is conceivable related to their position at the northern end of street canyon subjected to south-westerly winds. For example, Berkowicz (2000) illustrated the flow condition in a street canyon whereby the one side a street canyon is effectively leeward, leading to higher pollution concentrations (Figure 6-21). This would be consistent with higher pollutant concentrations at location D (effectively leeward) compared to location E (effectively windward). It is noted that wind speeds were not high during data collection, and that both measurement locations are well-ventilated. Whilst meteorology can be a useful explanatory for pollution conditions, and the subject of much research, it is outside the scope of this research due to the lack of control afforded to traffic engineering and transport planners.
As discussed in chapters 2, 3 and 4, there are several different ways that the characteristics of the traffic may influence the pollutant concentration measured at a given location.

Each location is also characterised by a particular sort of vehicle operating behaviour. For example, location D is close to the stop line for northbound traffic on Byres Road. Vehicles are therefore, more likely to be idling and accelerating at D than at location A, where northbound traffic exits the junction. The disparity between locations E and D has been mentioned. The differing types of operating behaviour – queuing, associating with vehicle idling and acceleration at D compared to free flow traffic at E – may be in part contributing towards the higher level of BC seen at D. This is despite approximately 50% higher vehicle flows at location E.

It is recognised that black carbon emissions are strongly associated with diesel engines, and are higher for larger vehicles (such as buses and heavy goods). As such, the fleet composition adjacent to a given location will likely influence measured levels of pollution. The highest proportion of heavy vehicles was observed on the Byres Road south approach (location D, 8%), more than twice that observed on Highburgh Road (location F, 4%) and Byres Road north (location G, 3%). Given the low proportions of these vehicles, it is unlikely that there is a systematic relation to overall concentration, but rather the presence of these vehicles may be shown to be associated with individual high magnitude pollution events. The volume of traffic will also influence, with a larger number of vehicles leading to higher levels of pollution. This is especially true if the junction is not optimised for vehicle flows. Figure 6-10 showed that the highest approach flows were on the eastbound and southbound approaches, corresponding to locations B and G/H respectively.
6.2.6 Identifying peak events

An approach is required for identifying high-magnitude BC episodes, described as peak events. For instrument characterisation and alignment (Chapter 5) this was achieved through a visual inspection of time-series data. This does not, however, represent a systematic method which enables conclusions to be drawn over the entire dataset.

Peak spotting can be considered analogous with outlier detection. For normally distributed data this is often done in reference to the mean and standard deviation of the data. As the data has been shown to be non-parametric, this would not be appropriate for this situation. Due to the concern regarding the health effects of BC, a peak spotting algorithm would ideally be developed with epidemiological applications in mind. In the case of regulated pollutants, the limits set by regulatory bodies (such as governments) give an indication of acceptable limits (for example, those seen in Table 4-2). However, these limits, and the epidemiological understanding behind them, are not based on the same temporal resolution as that considered in this research. The WHO publication “Health Effects of Black Carbon” (Janssen et al, 2012) refers to short-term changes in health and short-term changes in black carbon concentration as being daily variations. Given the lack of robust evidence of the medical impacts of exposure to black carbon endured by pedestrians crossing the road, a statistical approach is adopted.

The 90\textsuperscript{th} percentile for all data measured at Byres road was calculated as 7.25µgm\textsuperscript{3}. By computing this for the entire dataset (all locations), a consistent basis for peak identification will be used. Although largely arbitrary, based on Figure 6-19, this appears as a point where the distribution of data at different locations diverges.

Figure 6-22 shows an example peak event in relation to the underlying trend. On identification of the event, characteristics of duration and average concentration can be calculated.

Table 6-3 shows peak event characteristics by location. Alongside these statistics, the minimum peak duration was calculated also. This was performed as a diagnostic event to ensure that noise had been sufficiently reduced in the dataset (a peak of duration 1-second is an unlikely occurrence). Across all locations, the minimum peak duration was 6-seconds.
Figure 6-22: Capturing a peak episode at location C.

![Graph showing BC concentration over time with a peak event highlighted along with the peak threshold.]

Changes in the underlying trend (such as that shown between 09:22:30 to 09:23:00) are not recognised as being peak events as they do not exceed the peak threshold value.

Table 6-3: Peak event characteristics by location.

<table>
<thead>
<tr>
<th>Location</th>
<th>Number of peak events</th>
<th>Average peak duration</th>
<th>Maximum peak duration</th>
<th>% peak time</th>
<th>Average BC concentration during peak*</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>37</td>
<td>38.0</td>
<td>83</td>
<td>13.0%</td>
<td>11.3</td>
</tr>
<tr>
<td>B</td>
<td>45</td>
<td>33.3</td>
<td>79</td>
<td>13.9%</td>
<td>13.4</td>
</tr>
<tr>
<td>C</td>
<td>15</td>
<td>24.1</td>
<td>44</td>
<td>3.3%</td>
<td>26.5</td>
</tr>
<tr>
<td>D</td>
<td>50</td>
<td>33.0</td>
<td>134</td>
<td>15.3%</td>
<td>20.7</td>
</tr>
<tr>
<td>E</td>
<td>10</td>
<td>20.5</td>
<td>45</td>
<td>1.9%</td>
<td>20.1</td>
</tr>
<tr>
<td>F</td>
<td>24</td>
<td>26.7</td>
<td>56</td>
<td>5.9%</td>
<td>14.9</td>
</tr>
<tr>
<td>G</td>
<td>60</td>
<td>29.8</td>
<td>108</td>
<td>16.5%</td>
<td>17.8</td>
</tr>
<tr>
<td>H</td>
<td>44</td>
<td>24.5</td>
<td>48</td>
<td>10.0%</td>
<td>14.3</td>
</tr>
</tbody>
</table>

Event duration is measured in seconds, and BC concentration in µgm⁻³. Data related to 3 hours of monitoring, 7:30am-10:30am.

*An average for each peak event is calculated, which is then averaged by location. Given that a threshold has been set for a peak event as being above the 90th percentile, this field does not reflect general trends in BC concentration at a location.
Locations A and B were previously identified as having the highest median BC values, followed by G, H and D (Table 6-2). When considering peak events, G has the largest number within the 3-hour monitoring period, with 60, followed by D, B and H. The occurrence of peak events is tempered somewhat by the average peak duration, which is highest at locations A and B.

Locations previously identified as having low median values are E and C particularly, with median BC concentration less than half that of A and B. These locations also have the lowest occurrence of peak events and the shortest average peak duration. Combining these metrics yields the percentage of time above the peak threshold at each location. The disparity between locations is evident, with location D and G at more than 15%, and locations C and E under 5%.

The link between median values and peak events further asserts their importance in characterising air pollution at a location, and highlights the variability present at a small geographical location such as this. The varying effect of location on this can be seen in Figure 6-23. This compares the total BC concentration time-series integral at a location to that of just the peak events.

Much like the results of Table 6-3, the contribution of peak events to the total is much higher at some locations than other. Again, the disparity between locations D and E is particularly evident; whilst more than 50% of total BC concentration (measured) at location D is accounted for through peak episodes, this is less than 18% at location E.

Furthermore, the non-peak concentration is visibly less variable between sites. Locations G and H show near identical non-peak concentration, yet in terms of total BC concentration (integral, Table 6-2), G is more than 30% greater than H. The differentiating factor between these locations is distance to the roadside. Whilst the monitor at G is less than 1m from the road, H is 7m away. The results shown in Table 6-3 and Figure 6-23 show that H has fewer peak events of lower average concentration – this may be due to a lower direct impact of passing traffic on levels of BC.
As identified in Section 6.1.1, it is of interest to consider how the temporal variability of BC peak episodes may be impacted by explanatory factors.

### 6.2.7 Periodicity

Periodicity refers to the reoccurrence of events at fixed time intervals. It is of interest as to whether the peak events identified here have a fixed periodic structure. Namdeo et al (1999) found a lack of periodicity (demonstrated through autocorrelation) when considering fine particles. It was suggested that trends of fine particles do not follow patterns of possible explanatory factors such as periodic traffic flow.

An initial consideration of the peak duration (Table 6-3) suggests that these may be linked to the traffic light cycle, with average peak durations of the same order of magnitude as stage lengths (~30-seconds). However, consideration of time-series data of BC concentration through autocorrelation and Fourier transform also did not yield any evidence of a fixed periodic structure.
Lag (defined as the time between the conclusion of one peak event and commencement of the next) between peak events identified in Section 6.2.6 were analysed further for any discernible pattern. For each location, the time between peak events were computed. An example plot of this, for location G, is shown in Figure 6-24.

Figure 6-24: Visualisation of lag between peak events (location G).

The upper panel shows the lag of successive peak events. It is hypothesised that in cases of a particular large lag, there may have been preceding events, which although the result of local maxima, were not of sufficient magnitude to be considered peaks. Consideration of the time-series does demonstrate such events, but not any of a recurring frequency.

The lower panel of Figure 6-24 shows the lag of observations arranged in descending rather than chronological order. The distribution is clearly not uniform, reaffirming the lack of periodicity in the data. Video data was available with a direct view of location D. This was observed for association between peak events and particular traffic situations. Whilst some peaks were seemingly associated with the presence of high emitting vehicles (such as in Figure 6-25), this was not evidenced in all cases.

---

56 Peak events previously defined as exceeding the 90th percentile across all locations at the site.
The presence of two diesel buses at location D is seemingly followed by a peak event.

Lack of a systematic relationship between traffic and high-magnitude pollution events is a crucial result. This demonstrates that, at this site, peak events of BC concentration are not necessarily related to traffic parameters on a micro-scale (i.e. not necessarily related to measureable traffic parameters such as discharge of queuing traffic or the presence of a high-emitting vehicle). As such, transport planners and traffic engineers could focus efforts on reducing total emissions at a hotspot location and in the management of receptors away from these locations.

This is useful, as the alternative of focusing on the impact of traffic control and general transport management (such as operational bus scheduling) on variability of such hotspots, is much more complex.

6.2.8 Location interdependence

In order to more easily visualise the occurrence of peak episodes at individual locations, each time-series is transformed so that a binary state is adopted\(^{57}\). A peak occurrence is defined as 1, whilst a non-peak data point is given a value of 0. Figure 6-26 shows a comparison of peak occurrence plotted in this way for locations A and D.

Whilst there is some overlap between peak events, it is clear from this sample that peak BC concentration episodes at the junction do not occur at the same time for all locations.

\(^{57}\) The method of treatment was previously discussed as a means of ensuring consistency between devices in Section 5.7. It was discarded due to the loss of precision; in this case it is used only to better visualise the interdependence of peak events at locations around the site.
For a given point in the BC time-series, there are a maximum of eight locations (A – G) where a peak episode may be occurring. Each data point that satisfies the peak event criteria is given the identifier of 1. By considering the data longitudinally and summing across locations, the peak episodes across the site can be represented by a single number, s. For example, if at data point $t$ there are peak episodes occurring at four locations, $s = 4$. Figure 6-27 shows a histogram of this data. The majority (80%) show either zero or one peak events to be in occurrence.

Figure 6-27: Frequency of simultaneous hotspot locations (max eight).
This shows that the factors that cause short-term peak episodes tend to be specific to the individual location (A – H). This highlights the potential for difference in pedestrian exposure profiles and the need for a more detailed consideration of sites than that offered by current monitoring sites. This result doesn’t, however, rule out a relationship between individual locations. It is possible that this is linked to the traffic state or meteorological conditions. For example traffic movements from one arm of a junction negate those from another arm occurring. A simple way of investigating this relationship is through scatter plots of measured BC concentration at each location. Performing this for each pair of monitors yields some interesting results.

Locations A and B are in the north-west of the site. These locations shared the highest observed median values (4.04) and exhibited similar variability (IQR of 2.75 and 2.76). Figure 6-28 shows the relationship between observed values of BC concentration at location A and B. There is an evident positive correlation ($r^2 = 0.72$), with the highest values at location A also associated with the highest values at location B. There are also cases of high values at location A associated with low values at location B (and vice versa) – this suggests that multiple factors influence the concentration at these two locations (as expected given the discussion in earlier chapters).

Figure 6-28: Scatter plot showing the relationship between location A and location B.

A further example is given by comparing location D and E, situated on opposite sides of Byres Road on the south side of the site. Location D represents a site where vehicles queue,
and is therefore subject to the full range of vehicle operating modes. Location E, conversely, is where vehicles discharge from the junction, and would not (in normal operation) be a place where vehicles idle or accelerate from a stop. A scatter plot of BC concentration at these locations is shown in Figure 6-29.

Figure 6-29: Scatter plot showing the relationship between location D and location E.

Unlike the relationship between A and B, for this pair high concentrations at location D are only associated with low concentrations at location E. The resulting linear correlation coefficient between the two is expectedly low (0.03). It can be concluded from this data that high-magnitude events at these locations are mutually exclusive. Whilst a traffic explanation has been provided, meteorology (discussed in Section 6.2.5) may also be a factor. For example, a period high-wind event may result in additional turbulence in street canyon, displacing pollution from one location to the other. Whilst there is no empirical data to support this for this example, the mechanism is accepted.

In both of these examples there are a large cluster of points around the origin, demonstrating the high frequency of low magnitude data (and a positively skewed distribution).

Table 6-4 shows linear correlation coefficients for each pair of monitored locations. A and B have the strongest linear correlation (0.72), followed by locations G and H (0.48). G and H
are both situated in the north east quadrant of the junction, with H located at the air quality monitoring station around 7m away from the roadside.

Table 6-4: Pair-wise linear correlation coefficient matrix.

<table>
<thead>
<tr>
<th>Unit</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
<th>H</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1.00</td>
<td>0.72</td>
<td>0.12</td>
<td>0.05</td>
<td>0.01</td>
<td>0.02</td>
<td>0.17</td>
<td>0.19</td>
</tr>
<tr>
<td>B</td>
<td>0.72</td>
<td>1.00</td>
<td>0.18</td>
<td>0.06</td>
<td>0.00</td>
<td>0.01</td>
<td>0.26</td>
<td>0.16</td>
</tr>
<tr>
<td>C</td>
<td>0.12</td>
<td>0.18</td>
<td>1.00</td>
<td>0.05</td>
<td>0.00</td>
<td>0.10</td>
<td>0.17</td>
<td>0.17</td>
</tr>
<tr>
<td>D</td>
<td>0.05</td>
<td>0.06</td>
<td>0.05</td>
<td>1.00</td>
<td>0.03</td>
<td>0.07</td>
<td>0.13</td>
<td>0.04</td>
</tr>
<tr>
<td>E</td>
<td>0.01</td>
<td>0.00</td>
<td>0.00</td>
<td>0.03</td>
<td>1.00</td>
<td>0.25</td>
<td>0.05</td>
<td>0.02</td>
</tr>
<tr>
<td>F</td>
<td>0.02</td>
<td>0.01</td>
<td>0.10</td>
<td>0.07</td>
<td>0.25</td>
<td>1.00</td>
<td>0.10</td>
<td>0.12</td>
</tr>
<tr>
<td>G</td>
<td>0.17</td>
<td>0.26</td>
<td>0.17</td>
<td>0.13</td>
<td>0.05</td>
<td>0.10</td>
<td>1.00</td>
<td>0.48</td>
</tr>
<tr>
<td>H</td>
<td>0.19</td>
<td>0.16</td>
<td>0.17</td>
<td>0.04</td>
<td>0.02</td>
<td>0.12</td>
<td>0.48</td>
<td>1.00</td>
</tr>
</tbody>
</table>

There is a lack of association between locations on opposite sides of the road (such as A and B, D and E or F and G) and between those in a similar locale (with the exception of A and B, G and H). This is further evidence that pollutant concentration is not homogenous across the sites, and that high-magnitude concentration episodes are localised, and of short duration.

6.2.9 Byres Road summary

An eight sensor deployment at a busy crossroads in Glasgow, UK, has yielded information regarding the spatial and temporal variability in black carbon concentration. There is a disparity in both the temporal and spatial variability in BC at the junction, with median values at sites A, B and G more than twice that of sites C and E.

Whilst several mechanisms (both traffic related and meteorological) have been suggested, no robust association has been found between explanatory traffic factors and the magnitude of BC. Furthermore, the location of the air quality monitoring station (H) does not correlate well with the locations identified as important for pedestrian waiting (A – G) and therefore pollutant exposure. This shows the inadequacy of air quality monitoring stations in assessing pollution at a site.
6.3 Cromwell Road

This section details an experimental campaign at Cromwell Road, London, UK. This site was previously described as location C in Section 5.4. The experiment described was carried out during the AM peak on a weekday (18\textsuperscript{th}) in July 2013.

6.3.1 Site description

This site is the intersection between Queen’s Gate and Cromwell Road in the South Kensington area of London, UK. The site is in close proximity to the Natural History Museum and other tourist attractions, and forms part of the major A4 arterial to central London. As such, the site is heavily trafficked, with annual average daily flows of 45,000 vehicles. The site has buildings (height ~ 20m) on all sides with the exception of a wildlife garden in the north-east quadrant (Figure 6-30). The intersection is wide and well ventilated, with carriageway (including pavement) widths ranging from 27m to 35m.

*Figure 6-30: Intersection of Queen’s Gate and Cromwell Road.*

*The intersection has buildings in all corners with the exception of the Natural History Museum Wildlife Garden (shown on map).*

Unlike the site at Byres Road, the junction is a complex crossroads with staggered pedestrian crossings on each arm. The staggered crossings allow additional traffic capacity at the junction (see Section 3.2 for greater discussion), but result in pedestrians waiting on mid-carriageway islands. The traffic control is also more complex, and will not be considered in the same level of detail as the previous case study. Right turns are banned for all except the southbound traffic stream. The junction therefore essentially operates on two stages (Figure 6-31), with cycle time between 75 and 85-seconds (variation based on SCOOT). One stage is dedicated for north-south traffic and the other is dedicated to east-west traffic.
Pedestrian crossing movements are more complicated, with no dedicated stage. Whereas traffic is stopped as part of the normal traffic management of the intersection, pedestrian crossings on the lanes exiting the junction are operated by means of a push-button request. Left turning traffic from all arms of the junction may therefore be subject to additional delay at the pedestrian crossing stop line on the exit link.

*Figure 6-31: Simplified stage diagram for Cromwell Road intersection.*

<table>
<thead>
<tr>
<th>Stage 1</th>
<th>Stage 2</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image" alt="Diagram" /></td>
<td><img src="image" alt="Diagram" /></td>
</tr>
</tbody>
</table>

For this particular study, attention was focused on the eastern arm of the junction. In the vicinity of the staggered pedestrian crossing, this consists of three lanes eastbound and two lanes westbound (Figure 6-32).

*Figure 6-32: Eastern arm of the junction (Cromwell Road).*

*The pedestrian crossing on the north side of Cromwell Road is not automatically free of traffic for any traffic stage, and is operated on request.*
The additional pedestrian ‘stage’ on the eastern arm occurs during stage 1 traffic movements (Figure 6-31), and has the effect of inducing additional vehicle deceleration and acceleration movements (and associated pollutant emissions). Traffic on the northern arm of the junction who wish to turn left (Queen’s Gate to Cromwell Road, to travel east) may therefore accelerate from the stop line on Cromwell Road, turn left, and then decelerate and stop to allow pedestrian crossings. This is shown in Figure 6-33.

Figure 6-33: Additional acceleration and deceleration caused by crossing request.

During times of low pedestrian flow, the crossing request is activated less frequently and the effect is not present. In addition, the staggered nature of the crossing may encourage pedestrians to seek more direct crossing opportunities. It is also recognised that vehicles do not always comply with the second stop line associated with the pedestrian crossing.

6.3.2 Background data

Cromwell Road is also the site of an air quality monitor, forming part of the London Air Quality Network58. The station is situated around 4m from the roadside of the southbound link of the northern arm of the junction.

58 Cromwell Road site – www.londonair.org.uk
Time-series data form PM$_{10}$, PM$_{2.5}$ and NO$_2$ data are publicly available to download. Figure 6-34 shows the hourly averages for PM$_{2.5}$ concentration for the weekdays of the data collection week. The day of deployment, 18$^{th}$ July, appears representative. Whilst it is recognised that hourly mean concentration of PM$_{2.5}$ is not equivalent to high-resolution BC measurements, a range of data is noted.

*Figure 6-34: Hourly mean concentrations of PM$_{2.5}$ for the week of data collection.*

17$^{th}$ July is omitted due to missing data.

6.3.3 Instrument deployment

Figure 6-35 shows the deployment of six micro-aethalometers at the junction of Cromwell Road and Queen’s Gate. Monitors at locations B, C, D and E were temporarily fixed to signal posts directly above pedestrian call boxes, in the manner described in Section 6.1. A further two aethalometers (A and F) were placed on street furniture.
The location of monitors on the mid-carriageway island introduces a new pedestrian waiting environment. Alongside this, measurement was conducted at locations set back from the road side, in an effort to further understand the direct influence of passing traffic on pollutant concentration. The locations are described in Table 6-5.

**Table 6-5: Cromwell Road measurement location characteristics.**

<table>
<thead>
<tr>
<th>Location</th>
<th>Unit</th>
<th>Height of inlet</th>
<th>Distance from kerb</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>670</td>
<td>1.30m</td>
<td>3.00m</td>
<td>On telecoms box set back from road side</td>
</tr>
<tr>
<td>B</td>
<td>347</td>
<td>1.70m</td>
<td>0.70m</td>
<td>Signal post (north pavement)</td>
</tr>
<tr>
<td>C</td>
<td>581</td>
<td>1.65m</td>
<td>0.80m</td>
<td>Signal post (north side of island)</td>
</tr>
<tr>
<td>D</td>
<td>432</td>
<td>1.70m</td>
<td>0.70m</td>
<td>Signal post (south side of island)</td>
</tr>
<tr>
<td>E</td>
<td>577</td>
<td>1.70m</td>
<td>0.70m</td>
<td>Signal post (south pavement)</td>
</tr>
<tr>
<td>F</td>
<td>571</td>
<td>1.00m</td>
<td>3.30m</td>
<td>On low wall set back from road side</td>
</tr>
</tbody>
</table>

**6.3.4 Results**

Data collection was carried out on the 18th July 2013 between 10am and 11am. Table 6-6 shows descriptive statistics for each location. The highest median values are at D and C respectively, both of which are situated on the central island. These locations also exhibit the
highest variability, as demonstrated by the inter-quartile range. The lowest BC concentration, incorporating median, IQR and the time-series integral, was observed at location F, on the south side of the site. Figure 6-36 shows the cumulative distribution plot for all locations.

Table 6-6: Descriptive statistics by location (BC concentration, µgm⁻³).

<table>
<thead>
<tr>
<th>Location</th>
<th>Maximum</th>
<th>Minimum</th>
<th>Median</th>
<th>IQR</th>
<th>ΔATN</th>
<th>Time-series integral*</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>99.61</td>
<td>2.26</td>
<td>5.89</td>
<td>5.85</td>
<td>13.61</td>
<td>30,501</td>
</tr>
<tr>
<td>B</td>
<td>62.38</td>
<td>0</td>
<td>5.23</td>
<td>6.01</td>
<td>15.26</td>
<td>26,688</td>
</tr>
<tr>
<td>C</td>
<td>87.48</td>
<td>2.17</td>
<td>6.16</td>
<td>6.71</td>
<td>14.72</td>
<td>33,453</td>
</tr>
<tr>
<td>D</td>
<td>255.79</td>
<td>2.39</td>
<td>7.17</td>
<td>8.11</td>
<td>17.72</td>
<td>40,364</td>
</tr>
<tr>
<td>E</td>
<td>135.80</td>
<td>1.75</td>
<td>5.08</td>
<td>4.70</td>
<td>12.26</td>
<td>28,603</td>
</tr>
<tr>
<td>F</td>
<td>104.35</td>
<td>1.86</td>
<td>4.77</td>
<td>5.08</td>
<td>12.20</td>
<td>24,303</td>
</tr>
</tbody>
</table>

ΔATN for each device filter ticket does not exceed 20.

*As BC rate is not measured, it would be incorrect to refer to the integral of the time-series as ‘total BC concentration’

Figure 6-36: Empirical cumulative distribution function for all locations (A – F).
Consideration of the time-series of location B indicated an instrument fault, rendering the last 10 minutes of data unusable. The 90th percentile across all measurement locations was 16.7µgm\(^{-3}\), more than twice that of the Byres Road, Glasgow site (7.3µgm\(^{-3}\)). In the same fashion, this boundary was used to identify peaks, with data points exceeding the 90th percentile deemed representative of elevated level representing a high magnitude event. These are summarised in Table 6-7. The average BC concentration during a peak episode is between five and six times that of the time-series median.

Table 6-7: Peak event characteristics by location.

<table>
<thead>
<tr>
<th>Location</th>
<th>Number of peak events</th>
<th>Average peak duration</th>
<th>Maximum peak duration</th>
<th>% peak time</th>
<th>Average BC concentration</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>18</td>
<td>16.5</td>
<td>29</td>
<td>8.2%</td>
<td>28.2</td>
</tr>
<tr>
<td>B*</td>
<td>18</td>
<td>21.2</td>
<td>51</td>
<td>10.6%</td>
<td>27.3</td>
</tr>
<tr>
<td>C</td>
<td>26</td>
<td>19.3</td>
<td>46</td>
<td>13.9%</td>
<td>26.2</td>
</tr>
<tr>
<td>D</td>
<td>33</td>
<td>18.6</td>
<td>58</td>
<td>17.1%</td>
<td>29.9</td>
</tr>
<tr>
<td>E</td>
<td>18</td>
<td>19.1</td>
<td>74</td>
<td>9.5%</td>
<td>27.4</td>
</tr>
<tr>
<td>F</td>
<td>13</td>
<td>17.3</td>
<td>65</td>
<td>6.2%</td>
<td>28.0</td>
</tr>
</tbody>
</table>

Event duration is measured in seconds, and BC concentration in µgm\(^{-3}\). Based on a dataset of 5/6 of the other locations. Equivalent peak event rate for 1 hour of data is 21.6. Data relates to 1 hour of monitoring.

*An average for each peak event is calculated, which is then averaged by location. Given that a threshold has been set for a peak event as being above the 90th percentile, this field does not reflect general trends in BC concentration at a location.

Locations C and D (situated on the central island) display the greatest number of peak events and the largest proportion of data points above the 90th percentile. Given knowledge of traffic-induced pollution hotspots, this is an expected result. Locations on the mid-carriageway island (C and D) are in close proximity to two streams of traffic (eastbound and westbound), whereas those on either side of the road would be expected to be more heavily influenced by a single stream of traffic.

The junction operates as two stages, rather than separate stages for each arm as at Byres Road. Therefore, eastbound and westbound traffic occur at the same time. Figure 6-37 shows the time-series trend for BC for a five minute period. Three plots show the association between locations on the north side of the site (A, B), locations on the central island (C, D) and locations on the south side (E, F). The same peak events are recognised, and there is a degree of association between the time-series’.
Figure 6-37: Association of BC concentration between sites (different y-axis scales are used on each plot to allow trends to be more easily see).

Observing across the different plots, it is hypothesised that the same peak episodes are captured at different sites. There is a recognisable difference in magnitude (likely caused by proximity) and lag (likely caused by dispersion time to each location).
Given the common traffic factors expected to impact BC concentration across the site, a single signal for the entire site was created by averaging across all locations. Figure 6-38 shows this for the entire time-series and for a constrained period.

*Figure 6-38: Time-series of average BC concentration across all monitoring locations.*

This confirms that the same peak events are picked up across the locations, as averaging across still results in a dynamic signal. However, treating the data in this fashion does not account for the relative magnitude of peak events shown in Figure 6-37; whilst the same events were picked up, the magnitude of the peak at location D was more than four times as high as that at A and B.
Local maxima were determined for each location, and the time between each was computed to give a lag between peak events. Rather than calculate peak events based on the 90th percentile, the algorithm\textsuperscript{59} locates local maxima by the second derivative test.

Local maxima are identified where:

\[
\frac{d^2y}{dx^2} < 0
\]

\textit{Equation 6-3}

Figure 6-39 shows a histogram of the time between local maxima (lag) by location. The median values are shown to be in the order of 60 to 90-seconds.

\textit{Figure 6-39: Histogram of lag between local maxima, by location.}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{histogram}
\caption{Histogram of lag between local maxima, by location.}
\end{figure}

The time between local maxima appears to be related to the length of the traffic light cycle, which is around 75-seconds. It is also recognised that some local maxima are not elevated.

\textsuperscript{59} The MATLAB function \textit{findpeaks} was used
levels of BC. These were removed from the signal, based on the criteria that maximum values below the median BC concentration did not represent a peak pollution episode. Figure 6-40 shows a histogram for the lag between peak events where the BC time-series is based on an average of all locations. The median value is 74-seconds, close to the traffic light cycle time (75-seconds) for the junction.

*Figure 6-40: Histogram of lag between peak events.*

![Histogram of lag between peak events](image)

*BC time-series is averaged over all locations to produce a single time-series trend. The median value is 74s, and the arithmetic mean 79s.*

Whilst there appears to be a periodic structure associated with traffic light cycles, this does not explain all of the variability. The events to the right of the distribution as displayed in the histogram may be an instance of a particular traffic cycle not yielding a high-magnitude event. This could be cause by generally low levels of traffic flow or by a network disruption elsewhere. Other events at the tails of the distribution may be explained by short-term meteorological events (gusts) or localised high-emitting mobile sources (particularly high emitting vehicles or smokers in the vicinity of the monitor).

A deployment of micro-aethalometers on one arm of the Cromwell Road junction has yielded several interesting results. Firstly, the measurement locations on the mid-carriageway pedestrian island were shown to have a higher concentration of BC and a greater number of high-magnitude pollution events. This is expected given the location between two opposing traffic streams, and has been borne out of the data. Secondly, a periodicity of BC at the junction is shown to occur at intervals similar to that of the traffic light cycle. This suggests that BC levels are strongly linked to the presence of traffic.
### 6.4 Site comparison

Two urban intersections (termed ‘sites’) have been surveyed at multiple locations for spatial and temporal variability in black carbon concentration. This section compares and contrasts the results obtained, and explains the differences.

#### 6.4.1 Similarities

The sites are generally comparable as they are both urban traffic intersections. However, the fundamental management of the traffic is different as discussed in subsequent sections. In terms of results, both sites demonstrate some of the points raised in earlier discussions (particularly Chapter 4) regarding the heterogeneity of pollutant concentration in urban areas. Pollutant concentration was found to vary spatially, with locations (defined by letter) within the same site exhibiting different median values. At Byres Road, median values were more than twice as high in some sites compared to others. Although, the difference was less at Cromwell Road, the median values at the most polluted sites were more than 50% higher than at the least polluted. Similar patterns were seen for the location specific time-series integral, used as an indicator of total concentration observed. Temporal variability was also seen to vary within sites, with the magnitude and occurrence of peak events not consistent across the measurement locations at a given site.

The conclusion from the results above is that a micro-scale assessment, consisting of measurements in the order of metres (spatially) and seconds (temporally) is a better indicator of the dynamic variability than more coarse measures. The extent to which pollution is seen to vary at a given location in both space and time is evidence that the standard means of monitoring air pollution is inadequate. Sparse fixed sensor networks with longer (~15 minutes – 1 hour) sampling times are insufficient for accurate exposure assessment or for investigating the associations between pollution, exposure and traffic management. This is consistent with knowledge of the variability in mobile source emissions (Chapter 3) and pedestrian behaviour (Chapter 4), and with the results of other literature (e.g. Kaur et al, 2005, Wang et al, 2011).

#### 6.4.2 Relative magnitude and peak event occurrence

Whilst there is a demonstrable in-site variation (i.e. between letter-defined locations at a given site) in both case studies, the nature of this variation is not consistent. Figure 6-41 shows the difference in median concentration by site (Byres Road or Cromwell Road) and
location (letter designated A – H). The median values are lower at Byres Road for all locations, reflecting the generally lower levels of traffic.

Figure 6-41: Median BC concentration by site (Byres Road, Cromwell Road) and location (A – H).

In addition to the sites being geographically distinct, data collection was also not carried out at the same time. Byres Road data collection was conducted between 7:30am and 10:30am on a weekday morning in May 2013. Cromwell Road was also conducted on a weekday morning, although between 10:00am and 11:00am. This later time was chosen due to the increased levels of pedestrian movements at these times, as the site is in close proximity to several tourist attractions. As the data collection period was shorter, less variability may be expected from the site. However, the background data for Byres Road (Section 6.2.3) suggests that pollution levels would be lower at a later time of day – as such, the disparity between the two sites for the identical time of day would be expected to be even greater.

Whilst the distribution of data is of a similar type at both sites and all locations (positively skewed, with low-occurrence of high-magnitude events), the parameters of the distribution
vary markedly. Figure 6-42 shows the cumulative distribution function for selected locations at each site. For ease of viewing, only the locations with the highest 90th percentile value (previously identified in Figure 6-19 and Figure 6-36) have been included.

*Figure 6-42: Empirical cumulative distribution function showing most and least polluted (defined by median values) by site.*

![Empirical cumulative distribution function](image)

The probability of being exposed to – for example – 10µg m⁻³ at Cromwell Road is clearly much higher than at Byres Road. This is consistent with air quality reporting that identifies certain areas as being more polluted than others, such as is shown Figure 6-43.

These differences are largely attributed to the type of location (for example, roadside sites are more heavily polluted than urban background sites due to proximity to traffic), but variability within the location types can be seen also.
The occurrence of peak events is not consistent across the sites, as shown in Figure 6-44. This is shown as a peak event rate – the number of peaks per hour. Whilst peak events were defined according to the same methodology (as exceeding the 90\textsuperscript{th} percentile of all data at a given site), in absolute terms this produces a markedly different threshold. At Byres Road, the 90\textsuperscript{th} percentile for this dataset is 7.3µgm\textsuperscript{-3}, which is less than 50% of the value for Cromwell Road (16.7µgm\textsuperscript{-3}). Although the peak identification methodology was defined to identify local instances of low-occurring, high-magnitude events, the direct health implications of vehicle-induced BC exposure do not change based on location. Therefore, for a reasonable comparison, the same threshold should be applied.

The upper value of 16.7µgm\textsuperscript{-3} is applied to both sites to identify localised high-magnitude peak events. Peak event rate and average peak duration for each site are shown in Figure 6-45.
Figure 6-44: Peak event rate (number of peaks per hour).

A peak is defined as being above the 90th percentile of a particular site.

Figure 6-45: Peak event rate (number of peaks per hour) and average duration, by site and location.
Whereas the occurrence of high magnitude episodes at Cromwell Road was associated with a fixed periodic structure, no such relationship was established for the Byres Road site. This is a significant result. As would be expected, the disparity between peak event rates across the two sites is large, with the rate of occurrence much lower at Byres Road. Although the average peak event durations appear lower at Byres Road, they are visibly closer in magnitude to those at Cromwell Road.

6.4.3 Discussion of mechanisms responsible

Explanatory factors of meteorology and traffic have already been discussed to explain variability between locations at a site. However, these factors could also be responsible for the difference in BC concentration and peak occurrence at the two locations. Data collection was carried out in the same season (summer), with approximately similar weather conditions of clear skies and low wind observed. Therefore, attention is turned to differences in traffic.

Classified count survey data was obtained for both sites for an initial investigation into the traffic state. For Cromwell Road, the data were provided by Transport for London for a weekday in March 2011. Flows are summarised in Table 6-8, alongside the percentage of buses and heavy goods vehicles. Based on the discussion of vehicle emissions of Chapter 2, these are considered the heavy emitters in the vehicle fleet.

**Table 6-8: Cromwell Road vehicle flow and percentage of buses and HGVs.**

<table>
<thead>
<tr>
<th>Period</th>
<th>Peak hour</th>
<th>Vehicle flow (veh/hr)</th>
<th>% buses &amp; HGVs</th>
</tr>
</thead>
<tbody>
<tr>
<td>AM peak</td>
<td>08:00 – 09:00</td>
<td>4106</td>
<td>5%</td>
</tr>
<tr>
<td>Inter-peak</td>
<td>11:30 – 12:30</td>
<td>3558</td>
<td>5%</td>
</tr>
<tr>
<td>PM peak</td>
<td>17:45 – 18:45</td>
<td>4300</td>
<td>3%</td>
</tr>
</tbody>
</table>

*Data for all arms of the intersection. Data is for a weekday in March 2011.*

Flows are around 15% lower outside the peak periods. The proportion of heavy vehicles remains at an equivalent level. In contrast, data for Byres Road (also detailed in Section 6.2.1) are shown in Table 6-9.

**Table 6-9: Byres Road vehicle flow and percentage of buses and HGVs.**

<table>
<thead>
<tr>
<th>Period</th>
<th>Peak hour</th>
<th>Vehicle flow (veh/hr)</th>
<th>% buses &amp; HGVs</th>
</tr>
</thead>
<tbody>
<tr>
<td>AM peak</td>
<td>08:00 – 09:00</td>
<td>1663</td>
<td>5%</td>
</tr>
</tbody>
</table>

*Data for all arms of the intersection. Data is for a weekday in June 2013.*
Vehicle flows are much lower (around 40% of the AM peak at Cromwell Road), and as such traffic intensity at a given location is also lower. Whilst these data cannot be used to directly explain the trends shown elsewhere in this chapter, they are indicative of the traffic situation at this site.

Section 6.2.1 described the traffic flow profile of Byres Road in the context of traffic control. Byres Road operates with a separate stage for each arm of the junction. The southern side of Byres Road is considered, relating to monitoring locations D and E. Figure 6-46 shows peak hour (8am – 9am) vehicle flows for this arm of the junction.

*Figure 6-46: Peak hour vehicle flows for Byres Road south.*

The traffic movement directly past location D (298 vehicles/hour) is permitted only in stage 3 of the junction. Based on the cycle time of 144s and stage length of 24s, this is permitted for approximately 17% of the hour. Conversely, the traffic movement directly past location E (453 vehicles/hour) is permitted in stages 1, 2 and 4 (the two movements do not occur at the same time). In total, the arm has bi-directional flow of 751 vehicles/hour.

Table 6-10 shows that despite the higher number of vehicles passing location E over the course of the busiest hour, due to the permitted traffic movements, traffic intensity is lower than at location D. This explains the difference in black carbon concentration previously discussed. Traffic intensity in this case is demonstrated by headway, the average temporal separation between vehicles.
Table 6-10: Hourly flow, proportion of time movement is permitted and headway.

<table>
<thead>
<tr>
<th>Location</th>
<th>Hourly flow (vehicles/hour)</th>
<th>Time in hour movement is permitted (seconds, % in brackets)</th>
<th>Headway (seconds/vehicle)</th>
</tr>
</thead>
<tbody>
<tr>
<td>D</td>
<td>298</td>
<td>600 (16.7%)</td>
<td>2.01</td>
</tr>
<tr>
<td>E</td>
<td>453</td>
<td>2350 (65.2%)</td>
<td>5.19</td>
</tr>
</tbody>
</table>

This information can be used to construct a stage-specific flow diagram for this arm of the junction. This is shown in Table 6-11 and Figure 6-47. Stage 5 is the pedestrian phase for all arms of the junction, and therefore, the traffic flow rate is 0.

Table 6-11: Byres Road south stage-specific headway, flow and traffic flow rate.

<table>
<thead>
<tr>
<th>Stage</th>
<th>Headway (seconds/vehicle)</th>
<th>Flow (vehicles)</th>
<th>Time (hours)</th>
<th>Traffic flow rate (vehicles/hour)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1,2,4</td>
<td>5.19</td>
<td>453</td>
<td>2350/3600</td>
<td>694</td>
</tr>
<tr>
<td>3</td>
<td>2.01</td>
<td>298</td>
<td>600/3600</td>
<td>1788</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
<td>0</td>
<td>650/3600</td>
<td>0</td>
</tr>
</tbody>
</table>

Figure 6-47: Stage-specific traffic flow rates, Byres Road south.
This can be compared to the pattern seen at the Cromwell Road site. Traffic counts performed at the same time as BC data collection give flows for each direction at the site. Eastbound flows are 1064 vehicles/hour, of which 996 are from Cromwell Road west and 68 are left-turning traffic from the northern arm of the junction (Queen’s Gate). Westbound flows are 892 vehicles/hour, and the total flows for this arm of the junction are 1956 vehicles/hour.

*Figure 6-48: Cromwell Road vehicle flows from the day of data collection (10am – 11am).*

In addition to the generally higher flows at this site, as the junction operates on only two stages (Section 6.3.1), the majority of these vehicle movements occur at the same time. Table 6-12 shows stage-specific traffic flow rates for the Cromwell Road site.

*Table 6-12: Cromwell Road stage-specific directional flow and traffic flow rate*

<table>
<thead>
<tr>
<th>Stage</th>
<th>Eastbound flow (vehicles)</th>
<th>Westbound flow (vehicles)</th>
<th>Total flow (vehicles)</th>
<th>Time* (hours)</th>
<th>Traffic flow rate (vehicles/hour)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>68</td>
<td>0</td>
<td>68</td>
<td>1640/3600</td>
<td>149</td>
</tr>
<tr>
<td>2</td>
<td>996</td>
<td>892</td>
<td>1888</td>
<td>1960/3600</td>
<td>3468</td>
</tr>
</tbody>
</table>

*Stage and cycle lengths estimated from video data. Inter-green stages omitted for simplification.*

The flow rate that occurs during stage 2 of the cycle at Cromwell Road – 3468 vehicles/hour – is nearly twice that of the most traffic intense stage of Byres Road (stage 3, 1788 vehicles/hour). In addition, stage to stage variation in traffic flow rate is much higher on Cromwell Road than at Byres Road. As such, the influence of traffic control on measured BC concentration is more apparent at this site, demonstrated by a recurring periodic structure to peak events.
Figure 6-49: Stage-specific traffic flow rates, Cromwell Road.

High emitting vehicles, classified as either heavy goods vehicles or buses, were observed at around the same proportions at each site. However, at Byres Road such a vehicle is more likely to correspond to a particular isolated event in BC concentration. This is because the presence of a dense platoon of vehicles at Cromwell Road would serve to diminish the relative impact of a single heavy emitter.

6.5 Local meteorological impacts

Two important mechanisms have been discussed for the magnitude and distribution of BC pollution at an urban intersection. One of these, the traffic state, has been considered in detail in the earlier sections of this chapter. This section details an experimental campaign to determine the magnitude of the impact of local meteorology on measured levels of BC.

6.5.1 Approach

Several studies have investigated seasonal trends in black carbon, incorporating traffic-induced pollution and non-mobile sources such as biomass. For example, Tiwari et al (2013) showed that BC concentrations in Delhi, India are highest during the winter months. Monthly means varied from a low of 2.6µgm\(^{-3}\) in September to a high of 17.9µgm\(^{-3}\) in December.
Saha and Despiau (2009) investigated season variations in BC in a coast region of southeast France, also demonstrating that the highest concentrations were during the winter months. Interestingly, both of these studies investigated annual and diurnal variability, with little discussion of day-to-day variation.

It is, however, recognised that there are day-to-day variability in pollution levels. For example, Figure 6-50 shows the variability in daily mean PM$_{2.5}$ for weekdays in July 2013. Even without the impact of seasonality, the highest daily means are more than twice that of the lowest.

*Figure 6-50: Daily mean PM$_{2.5}$ pollution levels at the Cromwell Road air quality monitoring site (2013).*

In this section, day-to-day variability in black carbon is considered. As the data collection was carried out within summer months only, this investigation aims to qualify the impact of local meteorology without the impact of seasonality. A single location (A, at the Cromwell Road site) was monitored on multiple weekdays over a six week period, between 29th June 2013 and 8th August 2013. The monitoring location in the wider context of the previous Cromwell Road study is shown in Figure 6-51.
By keeping the location and time of day (10am – 11am) constant, it is assumed that the general impact of traffic was consistent. High level data relating to the traffic situation was obtained from the traffic control provider, Transport for London. This data consisted of average vehicle flows by 15-minute time period and day of the week over a 3 month period (May – July, 2012). Whilst the data are not for the same monitoring period, it gives an indication of the variability that can be expected of summer traffic patterns.

The data are output from the SCOOT traffic management system, and refers to eastbound traffic flows on Cromwell Road. The data in Table 6-13 refers to the same period as pollutant measurement, 10am – 11am.

Table 6-13: Traffic flow statistics for eastbound traffic at the Cromwell Road site.

<table>
<thead>
<tr>
<th>Day of the week</th>
<th>Mean vehicle flow (vehicles/hour)</th>
<th>Standard deviation (vehicles/hour)</th>
<th>Coefficient of variation*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monday</td>
<td>1116</td>
<td>46</td>
<td>0.041</td>
</tr>
<tr>
<td>Tuesday</td>
<td>1144</td>
<td>52</td>
<td>0.045</td>
</tr>
<tr>
<td>Wednesday</td>
<td>1159</td>
<td>29</td>
<td>0.025</td>
</tr>
<tr>
<td>Thursday</td>
<td>1136</td>
<td>42</td>
<td>0.037</td>
</tr>
<tr>
<td>Friday</td>
<td>1068</td>
<td>65</td>
<td>0.061</td>
</tr>
<tr>
<td>Saturday</td>
<td>969</td>
<td>33</td>
<td>0.034</td>
</tr>
<tr>
<td>Sunday</td>
<td>987</td>
<td>42</td>
<td>0.043</td>
</tr>
</tbody>
</table>

*Defined as the ratio of the standard deviation to the mean. Data for 10am – 11am, and averaged over a 3-month period.

Mean flows are around the same magnitude for Monday, Tuesday, Wednesday and Thursday. Flows appear slightly lower on Fridays, with further reductions for weekend observations. This is further apparent in Figure 6-52, where the observation for the day of the week with the largest mean traffic flow (Wednesday) has been set to 100.
Figure 6-52: Cromwell Road intersection weekday traffic flow index.

Average flow of the greatest observation (Wednesday) is equal to 100.

In addition to displaying the highest average mean flow, Wednesdays also demonstrate the least variation (in the form of the standard deviation). Of particular interest is the ratio of the standard deviation to the mean, known as the coefficient of variation (also shown in Table 6-13). This is less than 0.05 for all examples other than Friday. So, whilst data for Friday demonstrate the lowest mean values (of weekdays), it is also shown to be the most variable.

For the purposes of this data collection, it can be concluded that traffic patterns are largely invariant for the 10am – 11am time period. Whilst this does not take into account changes in fleet mix, it is further assumed that cycle to cycle differences in heavy vehicle proportions average out over the hour. Due to the particular difference in flows, data collection is restricted to weekdays, omitting Saturday and Sunday. Traffic remains a potential explanator for differences in measured pollution, it is initially assumed that the impact of traffic at this location is consistent over different observations, and therefore, the impact of meteorology can be discussed.

6.5.2 Results

Prior to analysis, raw BC concentration data were processed in the manner previously described in this chapter. Figure 6-53 shows the median and 90th percentile black carbon concentrations for the 10am to 11am time period for each data collection day.
Median values range for a low of 3.26µg m⁻³ on 10th July to a high of 7.98µg m⁻³ on 2nd July. Values for the 90th percentile range from 8.32µg m⁻³ to 20.22µg m⁻³. Data for July 10th is particularly low for the 90th percentile, relative to the other days. Also shown in Figure 6-53 are daily mean PM$_{2.5}$ concentrations; 10th July does not appear significantly lower than other observations. Whilst PM$_{2.5}$ and BC are not directly equivalent, this further demonstrates the limitations of using daily means to characterise air quality.

Figure 6-54 shows cumulative distribution functions for all observed days. Again, the observation for 10th July appears markedly different. Whilst the shape of the function is more similar for the other observation, there is evident spread. This appears particularly true for decreasing values of F(x). The previous experimental campaign at Cromwell Road (18th July 2013, detailed in Section 6.3) is shown also.
Figure 6.54: Empirical cumulative distribution function plots for all observed days.

The previous Cromwell Road experiment (detailed in Section 6.3) is marked (18th July).

Of 11 observations, there is one noticeable outlier of BC concentration data, collected on 11th July. Several studies have detailed the impact of wind speed on black carbon concentration. In general, it has been demonstrated that a linear association exists between increasing BC concentration and decreasing wind speed (for example, Saha and Despiau, 2009). Hourly mean wind speed\textsuperscript{60} and temperature\textsuperscript{61} data were obtained for monitors approximately 5 miles from the Cromwell Road site.

Figure 6.55 displays the data for the 10am – 11am data collection period for each observation day. The mean wind speed does not exceed 3.4m/s (light breeze – gentle breeze on the Beaufort scale), and is not shown to be high on 10th July.

\textsuperscript{60} Ealing Western Avenue site – London Air Quality Network (http://www.londonair.org.uk/london/asp/publicdetails.asp?Site=El1&View=Details&region=0)

\textsuperscript{61} Ealing Southhall site – London Air Quality Network (http://www.londonair.org.uk/london/asp/publicdetails.asp?Site=EA7&View=Details&region=0)
Temperature data are also not considered markedly different for this day. There was no recorded rainfall on any of these days, or the preceding days (data also sourced from the London Air Quality Monitoring Network).

Figure 6-55: Mean wind speed and temperature.

Data is for the relevant hour, 10am – 11am. Data for a site approximately 5 miles away from Cromwell Road. Data unavailable for August 8th.

There is no particular explanatory data regarding meteorology that can explain this variability. Based on this level of analysis, this is an unexplained outlier. However, the BC data collected further demonstrate the potential for day-to-day variation in concentration. Further work regarding the local impact of meteorology is required, and is discussed in Section 8.2.
6.6 Summary: black carbon concentration

The third research objective, specified in Section 1.4 is to:

Identify the spatial and temporal variability in black carbon concentration and its relation to explanatory variables at traffic management infrastructure.

Several specific questions were raised in Section 6.1.1; for completeness, these will be referred to here. Similarities and differences between the two case studies will be discussed throughout this section.

- How does black concentration vary in space at traffic-controlled urban intersections?
- How do black carbon concentrations at two locations relate to each other?
- Can spatial variation be explained by the micro-scale traffic characteristics of a site?

In the first instance, it has been shown that vehicle induced pollution, represented by the concentration of black carbon, varies greatly within small urban areas, such as a traffic intersection. Median values may be more than double at one location around a junction compared to another. This has clear implications for the exposure of pedestrians to pollution, explored further in Chapter 7.

This variability has been seen at two sites; whilst a different level of absolute pollution was present at each site, the relative difference between measurement locations was apparent at each. The use of a single monitoring station to characterise an urban environment is shown to be inadequate, with on-street average values potentially varying by more than 100%. When such data are used as a means of selecting urban locations in need of action to reduce levels of pollution, the information available may be misleading.

In some cases it was possible to explain the level of pollution at a given location, and the relative magnitude between two or more locations, by differences in traffic patterns. For example, it was hypothesised that BC magnitude at locations A and B at Byres road were due to the same traffic movements. Equally it was recognised that BC peak events at locations D and E at Byres Road were mutually exclusive due to the fundamental difference in traffic patterns at these sites. This is seen as a clear mechanism for the influence of traffic engineering and control on vehicle emissions and the resulting on-street pollution levels.
Therefore, the spatial variation at a given site can be explained by local traffic patterns. However, it was not possible to completely separate the impact of local meteorology from traffic factors. This raises the possibility that efforts to reduce pedestrian exposure to pollution may also focus on reducing system-wide emissions.

- How does black carbon concentration vary in time?
- Is there a fixed periodic structure to the occurrence of peak events?
- Can the occurrence of peak events be linked to individual vehicles?
- To what extent do peak events dominate BC concentration at a location?

The variability of BC concentration in time is shown to be positively skewed, with a low-occurrence of high-magnitude values. Therefore, the use of mean averages to characterise a site is also misleading, as the arithmetic mean is not a good measure of central tendency for skewed distributions. At both sites, peak events were seen to occur with sub-minute durations and at frequencies much higher than that captured by fixed monitoring stations.

It has been shown that in areas that are subject to high traffic flows, a fixed periodic structure of pollutant concentration can be found in association with the traffic control cycle. In these cases the volume of traffic is of sufficient magnitude to influence BC concentration in a periodic fashion. At sites with lower traffic flows, the periodic cycle of traffic does not influence BC concentration to a greater extent than other drivers of pollution, such as the occurrence of individual high-emitting vehicles and local meteorology events. Day-to-day variability (excluding effects of seasonality) in meteorology were not generally found to influence the character of the black carbon distribution, determining that a probabilistic approach to assessing concentration and exposure is suitable. A lack of data regarding local meteorology makes it impossible to draw full conclusions, and this is an area that should be explored further (discussed in Section 8.2).

Chapter 7 furthers this investigation by considering what the implications of spatial and temporal and spatial variability in black carbon concentration mean for pedestrian exposure.
7  Pedestrian exposure to black carbon

Chapter 4 introduced the term 'exposure', which acknowledges the interaction of humans (pollution receptors) and pollution concentration (Zou et al., 2009). The measurement campaigns detailed in Chapter 5 and 6 investigated variability in black carbon concentration, with no knowledge of the human activity patterns that lead to variations in exposure.

This chapter extends this work to demonstrate the applications of high spatial and temporal resolution pollutant concentration data to studies in human exposure. In doing so, it seeks to address the fourth research objective, which is to:

*Assess the exposure of pedestrians using traffic management infrastructure to black carbon pollution and identify the relationship to traffic management.*

Three particular applications are explored:

- A probabilistic examination of BC concentration and consequent pedestrian exposure to pollution (Section 7.1);
- An assessment of BC concentration and pedestrian exposure as a function of traffic control (Section 7.2);
- An evaluation of exposure based upon BC concentration and patterns of pedestrian activity (Section 7.3).

7.1 Probabilistic examination of BC concentration and exposure

Chapter 6 demonstrated that the spatial variability around an urban intersection was such that the median values in some locations were twice as high as those in others. In addition, the distribution of values was shown to be positively skewed, with a low-occurrence of high-magnitude values. This was shown extensively in Chapter 5 and Chapter 6 and illustrated through the use of various plots (for example, Figure 5-11, Figure 6-15, Figure 6-19).
The implication for pedestrian exposure is that, at certain locations\textsuperscript{62}, pedestrians have a greater probability of exposure to high levels of pollution which may be detrimental to health. In order to make such assessments, a suitable probability distribution must be associated with the air pollution concentration data. Chapter 6 also showed that it was not possibly to separate the influence of variables concerning meteorology and emissions production. As such, model building and prediction is a difficult task. Therefore, probability distributions for air pollution can play an important role in understanding the potential for exceedances (Section 4.2.1) and in forecasting compliance with air quality standards (Kan and Chen, 2004; Seinfeld and Pandis, 2012).

7.1.1 Statistical distributions for air pollution

Pollutant concentration, such as that of BC, can be treated as the continuous (positively-signed) random variable, \( x \), which may be described in terms of its probability density function, \( f(x) \). The probability of \( x \) can be determined as:

\[
P(a \leq x \leq b) = \int_{a}^{b} f(x) \, dx
\]

\textit{Equation 7-1}

The probability density function \( f(x) \) can be estimated from a number of empirical observations, \( x_1, x_2, x_3 \ldots x_n \). As demonstrated previously, (for example, Section 6.2) the data are not normally distributed.

As such, standard parametric approaches for estimating a distribution (for example, that \( f(x) \) follows a normal distribution with mean \( \mu \) and standard deviation \( \sigma \) ) are not appropriate.

Numerous approaches have been taken in order to fit a suitable probability distribution to air pollution data. Marani et al(1986) demonstrated that a generalised gamma distribution was a better fit than the other non-parametric model forms of standard gamma, Weibull and lognormal. This work was carried out with regard to daily sulphur dioxide concentrations at a series of monitoring stations in an urban area.

\textsuperscript{62} The results of Chapter 6 demonstrate that this is also likely to vary in time in relation to measureable explanatory factors, such as the state of traffic control.
Morel et al (1999) generated a two-parameter distribution by fitting of moments to characterise daily averages of particulate matter (PM$_{2.5}$ and PM$_{10}$). However, the authors were unable to demonstrate it as being superior to more standard distributions.

Wang et al (2013) investigated the appropriateness of several different distributions to daily averages of particulate matter (PM$_{10}$) for five cities in China, finding that the lognormal provided the best fit. Taylor et al (1986) investigated how different distributions are suitable for different pollutants (based on 24-hour average concentrations). It was concluded that the lognormal distribution was most appropriate for particulates, nitric oxide, oxides of nitrogen and sulphur dioxide, and that, depending on the source data, either the gamma or Weibull distribution is the most appropriate for carbon monoxide, nitrogen dioxide and ozone.

In addition to considering different types of distribution, the averaging period is important also. Larsen (1971) determined that pollutants are log-normally distributed regardless of averaging time. The averaging times used varied from 1 hour to 1 year, with no assertion made regarding shorter averaging periods.

The literature discussed so far in this section refers to various pollutant species, including particulates, oxides of nitrogen and sulphur dioxide. Whilst there is much literature on the measured levels of fine particulates and black carbon concentration, no evidence has been found of studies into the appropriate statistical distributions. Therefore, a range of distributions is investigated below to determine the most suitable for black carbon concentration acquired at a high-time resolution.

### 7.1.2 Distribution fitting and goodness-of-fit

BC data are tested for a range of non-parametric models of the type seen in other work of this nature (Section 7.1.1). The distribution parameters are estimated through the use of the maximum likelihood estimation (MLE) method. This method seeks to minimise the sum of the squared errors (SSE) in a similar fashion to other statistical estimation methods, such as ordinary least squares.

As noted in Section 7.1.1, BC is a continuous random variable $x$, for which the empirical probability density function is $f(x)$. The sample empirical data was captured as detailed in Chapter 5 and Chapter 6.
Each sample is a vector of the form:

\[ x = x_1, x_2, x_3 ... x_n \]

Equation 7-2

The joint probability density function across all observations is therefore:

\[ f(x | \theta) \]

Equation 7-3

This specifies the probability of the observed data sample \( x \) given the parameter set \( \theta \). The exact parameter set \( \theta \) is dependent upon the particular statistical distribution. MLE seeks the value(s) of \( \theta \) whereby the likelihood of obtaining vector \( x \) is maximised. This is termed the likelihood function, \( L \), whereby the probability of observing sample \( x \) given the parameter set \( \theta \) is equated to the likelihood of parameter set \( \theta \) given the observed values \( x \).

\[ L(\theta | x) = f(x | \theta) \]

Equation 7-4

In practice, the estimate is obtained through maximisation of the log-likelihood function\(^{63} \), resulting in the partial differential (likelihood equation) which maximises \( L \) with respect to \( \theta \).

\[ \frac{\partial \ln L(\theta | x)}{\partial \theta} = 0 \]

Equation 7-5

The result of the estimation is subject to the same second-derivative checks normally associated with locating maxima. For the purposes of this work, the parameter estimates for each distribution are computed with the MATLAB function \textit{fitdist}.

The parameters for a series of common non-normal model forms were investigated, as detailed in Table 7-1. This is not an exhaustive list of potential forms, but the options present here represent three commonly used probability models that, as Holland and Fitz-Simons (1982) state have “proven to be useful tools in air quality data analysis”.

Whilst these models have been used extensively (Section 7.1.1), they have previously not been applied to high-resolution black carbon or ultrafine particulate concentration data.

\(^{63} \text{This is done for mathematical simplicity; the same estimation is obtained through maximisation of either likelihood function.} \)
### Table 7-1: Distribution, parameter set and model form.

<table>
<thead>
<tr>
<th>Distribution</th>
<th>Parameter set (θ)</th>
<th>Model form</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gamma</td>
<td>(a, b)</td>
<td>(f(x</td>
</tr>
<tr>
<td>Lognormal</td>
<td>(\mu, \sigma)</td>
<td>(f(x</td>
</tr>
<tr>
<td>Weibull</td>
<td>(A, B)</td>
<td>(f(x</td>
</tr>
</tbody>
</table>

Whilst the most likely parameter set for a given distribution is obtained, this operation does not determine which distribution is most appropriate. Goodness-of-fit statistics are used to measure how good the estimated distribution fits the empirical data. Taylor et al (1986) discussed various methods, which were re-visited by Wang et al (2013). Taylor et al (1986) state that goodness-of-fit test statistics provide “a useful relative measure of fit when comparing alternative distributional models”.

A two stage process is used to judge the fit of a particular distribution. Firstly, a goodness-of-fit statistic can be computed. The Kolmogorov-Smirnov test quantifies the distance between an empirical distribution \(F(x)\) and the hypothesised distribution \(G(x)\).

\[
D^* = \max(|F(x) - G(x)|)
\]

This goodness-of-fit is reported alongside the likelihood. Secondly, the cumulative distribution function of the estimated distribution is compared to the empirical distribution function of the collected data.

#### 7.1.3 Data

Chapter 6 described a series of measurement campaigns designed to characterise the spatial and temporal distribution of black carbon in traffic-affected urban environments. A particular dataset has been formed as a result, and is described here. Repeated measurements were conducted over a six week period at location A (Figure 7-1). The subsequent analysis is detailed in Section 6.5.
Figure 7-1: Monitoring location A.

Repeated measurements are made with a micro-aethalometer (AE51) placed on a telecommunications cabinet approximately 3m from the roadside.

The location is on top of a telecommunications access box, approximately 3m from the roadside with the inlet 1.30m from the ground. This provides a convenient location for repeat deployments as it is not affixed to any traffic management infrastructure. However, if it is to be used as a proxy for a pedestrian waiting location, it must be demonstrated to be representative.

A simple experiment was conducted whereby locations A and B were monitored simultaneously between 10am and 11am on 25th June 2013. These locations represent the extremes of the pedestrian waiting area in terms of distance from the roadside. Table 7-2 displays descriptive statistics for the two locations (A and B) over the course of the monitoring period. The two locations are in broad agreement, especially considering the magnitude of difference seen between monitoring locations at this intersection during previous experiments (detailed in Section 6.3). Location B, closer to the road, exhibits a higher median value, higher maximum and a higher 90th percentile. A linear correlation of 0.78 is present between the two time-series.

Table 7-2: Descriptive statistics for locations A and B

<table>
<thead>
<tr>
<th></th>
<th>Location A</th>
<th>Location B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Median</td>
<td>4.17</td>
<td>4.64</td>
</tr>
<tr>
<td>IQR</td>
<td>6.98</td>
<td>5.96</td>
</tr>
<tr>
<td>Max</td>
<td>82.31</td>
<td>169.86</td>
</tr>
<tr>
<td>Min</td>
<td>1.50</td>
<td>0.96</td>
</tr>
<tr>
<td>90th percentile</td>
<td>16.63</td>
<td>17.56</td>
</tr>
</tbody>
</table>

64 These data also exist for the multiple sensor experiments conducted to determine variability in BC across the site, detailed in Section 6.3. However, due to an equipment malfunction, a full time-series was not available for location B.
Whilst there is not a perfect association between the two locations, for the purposes of this analysis it is concluded that A is an adequate representation of the pedestrian waiting area for the purposes of further research.

The dataset for use is formed of multiple time-series over 10 observation days. All data was collected using the same micro-aethalometer (unit 670) and during the same time period 10am – 11am. The data characteristics were discussed in Section 6.5 with the single outlier (10th July) omitted in this analysis. It was not possible to attribute the differences in this data to different traffic or meteorological factors, and so it is assumed to be anomalous. The final distribution consists of 36,000 data points. Figure 7-2 shows the histogram and empirical cumulative distribution function plot for all data points.

Figure 7-2: Histogram (L) and empirical cumulative distribution function (R) for all data.

The data are evidently positively skewed, with a low proportion of high-magnitude events in occurrence. The median value is 5.90µgm⁻³, and the inter-quartile range is 6.57µgm⁻³. The 90th percentile value is 17.94µgm⁻³.

7.1.4 Results

Table 7-3 shows the parameter estimates and their associated standard errors. All results were obtained through maximum likelihood estimation to a confidence level of 95%. It is
noted that the standard error of parameter estimation is lowest in the case of the lognormal distribution fit. Figure 7-3 shows each model fit compared to the empirical distribution.

Table 7-3: Parameter estimates and standard errors.

<table>
<thead>
<tr>
<th>Distribution</th>
<th>Parameter</th>
<th>Estimate</th>
<th>Standard error of estimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gamma</td>
<td>$\alpha$</td>
<td>1.5876</td>
<td>0.0108</td>
</tr>
<tr>
<td></td>
<td>$b$</td>
<td>5.6261</td>
<td>0.0450</td>
</tr>
<tr>
<td>Lognormal</td>
<td>$\mu$</td>
<td>1.8428</td>
<td>0.0041</td>
</tr>
<tr>
<td></td>
<td>$\sigma$</td>
<td>0.7830</td>
<td>0.0029</td>
</tr>
<tr>
<td>Weibull</td>
<td>$A$</td>
<td>9.4808</td>
<td>0.0461</td>
</tr>
<tr>
<td></td>
<td>$B$</td>
<td>1.1506</td>
<td>0.0041</td>
</tr>
</tbody>
</table>

Figure 7-3: Distribution fits to empirical data (BC concentration, units $\mu$gm$^{-3}$).

As discussed in Section 7.1.2, the K-S statistic was computed for each distributional form. This is shown in Table 7-4 alongside the maximum log likelihood calculated in the parameter estimation. For the K-S statistic, a smaller value indicates a better fit. This, alongside a
higher maximum log likelihood value, indicates that the lognormal distribution is most suitable, amongst these model forms, for these data.

Table 7-4: Maximum log-likelihood and K-S statistics for each model form.

<table>
<thead>
<tr>
<th></th>
<th>Log-likelihood</th>
<th>K-S statistic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gamma</td>
<td>-112796</td>
<td>0.1073</td>
</tr>
<tr>
<td>Lognormal</td>
<td>-108615</td>
<td>0.0432</td>
</tr>
<tr>
<td>Weibull</td>
<td>-114130</td>
<td>0.1087</td>
</tr>
</tbody>
</table>

Table 7-4 shows a cumulative distribution plot of the empirical data and fitted model. Of particular interest is the occurrence of high magnitude values. Whilst these are low frequency in the empirical data, they are critical to pedestrian exposure.

Figure 7-4: Cumulative distribution function for empirical data and the lognormal model.
A probability plot of the empirical data and the fitted lognormal model is shown in Figure 7-5. The logarithmic scale on the y-axis emphasises the performance of the model. The two plot lines diverge at around 20µgm$^{-3}$. This means that, for points beyond this, the probability of occurrence is greater for the fitted model than for the empirical data. The distribution of data is such that high-magnitude events are of great importance for determining total exposure.

*Figure 7-5: Probability plot of empirical data and the fitted lognormal model.*

Low-frequency, high-magnitude events are not well represented, with the fitted model under-representing their occurrence.

Given the importance of these extreme values in determining pedestrian exposure to pollution, this is clearly inadequate.

### 7.1.5 Additional model forms

The previous sections focused on model forms that have been shown to be suitable in other air quality applications. However, the best-fitted models do not properly account for the peak events thought to be important to assessing pedestrian exposure.
Two additional model forms are tested, with a particular view of representing low-occurring, high-magnitude events. These are the generalized extreme value (GEV) distribution and the log-logistic distribution.

The basic components of these model forms (and the inclusion of an exponential function) are not dissimilar from the distributions used in Section 7.1.2. However, little evidence has been found for their application to air pollution data. These model forms are displayed in Table 7-5. The parameter estimates and standard errors are shown in Table 7-6.

### Table 7-5: Generalized extreme value and log-logistic probability density function model forms and parameters for estimation.

<table>
<thead>
<tr>
<th>Distribution</th>
<th>Parameter set ($\theta$)</th>
<th>Model form</th>
</tr>
</thead>
<tbody>
<tr>
<td>Generalized extreme value</td>
<td>$k, \mu, \sigma$</td>
<td>$f(x</td>
</tr>
<tr>
<td>Log-logistic</td>
<td>$\mu, s$</td>
<td>$f(x</td>
</tr>
</tbody>
</table>

### Table 7-6: Parameter estimates and standard errors for generalized extreme value and log-logistic distribution functions.

<table>
<thead>
<tr>
<th>Distribution</th>
<th>Parameter</th>
<th>Estimate</th>
<th>Standard error of estimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Generalized extreme value</td>
<td>$k$</td>
<td>0.4762</td>
<td>0.0051</td>
</tr>
<tr>
<td></td>
<td>$\mu$</td>
<td>4.6596</td>
<td>0.0190</td>
</tr>
<tr>
<td></td>
<td>$\sigma$</td>
<td>3.1562</td>
<td>0.0179</td>
</tr>
<tr>
<td>Log-logistic</td>
<td>$\mu$</td>
<td>1.8076</td>
<td>0.0040</td>
</tr>
<tr>
<td></td>
<td>$s$</td>
<td>0.4404</td>
<td>0.0019</td>
</tr>
</tbody>
</table>

Once again, an element of goodness-of-fit can be assessed through consideration of the maximum log-likelihood obtained during estimation, and through the K-S statistic computed on the empirical dataset. The results are shown in Table 7-7, alongside the lognormal statistics previously obtained. The GEV model performs best on both accounts, with the greatest log-likelihood value and the smallest K-S statistic.
Table 7-7: Maximum log likelihood and K-S statistics for additional model forms, compared to previously preferred lognormal estimate.

<table>
<thead>
<tr>
<th>Distribution</th>
<th>Log-likelihood</th>
<th>K-S statistic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lognormal</td>
<td>-108615</td>
<td>0.0432</td>
</tr>
<tr>
<td>Generalized extreme value</td>
<td>-108035</td>
<td>0.0215</td>
</tr>
<tr>
<td>Log-logistic</td>
<td>-108593</td>
<td>0.0319</td>
</tr>
</tbody>
</table>

Based on this evidence, it may be concluded that the GEV distribution offers the best representation of the data. However, given this is better assessed with the representation of extreme values in mind, and as such a probability plot (restricted to probability greater than 0.75 for ease of viewing) showing all three distributions is shown in Figure 7-20.

*Figure 7-6: Probability plot of empirical data and three fitted distribution (y-axis is restricted to probability > 0.75 for ease of viewing).*
The already discarded lognormal distribution (Section 7.1.4) is a visibly worse fit for high-magnitude, low-frequency values of black carbon. There is, however, little to distinguish between the alternate model forms of log-logistic and GEV at this juncture.

Whilst the GEV model is judged a more suitable fit based on a lower KS test statistic (Table 7-7), the log-logistic model form has a conceptual advantage in that the lower bound is zero, rather than minus infinity (as is the case for both GEV and lognormal models). The success of these model forms in predicting \( F(x) \) is shown in Table 7-8.

Table 7-8: Empirical and modelled \( F(x) \) for GEV and log-logistic functions.

<table>
<thead>
<tr>
<th>( x )</th>
<th>Empirical data</th>
<th>GEV (modelled / actual)</th>
<th>Log-logistic (modelled / actual)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>0.7418</td>
<td>0.7490 (1.0097)</td>
<td>0.7547 (1.0174)</td>
</tr>
<tr>
<td>25</td>
<td>0.9455</td>
<td>0.9489 (1.0036)</td>
<td>0.9610 (1.0164)</td>
</tr>
<tr>
<td>50</td>
<td>0.9896</td>
<td>0.9868 (0.9972)</td>
<td>0.9917 (1.0021)</td>
</tr>
<tr>
<td>100</td>
<td>0.9985</td>
<td>0.9968 (0.9983)</td>
<td>0.9983 (0.9998)</td>
</tr>
<tr>
<td>150</td>
<td>0.9997</td>
<td>0.9986 (0.9989)</td>
<td>0.9993 (0.9996)</td>
</tr>
</tbody>
</table>

Residuals are obtained by comparing the actual occurrences to those predicted by the model. These are shown in Figure 7-7, with a positive value indicating the fitted model overestimates \( F(x) \) for a given value of BC concentration. A constrained range is also shown to more clearly illustrate the difference in the distribution tails.

Whilst there appears to be systematic variation in model residuals at lower values of \( x \), \( F(x) \) is suitably estimated by the log-logistic form to make it a more viable statistical model. This is illustrated by the lower residual values at higher BC concentration (> 70\( \mu \)gm\(^{-3} \)). Given the importance of high-magnitude, low-occurrence BC concentration events, the log-logistic is concluded to be the more suitable statistical model.
Figure 7-7: Fitted model residuals.

The top panel shows residuals for the entire range of data, whilst the bottom panel is restricted to values of BC exceeding 50µgm⁻³. Model residuals are lower for the log-logistic form at higher values of BC.
7.1.6 Applications

The application in fitting statistical distributions of this sort is in forecasting future occurrences of extreme values. Additional samples were collected at the site in September 2013, and predicted event occurrence from the estimated log-logistic model was compared to the observed. The results are shown in Table 7-9.

Table 7-9: Actual and predicted BC concentration occurrence.

<table>
<thead>
<tr>
<th></th>
<th>Predicted</th>
<th>Sample 1</th>
<th>Sample 2</th>
<th>Sample 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Events &gt; 25µgm$^{-3}$</td>
<td>146</td>
<td>208</td>
<td>188</td>
<td>100</td>
</tr>
<tr>
<td>Events &gt; 50µgm$^{-3}$</td>
<td>31</td>
<td>43</td>
<td>26</td>
<td>29</td>
</tr>
<tr>
<td>Events &gt; 100µgm$^{-3}$</td>
<td>6</td>
<td>9</td>
<td>0</td>
<td>11</td>
</tr>
<tr>
<td>Events &gt; 150µgm$^{-3}$</td>
<td>3</td>
<td>0</td>
<td>0</td>
<td>6</td>
</tr>
</tbody>
</table>

The model is relatively successful at predicting the number of BC concentration events in excess of 50µgm$^{-3}$. In addition, the modelled and observed values follow the same pattern of decreasing occurrence with increasing magnitude. However, the frequency of low-occurring, high-magnitude events that have been deemed so important to pedestrian exposure are not well-represented.

The theoretical basis on non-parametric model forms is by the mechanism of pollutant emission production and the low-occurrence of high-magnitude events. However, there is no particular theoretical basis through which to choose between the model forms shown here. As such, there is also no guarantee that future levels of BC concentration will follow a similar distribution, either in terms of functional form or estimated parameters. This highlights the need for rigorous empirical data collection when assessing air pollution and estimating health effects.

The log-logistic model form has been selected due to the representation of peak concentrations. Whilst this model form has been shown to be more suitable than others in representing the empirical distribution present, there is only partial success in forecasting future levels of BC. This suggests more work is required, and in particular more data. This is discussed further in Section 8.2.
7.2 Exposure as a function of traffic control state

Previous sections have assumed that probability of exposure was not related to the state of traffic control. Whilst this appears to be largely true at low-trafficked sites such as Byres Road, the Cromwell Road measurement campaign demonstrated periodicity in BC concentration linked to the state of traffic. Since control of pedestrian movements, through pedestrian crossings, is part of the traffic control cycle, the probability of exposure to peak events will not be uniform. Exposure assessments also require information regarding pedestrian activity, which will be discussed here and in Section 7.3. For this example, the probability of exposure to a peak pollution event will therefore depend not only on the roadside BC concentration but also on pedestrian arrival at the site.

7.2.1 Determination of traffic control state

A simple experiment was constructed whereby the state of traffic control could be linked to ambient black carbon concentration. A video camera was mounted alongside a micro-aethalometer at monitoring location A (as detailed in Section 7.1). This camera produced a time-stamped video with a view of the pedestrian crossing signal head.

Figure 7-8: Camera co-located with micro-aethalometer (L) and time-stamped video of pedestrian signal head (R).

Both the camera and the micro-aethalometer were time-synchronised prior to data collection, which was conducted between 10am and 11am on a weekday in July 2013\(^{65}\). A visual analysis of the video data enabled the determination of the traffic control state. This consists of the state of pedestrian crossing signal head, shown in Figure 7-8. There are three potential signals from the pedestrian signal head: red, green and black-out. In the case of this crossing, the green man (also known as the invitation to cross) lasts for 5-seconds,

\(^{65}\) This data was collected at the same time as the experiment detailed in Section 6.3.
immediately followed by a 4-second black-out period. The black-out period is the pedestrian clearing time, referring to the time needed for all pedestrians to complete the crossing movement (having begun during the green man), before the signal turns red.

For the purposes of this analysis, this entire 9-second period is considered as ‘available’ for pedestrians to cross. This junction, along with others in the area, is adaptively managed, with varying cycle and stage lengths implemented to optimise vehicle delay\textsuperscript{66}. Therefore, the length of the red signal for pedestrians varies in line with the length of traffic stages.

A metric (T) was established to represent the time (in seconds) before the pedestrian green man. This value is greatest immediately after completion of a pedestrian phase. The evolution of this metric over time for a hypothesized example is shown in Figure 7-9. At the start of the pedestrian crossing phase, T is equal to zero. During the pedestrian crossing phase (green man and black-out period), the value of T becomes increasingly negative.

\textit{Figure 7-9: Formation of T, time to pedestrian green man.}

The example shown in Figure 7-9 as idealised, as the local maximum value of T varies according to the changing characteristics of the traffic control system. In this experiment, no assumptions regarding cycle and stage lengths are made, and T is determined from video data for each traffic light cycle (and the associated pedestrian crossing phase).

\textsuperscript{66} Optimised through SCOOT (Split Cycle Offset Optimisation Technique)
On completion, each value of black carbon concentration recorded by the micro-aethalometer (and post-processed as detailed in Chapter 5) is associated with a specific value of $T$.

### 7.2.2 Results

A total of 47 traffic light cycles were observed during the monitoring period. All BC observations were averaged for a particular value of $T$. The resulting data are shown in Figure 7-10.

*Figure 7-10: Average black carbon concentration by time-to-green for pedestrians.*

The two phases are marked. Values of $T$ with fewer than 10 observations of BC were discarded.

The average BC concentration is shown to increase with decreasing values of $T$, reaching a maximum value of $13.33 \mu g m^{-3}$ 17-seconds prior to the commencement of the pedestrian phase. Between $T=70s$ and $T=50$ there is an extended period when BC concentration is approximately $6 \mu g m^{-3}$, relating to low levels of eastbound traffic passing the monitor. This may be considered the ‘background’ level of BC for the monitoring period.

Figure 7-11 shows error bars of +/- 1 standard error, demonstrating that variability is highest between 30 and 35-seconds before the pedestrian phase.
7.2.3 Pedestrian crossing compliance

The work to date has worked on the assumption that pedestrians will cross at the prescribed time and place. Wider consideration of traffic control at the junction indicates that, outside of the designated pedestrian crossing times, there are occasions when crossing the carriageway is more likely to be achievable.

The Cromwell Road junction operates on effectively two stages of traffic control, with north-south traffic in stage 1 and east-west traffic in stage 2. Right turns are mostly banned, whilst left turns are permitted in both stages (Figure 7-12). As such, an additional pedestrian stage may be requested during stage 2, providing opportunity to cross the north carriageway of the eastern arm (this was previously discussed in Section 6.3).

Section 6.4 indicated that traffic movements at the site (circled on Figure 7-12) were dominated by stage 2 of the traffic control. The equivalent traffic flow rate on this arm of the junction (both directions) for each stage of the junction were determined to be 149 vehicles/hour during stage 1 and 3488 vehicles/hour during stage 2.
Figure 7-12: Junction layout and stage control.

A pedestrian stage is requested to enable crossing of the northern carriageway of the eastern arm (circled).

In general, it was observed that the pedestrian crossing phase occurs approximately 10 seconds into stage 1 of the traffic control cycle. However, the lower vehicle flows during this stage result in crossing being plausible at any time. Therefore, this is the preferred stage for crossing. Consequently, pedestrians are more likely to be waiting at the kerbside (including at monitoring location A) during stage 2 of the traffic control cycle. Analogous to the metric T, established in Section 7.2.1, W is used to refer to the time until commencement of the preferred stage for crossing (Figure 7-13). In this case, W is equal to 0 at the beginning of stage 1, becoming increasingly negative during stage 1, and is greatest at the beginning of stage 2.

Figure 7-13: Formation of W, time to preferred traffic control stage for crossing.
In the same manner as the pedestrian crossing, the green and red times for the traffic control stages were determined from video data collected alongside black carbon concentration (previously described in Section 7.2.1). An average black carbon concentration was then calculated for each value of W. The results are shown Figure 7-14.

The average black carbon concentrations are shown to increase during stage 2, with a clear peak occurring in the latter half. The highest average black carbon concentration is 12.62µgm$^{-3}$ observed 11-seconds before the commencement of stage 1. Average concentrations then decrease during stage 2. Given the periodicity in pollution demonstrated at this junction previously (Chapter 6), this is an expected result. During stage 1, mobile source emissions are not in the vicinity of the monitor, and therefore, measured levels of BC are lower.

Figure 7-14: Average black carbon concentration by time to preferred traffic control stage (W) for pedestrians to cross.

The two traffic control stages, and the pedestrian stage, are marked. Values of W with fewer than 10 observations of BC were discarded.

67 Unlike previous reporting of BC concentration, data here are categorised as a function of T (or W) – for these data there is no evidence of a skewed distribution, and the mean average is taken.
7.2.4 Implications for pedestrian exposure and traffic management

A systematic link between the state of traffic control and the average level of black carbon concentration has been established. In particular, it has been determined that at the time immediately prior (in the region of 10-second duration) to the moment of crossing, pedestrians may be exposed to more than twice the concentration of black carbon than at other times.

Pedestrians are assumed to arrive at a uniform rate starting at the end of the previous stage, and comply with traffic regulations concerning time and location of crossings. This implies that pedestrians wait at location A until a green man is signalled, and do not cross beforehand. Given this, it is clear that a higher number are exposed to high magnitude events than the preceding low level. A simple example is shown in Figure 7-15.

*Figure 7-15: Black carbon concentration and number of waiting pedestrians.*

*Pedestrians are assumed to arrive in a uniform fashion, at a rate of 1 every 5-seconds.*
The exposure, $\lambda$ of a single pedestrian $i$ can be defined as the total black carbon concentration between the arrival time $T_1$ and the departure time $T_2$.

$$\lambda_i = \int_{T_1}^{T_2} BC$$  \hspace{1cm} \text{Equation 7-7}

The total pedestrian exposure $\Lambda$ for a given time period is therefore, the sum of all individual pedestrian exposures.

$$\Lambda = \sum_{i}^{i} \lambda_i$$  \hspace{1cm} \text{Equation 7-8}

This exposure metric does not take account of breathing rate or inhalation of the pollutant, being merely a multiplication of the number of pedestrians present and the black carbon concentration. However, by applying this to the simple example of uniform arrival rate, a cumulative BC concentration exposure is calculated (Figure 7-16). The higher concentration and greater number of waiting pedestrians leads to a higher exposure at smaller values of T. The cumulative exposure function demonstrates the importance of understanding the profile of concentration and of likely pedestrian arrival.

Two categories of approaches can be used to reduce exposure at sites like the one investigated here. Firstly, a reduction in BC concentration may be sought through systematic management of the traffic (including technological improvements and reducing the demand for travel as detailed in Section 2.4).

Secondly, a reduction in the number of pedestrians present during episodes of higher pollution would also have the desired effect of reducing cumulative exposure. This could be achieved through demand management and transport planning. Given that the concentration of BC has been shown to be related to the state of traffic control, some these approaches (such as junction reconfiguration) are unlikely to be independent. Separation of receptors and emission sources in space (rather than time), through the use of bridges and subways would at least serve to isolate the relationship. However, grade-separated infrastructure has proved unpopular due to concerns of safety and accessibility (discussed in Section 3.2). This result does provide advice to individual pedestrians, as exposure to pollution can be reduced by minimising waiting times at certain locations.
Figure 7-16: BC concentration exposure and cumulative exposure as a function of time to pedestrian green man.
7.3 In-transit pedestrian exposure

The analysis in this chapter has so far focused on the idea of waiting locations as a proxy for the position of pedestrians as pollution receptors. This idea has been useful in determining the location of a limited number of pollution sensors for the assessment of the variability in BC concentration at an urban intersection, and for subsequent analysis of pedestrian exposure.

However, this approach has a serious limitation in that it fails to acknowledge exposure of the pedestrian to BC concentration away from these waiting locations. In the case of pedestrian crossings, this is in reference to the time spent walking between waiting locations, including traversing the carriageway.

7.3.1 Exposure indices

Ishaque and Noland (2008) investigated the impact of pedestrians being delayed at a crossing. They determined that longer cycle times resulting in overall lower levels of vehicle emissions. However, this resulted in pedestrians being exposed to higher levels of pollution. This was due to the greater amount of time spent waiting. They described a pollutant exposure index by which pedestrian exposure to pollutants per distance unit travelled could be calculated. This can be generalised for a pedestrian travelling between points $a$ and $b$ at scenario $x$. An example is of a staggered pedestrian crossing (Figure 7-17).

*Figure 7-17: Staggered pedestrian crossing (from Ishaque and Noland, 2008).*

The crossing is divided into two segments, $x_1$ and $x_2$. Pollution receptor locations are marked as REC A and REC B. Image reproduced with permission of the rights holder, Elsevier.
Ishaque and Noland (2008) performed a modelled analysis, incorporating the traffic micro-simulation software VISSIM, the model emission model CMEM and the dispersion model CAL3QHC. The outputs of this modelling process are estimated pollutant concentrations at a series of receptor locations. The receptor locations A and B as marked on Figure 7-17. Due to the limitations of this approach, the pollutant concentration at the central island is assumed to be the mean of the receptor concentrations A and B. The exposure index is therefore equal to:

$$I_x = \frac{\tau_{1x}(3\zeta_a + \zeta_b) + \tau_{2x}(\zeta_a + 3\zeta_b)}{4(x_1 + x_2)}$$

Equation 7-9

Where:

- $I_x$ = exposure index (pedestrian exposure to pollutants per unit distance travelled)
- $\tau_{1x}$ = time taken to cover the distance $x_1$
- $\tau_{2x}$ = time taken to cover the distance $x_2$
- $\zeta_a$ = pollutant concentration at receptor $a$
- $\zeta_b$ = pollutant concentration at receptor $b$

Conceptually, this can be seen as the product of pollutant concentration and duration of exposure, normalised by the total distance travelled (as shown in Figure 7-18). If the time taken to complete both stages of the crossing is equal, this index is equivalent to linearly interpolating between the two receptor concentration points.

Figure 7-18: Exposure index for a staggered pedestrian crossing (from Ishaque and Noland, 2008).

**Note:** The Exposure Index equals the enclosed area (product of pollutant concentrations and duration of exposure) divided by the total length of crossing.

Exposure at the central carriageway is assumed to be the average of the two receptor concentration points (A and B). Image reproduced with permission of the rights holder, Elsevier.
The Cromwell Road site, detailed in Section 6.3, is also a staggered pedestrian crossing. Results presented in Section 6.3 demonstrated that assuming the concentration at the central island to be the mean average of that on either side of the link is inadequate, with the central island displaying the highest average concentrations. For example, median values at location D were shown to be 40% higher than those at E. The exposure index approach can be improved by introducing more points of concentration measurement, such as is shown in Figure 7-19 and Figure 7-20.

*Figure 7-19: Receptor locations and crossing segments at Cromwell Road intersection.*

![Diagram of receptor locations and crossing segments at Cromwell Road intersection.](image)

*Letter designations are equivalent to those used in Section 6.3 of this thesis.*

*Figure 7-20: Exposure index formulation for Cromwell Road staggered crossing.*

![Diagram of exposure index formulation for Cromwell Road staggered crossing.](image)

*Letter designations are equivalent to those used in Section 6.3 of this thesis.*
Whilst this approach results in a better estimate of exposure than the use of only two concentration points, the same fundamental flaw is present. That is, to assume that concentration changes linearly between two points in space.

For the initial index calculation used by Ishaque and Noland (2008), this has been demonstrated not to be the case, as the central island has greater average concentration than those on either side of the link, and can therefore, not be estimated from the average of these two locations. For the exposure index as proposed in Figure 7-20, the assumption is that pollutant concentration increases or decreases linearly when crossing from one side of the link to the central island, or between the two receptor locations on the central island. In the same fashion, there is no particular reason to believe that this is the case.

Some literature has indicated that mid-carriageway concentrations are significantly higher than those at the roadside (Colwill and Hickman, 1980; Holgate et al, 1999). However, such studies are generally conducted with vehicles and drivers in mind, and not pedestrians. Measurements may therefore be unfairly biased towards higher values. A lack of empirical data does not allow further investigation into this for this thesis, but is discussed further in Section 8.2. However, the improvements to the exposure index presented here now account for all possible waiting locations, and so all places of delay at the junction are captured.

7.3.2 Variability in pedestrian exposure

This method of exposure assessment is investigated further through empirical data collection. A pedestrian traversed the junction whilst information on black carbon concentration was collected at each of the receptor points. The pedestrian was equipped with a video camera that produced a time-stamped video, allowing location to be assessed. The pedestrian followed all traffic rules, crossing only when indicated to by the green man and at the designated location.

Data was collected between 10am and 11am on a weekday in July 2013\textsuperscript{68}. The pedestrian followed the same route throughout the data collection, continually traversing the pedestrian crossing, from one side to the other and back again; the route is B-C-D-E-D-C-B. This is split into segments so that exposure for each component of the crossing can be assessed (Table 7-10).

\textsuperscript{68} This data were collected at the same time as the experiment detailed in Section 6.3 and Section 7.2.
Table 7-10: Segments for pedestrians crossing the eastern arm of the Cromwell Road intersection.

<table>
<thead>
<tr>
<th>Segment</th>
</tr>
</thead>
<tbody>
<tr>
<td>B – C</td>
</tr>
<tr>
<td>C – D</td>
</tr>
<tr>
<td>D – E</td>
</tr>
<tr>
<td>E – D</td>
</tr>
<tr>
<td>D – C</td>
</tr>
<tr>
<td>C – B</td>
</tr>
</tbody>
</table>

The exact timing of the pedestrian crossing and the current state of traffic control means that transit times vary. For example, whilst the time taken to cross between B and C is likely to be constant, the amount time waiting at location B varies. Therefore, the amount of pollution exposed to which a pedestrian is exposed also varies.

Table 7-11: Crossing movements, waiting locations and BC measurement locations.

<table>
<thead>
<tr>
<th>ID</th>
<th>Action</th>
<th>BC measurement (exposure index component)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Wait at B</td>
<td>B</td>
</tr>
<tr>
<td>2</td>
<td>Cross B – C</td>
<td>½ B + ½ C</td>
</tr>
<tr>
<td>3</td>
<td>Walk C – D</td>
<td>½ C + ½ D</td>
</tr>
<tr>
<td>4</td>
<td>Wait D</td>
<td>D</td>
</tr>
<tr>
<td>5</td>
<td>Cross D – E</td>
<td>½ D + ½ E</td>
</tr>
<tr>
<td>6</td>
<td>Wait E</td>
<td>E</td>
</tr>
<tr>
<td>7</td>
<td>Cross E – D</td>
<td>½ E + ½ D</td>
</tr>
<tr>
<td>8</td>
<td>Walk D – C</td>
<td>½ D + ½ C</td>
</tr>
<tr>
<td>9</td>
<td>Wait C</td>
<td>C</td>
</tr>
<tr>
<td>10</td>
<td>Cross C – B</td>
<td>½ C + ½ B</td>
</tr>
</tbody>
</table>

Since the distance travelled is equivalent for both crossing movements, the results are not normalised as per the exposure index equation. ‘Exposure’ is therefore, a concentration metric, with units of $\mu$gm$^{-3}$. This is calculated as the integral of a concentration curve (as in Figure 7-20).
7.3.3 In-transit exposure results

In total, 35 crossings were made during the data collection period. This consisted of 18 in the southbound direction (B – E) and 17 northbound (E – B). Results are shown in Table 7-12.

Table 7-12: Exposure index concentration by crossing movement, summary statistics.

<table>
<thead>
<tr>
<th></th>
<th>Southbound B – E</th>
<th>Northbound E – B</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Duration (seconds)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean average duration</td>
<td>113.6</td>
<td>91.5</td>
</tr>
<tr>
<td>Maximum duration</td>
<td>204</td>
<td>153</td>
</tr>
<tr>
<td>Minimum duration</td>
<td>84</td>
<td>35</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>32.0</td>
<td>34.9</td>
</tr>
<tr>
<td><strong>Exposure index (concentration, µgm⁻³)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean average* concentration</td>
<td>1095.97</td>
<td>679.10</td>
</tr>
<tr>
<td>Maximum concentration</td>
<td>3364.69</td>
<td>1322.85</td>
</tr>
<tr>
<td>Minimum concentration</td>
<td>307.97</td>
<td>159.04</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>768.26</td>
<td>355.47</td>
</tr>
</tbody>
</table>

35 total crossings: 18 southbound, 17 northbound.

*The average is calculated over equivalent crossings. As in Section 7.2, the concentration is a function of traffic control state and pedestrian position, and as such there is no reason to believe the data are skewed as in point concentrations.

Average exposure index concentrations are 60% higher on the southbound crossing when compared to the northbound. Standard deviation of exposure index concentration is much greater for the southbound crossing. This indicates that pedestrians crossing southbound are subject to more variable levels of pollution that those crossing northbound. This is associated with a longer mean duration of 114-seconds on the southbound crossing compared to 92 on the northbound. The standard deviation of duration is similar for both crossings.

Further consideration can be given to the particular components of each crossing. Table 7-13 shows the average duration of each crossing movement (from Table 7-11), and the average concentration present during the movement. Both northbound and southbound crossings are dominated by the time spent waiting to commence the initial crossing, either at location B or E. Of the average total concentration exposure on the southbound crossing, 67% is incurred waiting at location B. For the northbound cross, 61% is incurred at location E.
Table 7-13: Average duration and exposure index concentration by crossing movement.

<table>
<thead>
<tr>
<th>Southbound B – C – D – E</th>
<th>Locations</th>
<th>Northbound E – D – C – B</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Wait B</strong></td>
<td></td>
<td><strong>Wait E</strong></td>
</tr>
<tr>
<td>75.4 seconds</td>
<td></td>
<td>54.4 seconds</td>
</tr>
<tr>
<td>9.68 µgm(^{-3})</td>
<td></td>
<td>7.60 µgm(^{-3})</td>
</tr>
<tr>
<td><strong>Cross B – C</strong></td>
<td></td>
<td><strong>Cross E – D</strong></td>
</tr>
<tr>
<td>5 seconds</td>
<td></td>
<td>5 seconds</td>
</tr>
<tr>
<td>7.96 µgm(^{-3})</td>
<td></td>
<td>8.99 µgm(^{-3})</td>
</tr>
<tr>
<td><strong>Walk C – D</strong></td>
<td></td>
<td><strong>Walk D – C</strong></td>
</tr>
<tr>
<td>6.5 seconds</td>
<td></td>
<td>6.7 seconds</td>
</tr>
<tr>
<td>7.35 µgm(^{-3})</td>
<td></td>
<td>10.17 µgm(^{-3})</td>
</tr>
<tr>
<td><strong>Wait D</strong></td>
<td></td>
<td><strong>Wait C</strong></td>
</tr>
<tr>
<td>21.9 seconds</td>
<td></td>
<td>20.4 seconds</td>
</tr>
<tr>
<td>10.91 µgm(^{-3})</td>
<td></td>
<td>5.54 µgm(^{-3})</td>
</tr>
<tr>
<td><strong>Cross D – E</strong></td>
<td></td>
<td><strong>Cross C – B</strong></td>
</tr>
<tr>
<td>4.7 seconds</td>
<td></td>
<td>5 seconds</td>
</tr>
<tr>
<td>8.18 µgm(^{-3})</td>
<td></td>
<td>7.91 µgm(^{-3})</td>
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</table>

Furthermore, time spent on and waiting at the central island is also shown to be significant accounting for around 26% of average total concentration exposure on the southbound crossing, and 27% on the northbound. This is illustrated by Figure 7-21, which shows the
contribution to total exposure index contribution. This is based on the average values shown in Table 7-13. In this case, actual crossing of the carriage way does not contribute a large proportion to the total due to the short duration of these segments. This is dependent on the assumption that the BC concentration on these segments is an average of the surrounding receptor points. Should this be an unfair assumption, it is possible that crossing the carriageway accounts for a much greater proportion of the exposure than seen here.

This situation represents a worst case scenario in that the time spent waiting at B/E is likely to be the maximum incurred. In these situations, a pedestrian is waiting the maximum possible time until a green man is available to cross. Assuming that the duration of the other crossing segments are fixed, the wait time at B (and E) can be varied to give an additional range of possible exposures for pedestrians using the junction.

To achieve this, results from Section 7.2 are used. Since the data were collected at the same time, and are for location B, this is appropriate.

Figure 7-22: Variation in concentration exposure with increasing wait time at location B.

Total concentration is calculated by summing the concentration as in Table 7-13. The amount of time spent at location B varies, and as such the total concentration (exposure index) also varies.
Figure 7-10 showed that the BC concentration pedestrian were exposed to varies by $T$, defined as the time to the pedestrian green man. From this, a vector of concentration varied by $T$ is produced. This was incorporated alongside average values for other crossing segments, giving a variable total black carbon concentration exposure for the southbound crossing. The results are shown in Figure 7-22. This shows that the total exposure to black carbon does not increase linearly with increasing time spent waiting at location B. The second curve (dashed line) in Figure 7-22 increases at a greater rate initially before the rate decreases. However, there is no plateau; as would be expected a longer time spent waiting will always increase total exposure.

From a policy perspective, this suggests that optimising traffic networks through parameters such as vehicle delay may be inadequate if they are at the expense of pedestrian wait times.

### 7.4 Summary: pedestrian exposure to black carbon

Chapter 6 yielded a rich dataset, comprising of multiple monitoring locations at an urban intersection at a high time resolution. This chapter has demonstrated various uses of these data with the ultimate aim of modelling human exposure to pollution. In doing so, the third research objective has been addressed. This objective, specified in Section 1.4, was to:

*Assess the exposure of pedestrians using traffic management infrastructure to black carbon pollution and identify the relationship to traffic management.*

Section 7.2 detailed a probabilistic examination of BC concentration and discussed the consequences for predicting air quality exceedances. Despite satisfying goodness of fit parameters, several model forms typically used for the air quality data were discarded due to their inability to capture low-occurring, high-magnitude events deemed important for studies in pedestrian exposure. The chosen model, of the log-logistic form, proved relatively successful in predicting the number of BC concentration events above stated thresholds. However, the prediction is noticeably worse as concentration increases. As there is no particular theoretical basis for this type of model, other than displaying a positive skew\(^69\), this highlights the need for rigorous empirical monitoring of on-street pollution.

High-magnitude events must be accompanied by the presence of human pollution receptors to form a pollution exposure ‘hotspot’. To incorporate pedestrian activity patterns into the

\(^{69}\) This was not unique to the log-logistic model, but a feature of all models tested.
assessment, two further applications were demonstrated. First of all, assuming compliance, BC concentration was analysed as a function of traffic control (Section 7.2). A systematic link between traffic control state and BC concentration was established. It was also determined that at the time immediately prior to the moment of crossing, pedestrians at this site may be exposed to more than twice the level of BC concentration that at other times. This peak further demonstrates the link between pedestrian exposure to pollution (receptors) and the operating characteristics of the vehicles (sources). By forming a metric relating to the green man signal at a crossing (the invitation to cross), an assessment can be made regarding the likely times that pedestrians wait at roadside locations. It has been shown that roadside concentration of black carbon, to which pedestrians are exposed, varies systematically with this metric.

A key result of Chapter 6 is that the concentration of a pollutant of interest (in this case black carbon) varies in space and time at a resolution higher than that of conventional monitoring networks. Both sites, Byres Road and Cromwell Road, contain measurement locations where the highest recorded median value was around twice that of the lowest recorded median value. Furthermore, this variability has been shown to follow a fixed periodic structure in relation to the traffic control state. This is a key result: i.e. by understanding the drivers of pollution, avenues can be sought to reduce the effects. Section 7.3 evaluated the variability of pedestrian exposure to pollution through different activity patterns and routes. The main contributor to exposure was shown to be waiting to cross the road. This was due to a combination of delay and high pollutant concentration. This result is significant, and should lead transport planners and traffic engineers to rethink the management of pedestrians in urban areas. In particular, where infrastructure induces pedestrian delay in highly polluted locations, such as the middle of a the road in the case of a staggered pedestrian crossing, guidance should be changed.

A greater understanding of the mechanisms by which exposure to black carbon is precipitated will assist in reducing the human health impact of vehicle induced poor air quality. This can be achieved through either systematic management of traffic (and by extension pedestrians) to concentration, or by management of pedestrian to avoid the interaction.
8 Conclusions and further work

This research has demonstrated the mechanism by which elevated levels of vehicle emissions are induced at urban intersections, with the ultimate result a degradation of urban air quality and increased pedestrian exposure. The use of aethalometers for simultaneous high-resolution measurement is achieved, producing a rich dataset from which variability in concentration is assessed and pedestrian exposure estimated.

This chapter will restate the research objectives and detail how each has been addressed over the course of this thesis. In summarising the findings, reference will also be made to the potential policy implications. Future research directions are discussed, with particular focus on elements of this thesis which may be developed.

8.1 Research objectives and conclusions

Chapter 1 explained the context and major themes of this research. As a result, four research objectives were defined, seeking to:

(1) Demonstrate the mechanism and evaluate the extent to which vehicle operating behaviour and emissions vary in the vicinity of traffic management infrastructure;

(2) Specify, evaluate and refine techniques for the measurement of black carbon concentration around traffic management infrastructure, for the use in studies of personal exposure;

(3) Identify the spatial and temporal variability in black carbon concentration and its relation to explanatory variables at traffic management infrastructure;

(4) Assess the exposure of pedestrians using traffic management infrastructure to black carbon pollution and identify the relationship to traffic management.

This section will discuss how each of these objectives has been achieved by making reference to relevant research findings.
8.1.1 Objective 1: Traffic infrastructure induced emissions

Road transport has many impacts of the environment and human health, contributing to problems of global climate change and poor local air quality. In order to address these problems, there is a particular need for research surrounding locations which are hotspots for vehicle emissions and pedestrian activity, and therefore human exposure to pollution:

- A thorough review of academic and technical literature was conducted to establish the factors which influence the formation of vehicle emissions in urban areas and subsequently identify pathways for improvement;

- It was argued that signalised urban intersections and pedestrian crossings (as two examples) are areas more likely to experience poor air quality due to the delay and subsequent acceleration of vehicles and the associated elevated demand for power;

- However, whilst research to date has investigated the influence of traffic management on vehicle emissions, it has generally failed to acknowledge the importance of pedestrians and other receptors;

- Furthermore, research has been carried out on too coarse a measurement scale to identify trends which are relevant to pedestrians, whom generally only occupy the pedestrian crossing or intersection site for a matter of seconds or minutes;

- Given this understanding of the underlying mechanisms, an experimental campaign was specified to provide an evaluation to the extent to which vehicle operating behaviour and emissions vary in the vicinity of traffic management infrastructure;

- Vehicle trajectory measurement through GNSS yielded acceleration noise as a single metric whereby the dynamic behaviour of a vehicle can be described. Through the use of this metric, behaviour of the vehicle was seen to vary both between multiple observations at a single infrastructure site, and between sites;

- It was demonstrated that vehicle behaviour is more variable at zebra crossings (where pedestrians cross on-demand) than at signal-controlled crossings. This was linked to the operation of the infrastructure, as in giving right-of-way to the pedestrians, vehicles will experience delay related to the arrival rate of the pedestrians;
In addition to the mechanism for increased emissions at places where pedestrians wait being demonstrated, in the case of on-demand infrastructure such as a zebra crossing it is suggested that the presence of a pedestrian will not only induce vehicle delay, but also increased vehicle emissions, which could lead to a degradation of location air quality;

Modelled results of NO\textsubscript{X}, PM\textsubscript{10} and total carbon demonstrated the implication for vehicle emissions, with the metric acceleration noise seen as a potential explanator and objective for minimisation through control;

The ratio of maximum to minimum observations of a pedestrian crossing site was shown to be at least 20% greater for all pollutants (petrol and diesel);

Diesel NO\textsubscript{X} emission rates have been identified as displaying a large variation, with multiple sites exhibiting a ratio of maximum to minimum in excess of 10;

It is also shown that high measurement resolutions (of at least 1Hz) are required, with further work required to determine the extent to which variability is lost currently (discussed in Section 8.2).

The findings of this work have implications to street design and traffic management policy in urban areas. Chapter 3 discussed the preference for at-grade pedestrian crossings due to issues of safety and security associated with grade-separated infrastructure. The potential for at-grade crossings to increase pollutant emissions from road vehicles in the vicinity of waiting pedestrians should also be incorporated into such decisions. It is therefore recommended that guidance on pedestrian crossings in urban areas be re-visited.

8.1.2 Objective 2: Measurement of black carbon

Black carbon has been identified as a pollutant of interest, forming a major component of exhaust particulate matter (especially for diesel vehicles such a public transport buses). In addition, as it has no non-combustion sources it is seen as a useful proxy for the presence of all vehicle tailpipe emissions:
• Despite the lack of regulations concerning black carbon concentration in urban areas, it is recognised as being harmful to human health in the same manner as other gaseous and aerosol species;

• Furthermore, whilst BC is a component of particulate matter, a review of relevant studies demonstrates that the proportion of BC in PM in urban areas is not constant. As such, measurement of PM alone is insufficient;

• In order to capture the expected variability in pollution and exposure, determined by the variability in explanatory factors, a high spatial and temporal resolution is required;

• Current research into personal exposure to black carbon fails to achieve this, and so there is a gap in understanding that should be addressed;

• Whilst the micro-aethalometer is an established and practical device for the high-resolution measurement of black carbon, much of the relevant literature concerning applications in urban environments fails to acknowledge the significant sources of error;

• In particular, instrument noise and operational procedures lead to measurement noise and the systematic occurrence of negative values when measuring at high-resolution (~1Hz). Whilst this can be combated through the use of longer time-averaging periods, this is not sufficient for studies of variability in pedestrian exposure;

• Further to this, second-order effects caused by filter-loading, specific to optical measurement of this kind, may lead to systematic under-estimation of black carbon concentration during prolonged measurement at high pollution sites;

• Performance of the instrument in urban environments relevant to this research is characterised with particular attention paid to the reported deficiencies and the ability to measure at a high time resolution (~1 Hz);

• A post-processing methodology is evaluated, incorporating use of ONA (the Optimized Noise Reduction Algorithm) for the elimination of negative values and the reduction of measurement noise;
- The potential for filter-loading effects to impact upon experimental results are also investigated, with a degradation in in measurement accuracy seen if $\Delta ATN$ exceeds 20;

- A linear correction is not thought to be appropriate, and recommendations are restricted to operational procedures of changing the sample filter ticket to ensure total $\Delta ATN$ does not exceed 20;

- Finally, in order to simultaneously monitor multiple locations independently, the agreement between multiple sensors was investigated;

- It was concluded that the use of an averaging-window (5-seconds) satisfactorily improves synchronisation between instruments without being at the expense of capturing the dynamic trend inherent within roadside pollution data.

Chapter 4 highlighted the lack of scrutiny that research into urban air pollution places on measurement techniques. This undermines the findings of such studies, and the subsequent understanding which potentially influences policy. Measurement rigour should not extend only to the instrument and measurement community, but also to practitioners.

8.1.3 Objective 3: Variability of black carbon

Using the framework for monitoring established in Chapter 5, an experimental campaign was conducted at two urban sites in the UK (London and Glasgow), designed to assess the spatial and variability of black carbon:

- BC concentration was shown to vary greatly between measurement locations in relatively small urban areas, with median values potentially more than double at one pedestrian waiting location at a junction compared to another;

- As such, the ability of coarse sensor networks to assess spatial variability in pollutant concentration is questioned and confirmed to be inadequate for local micro-environments such as signalised intersections;

- In particular, the use of a single monitoring station to characterise an urban environment is shown to be insufficient, with on-street average values potentially varying by more than 100% between locations around a site;
It was also shown that high pollution events at pedestrian waiting locations can be mutually exclusive, linked to the state of traffic at the time;

This demonstrates the potential for traffic engineers and transport planners to reduce exposure through careful management of the relative position of sources and receptors;

The variability of BC concentration in time is shown to be non-normal and positively-skewed, showing that the used arithmetic mean as a measure of central tendency is inappropriate;

This, along with the temporal variability present, questions how representative daily, hourly and 15-minute averages are of a particular time;

In areas subject to high levels of traffic flow (such as the Cromwell Road case study), a fixed periodic structure was found to determine the occurrence of high magnitude black carbon concentration, which in turn was related to the traffic control cycle;

Conversely, in areas of lower traffic flow, the periodic cycle of traffic is not found to influence BC concentration more than other explanators, including local meteorological events and the occurrence of high-emitting vehicles.

Current European and UK air quality regulations are based on coarse, point measures of air pollution. Whilst the scientific community may recognise the limitations of measurements made in this fashion, this research highlights the inadequacy of regulation in tackling problems of air pollutions. Furthermore, much research is based on data from monitoring networks which are designed to report for regulatory purposes. This not only misrepresents the problem of air pollution in urban areas, but endorses the idea that such networks are of sufficient resolution. A first step towards tackling air pollution problems in urban areas such as London should be to recognise that the problem is not currently understood, and therefore more effort should be focused on adequate measurement techniques.
8.1.4 Objective 4: Pedestrian exposure

Time-series outputs of the spatial variability of black carbon concentration at the Cromwell Road intersection were used to assess the variability and drivers of pedestrian exposure to black carbon:

- In a similar fashion to other pollutant species, it is demonstrated that a probabilistic approach to understanding high-magnitude BC concentration events may assist in forecasting future levels;

- Given the skewed nature of the data, several conventional and less conventional statistical model forms were tested, with the generalized extreme value providing the best statistical fit to the data;

- Several exponential-termed models were found to reproduce the general trend in peak pollution events, of decreasing occurrence with higher magnitude;

- However, a log-logistic model was selected based on being most able to account for low-occurring, high-magnitude events that are of importance for pedestrian exposure;

- As trends in concentration level were previously determined to be following of a fixed periodic structure, a systematic link between traffic control infrastructure and pedestrian exposure to pollution was sought;

- For the case of a signalised intersection, it was demonstrated that roadside concentration at the pedestrian waiting area increases as time approaches the crossing green man (invitation to cross), with a peak at around 10-seconds before crossing time;

- As such, waiting pedestrians are exposed to higher pollution as they wait for longer at the side of the road, with total exposure increasing in a non-linear fashion;

- Chapter 6 outputs were used in a model of pedestrian exposure at the junction, with an association between direction of crossing and total exposure, and in-transit exposure to BC varying by more than ten times as a result of different activity patterns;
- Time spent waiting at the side of the road was found to be potentially responsible for two-thirds of total exposure when using a pedestrian crossing;

- However, this was also recognised as variable depending on the preceding pedestrian behaviour, and therefore there is potential to reduce total exposure at these locations through management of the position of pedestrians.

The contribution to personal exposure of pedestrian delay at locations has important implications for street planning and traffic control engineering. In particular, this research highlights the need to consider both sources and receptors when managing transport networks for pollutant emissions. For example, optimisation of traffic networks to minimise traffic delay may be shown to also be beneficial for emissions. However, without an understanding of the movement of, and delay incurred by, pedestrians, an assessment of human exposure cannot possibly be made. Again, effort should be focused on better understanding the problem and to the development of analytical tools to assist planning and design.

8.2 Further research

In meeting the specified objectives, this research has successfully assessed the variability in vehicle dynamics, black carbon concentration and pedestrian exposure to pollution in the vicinity of at-grade pedestrian infrastructure. This section will, without being exhaustive, detail several areas of potential further research in this area which would benefit understanding of these topics.

8.2.1 Limitations of this work

As a starting point to specifying further research in this area, the limitations of the work contained in this thesis are summarised:

- The study into vehicle dynamics contained in Chapter 3 was purposefully limited to the study of a single driver and single vehicle. Whilst this allowed for robust interpretation of results, conclusions are limited to this single example;
In addition, whilst observations were made for a number of sites, the results are valid only for London, which may have different traffic management conditions than other urban areas;

Emissions can only be considered within the limitations of available models. As those used in this work are not vehicle specific, results can only be classed as indicative for the general vehicle fleet;

Whilst a measurement framework has been established for the use of micro-aethalometers, transferability to other situations (e.g. non-UK vehicle fleet or different combustion sources) has not been established;

Measurement campaigns are only valid for the particular time of observation. Whilst results, and particularly the mechanisms demonstrated, may be considered transferrable and relevant for other locations, time periods and seasons, this is unproven. As such, general principles cannot be derived until additional data is collected;

Assessment of personal exposure is limited by the use of static monitors as a proxy for pedestrian waiting locations. There is no evidence to support this as a reasonable assumption.

The conclusions drawn in Section 8.1 should be considered in the context of these limitations. Furthermore, they are helpful in specifying further research that is required in this subject area.

8.2.2 Transport, environment and health policy

This research has highlighted the need for better data concerning the spatial and temporal variability of poor air quality in urban areas. As understanding improves, transport, environmental and public health professionals will be better equipped to address existing and future problems associated with poor air quality.

Modelling and assessment tools should be designed with cross-disciplinary purposes in mind. Furthermore, there is a need to re-evaluate existing measures and policies to better determine their impact on local air quality and human health.
8.2.3 Vehicle dynamics and emissions formation

A relatively coarse resolution of 1Hz was used to assess vehicle dynamics in the vicinity of at-grade pedestrian infrastructure. Whilst variability is demonstrated, it has not been sufficiently concluded that the complete dynamic character of the vehicle has been fully captured. In order to be satisfied that a resolution is sufficient, a higher measurement resolution should be obtained to show that variation that is lost. This is especially important given the relatively small spatial area, as poor precision at the 1Hz measurement level could lead to substantial errors in spatial and temporal measurement. The measurement device used should also be validated against a recognised, high-precision positioning technique to ensure fidelity.

Allied to this is the use of instantaneous emissions databases for the assessment of vehicle tailpipe emissions. Whilst these offer a granularity beyond that of commonly utilised average speed models, there are several limitations which should be further addressed:

- They are not demonstrated to be applicable to individual vehicles;
- They are not demonstrated to representative of on-street emissions;
- They are not demonstrated to offer sufficient temporal resolution.

Given technological advances associated with portable emissions measurement systems (PEMS), the limitations of this research may be addressed by further study, particularly involving collection of empirical data regarding on-road tailpipe emissions of black carbon and other pollutant species. Development of better emissions assessment tools may have significant policy implications, better enabling transport planners and traffic engineers to evaluate schemes and proposals for interventions on the network.

8.2.4 Measurement of black carbon

This research has comprehensively characterised the limitations of black carbon measurement through micro-aethalometers. Whilst these offer a practical solution for high-resolution measurement of BC, further work is required to refine the techniques and yield more reliable results.

In particular, formation of a network of sensors that offers real-time reporting will most likely lead to better understanding of the error bounds associated with measurement at the 1Hz level. Whilst the advocated ONA technique for post-processing is shown to be successful in
eliminating measurement noise and the occurrence of negative values, the lack of (immediate) agreement between devices monitoring in the exact same location is evidence that there are further errors of measurement. Whilst it may not be possible to achieve a perfect alignment, formation of a time-synchronised dataset would result in a large volume of data which may indicate a systematic reason for error, and further development of an error correction model.

Whilst mitigated for, the problem of filter loading was not fully address in this research. It has been demonstrated that a linear correction is not appropriate, and therefore formation of a more appropriate correction form to combat filter loading effects is a logical next step. Filter loading is only one example of variations in the assumptions regarding the attenuation coefficient ($\sigma$), a proportionality constant. Since this defines the relationship between ATN (which is measured) and BC (the quantity of interest), further research into how this varies in different environments should be considered a priority.

### 8.2.5 Variability in black carbon concentration

This research demonstrated the variability in BC concentration, both temporally and spatially, at urban intersections. For practical reasons, monitors were deployed at proxy locations for pedestrian wait areas. In order to demonstrate the applicability of these, the variability of BC concentration over smaller areas should be assessed.

There are two other clear ways in which understanding of variability can be expanded. First of all, measurements may be conducted at other locations judged to be exposure ‘hotspots’, such as the mid-link pedestrian crossings and bus stops mentioned elsewhere in this thesis.

Secondly, in order to demonstrate the relevance of hotspots in the context of daily exposure profiles, further effort should be made to understand characterisation of BC concentration at other areas of, and away from, vehicle-induced pollution.

Meteorology was determined to be outside the scope of this thesis. This was justified due to the lack of capability transport planners have in influencing local micro-climates. Whilst effort was made to manage local variations in meteorology, both through experimental design and limited data collection, this is insufficient for the wider research problem. In order to properly specify solutions for problems of urban air quality, all drivers of pollution should be understood, even if the capacity to influence them is limited.
8.2.6 Exposure to black carbon

Statistical distributions which represent skewed data were investigated. Whilst a good model fit was identified, there are some concerns over the ability of these model forms to reproduce the low-occurring, high-magnitude events that are particularly important for pedestrian exposure. Since there is limited theoretical basis with which to select a model form, there is no particular reason to believe that future levels of BC concentration will follow such a distribution. Investigating this further requires more data, and particularly data of the same phenomena (BC concentration) at a different location (urban traffic-induced and otherwise).

This research has estimated black carbon exposure for pedestrians using an urban intersection through the use of concentration measurements at fixed locations and recorded trajectories. It is recognised this is limited as it assumes a linear change in concentration level between one fixed location and the next. There is no reason to believe this is the case. For example, closer proximity to pollutant sources may result in higher black carbon concentrations. Conversely, turbulence caused by vehicle wake may result in dispersion of emissions and lower black carbon concentrations. Further work should be conducted into measurement techniques so that in-transit pedestrian exposure can be measured at a high time resolution. In the case of the micro-aethalometer, this is not currently possible due to instrument noise. As such, alternative measurement techniques or technological advancement are required.

In addition, this research has considered only pedestrians using the intersection. In practice, motorists and other road users are also exposed to pollution in this locale. Before any optimisation of emissions, air quality and exposure can take place, the variability of other human exposure in the local should also be assessed.

Although based on empirical data, assessment of pedestrian activity was limited to an individual. Furthermore, this was conducted as part of the experiment, and therefore is not necessarily a proper representation of real-world activity patterns. In order to complete a full and integrated assessment of pedestrian exposure, activity patterns of a range of pedestrians in urban areas is required. Different characteristics of pedestrians, including walking speed, breathing rate and compliance with traffic rules must be considered to properly assess pollutant exposure and dose.
References


Jimenez-Palacios, J. L. (1999) Understanding and quantifying motor vehicle emissions with vehicle specific power and TILDAS remote sensing. PhD, Massachusetts Institute of Technology.


Appendices

Appendix I: European emission standards for passenger cars

Emission standards must be met before a passenger car is approved for sale in the European Union. Standards are defined by the vehicle and fuel type. Vehicles are tested over a regulatory test cycle, simulating urban and suburban driving.

The standards tabulated below are relevant to passenger cars; other standards exist for light-duty and heavy-duty commercial vehicles (including buses).

European emission standards for new diesel passenger cars

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European emission standards for new petrol passenger cars

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*Applies only to direct-injection engine vehicles
Appendix II: Example GPS output

An ANTARIS 4 GPS receiver was used for the collection of vehicle trajectories for analysis in Chapter 3. An example of the data output used for this investigation is shown below.

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</table>
Appendix III: GPS trajectory/AIRE conversion processing script

The use of AIRE was described in Section 3.7. Since AIRE was designed to be used with traffic micro-simulation software, AIRE input (car position) were generated from imported 1Hz vehicle speed trace data (named ‘data’) using the MATLAB processing script below. Input data consists of one or more columns of vehicle speed data, assumed to be in units of miles/hour at a frequency of 1Hz.

```
filenumber=size(data,2);
datahold=cell(filenumber,1);

for i=1:filenumber
    a=data(:,i);
a(isnan(a(:,1)),:)=[ ];
datahold{i,1}=a;
clear a
end

filename=cell(999, 1);
for i=1:9
    filename(i)=sprintf('carpositions00000%d.csv', i);
end
for i=10:99
    filename(i)=sprintf('carpositions0000%d.csv', i);
end
for i=100:999
    filename(i)=sprintf('carpositions000%d.csv', i);
end

header=['Timestamp,Link,Tag number,Base Type,Vehicle Type,Section Number,PosX (m),PosY (m),PosZ (m),Bearing (deg from N),Elevation (deg),Gradient (%),Acceleration (mpss),Speed (mph),Angular Velocity (deg/sec),Brake,Right Indicator,Left Indicator,Busboard'];

lk='''1:';
for i=1:filenumber
    speed=datahold{i,1};
    vector_length=length(speed);
t1=[1:vector_length];
t2=[1:0.5:vector_length];
    new=spline(t1, speed, t2);
```
nlength=length(new);
for j=1:nlength
    if new(j)<0;
        new(j)=0.0;
    end
end
sp=ones(nlength, 1);
for m=1:nlength
    sp(m)=new(m)*0.44704;
end
accel=ones(nlength, 1);
for n=2:nlength
    p=n-1;
    accel(n)=sp(n)-sp(p);
end
for n=1:1
    accel(n)=0;
end

link=cell(nlength, 1);
z=i+1;
link(:)={'link'};

for n=1:nlength
    link(n)=sprintf('%s%d',lk,z);
end

tagnumber=ones(nlength, 1);
basetype=ones(nlength, 1);
vehicletype=ones(nlength, 1);
sectionnumber=ones(nlength, 1);
posx=zeros(nlength, 1);
posy=zeros(nlength, 1);
posz=zeros(nlength, 1);
bearing=zeros(nlength, 1);
elevation=zeros(nlength, 1);
gradient=zeros(nlength, 1);
angular=zeros(nlength, 1);
brake=zeros(nlength, 1);
right=zeros(nlength, 1);
left=zeros(nlength, 1);
busboard=zeros(nlength, 1);

for n=1:nlength
    tagnumber(n)=5;
end

t2=t2';
new=new';

outid = fopen(filename{i}, 'w+');
fprintf(outid, '%s', header);
fprintf(outid, '
');
for k=1:nlength
    fprintf(outid, '%f,', t2(k));
    fprintf(outid, '%s,', link{k});
    fprintf(outid, '%d,', tagnumber(k));
    fprintf(outid, '%d,', basetype(k));
    fprintf(outid, '%d,', vehicletype(k));
    fprintf(outid, '%d,', sectionnumber(k));
    fprintf(outid, '%d,', posx(k));
    fprintf(outid, '%d,', posy(k));
    fprintf(outid, '%d,', posz(k));
    fprintf(outid, '%d,', bearing(k));
    fprintf(outid, '%d,', elevation(k));
    fprintf(outid, '%d,', gradient(k));
    fprintf(outid, '%f,', accel(k));
    fprintf(outid, '%f,', new(k));
    fprintf(outid, '%d', busboard(k));
    fprintf(outid, '
');
end
fclose(outid);
end
Appendix IV: Micro-aethalometer output data

The micro-aethalometer AE51 (used extensively in chapters 5, 6 and 7 of this thesis) produces output files in a .DAT format. This file format is used with device-specific AethLabs software, and can be exported to other data manipulation tools. An example output, including diagnostic information regarding flow, time-base and battery is shown below.

AethLabs
Device ID = AE51-S3-432-1107
Application version = 1.2.0.1
Flow = 100 mlpm
TimeBase = 1 s

Date/yyyy/MM/dd;Time;Ref;Sen;ATN;Flow;Temp;Status;Battery;BC

2013/06/11;15:58:01;874845;833773;4.81;102;23;0;89;
2013/06/11;15:58:02;874887;833761;4.81;104;23;0;89;20448
2013/06/11;15:58:03;875106;833919;4.82;103;23;0;89;20118
2013/06/11;15:58:04;874884;833672;4.83;102;23;0;89;14207
2013/06/11;15:58:05;874875;833636;4.83;102;23;0;89;10991
2013/06/11;15:58:06;874878;833611;4.83;102;23;0;89;11166
2013/06/11;15:58:07;874875;833570;4.84;104;23;0;89;14994
2013/06/11;15:58:08;874897;833541;4.84;103;23;0;89;19832
2013/06/11;15:58:09;874901;833497;4.85;102;23;0;89;19165
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2013/06/11;15:58:11;874883;833402;4.86;102;23;0;89;15559
2013/06/11;15:58:12;874883;833375;4.86;104;23;0;89;10617
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2013/06/11;15:58:16;875006;833357;4.88;103;23;0;89;14598
2013/06/11;15:58:17;874859;833161;4.88;102;23;0;89;22455
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