Indoor and outdoor exposure to PM_{10} in properties in the vicinity of urban streets

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Abstract

Occupants of buildings are exposed to indoor pollution from cooking and smoking and infiltrated outdoor pollution. The fabric of a building (doors, windows, ventilation etc.) has an influence on the infiltration of outdoor pollution into the building. In some studies, personal exposure has been investigated within homes and different transport modes. However, there is a lack of knowledge about pollution level variations along congested, busy and quiet roads in urban areas and its infiltration into the buildings located some distance from or along the roads. Only a few studies have investigated dynamic and static indoor/outdoor monitoring simultaneously in the same urban area to establish relative levels of exposure in different microenvironments. The aim of this study was to investigate PM_{10} exposure to indoor and outdoor air pollution simultaneously as a function of activity patterns in urban streets/areas.

This thesis describes the research carried out to investigate indoor and outdoor monitoring of PM_{10} exposure within and outside the air quality management area (AQMA), in Gosforth, Newcastle upon Tyne, UK. It examined the results of several days (at a sampling rate of one second or one minute) of monitoring of particulate matter (PM_{10}) levels simultaneously indoors (static monitoring) and outdoors (static and dynamic monitoring). The static monitoring was conducted in a number of houses and commercial premises in Gosforth and Jesmond areas in Newcastle whilst dynamic monitoring was conducted along the High Street in Gosforth. For static monitoring, PM_{10} monitors were installed in the lounge and kitchen in houses and the reception areas of the commercial properties. The property owners were asked to record activity (such as cooking, vacuum cleaning, door opening etc.) in a diary for at least one day during the week and a day at weekends. For dynamic monitoring along the High Street Gosforth, the observer carried a portable PM_{10} monitor and a GPS monitor in a back pack and walked on the pavement alongside the street. The observer also noted the traffic condition, passing of HGV and buses, crossing of junctions and other activities, such as street cleaning, construction, cigarette smoking, all of which influence PM levels.

Arc GIS software and statistical techniques were used to map spatial and temporal variations in PM_{10} levels recorded during several dynamic monitoring campaigns. Similarly, temporal variations in PM_{10} levels in houses were also plotted. Statistical techniques were used to fit distributions to the temporal variations in PM_{10}

concentrations. Timestamps of traffic activities and events aligned with the time series for the dynamic monitoring have helped to identify their influence on PM_{10} levels. This research applied the basic theory of the statistical technique known as 'decomposition' to reveal features in the probability density functions (pdfs) derived from static measurements (indoor/outdoor) as well dynamic. The decomposition technique was used to characterise the influence of various sources and events on indoor and outdoor PM_{10} levels, to provide a richer understanding of whether exposure is influenced by the traffic flow regimes in the vicinity of properties. The decomposition technique was used to characterize pollution measured indoors disaggregating the contributions to the total pdfs of sources such as cleaning, cooking, sleeping as well as from outdoors with sources mainly traffic activity, street works. The dynamic second by second averaged to one minute PM_{10} levels were also decomposed to map onto sources associated with traffic condition. Component distributions fitted by the decomposition technique were lognormal for both static and dynamic monitoring.

The results of the time series analysis have shown that monitored exposures vary substantially and are unique to the location and temporal variation of the measured microenvironment whether indoors in a kitchen or lounge, inside a commercial property or whether out of doors at the facade of a building or dynamically on a pavement alongside a road. The application of the decomposition technique was demonstrated to be promising. Static indoor and outdoor pdfs were mainly characterised by three or more log-normal distributions whilst the dynamically monitored data were fitted with three. Activities such as cooking, those associated with doors and windows opened or closed, use of extractor fan in the kitchen and vacuum cleaning were found to have a strong influence on indoor PM_{10} concentrations. Also, outdoor PM_{10} levels were governed more by the stop-start and idling characteristics of traffic rather than level of flow and traffic has little influence on temporal variations in indoor PM_{10} over time of the day. Instead it is the indoor activity that mainly governs the temporal variations in measured indoor concentrations of PM_{10}. Multi-lognormal distributions explained typically 83% to 98% of the measured variance in the total pdfs.

Finally, the author is not aware of any studies which have used the decomposition statistical technique to analyse dynamic and static indoor/outdoor monitoring in the same urban area to develop a fundamental understanding of the relative importance of the different sources of pollution in different microenvironments on personal exposure levels.

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Glossary of Terms

Term	Definition
AADT	Annual average daily traffic
ADF 2006	Approved Document F 2006 Ventilation and Indoor Air Quality Homes
AQMA	Air Quality Management Area
AQMS	Air Quality Monitoring Station
AQS	Air Quality Strategy
ASYM	Asymmetry (Model Parameter)
AURN	Automatic Urban and Rural Network
BRE	Building Research Establishment
C	Celsius
c	Centre (Model Parameter)
CO	Carbon monoxide
DEFRA	Department for Environment, Food and Rural Affairs
$f(x;a_i)$	Model Function
GHG	Greenhouse Gas
GPS	Global Positioning System
h	Height (Model Parameter)
HGV	Heavy good vehicle
HOPE	Health Optimisation Protocol for Energy-efficient Buildings
hwhm	Half width at half maximum (Model Parameter)
LA	Local Authority
LAQM	Local Air Quality Management
LAQMA	Local Air Quality Management Area
ME	Microenvironment
$\mu g\ m^{-3}$	Microgram per cubic metre
ms^{-1}	Metre per second
NAQS	National Air Quality Strategy
NO	Nitric oxide
NO_2	Nitrogen dioxide
NO_x	Nitrogen oxides
O_3	Ozone
PAHs	Polycyclic Aromatic Hydrocarbons
pdfs	Probability density functions
PM	Particulate matter
PM_{10}	Particulate matter with diameter of 10 micrometres or less
ppb	Parts per billion
ppm	Parts per million
RPMs	Roadside Pollution Monitors
SO_2	Sulphur Dioxide
TADU	Traffic and Accident Data Unit
veh/h	vehicles per hour
w	width (w = 2*hwhm) (Model Parameter)

Term	**Definition**
WHO	Word Health Organization
w_i	weight of each point (Model Parameter)
WSSR	Weighted sum of squared residuals
y_i	Actual data (Model Parameter)
χ^2	Chi square

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1 Introduction

Pollution is defined as "*The introduction by man into the environment of substances or energy to cause hazard to human health, harm to living resources and ecological systems, damage to structure or amenity or interference with legitimate use of the environment*" (Tiwary and Colls, 2010). The US Environmental Protection Agency has defined air pollution as "*The presence of contaminants or pollutant substances in the air that interfere with human health or welfare, or produce other harmful environmental effects*" (Environmental Protection Agency, 2006). Pollution can be solid, liquid or gaseous material. Air pollution emissions are either gaseous or particles, and can be divided into primary and secondary types. Primary pollutants are emitted directly into the air from a source. Secondary pollutants form when primary pollutants react in the atmosphere.

1.1 Background

Since the 1930s smog has been documented in some major cities as a result of using oil and coal, such as Los Angeles in the 1940s and London in 1952 (Vallero, 2008). Thus, researchers and legislators have addressed air pollution issues for a long time. The air quality concept and standards concerning it were introduced in the early 1970s. The Word Health Organization (WHO) published the first personal exposure guidelines for ambient particulates PM, sulphur dioxide SO_2, nitrogen dioxide NO_2 and ozone O_3 in 1987 (WHO, 1987). Subsequent guidelines (WHO, 2006), reduced the allowed personal exposure by more than 50% based on observable health effects. Epidemiological studies of mortality have supported the radical changes in the guidelines (Anderson, 2009).

Indoor air pollution has two sources: indoor and outdoor. Road transport, mainly vehicles, is the main cause of air pollution that is emitted in urban areas. The emissions concentrations outdoors are affected by meteorological conditions, site topography and traffic conditions (Murena and Favale, 2007). A canyon-shaped site may lead to an increase of emissions concentrations depending on meteorological conditions (Currie and Capper, 2009). The indoor sources are from cooking, cleaning (using a vacuum cleaner) and smoking activities. The usage of gas for cooking produces emissions, but its effects do not last more than a few hours (Bell *et al.*, 2004). Occupants of buildings face indoor air pollution from all of these sources.

Industry and road transport are the main sources of air pollution indicated by the report. Exposure and emissions vary greatly depending on the location. Industrial emissions of oxides of nitrogen NO_x and particulate matter of diameter up to 10 µm PM_{10} are one and a half times greater than those of road transport emissions (Environmental Audit Committee, 2010). However, road transport has been found to be responsible for up to 70% of air pollution in urban areas, so road transport contributes far more to the public's exposure to pollutants in these areas (Environmental Audit Committee, 2010). The report regarding air pollution in the UK (Environmental Audit Committee, 2010) stated that poor air quality affects up to 50,000 people a year in the UK, reducing life expectancy by seven to eight months on average.

1.2 Aim and Objectives

1.2.1 Aim

The main aim of this study was to investigate a novel approach to the analysis of PM_{10} exposure data monitored indoor and outdoor as a function of activity and whilst walking along quiet, busy and congested roads in UK urban areas using the decomposition technique.

1.2.2 Objectives

The main objectives of this study were:

1. To carry out a literature search of the policy background and relevant research.
2. To classify the roads in the study area according to the traffic flow regimes.
3. To identify properties on different road types at which to study indoor and/or outdoor concentrations and the road along which to carry out the dynamic measurement.
4. To identify and test the equipment available for the study and develop a methodological approach.
5. To statically monitor exposure to air pollution indoor and outdoor.
6. To collect dynamic data sets whilst walking along a street to understand the spatial and temporal variation of roadside pollution concentrations.
7. To apply the decomposition technique to both static and dynamic data sets to establish whether exposure events can be identified within probability density functions, pdf.

8. To interpret and discuss the results in the context of the suitability of the decomposition technique to identify pollution sources in both static and dynamic data.

1.3 Thesis Overview

This thesis is divided into nine chapters. This first chapter introduces general background of air pollution and its effects and the aim and objectives. The second chapter provides the state of art literature review on air pollution and personal exposure. This is followed by the third chapter with the development of the methodology. The result of equipment testing and the pilot survey are presented in chapter four. Chapters six to eight present the results and discussion of static and dynamic measurements. Finally, in chapter nine the conclusions are drawn and recommendations for further work presented.

2 Literature Review on Air Quality Policy and Personal Exposure

2.1 Introduction

This chapter presents the literature review on air pollution policy, personal exposure to air pollution and the analytical approach applied to static and dynamic personal exposure studies. This chapter begins with an overview of the air pollution policy, followed by the definition of key pollutants and their health effects on humans. The next section outlines the correlation between indoor and outdoor pollutant levels and provides the results of several studies of air pollution levels varying with respect to a number of factors. The personal exposure concept is explained in section 2.5, and then section 2.6 reviews a number of important personal exposure studies. Finally, section 2.7 gives a summary of this chapter and identifies the research gap.

2.2 Development of Air Pollution Policy in the UK

Air quality plays an important part in public health and well-being and is an essential element for all living organisms. The improvement of air quality will enhance the quality of living and extend life expectancy (Walters, 2010), and as a consequence there will be an improvement in economic development (Autrup, 2010).

The term 'standard' means *"a set of laws or regulations that limit allowable emissions (...) of air quality beyond a certain limit"* and guideline means *"a set of recommended levels against which to compare air quality from one region to another over time"* (Yassi, 2001).

Air pollution standards are designed to protect humans and the environment from harm based on emission rates, concentration or deposition rates. There are no precise concentrations, which cause observable harm to occur and therefore, setting air pollution standards is consequently a tough task. Setting standards has mainly been achieved by specific tests conducted in controlled conditions and short or long-term observations of the impact of environmental pollutants. Numerous paradigms have been used to conceptualize and address air pollution and in the UK, the main concept employed is emission standards for modelling air pollution.

National legislation for industrial emissions in the UK was passed as early as 1863; nevertheless, there was no regulation for domestic emissions until much later. In 1956, the Clean Air Act was passed as a result of the Beaver Committee report of December

1952 after the smog pollution event that occurred in London. In 1968 the Clean Air Act was extended, and the Clean Air Act 1993 was the integration of both of these previous acts. Controlling dark and black smoke emissions from chimneys was the main revision of the Clean Air Act. The main focus of this act was to regulate the processes of and emissions from boilers, for instance smoke, grit, dust and fumes, which were not previously regulated by the Environment Agency. In general, dark smoke is prohibited. Three standards of emission limits were set to regulate small boilers that initially start up from cold. In order to control air pollution, solid waste and water quality management have to be applied and regulated by one body across all these boundaries; and as a result, this led to the creation of the Environment Agency.

In 1997 the first National Air Quality Strategy (NAQS) was implemented in the UK. Since then, it has been updated, in 2000, in 2003 and finally, in 2007. The main theme of the 2007 update was the targeting of nine pollutants to be reduced to certain levels by 2010 and 2020. In order to meet these long-term standards and objectives, additional measures were imposed to target specific pollutants (NO_2 and O_3 were identified as particularly problematic pollutants).

A legal framework was established for Local Air Quality Management (LAQM). According to NAQS objectives, Local Authorities (LAs) have to conduct assessments and reviews of air quality in their districts. The LAs are assisted in this by intensive guidance from the Department for Environment, Food and Rural Affairs (DEFRA). Initial screening of all sources is reviewed in the first stage. Modelling and motoring could be required in the first stage. In case the objectives are substandard at this point, the second and third stages may be required. These two stages require further monitoring and modelling of locations, where objectives were not met for the proscribed pollutants. The Local Air Quality Management Area (LAQMA) must be declared by the Local Authority (LA) when the NAQS objectives are not met by the appropriate dates. Then the LA is required to produce a work plan for the LAQMA to achieve the air quality objectives. Low Emission Zones, park and ride, increased parking charges and improved traffic management are some of the schemes used in the working action plan.

Greenhouse gas, GHG, emissions were the main subjects of the Climate Change Act (2008). It established the target of lowering GHG emissions by 80% by 2050 and carbon dioxide CO_2 emissions by 20% by 2020. As part of this project, pollutants discharged from engines (diesel PM, NO_x, hydrocarbons HC and carbon monoxide CO) are regulated by exhaust pipe emission standards.

2.3 Sources and Health Effects of Air Pollutants

The association between health and air pollution has been demonstrated by several previous studies (Touloumi *et al.*, 1996; Brunekreef and Holgate, 2002). A 2010 report regarding air pollution in the UK (Environmental Audit Committee, 2010) stated that poor air quality affects up to 50,000 people a year by reducing their life-expectancy by on average seven to eight months. Also, long term exposure to particulates less than 2.5μm $PM_{2.5}$ has been estimated to cause about 29000 deaths over 25 years age group annually with equivalent to 306835 life years lost in the UK (PHE, 2014). As suggested by the results of three prospective cohort studies (Dockery *et al.*, 1993; Pope *et al.*, 1995; Abbey *et al.*, 1999), long-term exposure to PM is linked to an increase in mortality caused by respiratory and cardiovascular disease, and lung cancer. An association between PM concentrations in urban areas and the short-term cardiopulmonary effects has been indicated by many epidemiological and panel studies (Brunekreef and Holgate, 2002; Pope and Dockery, 2006; M. L. Scapellato and Lotti, 2007). Moreover, a further study described in detail the health effects of CO exposure (Pérez Ballesta *et al.*, 2008). In addition, a study by Touloumi *et al.* (1996) linked the short-term increase of ambient urban CO concentrations and significant increases in mortality.

Industry and road transport were the main sources of air pollution indicated by the Environmental Audit Committee (2010). Industrial emissions of PM_{10} are one and a half times those of road transport emissions. However, road transport was found to be responsible for up to 70% of air pollution in urban areas, consequently, road transport exposes the public to far more pollutants in these areas (Environmental Audit Committee, 2010). Furthermore, the number of vehicles has increased rapidly since the middle of the last century, with the motor vehicle growth rate surpassing the population growth rate by 3-4% (Tiwary and Colls, 2010). The transport sector is responsible for 40.2% and 25% of the total emissions of CO and PM_{10} respectively in the UK (Department for Transport, 2009). Therefore, transportation PM_{10} and CO emissions have to be examined due to the close proximity of these emissions to the human living space and the resulting exposure.

2.3.1 Particulate Matter (PM_{10})

The US Environmental Protection Agency defined particulates as, *"Fine liquid or solid particles such as dust, smoke, mist, fumes, or smog, found in air or emissions."* (Environmental Protection Agency, 2006). PM can vary in size, so PM_{10} are the particles that have an aerodynamic diameter equal to or less than 10 µm (see Figure 2-1). There are a number of sources of particulate matter as shown in Figure 2-2. The road transport sector accounted for 25% of PM_{10} emissions in the UK (Department for Transport, 2009). Diesel engines are associated with the production of coarse particles and petrol engines are associated with small particles (Air Quality Expert Group, 2005). During fuel combustion, solid carbonaceous agglomerates with volatile organic and sulphur compounds in the gas phase forms particulate matter though nucleation, adsorption and condensation procedures (Colls and Tiwary, 2009).

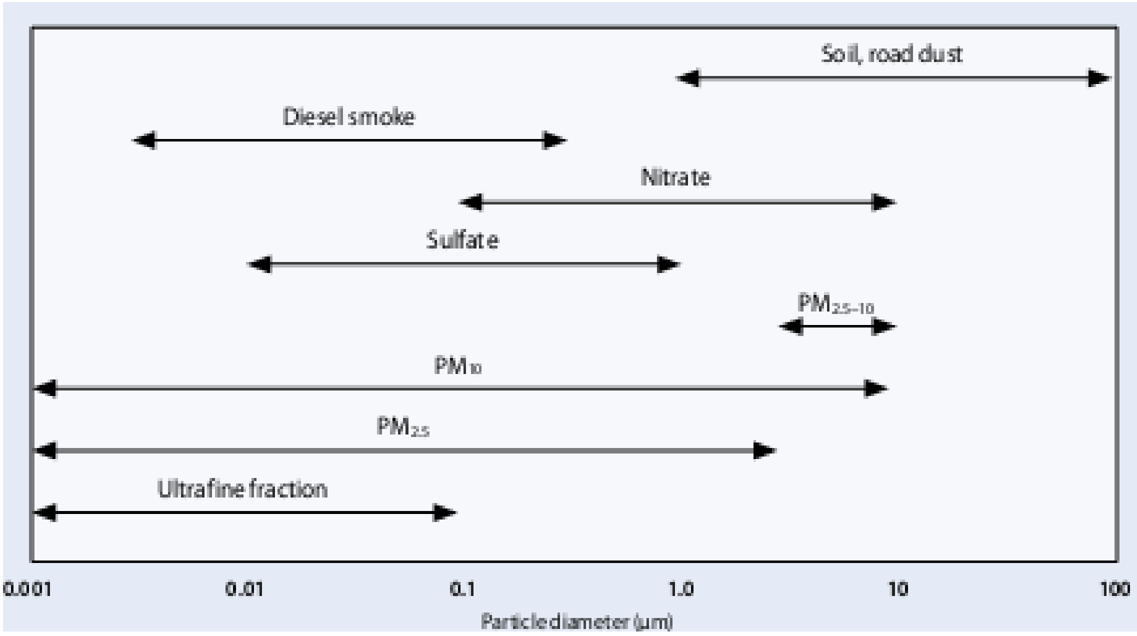

Figure 2-1 Size range of airborne particles and their major sources
(Source: (WHO, 2006))

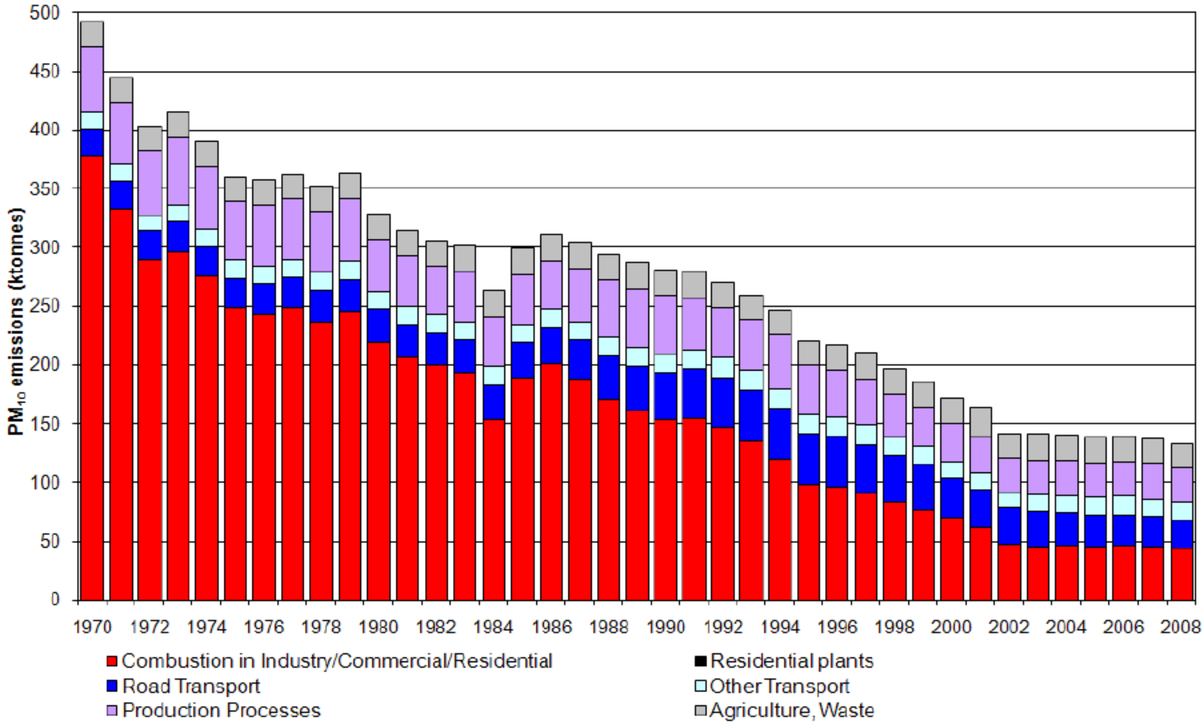

Figure 2-2 The UK emissions of PM_{10} for several sectors from 1970 to 2006 (Source: AEAT (2008) UK Emissions of Air Pollutants 1970 to 2006, AEA Group, Harwell, Oxfordshire,UK)

2.3.2 Carbon Monoxide (CO)

Carbon monoxide is defined as *"Colourless, odourless, poisonous gas produced by incomplete fossil fuel combustion"* (Environmental Protection Agency, 2006). The incomplete combustion of the fuel inside the combustion chamber produces CO, as the carbon molecules have not fully oxidized to CO_2 (Colls and Tiwary, 2009). The CO is mainly associated with petrol engines (DEFRA, 2007). There is a negative correlation between CO and vehicle speed (Chan *et al.*, 1996; Kristensson *et al.*, 2004) up to a speed of about 70 km/h. The concentration of CO is very low in the UK, and the mean concentration of 67 national sites is 2.3 mg m^{-3} (DEFRA, 2007). Since the early 1990s, there has been a decline in CO levels for a number of reasons. The introduction of catalytic converters, the agricultural field burning ban and switching to gas and electricity instead of coal in the domestic sector has caused a considerable reduction in CO emissions (DEFRA, 2007).

2.4 Indoor and Outdoor Pollution

In the 1960s and 1970s, health issues were reported by the occupants of institutional, commercial and residential buildings. Such problems included headaches, eye and respiratory irritation, breathing difficulties and asthma (Kreis, 1989). People spend a high proportion of the day indoors, so indoor air quality has a high correlation with personal exposure. The movement of people between different microenvironments was noted in the 1970s, when social scientists concluded that a considerable number of people in the USA spend most of their time indoors (Szalai, 1972; Chapin, 1974). Most people in urban areas in California spend more than 87% of their time indoors (Peggy L. Jenkins *et al.*, 1992). A UK study showed that people spend more than 80% of their time in the work place and at home (Kornartit *et al.*, 2010). Thus, it is necessary to focus on indoor air pollution and its relationship with the sources.

The indoor/outdoor ratio of air pollution has been investigated by a number of studies. Ní Riain *et al.* (2003) stated that there was a significant effect on indoor/outdoor ratios for naturally ventilated buildings located close to main roads, especially depending on the wind direction. However, indoor and outdoor temperature and a different wind speed had less effect on the indoor/outdoor ratio than wind direction. Moreover, indoor/outdoor ratio varies between summer and winter due to keeping windows closed during the winter. However, Chun Chen and Zhao (2011) discovered an enormous range in indoor/outdoor ratios as a result of the variation in the characteristics of buildings such as indoor sources, the geometry of cracks, metrological conditions, ventilation patterns and filtration use. Conversely, indoor combustion sources, for instance a fireplace, led to an increase in the indoor/outdoor ratio. The trickle ventilators provide a higher ventilation rate than the minimum design value when opened (Aizlewood and Dimitroulopoulou, 2006; Dimitroulopoulou, 2012). However, McKay *et al.* (2010) found that the trickle did not provide sufficient ventilation to meet the Approved Document F 2006 Ventilation and Indoor Air Quality Homes (ADF 2006 guidelines).

Aizlewood and Dimitroulopoulou (2006) found that the highest mean PM_{10} levels were recorded in smokers' homes. Indeed, Stranger *et al.* (2009) established that the indoor PM_{10} mean was much higher than the outdoor PM_{10} mean in a smoker’s house and furthermore that the indoor PM_{10} mean was lower than outdoor PM_{10} mean in a non-smoker’s house. This study concluded that smoking results in high PM levels. Jones *et al.* (2000) concluded that the average indoor PM_{10} levels for all sites were higher or equal to PM_{10} mean outdoor levels. Also, indoor PM levels are affected by indoor sources and the indoor/outdoor ratio varied. The presence of people and housework caused particles to re-suspend, and smoking and cooking activities caused the elevation of fine particles. Research concluded that high daily PM_{10} levels were due to the high rate of occupancy in a place (Krupińska *et al.*, 2012). The indoor and outdoor particles ratio was reviewed by Chun Chen and Zhao (2011). The $PM_{2.5}$ indoor/outdoor ratio was higher than the PM_{10} indoor/outdoor ratio due to the deposition rate and penetration factor characteristics. However, the particles indoor emission rates might result in significant differences between the indoor PM_{10} and $PM_{2.5}$, depending on the indoor sources characteristics. Indoor activities, for example cooking and smoking were the main indoor sources of pollutants.

A number of studies have been conducted to simultaneously monitor indoor and outdoor pollutants. Currie and Capper (2009) concluded that building a natural ventilation system can ease traffic pollutants (CO) peak concentration but that it varied according to the elevation across the building facade. Lawrence *et al.* (2005) found that NO and NO_2 indoor and outdoor levels had a positive correlation, although this was not the case for indoor and outdoor CO levels. Indeed, there was an increase in indoor CO levels only during the winter. The indoor weekly NO_2 mean was higher than the outdoor weekly NO_2 mean level only during winter (Krupińska *et al.*, 2012). Indoor NO_2 levels at properties with a gas stove were significantly higher than properties without a gas stove (Stranger *et al.*, 2009). The properties with a gas stove had a higher indoor/outdoor NO_2 ratio.

Ekberg (1995) stated that NO, PAHs and CO levels at peak hour traffic were more likely to be vehicle emission indicators. Another researcher, McAdam *et al.* (2011), concluded that NO and NO_x were better indicators of road traffic pollutants. In addition, NO and NO_x levels would increase due to a downwind, although NO_2 levels did not follow a similar pattern. Cassidy *et al.* (2007) developed a model to predict pollutants by using a predictive mean matching method and logistic regression method. They concluded that the model was valuable in representing the levels of pollutants. Halios and Helmis (2010) stated that outdoor NO and NO_2 levels peaked during morning and afternoon rush hours respectively. Also, indoor pollutants followed similar daily profiles to outdoor pollutants but with a different magnitude. Saraga *et al.* (2011) found that smoking, equipment emissions and re-suspension, which were caused by human movement, were found to be the main indoor sources of pollutants in office buildings. Furthermore, the air exchange rate, and the orientation and design of the buildings caused the variation in levels of pollutants (Saraga *et al.*, 2011).

2.4.1 Outdoor Levels of Pollutants

In one study, Chen *et al.* (2008) conducted cluster analyses by using the K means algorithm to classify a number of road links into six clusters. CO and NO_2 weekday profiles of a specific site of RPMs were associated with the cluster number at the closest road linked to this site. The correlation between $PM_{2.5}$ and PM_{10} concentration was better on the urban sites compared to the rural sites. Indeed, Namdeo and Bell (2005) found a correlation between PM_{10} and $PM_{2.5}$ at the urban sites studied but not at the rural sites. McAdam *et al.* (2011) concluded that there was no significant difference with respect to position of the monitored sample for SO_2, O_3 and CO. Also, $PM_{2.5}$ levels may differ with distance from the road; nevertheless, it was not affected by vertical distance near the main road. The wind direction had a significant effect on $PM_{2.5}$, NO, NO_2, and NO_x concentrations with distance and height away from the main road (McAdam *et al.*, 2011). The researchers concluded that NO and NO_x were better indicators of road traffic pollutants near the road than $PM_{2.5}$ and NO_2. Cassidy *et al.* (2007) concluded that the variables were useful for the model to represent the concentrations of pollutants. They used thirteen variables such as ambient pollution data and traffic flow. They used cluster analysis, which like other studies proved successful (Haibo Chen *et al.*, 2008).

2.4.2 Ventilation

Air pollution was investigated by a number of studies with respect to ventilation. Dimitroulopoulou (2012) published a review of ventilation, European regulation and health related to ventilation. The effect of major road closures on indoor and outdoor air pollution was investigated by Currie and Capper (2009). Preliminary results of this study showed that the natural ventilation of the building does alleviate the peak concentration of CO and this varies according to elevation across the building's facade. However, Lawrence *et al.* (2005) stated that outdoor sources of CO were not responsible for increasing the indoor CO levels and in fact indoor sources were responsible. No positive correlation between indoor and outdoor CO levels was identified. Ekberg (1995) concluded that there was an excellent correlation between the concentrations of combustion emissions which spread rapidly from outdoor air intake within buildings in urban areas. At traffic peaks, the concentrations of NO, PAHs and CO were more likely to be traffic emission indicators. Indoor NO and NO_2 concentrations followed a similar daily pattern as outdoors with some time lag (Halios and Helmis, 2010). Therefore, there are some pollutants that were most likely to be traffic emission indicators.

The driven factors (meteorological conditions and more specifically wind direction) of ventilation showed a significant effect on indoor/outdoor ratios for buildings located close to main roads (Ní Riain *et al.*, 2003). Also, the indoor/outdoor ratios vary between summer and winter, as the occupants tended to keep windows closed during the winter (Ní Riain *et al.*, 2003). However, the variation in the characteristics of buildings caused enormous ranges in the indoor/outdoor ratios such as indoor sources, the geometry of cracks, metrological conditions, ventilation patterns and filtration use (Chun Chen and Zhao, 2011). The reason for the inconsistency of the results of some indoor/outdoor ratio studies was due to the differences in measurement conditions. The $PM_{2.5}$ indoor/outdoor ratio was higher than the PM_{10} indoor/outdoor ratio due to the deposition rate and penetration factor characteristics. However, the particle matter source emission rates indoor might result in significant differences between PM_{10} and $PM_{2.5}$ levels, depending on the characteristics of indoor sources. The particle penetration factor would be equal to one in the case of opening the windows for natural ventilation of the buildings. While smoking or other specific indoor activities caused re-suspension of particulate matter, indoor/outdoor ratios might increase (Stranger *et al.*, 2007). In conclusion, there are several sources that result in poor air quality such as indoor smoke, poor ventilation and carpeting.

The trickle ventilators were found to provide a higher ventilation rate than the minimum design value when opened (Aizlewood and Dimitroulopoulou, 2006; Dimitroulopoulou, 2012). However, this study had a small sample size of 11 buildings. On the other hand, the trickle ventilators did not provide sufficient ventilation to meet the ADF 2006 guidelines (McKay *et al.*, 2010). In addition, the wind speed and temperature were found to be important variables (Lai *et al.*, 2006), and opening a door would cause indoor concentrations to be elevated (He *et al.*, 2004). Saraga *et al.* (2011) stated that levels of indoor pollutants were dependent on the air exchange rate and the orientation and design of the buildings, which varied from site to site without taking the emissions into the account.

2.4.3 Indoor Sources of Air Pollution

As expected indoor/outdoor ratios of the pollutants increases with the existence of indoor sources (El-Hougeiri and El Fadel, 2004). The indoor sources were found to vary in influence on particulate matter and other pollutants though the day. The presence of fine particles was elevated during cooking (Jones *et al.*, 2000). A finding consistent with He *et al.* (2004) who found that fine particle concentrations were higher during cooking specially grilling and frying. Indeed, $PM_{2.5}$ emissions were linked directly to cooking activities (Tan *et al.*, 2012) and found to be an important factor by Lai *et al.* (2006). CO concentration increased during cooking using a gas cooker and gas cookers are a significant source of NO_2 (Tan *et al.*, 2012). Moreover, De Bruin *et al.* (2004) concluded similar findings of a significant increase in CO exposure at home due to gas cooking. The mean concentrations of NO_2 at houses without gas stoves were significantly lower than those with gas stoves (Stranger *et al.*, 2009). However, Franklin *et al.* (2006) stated that there was no significant difference between houses with gas cookers and those without gas cookers in relation to the NO_2 concentration averages. Nevertheless, the peaks of NO_2 concentrations at houses with a gas cooker were significantly higher than the peaks of NO_2 concentrations at houses without one. In conclusion using a gas cooker elevated indoor pollutants levels.

2.4.4 Smoking Indoors

Indoor smoking causes an increase in levels of indoor particulate matter and it is an important variable (Jones *et al.*, 2000; He *et al.*, 2004; Lai *et al.*, 2006; Saraga *et al.*, 2011). A study by De Bruin *et al.* (2004) found that there was a significant increase in CO exposure at home due to smoking. Aizlewood and Dimitroulopoulou (2006) noted that the highest PM_{10} mean concentration was recorded in smokers' homes. The indoor PM_{10} was much higher than outdoors at a smoker's house (Stranger *et al.*, 2009). Also, the indoor PM_{10} was higher than the outdoors at a non-smoker's house. Smoking increased PM_{10} levels by 46% (Stranger *et al.*, 2007). In conclusion, particulate matter levels were the highest in a smoker's house if they choose to smoke indoors.

2.4.5 Summary

Re-suspended particles are caused by people present in a closed space particularly when undertaking activity such as housework (Jones *et al.*, 2000; Saraga *et al.*, 2011). Also, the amount of indoor activity has an effect on daily indoor PM_{10} levels (Krupińska *et al.*, 2012). The high daily PM_{10} levels were due to the high rate of occupancy during that time (Saraga *et al.*, 2011; Krupińska *et al.*, 2012). PM_{10} concentrations at schools were higher than in residential houses (Stranger *et al.*, 2009), which is caused by occupancy and high activity levels in schools. Salt crystals, mineral fibres, skin flakes and dust fragments were found to be the main composition of PM_{10} samples (Tan *et al.*, 2012). Also, an increase in fine particle concentrations were caused by burning a candle (He *et al.*, 2004). Internal door opening patterns during high $PM_{2.5}$ level periods influence personal exposure and indoor $PM_{2.5}$ (McGrath *et al.*, 2014). It should be noted that indoor pollutant levels can be affected by cultural practices and preferences, and living styles (Lai *et al.*, 2006). He *et al.* (2004) concluded that a specific type of activity was associated with a specific size range of particles such as sweeping a floor being associated with particle mass. In an office building, smoking and re-suspension caused by human movement inside the building and equipment emissions were found to be the main indoor sources of pollutants (Saraga *et al.*, 2011). Therefore, the number of occupants and their activities has an influence on the re-suspension of particulate matter.

2.5 Personal Exposure

2.5.1 Personal Exposure Definition

The significance of personal exposure was introduced in the early 1980s (Duan, 1982; Ott, 1982), which advocated that the human was the most important receptor of pollutants in the environment. Ott defined the term *"exposure"* as *"an event that occurs when a person comes into contact with the pollutant"* (Ott, 1982; Christian Monn, 2001). This is a definition of a moment at a specific time "t" when a person comes into contact with pollution at a concentration level of "c" as shown in Figure 2-3. It refers to pollutant contact, which does not necessarily mean inhaling or ingesting the pollutant. The duration of exposure is considered by integrating the concentration over time "t_a"; the result of this calculation is an integrated exposure (units: µg hr m^{-3} or ppmh), as shown in Figure 2-3. Exposure is the contact in the ambient media; the average exposure is the total exposure divided by the time over which the levels were measured in units of ppm. The integrated exposure is the integral (t = 0..t_a) $c_i(t)$ dt (e.g. ppmhr). However, this definition refers to pollutant contact, which does not necessarily mean inhaling or ingesting the pollutant.

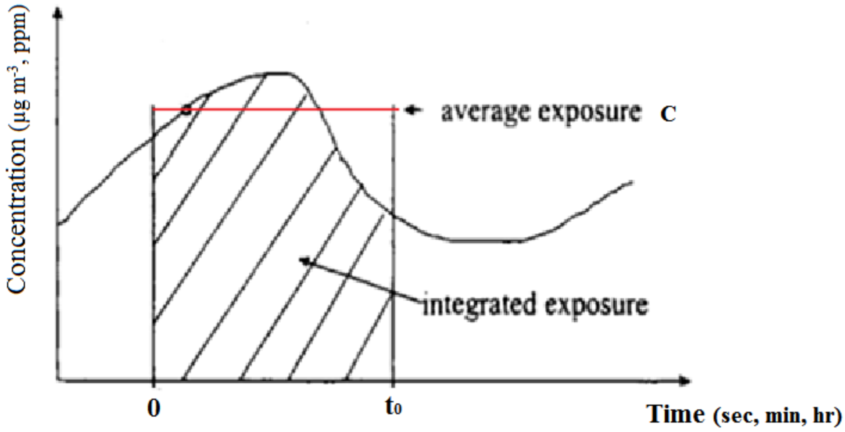

Figure 2-3 Exposure definition diagram
(modified from (Christian Monn, 2001))

There are direct and indirect assessments of personal exposure (Ott, 1982). A personal monitor (personal sampler/biological marker) is a direct assessment of air pollution exposure. A passive sampler is one of the most easily used and widespread devices for personal sampling. The indirect approach has two means to assess personal exposure, which are estimation by a model or by a stationary monitor (Ott, 1982; Paul J. Lioy, 1995). Models can be used to explore the proposed measures to reduce exposure, and can be useful when measurements are limited or unavailable. One of the indirect measurements is an ambient measurement, which has been used in many epidemiological studies. The assumptions are that people living in a defined area have similar exposure to the same pollution concentrations; consequently, populations can be measured by a unit rather than as individuals. In Europe and the USA, national institutions and local councils have established ambient monitoring networks, which provide online monitors with data which has sufficient time resolution, accuracy and precision. Personal exposure has three assessment methods, namely personal monitoring, ambient measurement and the microenvironment method.

The term microenvironment (ME) is used to define locations and is defined as a *"chunk of air space with homogeneous pollutant concentration"* (Duan, 1982). Indoor and outdoor locations, such as living rooms, bedrooms or the front of the home can be represented by microenvironments. The estimation of personal exposure needs selective MEs measurements and a time-activity/time-budget questionnaire. Whilst the MEs monitors are easy-to-use, time-activity diaries because they rely on a third party to complete they are often only indicative and need to be used with caution. However, together they can be very useful and form the basis for the approach adopted in this study.

2.6 Personal Exposure Studies

Personal exposure studies have been carried out by a number of researchers to measure exposure to indoor and outdoor pollutants. CO exposure occurred indoors as most of the participants spend over 90% of their time in indoor microenvironments (De Bruin *et al.*, 2004). These studies were divided into several groups based on people and the type of microenvironment.

2.6.1 Children

Child exposure to air pollution had been investigated by a number of researchers. They tried to discover the main variables that influence exposure of children to pollutants. By selecting a number of participants living or attending school at different distances from the main roads, they examined the effects of traffic pollution on the participants. Two studies identified considerable personal exposure to pollutants in some cases (Van Roosbroeck *et al.*, 2006; Van Roosbroeck *et al.*, 2007). Van Roosbroeck *et al.* (2006) found that children living near busy roads have a significantly higher exposure to soot, NO, NO_2 and NO_x than children living near roads that are less busy. Also, Van Roosbroeck *et al.* (2007) concluded that children attending school near a freeway have a significant increase in exposure to soot and NO_x. However, they did not find a noteworthy increase in exposure to pollutants for the children attending a school near a ring road.

2.6.2 Pregnant Women

Few studies have been conducted on the exposure of pregnant women to air pollution. One of these studies was conducted to predict personal exposure to traffic-related air pollutants in Vancouver, Canada (Nethery *et al.*, 2008). It established that gas stoves are a very important factor in predicting a variation in personal exposure to traffic related pollutants. This study corroborated the findings of another study in relation to the influence of a gas stove on exposure to pollutants (Franklin *et al.*, 2006; Stranger *et al.*, 2009).

2.6.3 Workers

A number of studies have examined air pollution exposure of workers. They started with personal and building characteristics, daily activities and cooking activities. Then, they took measurements of pollutants at specific microenvironments. They examined the influence of factors, such as smoking and cooking, on personal exposure to the pollutants. Thus, the main factors of personal exposure to the pollutants were identified.

The main cause of PM_{10} exposure was smoking (Maria Luisa Scapellato *et al.*, 2009). Ambient PM_{10} was the main source of PM_{10} of exposure to high pollutant areas for non-smoking participants (Maria Luisa Scapellato *et al.*, 2009). However, other studies stated that particles were caused by people present in a place and housework (Jones *et al.*, 2000; Saraga *et al.*, 2011). Therefore, indoor activity and the high number of occupants increased indoor PM_{10} levels (Saraga *et al.*, 2011; Krupińska *et al.*, 2012). The main composition of PM_{10} was salt crystals, mineral fibres, skin flakes and dust fragments (Tan *et al.*, 2012). Therefore, the main source of indoor PM_{10} was the number of occupants and their activities. Moreover, the seasons and temperature had a significant influence on PM_{10} exposure (Maria Luisa Scapellato *et al.*, 2009).

Employees' exposure to air pollution was investigated in a number of studies. Kornartit *et al.* (2010) demonstrated, firstly that NO_2 levels and gas cookers had a significant correlation compared with electric cookers, secondly personal exposure to NO_2 was a significant influence on indoor sources, especially with gas cookers and finally a further study of infiltration rates was recommended, such as open windows. Piechocki-Minguy *et al.* (2006) also found that there was an increase in exposure due to an increase use in gas appliances for indoor heating and meteorological conditions during the winter. Indoor activity, ventilation and meteorological conditions influence NO_2 exposure indoors (Piechocki-Minguy *et al.*, 2006; Kornartit *et al.*, 2010). Conversely, traffic emissions had a weak influence on indoor pollutants levels. Other studies discovered that NO_2 exposure was dependent on heating systems and cooking fuel. Furthermore, there was a very low correlation between personal exposure to NO_2 and fixed ambient air monitoring sites. In addition, personal exposure to pollutants on transport was high when travelling by car (Kousa *et al.*, 2001; De Bruin *et al.*, 2004). Using ambient fixed site monitoring data provided poor predictions for actual personal exposure to pollutants (Kousa *et al.*, 2001; De Bruin *et al.*, 2004). However, levels of microenvironment pollutants and data collected from time activity diaries provided a better prediction model for personal exposure to NO_2 (Kousa *et al.*, 2001). Indeed, work place location, coupled with outdoor NO_2 concentration and the use of gas appliances were shown to have a strong influence on NO_2 exposure (Kousa *et al.*, 2001).

2.6.4 Pedestrians

Dynamic and static monitoring of traffic pollutants was conducted in several studies on a number of streets. CO and $PM_{2.5}$ pedestrian exposure were higher than the fixed monitoring station data (Kaur *et al.*, 2005b). Street geometry, road traffic and meteorological conditions variables were examined in depth in some studies. Whitlow *et al.* (2011) concluded that there was no relationship between $PM_{2.5}$ levels and traffic flow and this finding contradicted other research. Fine particle concentrations were influenced by traffic and site topography after accounting for other factors (Boarnet *et al.*, 2011; McAdam *et al.*, 2011). In addition, particle concentrations varied significantly among different streets due to the traffic density (McAdam *et al.*, 2011). Higher fine particle concentrations were associated with lower wind speeds and higher temperatures (Boarnet *et al.*, 2011). The traffic variable was correlated with the pollutants levels, but wind speed and direction were not significantly associated with any of the pollutants (Zwack *et al.*, 2011). The position of the footpath relative to the road and which side of the road a person used had an influence on pedestrian exposure to $PM_{2.5}$ (Kaur *et al.*, 2005b).

Heavy traffic flow has a strong correlation with increasing levels of pollutants (Zwack *et al.*, 2011). Daily total exposure was significantly affected by high short-term pollutant concentration recorded as vehicles passed by McAdam *et al.* (2011). The pollutant measurements on both sides of the streets showed that narrow street canyons, which tend to obstruct air circulation, caused a similar or different level of concentration at different sides of the street, depending on the meteorological conditions; wider street canyons tend to have better ventilation (McAdam *et al.*, 2011). Indeed, $PM_{2.5}$ levels were influenced by atmospheric stability during the morning (Whitlow *et al.*, 2011). There was an important decrease in pollutant levels at 100-200 metres away from the road, which suggested the importance of a green space to reduce the pollutant levels (Zwack *et al.*, 2011).

2.6.5 Transport Microenvironment

Air pollution in transport microenvironment was monitored in several studies to investigate influencing factors. This section gives details of some of these studies. An increased time spent travelling in vehicles had a significant influence on the cumulative exposure to pollutants (Zhang and Batterman, 2009). CO exposure in a transport microenvironment was highest when travelling in vehicles, especially cars or taxis (De Bruin *et al.*, 2004).

There was a poor prediction of exposure to air pollution when using ambient air quality data (De Bruin *et al.*, 2004; J. Gulliver and Briggs, 2004). J. Gulliver and Briggs (2004) stated that PM_{10} personal exposure was higher when walking. However, personal exposure to total particulate matter during walking was significantly higher than when travelling in a vehicle (John Gulliver and Briggs, 2007; Briggs *et al.*, 2008). There was significant positive association between exposure to coarse particles and heavy goods vehicle density (Briggs *et al.*, 2008). Walking, individual vehicles (bus, lorry) and passing through hotspots (busy intersection) was found to influence exposure (John Gulliver and Briggs, 2007). Furthermore, coarse particle exposure during walking had a significant positive association with wind speed (Briggs *et al.*, 2008). Namdeo *et al.* (2014) found that PM_{10} exposure where commuting by electric vehicle and bicycle were lower than by bus during a study in Newcastle UK.

2.6.6 Personal Exposure near Major and Minor Roads

Indoor and outdoor air pollution was examined near main and minor roads in a number of studies. These studies examined the effect of road traffic on indoor personal exposure, considering to the distance between the road edge and the facades of properties, and other relevant factors.

Most of the studies have found that the levels of pollutants at houses near a major road are generally higher than those in the background (Heudorf *et al.*, 2009; Boogaard *et al.*, 2011; Lawson *et al.*, 2011). Outdoor particulate matter concentration was lower at rural sites than urban sites (Heudorf *et al.*, 2009). PM_{10} and NO_x levels were higher on major roads compared to an urban background location in Netherlands (Boogaard *et al.*, 2011). In addition, the mean levels of indoor PM_{10} and CO concentration for the houses less than 50m away from main roads were considerably higher than those more than 300m distance from main road (Lawson *et al.*, 2011). PM_{10} and $PM_{2.5}$ measurements outdoor were higher than indoor, which could be due to the absence of important indoor sources (Kingham *et al.*, 2000) during the surveys however a significant correlation between indoor and outdoor measurements of PM_{10} and $PM_{2.5}$ were observed. In contrast, indoor PM_{10} concentrations found by Lawson *et al.* (2011) not to be correlated with outdoors for houses near main roads. Boogaard *et al.* (2011) found that there was a limited contribution by traffic, particularly with winds parallel to the road. The researchers (Boogaard *et al.*, 2011) also found that were different patterns of behaviour of fine PM between different types of street, especially canyon type streets.

Interestingly, indoor particulate matter concentrations and the number of occupants in a building or activity had a high correlation (Heudorf *et al.*, 2009), which is similar to findings made in other studies (Jones *et al.*, 2000; Stranger *et al.*, 2009; Saraga *et al.*, 2011; Krupińska *et al.*, 2012). Heudorf *et al.* (2009) concluded that there was a decrease in indoor particulate matter concentrations caused by increasing cleaning activity to remove sediment. But, Heudorf *et al.* (2009) stated that ventilation did not have a consistent influence on particulate matter levels indoors.

2.6.7 Personal Exposure Estimation

A number of researchers used personal exposure models with indoor and outdoor pollutants measurements (Johnson *et al.*, 2000; Freeman and Saenz de Tejada, 2002; Pérez Ballesta *et al.*, 2008). Factor and cluster analyses along with the Pearson correlation were performed to examine the occurrence of an event of exceeding the PM_{10} limit with regard to meteorological conditions (Sfetsos and Vlachogiannis, 2010). Sfetsos and Vlachogiannis (2010) found that wind conditions, temperature, temperature differences, relative humidity and window/door configurations change over time and therefore, have an effect on the infiltration rate of particulate matter. Clench-Aas *et al.* (1999) developed a model to identify the areas that either exceed air quality guideline limits or have high pollution levels to predict personal exposure. Also, Gerharz *et al.* (2009) developed PM personal exposure model, which predicted PM levels during sleeping periods to be lower than the actual. Meteorological conditions and window/door configuration were the variables that had an influence on PM infiltration rates (Bennett and Koutrakis, 2006). Raymer *et al.* (2009) stated that personal exposure measurement was similar to indoor pollutants levels and was significantly higher than outdoor pollutants levels in general. Moreover, the resulting personal exposure model was successful in predicting actual exposure by taking real time data from diaries.

Indeed, activity patterns had a considerable influence on personal exposure (Harrison *et al.*, 2002). As found in previous studies, the most import factors of personal exposure were indoor sources and ventilation habits (Johnson *et al.*, 2000; Harrison *et al.*, 2002; Pérez Ballesta *et al.*, 2008; Gerharz *et al.*, 2009; Raymer *et al.*, 2009). Overall, microenvironment measurements were seen as a good representation of personal exposure to pollutants.

2.7 Techniques used to Identify Sources in Microenvironments

There are a number of techniques used to identify the different contributions to concentrations monitored in microenvironments made by indoor and outdoor sources. These include inspection of time series, chemical analysis and regression analysis. These will be discussed in turn.

2.7.1 Time Series Inspection

A simple inspection of time series was carried out by a number of researchers (Jones et al., 2000; Lai et al., 2004; Saraga et al., 2011; Tan et al., 2012). Jones et al. (2000) concluded from simple time series analysis that the presence of people and cooking activities caused the elevation of particulate matter. This was consistent with time series analysis which showed that the cooking activities were concurrent with high peaks of PM levels (Tan et al., 2012) in time series data. Lai et al. (2004) illustrated CO exposure peaks corresponded to cooking or smoking activity.

2.7.2 Chemical Analysis

Another method was particle composition analysis to identify the source of particulate matter. Tan et al. (2012) conducted elemental analysis of PM_{10} samples which revealed sources such as outdoor, cooking or from humans and indoor sources included cooking activity such as salt particles and burned food emission etc. Also, during cooking frying smells were prevalent as well as iron, sodium, zinc and sulphur particles, which were demonstrated could be due to outdoor sources as well. Krupińska et al. (2012) carried out PM_{10} elemental analysis to evaluate the effect of outdoor on indoor pollution levels. They found that particle matter indoor (museum) was due mainly to indoor activity rather than outdoor in most cases. The chemical analysis explained this because the particles monitored were generated by microorganism activity, clothing fibres and human skin particles. Stranger et al. (2009) found that the indoor and outdoor of each element of PM was correlated significantly for each house but not between different houses.

2.7.3 Regression Analysis

Another method using multiple regressions considered the factors that influence indoor pollution levels. These included air infiltration rate and indoor activities. Lawson et al. (2011) develop a model which illustrated that the background level has a significant influence on indoor levels consistent with the chemical analysis research of Stranger *et al.* (2009). Stranger et al. (2009) also examined the ambient indoor particle levels and confirmed that indoor sources such as smoking have influence on indoor air pollution levels. Pérez Ballesta et al. (2008) used multiple regression modelling to assess the important factors of specific activities and location and found that benzene was correlated with travel activity by bus or car excluding smoke activity. They found that indoor activities in home, work, bar, shop and restaurant were associated with the hydrcarbon pollutants (ethyl-benzene and m, p-xylene).

Gerharz et al. (2009) built a $PM_{2.5}$ indoor model by using GPS tracker, 24 hrs dairy and conducted a questionnaire survey. They derived two different models to estimate indoor and outdoor $PM_{2.5}$ levels. Outdoor levels were estimated by using a dispersion model and fixed site measurements. The indoor levels were estimated by considering indoor activities and developed a simple mass balance model based on estimated outdoor levels and infiltration rates. Gerharz et al. (2009) stated that their model has a number of limitations. It over estimated pollution levels during smoking periods and underestimated toward the end of the sleeping periods. Smoking and gas stove usage were the main factors in the indoor model of Lai et al. (2006) who also identified that there were common determinants in all three indoor models namely smoking, gas-stove usage, outdoor meteorological conditions (temperature, and wind being the first order influences).

McCreddin et al. (2014) used a series of modelling techniques including time activity weighted, Monte Carlo simulation and neural network modelling to predict 24-h personal exposure to PM_{10}. They concluded that the personal exposure estimation would be more reliable by using the Monte Carlo simulation approach. They stated that "As a general observation it is clear that all models gave a reasonably good level of predictive performance with the Pearson's correlation typically in the region of 0.55 to 0.84". Özkaynak et al. (1996) stated "Similar regression on personal exposures showed that indoor concentrations were the strongest predictor for personal PM_{10} particle mass." They showed that R^2 was 0.6 for linear regression of indoor PM_{10} model. Zolghadri and Cazaurang (2006) did not validate the model and they commented it is easy to incorporate traffic emissions into the model. Goyal and Khare (2011) used the mass based balance model to predicted indoor PM_{10} which showed poor R^2 of 0.4. They stated that their indoor model was underestimating PM_{10} levels when extensive movements or activities of occupants. Elbayoumi et al. (2014) concluded that the principal component analysis and principal component regression of annual PM_{10} levels gave R^2 values of 0.40. The performance of PM_{10} forecasting methods varied from 0.4 to 0.7 from other studies (Özkaynak et al., 1996; Zolghadri and Cazaurang, 2006; Goyal and Khare, 2011; Elbayoumi et al., 2014). The regression analysis research has revealed huge variations caused by the different types of sources present in the microenvironment which has resulted in regression models with a wide range of R^2 value. This finding is consistent with the chemical and time series analysis.

2.8 Summary

In this chapter, the development of air pollution policy in the UK, and indoor and outdoor air pollution were presented. An overview of air pollution policy development was discussed at the beginning of this chapter. Subsequently, a definition of pollutants and the health effects on humans was presented. Personal exposure and microenvironment terminology have been explained.

Indoor to outdoor ratios were examined in a number of studies. Natural ventilation in buildings located close to main roads had a significant effect on indoor/outdoor ratios, and in particular depended on the wind direction. The temperature difference and wind speed had less effect on the indoor/outdoor ratios. Also, there was a variation between summer and winter in the indoor/outdoor ratios. Indoor combustion sources such as a fireplace caused an increase in indoor/outdoor ratios. When a trickle ventilator was opened, it provided a higher ventilation rate than the minimum design value, although it did not provide sufficient ventilation to meet ADF 2006 guidelines.

Indoor and outdoor PM_{10} levels were investigated by a number of researchers. At smokers' homes, the highest mean PM_{10} levels were measured and the indoor PM_{10} mean was much higher than outdoor PM_{10} average. On the other hand, indoor PM_{10} mean was lower than the outdoor PM_{10} mean at a non-smoker's house. Other studies concluded that levels of PM_{10} means indoor were higher or equal to outdoor levels. For non-smoking participants, the main source of PM_{10} exposure was ambient PM_{10} in high pollutant area. PM_{10} exposure was significantly influence by the seasons and temperature. Furthermore, indoor sources and indoor/outdoor ratios had a varied influence on indoor PM levels. The elevation of fine particles was caused by people present in a room and when cooking and housework caused particles to re-suspend. Indeed, other papers concluded that the high rate of occupancy caused higher daily PM_{10} levels. The main indoor sources of pollutants were indoor activities, cooking and smoking.

The number of occupancies and activities had high correlation levels for the PM. Furthermore, indoor particulate matter levels decreased as result of cleaning activities to remove sediment. There was a limited contribution by traffic to the exposure, especially when the prevailing wind was at a particular orientation to the road as stated in one of the papers. In other papers, outdoor PM levels at urban areas were higher than rural areas. A number of studies examined personal exposure indoors to traffic pollutants at properties near main and minor roads. In the absence of significant indoor sources, it was noted on some papers that the indoor PM_{10} and $PM_{2.5}$ measurements were lower than outdoors.

The levels of pollutants alongside a road were studied (Kaur *et al.*, 2005b; Boarnet *et al.*, 2011; McAdam *et al.*, 2011; Whitlow *et al.*, 2011; Zwack *et al.*, 2011). There was an association between high levels of fine particles, higher temperatures and lower wind speeds. As the result of different traffic densities, there was an important variation in PM levels on different streets. Moreover, total daily exposure was appreciably affected by high short term pollutant level measurements such as vehicles passing by. At both sides of streets canyon, pollutant measurements were either similar or different depending on meteorological conditions. Therefore, topography, traffic fleet characteristics and flow regimes had an influence on pollutant levels. Conversely, other studies concluded that $PM_{2.5}$ levels did not correlate with the traffic flow.

The literature review suggests that cumulative exposure to pollutants is significantly affected by time spent travelling by a vehicle increase. It was noted that PM exposure while walking was significantly higher than travelling by a car. Also, coarse particles exposure was significant positive correlation with heavy good vehicle density were. In addition, wind speed and exposure to coarse particles were a significant positive association during walking. Alternatively, the PM_{10} exposure average during driving was higher than the PM_{10} exposure average while walking, which was found in one of the studies. Also, PM_{10} exposure was higher than the fixed monitoring station data while walking and driving. Moreover, there were no different patterns to pollutant levels on different street types. Indoor and outdoor PM_{10} levels were not significantly correlated at houses near the main road. However, Indoor and outdoor NO_2 levels at properties near a main road were significantly higher than properties far from a main road.

During winter, depending on meteorological conditions the use of gas appliances for indoor heating was found to increase exposure. Workers' exposure to air pollution has been examined in some studies. It was found that NO_2 levels had a significant correlation with gas cookers compared with electric. Also, indoor sources had a considerable influence on personal exposure to $NO_{2,}$ especially with gas cookers. It was discovered that traffic emissions have a weak influence on indoor levels of pollutants. NO_2 exposure was influenced by the heating system and cooking fuel. Also, personal exposure to NO_2 had a weak correlation with fixed ambient air monitoring. In addition, personal exposure to NO_2 was high in a transport microenvironment, especially when travelling by car or motorcycle. As most of the people spend most of their time in indoor microenvironments, CO exposure occurred indoors. In addition, using gas cooking and smoking activities notably increased CO exposure at home. It was noted that the highest CO exposure in a transport microenvironment occurred during travelling by car or taxi (De Bruin *et al.*, 2004). Ambient air quality data gave a poor prediction for hourly CO exposure.

Other studies modelled personal exposure by using indoors and outdoors measurements for pollutants. This was achieved by monitoring pollutant levels at different microenvironments under different conditions and activities. Indoor sources and ventilation habits were the most import factors with regards to personal exposure. In addition, other researchers found meteorological conditions had an influence on personal exposure. In general, personal exposure was similar to indoor pollutant levels and was significantly higher than outdoor pollutant levels. By taking data from diaries recorded in real time, actual exposure was successfully modelled. Indeed, personal exposure was appreciably influenced by activity patterns. In general, personal exposure to the pollutants was successfully represented by microenvironment measurements.

Dynamic and static monitoring of traffic pollutants was conducted in streets in a number of studies (Ní Riain *et al.*, 2003; Kaur *et al.*, 2005a; Murena and Favale, 2007; Briggs *et al.*, 2008; Heudorf *et al.*, 2009; Zhang and Batterman, 2009; McAdam *et al.*, 2011). In addition, personal exposure has been investigated in depth for vehicular modes of transport, although pedestrian personal exposure has not been examined to the same extent. A series of studies confirmed that indoor air pollution is influenced by activities and outdoor air pollution levels. Some of these activities were identified as smoking and cooking. Depending on the fabric of the building outdoor air pollution has an influence on indoor air quality. The pollutants have an effect on the human health. This effect is dependent on the duration of exposure and type of pollutants. There are two type of monitoring; personal monitoring and static monitoring (monitor station, outdoor/indoor monitor).

Turning now to analysis, there are a number of techniques which can be used to identify different contribution of indoor and outdoor sources to indoor pollution. A simple inspection of time series was carried out by a number of researches (Jones *et al.*, 2000; Lai *et al.*, 2004; Saraga *et al.*, 2011; Tan *et al.*, 2012). Jones *et al.* (2000) concluded from simple time series analysis that the presence of people and cooking activities caused the elevation of particles matter indoors. For the time series plots, the cooking activities were coincident with high peaks of PM levels (Tan *et al.*, 2012). Lai *et al.* (2004) illustrated CO exposure peaks corresponded to cooking or smoking activity. Another method was particle composition analysis to identify the source of particle matter. Tan *et al.* (2012) conducted elemental analysis of PM_{10} sample which revealed the PM sources included outdoor, cooking or from human activity and Krupińska *et al.* (2012) revealed the contribution of human skin to PM_{10} measured indoors. Stranger *et al.* (2009) stated that the indoor and outdoor of each element of PM was correlated significantly at each property but not between different houses. Lawson *et al.* (2011) developed model which demonstrated that the background level has a significant on indoor levels. Pérez Ballesta *et al.* (2008) used a multiple regression model and assessed the relative importance of activities and locations. However, Pérez Ballesta *et al.* (2008) did not give details of the activity types. Smoking and gas stove usage were main factors in the indoor model developed by Lai *et al.* (2006). Gerharz *et al.* (2009) built a $PM_{2.5}$ indoor model highlighting a number of limitations including pollution levels were overestimated during smoking and underestimated towards the end of the sleeping period.

Several research studies have been conducted on personal exposure and each one targeted a specific group, for instance children or a microenvironment such as a home or a car. Personal exposure is very dependent on a number of factors including the amount of cooking, open fire or if people smoke, whether properties are in the vicinity of outdoor sources and depending on the ventilation and building fabric itself. The literature review has identified that only a few studies have investigated dynamic and static indoor/outdoor monitoring in the same urban area to establish relative levels of exposure in the different microenvironments and none were found to specifically apply the decomposition technique but instead used time series, chemical or regression methods for the analysis. This thesis seeks to address this research gap by exploring a novel approach to the analysis using the decomposition technique and establishing whether it is applicable to both static and dynamic monitoring and thus, to create a consistent platform for comparing results.

This chapter has provided evidence that indoor air quality is influenced by indoor activities and outdoor air pollution and the challenge in this thesis is to create evidence to support this observation but instead using the decomposition technique. The methodology for this research will be developed in the next chapter based on the knowledge presented in this chapter. Property owners were identified to allow static measurements of PM_{10} levels to be conducted by installing equipment indoors and outdoors at a number of dwellings and requesting that activity diaries be kept. Dynamic measurement of PM_{10} levels was conducted by carrying the equipment along a busy road into the city centre whilst simultaneously recording the traffic events and other data. The basic theory of the statistical technique known as *'decomposition'* will be applied to reveal features in the probability density functions (pdfs) measured during static (indoor/outdoor) and dynamic monitoring campaigns both within and outside the air quality management area.

3 Methodology of Static and Monitoring Study

3.1 Introduction

The description of the methodology is presented in this chapter. This consists of several stages from instrument testing to the main survey and analysis, as shown in Figure 3-1. It focuses on indoor and outdoor pollution levels and the events influencing them. The first stage involves selecting the study area, testing the equipment, designing the questionnaire forms and undertaking indoor pilot study to formulate the procedure for the data collection in the main study. Statistical software is used for the analysis to fit a number of distributions to the measured levels. Descriptive statistical analysis, in addition to other analyses was conducted also. Next stage used an advanced statistical technique to decompose the data distribution.

Figure 3-1 Conceptual framework showing the methodology

Chapter 3 — **Methodology**
Study Area (two AQMAs in Newcastle upon Tyne)
Traffic Data and Selecting Sites
Recruitment of Volunteers (community meeting, leaflet, knocking on doors)
Form design (Personal and Building Questionnaire, etc.)

↓

Chapter 4 — **Equipment Testing and Pilot Study**
Field Work Procedure, Equipment Testing (Langan, DustTrak, GPS devices, etc.)
Static Monitoring Pilot Study

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Chapter 5 — **Static Monitoring**
First Campaign and Descriptive Analysis
Second Campaign and Descriptive Analysis

↓

Chapter 6 — **Decomposition analysis**
Static Monitoring

↓

Chapter 7 — **Dynamic Monitoring**
Descriptive and Decomposition Analysis

↓

Chapter 8 — **Discussion**
Static and Dynamic Monitoring

↓

Chapter 9 — **Conclusion and Recommendations**

3.2 Study Area

This section describes the study area for the static and dynamic monitoring campaigns. For the purpose of this research, the study area selected was Newcastle upon Tyne, a city located in the county of Tyne and Wear, in the north east of England. Newcastle upon Tyne has a population of 280,000 (NCC, 2011). Newcastle City Council in 2005 declared two air quality management areas (AQMAs), as shown in Figure 3-2 due to measured pollutant levels of nitrogen dioxide (NO_2) exceeding the national air quality standards (DEFRA, 2014a). The two AQMAs are Gosforth High Street and Newcastle City Centre including Jesmond. As indicated in Figure 3-2, three Automatic Urban and Rural Network (AURN) stationary precision monitors were installed in the AQMAs in Newcastle City Centre, Jesmond and Gosforth. Gosforth AQMA was chosen for this study. The High Street in Gosforth is a narrow canyon and a major radial route carrying high volumes of traffic to and from the City Centre. The air quality monitoring station (AQMS) is located on the heavily congested High Street and Church Road intersection. Jesmond Road within the Newcastle City Centre AQMAs is a major dual carriageway out to the coast carrying high volumes of traffic to and from the City Centre.

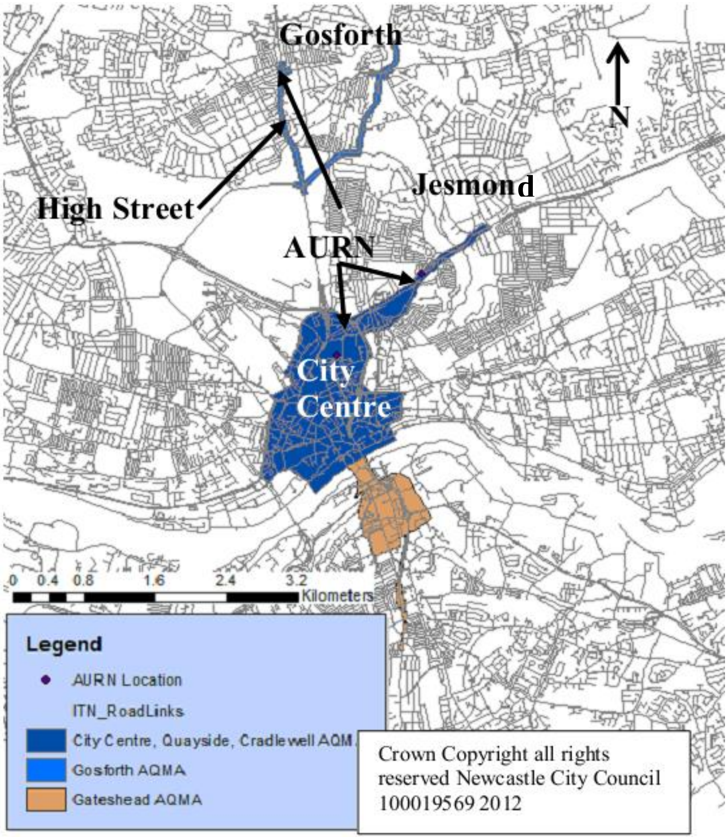


Figure 3-2 The Location of Air Quality Management Areas and air quality monitoring stations in Newcastle
(Source: Newcastle City Council)

The pilot and main monitoring studies were conducted in the selected study area. The plot study involved monitoring indoor pollution levels. Furthermore, a property in Kingston Park, located 5 km North West of city centre, was used for the second pilot study. Static monitoring was carried out by taking the measurement at fixed locations such as indoor and building facade. The static monitoring campaigns took place in dwellings in Kingston Park, Gosforth and Jesmond to reflect the effects of road traffic pollution. The dynamic monitoring campaigns took place along the High Street in Gosforth.

Recruiting volunteers was required for the static monitoring campaigns and possible sites were identified from the residential houses shown on the map in Figure 3-3. Therefore, the researcher and the supervisory team attended a South Gosforth Community meeting to recruit volunteers and to demonstrate the work required for the static monitoring campaigns. Although, three people registered to participate in the study, only two of them finally took part. The researchers knocked on residents' doors; however, only three households signed up and took part in this study. A number of leaflets were distributed to a number of houses along the High Street; nevertheless, there was no response from residents. Therefore, the researchers approached local businesses to take part in this study and recruited three from this cohort.

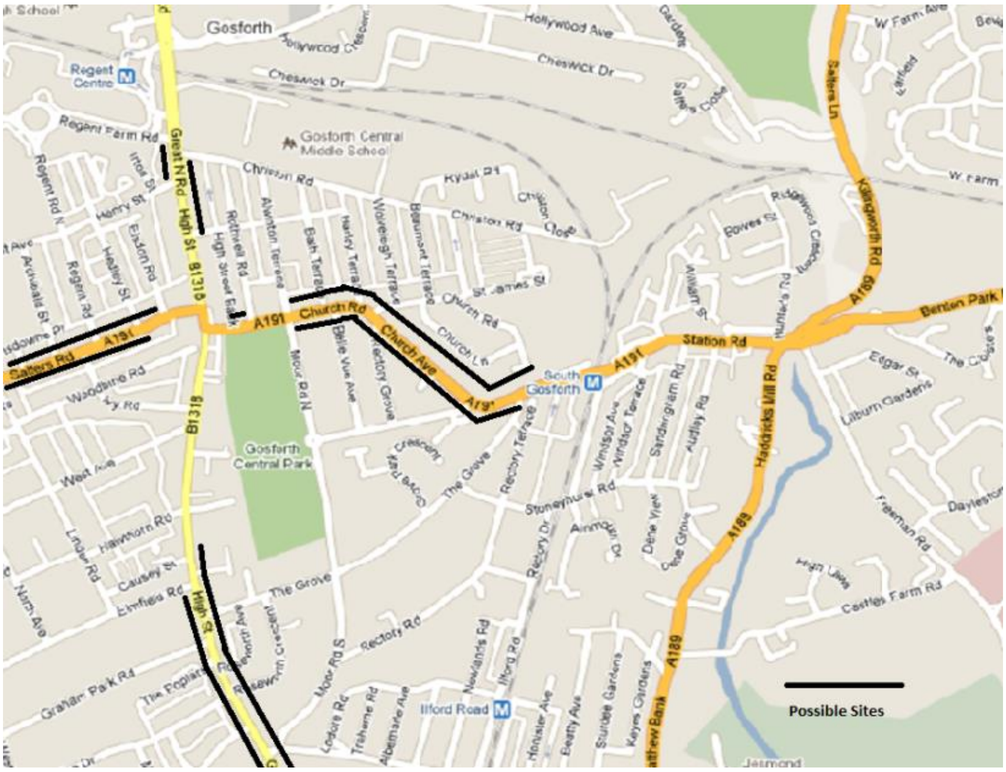


Figure 3-3 Possible monitoring sites for static monitoring
(Source: Google Map)

3.3 Traffic Data

Newcastle traffic data was initially used to classify the roads. Based on the classification, possible sites for static monitoring were identified. Cluster and factor analyses were planned to be conducted on some of Newcastle's traffic data to classify roads and identify possible sites. Traffic data were obtained from the Traffic and Accident Data Unit (TADU) at Gateshead Council. The traffic data from fixed detectors varied between daily records for the year (detector fixed permanently) or for a couple of weeks (temporary counter). This data was limited to traffic count only (no composition or speed). Therefore, traffic could not be classified into congested, busy or quiet roads as this requires plotting the speed-flow curve and using statistical techniques. Therefore, the sites were classified subjectively based on type of street environment located nearest to the property and the nature of the traffic using the road.

3.4 Questionnaire Design, Equipment Testing and Pilot Study

This section is about the design of the questionnaire forms, equipment testing and pilot study. The forms designed were the personal and building questionnaires, the activity diary and the information sheet. Equipment testing and backpack design were conducted for their durability and accuracy. The pilot study was carried out to identify the key indoor pollution sources.

3.4.1 Questionnaire/Activity Diary/Information Sheet Design

The study consisted of several stages and participation was essential to create useful data sets. Each participant was asked to complete a personal and home characteristics questionnaire at the beginning of the study. The questionnaire took approximately 15 minutes to complete. The personal questionnaire asked about age, employment status, travel, etc. The home characteristics questionnaire gathered information on the number of rooms, ventilation, heating, cooking, etc. Air pollution monitoring devices were installed during that time in the lounge only, lounge and kitchen or lounge and outdoors. The participants were asked to complete an activity diary during this study. The participants recorded details in the diary of when and where each activity type took place during a week day and one weekend day. The study involved air pollution monitoring over a full week.

3.4.2 Design of Questionnaire

A personal and home characteristics questionnaire was designed to include the key variables for air pollution in this study (see Appendix C and Appendix D). In the first two sections, respondents were asked about the demographic characteristics and commuting methods of the household occupants such as gender, age group and employment status. In the past, several air pollution studies collected information in relation to demographic characteristics and commuting methods of the households (De Bruin *et al.*, 2004; Nethery *et al.*, 2008; Maria Luisa Scapellato *et al.*, 2009). One study identified that socio-demographic characteristics are related to indoor pollution levels (Berry *et al.*, 1996). Berry *et al.* (1996) found that the number of occupants had an influence on pollution levels. Furthermore, other studies have suggested that the type of commute have a significant effect on personal exposure levels (De Bruin *et al.*, 2004; Lai *et al.*, 2004; Piechocki-Minguy *et al.*, 2006).

The last two sections of the questionnaire were about building characteristics and exposure. A number of studies have been conducted with regards to building characteristics, for example in some studies the type of residence was considered (Berry *et al.*, 1996; Kousa *et al.*, 2001; Coward *et al.*, 2002; Franklin *et al.*, 2006; Piechocki-Minguy *et al.*, 2006; Lawson *et al.*, 2011) whereas in other studies the age of the dwelling was required (Berry *et al.*, 1996; Kousa *et al.*, 2001; Lawrence *et al.*, 2005; Nethery *et al.*, 2008; Lawson *et al.*, 2011). It has been noted that the type of home had an effect on pollution concentration indoors (Berry *et al.*, 1996). Detailed information about the rooms, including kitchen and garage in the dwelling were reported (Nethery *et al.*, 2008). The heating system and cooking fuel were found to have a significant effect on indoor air pollution (Kingham *et al.*, 2000; Lai *et al.*, 2004; Franklin *et al.*, 2006; Van Roosbroeck *et al.*, 2007; Nethery *et al.*, 2008; Maria Luisa Scapellato *et al.*, 2009; Lawson *et al.*, 2011). Therefore, the questionnaire designed for this research presented in this thesis had a specific section on heating and cooking systems, and typical cooking activities. The ventilation may or may not have a significant effect on indoor air quality (Johnson *et al.*, 2000; Kingham *et al.*, 2000; Kousa *et al.*, 2001; Lawrence *et al.*, 2005; Lai *et al.*, 2006; Nethery *et al.*, 2008; Lawson *et al.*, 2011), but this was included in the questionnaire, as it has a possible influence on indoor air quality. Indoor smoking, burning of candles or other pollutants were examined by Van Roosbroeck *et al.* (2007), and therefore, these were included also. The key variables included in this study, in the personal and home characteristics questionnaire for indoor air quality are given in Appendix C.

The cleaning and cooking activities diary was designed based on previous findings on the key variables for personal exposure to air pollution. The cooking activities and ventilation were examined in a number of other studies (Lai *et al.*, 2004; Lai *et al.*, 2006; Nethery *et al.*, 2008; Lawson *et al.*, 2011). Nethery *et al.* (2008) did find that the gas stove was an important factor in forecasting differences in personal exposure to NO and NO_2. Lawson *et al.* (2011) concluded that NO_2 levels were significantly correlated with gas cookers. These observations were endorsed by Lai *et al.* (2004) who demonstrated that using a gas cooker has a significant influence on personal exposure NO_2. In summary, the cooking activities diary was designed to include cooking fuel type, ventilation, time and duration of cooking event and is shown in Appendix F.

3.4.3 Activity Diary

Daily activities diary forms have been designed by a number of researchers where time interval, activities and location were specified. Pérez Ballesta *et al.* (2008) designed an activities diary that divided the location into four categories with five minutes interval. Eleven microenvironments and three activities were included in the daily activities diary and logged at 15 minute resolutions (De Bruin *et al.*, 2004; Lai *et al.*, 2004). Nethery *et al.* (2008) recorded activities at 30 minute intervals and indicated the location whether indoors or outdoors or in a transit microenvironments. Over a period of seven days, the participants recorded their location and activities at 30 minute resolutions (Lawson *et al.*, 2011). There have been several studies conducted on daily activities diaries to evaluate personal exposure to air pollution (Kousa *et al.*, 2001; Maria Luisa Scapellato *et al.*, 2009). The activity diary used in the research presented in this thesis was designed based on these previous studies. A 30 minute time interval was selected for the diary and it accommodated two activities in one interval. It specified five categories and highlighted a number of potential activities to be noted. Passive smoking or smoking, cooking and ventilation conditions were required to be entered in the diary. The activities diary, used in this study is shown in Appendix E.

3.4.4 Information Sheet

An information sheet was designed to hand to participants. This gave an overview of the research and is shown in Appendix A. It starts by giving an introduction to personal exposure to air pollution, air pollution sources and the effects. It gives a general idea of the target areas for this research and who is responsible for the research. The information sheet for this study specified the target area as Gosforth, a locality in Newcastle. It states that a number of dwellings are to be located along quiet, busy and congested roads. The monitoring period was for one week and the participants were required to complete a number of forms, which included the personal/household questionnaires and a time/activity diary. It gives preferred information that was required to fill in the forms and that diary was to be completed for a minimum of one weekday and one weekend day. Ideally the diary information was required for the entire duration of the study but feedback from the participants who felt that this was impractical due to pressures on time meant that our expectation was too high and the requirement for completing the diary was reduced accordingly. Contact details were provided at the end for residents who wanted to participate in this study.

3.4.5 Equipment Selection and Testing for the Study

The instrument choice was primarily based on precision and durability. Although the available financial resources were a key determining factor in relation to this, the study did secure a precision instrument, on which a series of tests were conducted before implementation see section 4.1. The description of the equipment and the process used to detect the particles are addressed in this section along with the limitations of the equipment.

The instrument primarily used in this study for PM_{10} monitoring was the DustTrak 8534, chosen because of its level of precision, durability and given the budget constraints. The DustTrak 8534 is a portable and easy-to-use device, and can detect the mass concentration of particles with a diameter of less than 10 µm. DustTrak monitors PM_{10} to a resolution of 1 µg m^{-3} and a range from 1-150,000 µg m^{-3} (TSI Incorporated, 2011). DustTrak's monitoring is based on light scattering techniques (TSI Incorporated, 2013), where the amount of scattered light is proportional to the volume concentration of the aerosol.

DustTrak 8533 and 8534 are an advanced version of the DRX models. All models have the ability to measure size fractions of the aerosol sample and estimate the size mass fraction concentrations based on photometric measurement. The manufacture stated that "This method combines a photometric measurement to cover the mass concentration range and a single particle detection measurement to be able to size discriminate the sampled aerosol". The Figure 3-4 shows a schematic illustrating the process of detection of DustTrak. A diaphragm pump provides a continuous aerosol flow stream which is drawn through the sensing chamber. The aerosol stream is split in two, one part is passed through a HEPA filter then injected back to the main stream as sheath flow and combine back with the aerosol flow before passing through the sensing chamber. A light laser sheet is created from a laser diode which passes through a collimating lens and through a cylindrical lens before illuminating the aerosol stream in the chamber. The fraction of laser light scattered by particles is captured by a spherical mirror coated with gold and focused onto the photo detector. The signal from the photo detector is divided onto two components, the first is the photometric signal pulses to find the volume and thus to estimate the mass based on the Arizona Test Dust (ISO 12103-1, A1 test Dust) and the second is single particle pulses which were converted to aerodynamic size by proprietary factory algorithms based on the Arizona Test Dust or custom calibrations. The calibration factor can be modified by introducing correction factor. DustTrak 8533 can be fitted with filter cassette sampler which can be used to conduct a gravimetric analysis. This instrument was not used in this research.

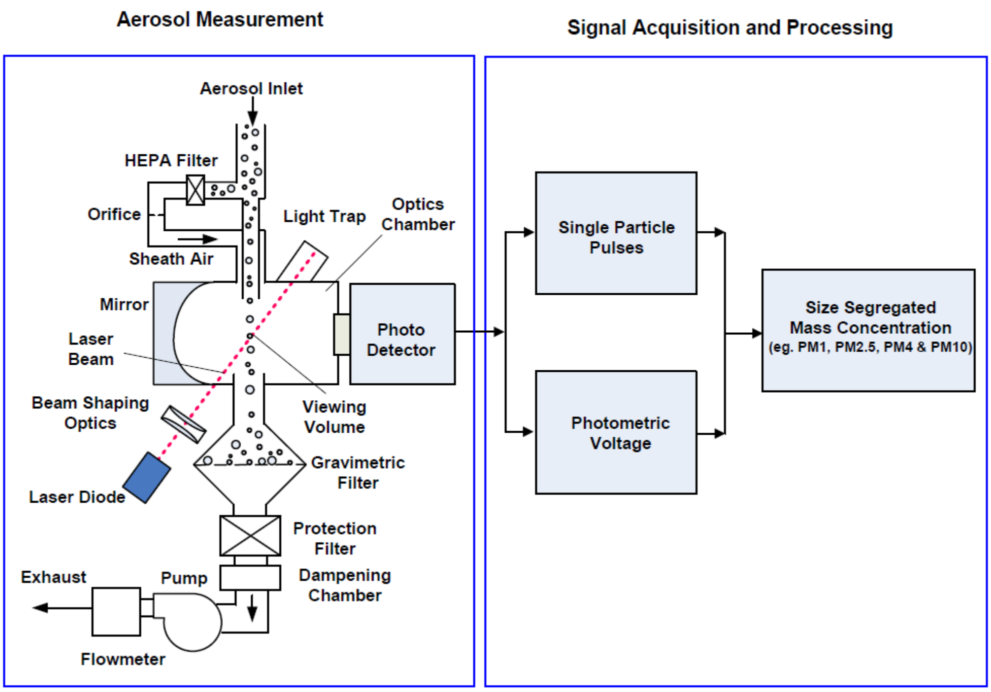


Figure 3-4 A schematic illustrating the process of detection using DustTrak (Source: TSI)

There are a number of studies that state that the measurements of PM by using the photometric method are overestimated by a factor of 2 to 3 (Lehocky and Williams, 1996; Ramachandran *et al.*, 2000; Chang *et al.*, 2001; Chung *et al.*, 2001; R. A. Jenkins *et al.*, 2004; Zhu *et al.*, 2011). Braniš and Kolomazníková (2010) concluded that the ratio between the DustTrak SidePak and the portable nephelometer measurements was approximately 3.5. As the two monitoring devices were not collocated therefore, it is not reasonable to compare the data from the two devices as they monitor different microenvironment and activity. However, there were a number of studies that have compared the data from similar DustTrak devices (or other equipment based on the photometric method) to that from gravimetric sampler measurements which found a different result to Braniš and Kolomazníková (2010). Instead, they concluded that DustTrak measurements were lower than gravimetric sampler measurement (Park *et al.*, 2009; Watson *et al.*, 2011; Goossens and Buck, 2012). Park *et al.* (2009) stated that DustTrak underestimated by an average factor of 0.48 compared to the gravimetric sampler. The DustTrak 8534 mass measurements based on photometric measurement were estimated based on the Arizona Test Dust calibration factor, which was the reason the PM_{10} levels were underestimated relative to the gravimetric sampler. The author was mindful of this limitation of the DustTrak throughout this thesis however, the data will not be rescaled. In this research at the beginning of each measurement conducted with DustTrak 8534, the zero calibration procedure was carried out according to the manufacture instruction. Given that two similar systems were used for simultaneous measurements there was consistency in the data collected and could be compared directly.

A Langan T15n was used to measure the level of CO in the range of 0-200 ppm with a resolution of 0.05 ppm (Langan Products Inc, 2006). The Langan T15n has been used in several studies (De Bruin *et al.*, 2004; Kaur *et al.*, 2005a; Kaur *et al.*, 2005b; McCreanor *et al.*, 2005). A number of tests were conducted to examine the CO monitors available for this study for their accuracy and reliability. Therefore, two scenarios were established with nine co-located Langan monitors with a view to evaluating the comparability of results. The monitors were seven Langan T15v monitors (10 years old) and two Langan T15n monitors (purchased new for this study). The first scenario was to place all the monitors in three microenvironments namely office, garden and living room for a specific period. Further details of these evaluation tests will be presented is section 4.1.1.

A GPS tracker was used to track the location of the back pack carrier second by second during dynamic monitoring. Four trackers were available namely the QStarz BT-Q1000XT, i-gotU GT-600 and three Garmin GPS devices and these were tested, with the aim of find the most suitable and accurate GPS device for the study. Details of these tests along with the results are presented in section 4.1.2.

3.4.6 Back Pack

For the dynamic surveys a bespoke solution was developed for carrying the equipment in a back pack. A back pack was used to house three instruments (see Figure 3-5). The main compartment of the back pack was reinforced by a plastic frame which housed the DustTrak 8534. The DustTrak 8534 inlet was fitted with a tube, which was positioned vertically by a plastic pipe, inside which the tube was passed. Two Langan T15n monitors were attached to the back pack and a QStarz BT GPS tracker was placed on top of the back pack's compartment. All the devices were time synchronised at the beginning of each day of the trial and were set to sample at intervals of one second.

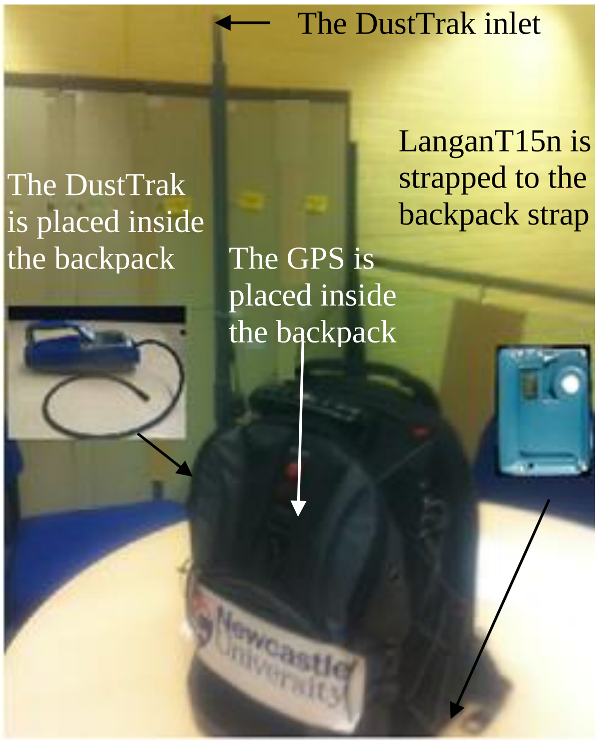


Figure 3-5 The back pack

3.4.7 Field Work Procedure for Dynamic Monitoring

A field work procedure was produced as a series of steps for dynamic monitoring, as given in Appendix H. This describes in detail the procedure to set up equipment before conducting the survey along with the process time synchronisation for the instrument. The data retrieved from the instruments are explained in detail in the procedure. This protocol was followed in all the trials and field surveys therefore, the data collection process was consistent in all cases similar and the results comparable.

3.4.8 Pilot Study

During the pilot study, two DustTrak 8534 and three Langan T15n monitor PM_{10} and CO pollutants levels respectively were used for both static and dynamic monitoring. The equipment were fully tested and validated for accuracy, see section 4.1, and regularly calibrated to comply with the manufacturer's recommendations. A house was selected to be monitored during the study in Newcastle for the static pilot study. The house (H01) is located north-west of the city centre at Kingston Park, as shown in the Figure 3-6. The kitchen was monitored for a number of days in order to identify the key factors that affect air pollution levels indoor under a number of scenarios. These will be discussed further in the next chapter.

3.5 Static Monitoring Campaigns

Static monitoring campaigns involved a number of dwellings located in Kingston Park, Gosforth and Jesmond. The sites were selected by carrying out an analysis of traffic flows in the vicinity of the AQMA ensuring a wide range of levels of source emissions to enhance our chances of measuring any differences. A preliminary trial was conducted at one of the properties (H01). In addition, the main monitoring campaigns took place in two periods. During the first campaign, the lounge and the kitchen of the same dwelling or the lounges of two dwellings were monitored simultaneously. These dwellings were selected according to whether they were located along quiet, busy and congested roads, although the classification used is subjective and statistical techniques were not used as explained on section 3.3. The dwellings which are located along major roads such as the High Street, Salters Road or Church Road, were monitored simultaneously for one week with the dwellings located along quiet roads during the first campaign. In some of the residences, indoor and outdoor monitoring was conducted simultaneously and for two dwellings monitoring was conducted indoors only during the second campaign. The participants were required to record cooking, cleaning and daily activities in their diaries, and complete personal and household questionnaires.

During the main study, eight houses, one apartment, one dental practice, one boutique and one restaurant were selected to be monitored. The locations of the properties are shown in Figure 3-6. One house (H01) is located in Kingston Park which is situated in the north west of the city centre and this house (H01) is in the vicinity of a busy junction. The methodological approach for the indoor/outdoor static monitoring campaigns was developed based on the pilot study in this house. The lounge and kitchen or lounge and outdoors were simultaneously monitored for four weeks. The other houses, the apartment (H06) and the dental practice (H09) are located in Gosforth situated north of the city centre. Three houses (H02, H05 and H08) were monitored for one week with the lounges and kitchens measured simultaneously. Two residential houses (H08 and H10) in the study are located on a very quiet, low flow cul-de-sac. A further house (H05) is a centre terraced house located along a busy road. In addition, to create a range of indoor microenvironments commercial properties, for instance, a boutique (H11), restaurant (H12) and dentist (H09) were monitored. The former two were located on a busy low flow, low speed commercial street with lots of conflict, including roadside parking, pedestrian crossing without priority, loading and unloading, whilst the latter was on a heavily trafficked dual carriageway. The boutique shop (H11) and the restaurant (H12) are located north of the city centre in Jesmond. The monitoring campaign was divided into two stages.

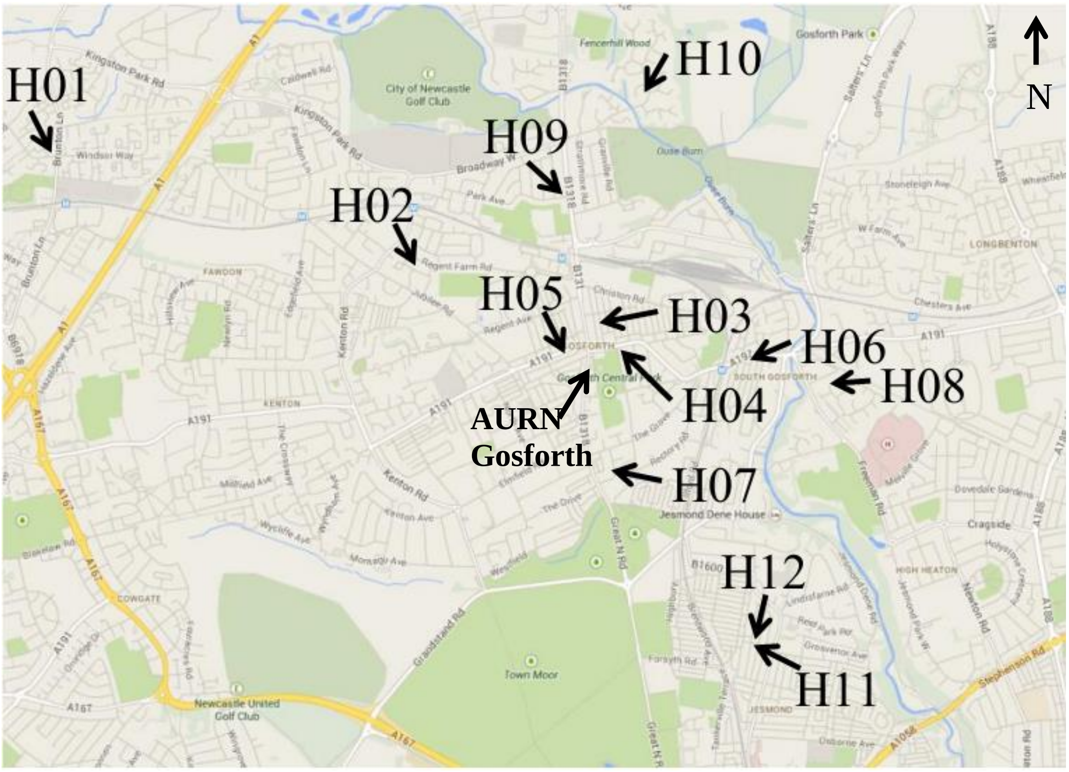


Figure 3-6 Location of properties where static monitoring campaigns were carried out (Source: Google Map)

During the first campaign, a number of dwellings, H01, H02, H03, H04, H05, H06, H07, H08, H09 and H10, were monitored. Simultaneous measurements were made in the lounge and the kitchen of H01, H02, H05 and H08. The lounges of H03, H04, H06, H07, H09 and H10 were monitored in pairs. Furthermore, the lounges in four of the houses, the apartment and the reception at the dental practice, with three pairs (H03 with H04, H06 with H07 and H09 with H10) were monitored simultaneously for one week. The dental practice (H09), the apartment (H06) and one of the houses (H04) are located along a busy road. The dental (H09) practice and house (H03) are in the centre of the terrace. The house (H03) is situated along a quiet road. The houses (H04 and H07) are semi-detached houses, with house (H10) being a detached house.

During the second campaign, three houses, a dental practice, a boutique shop and a restaurant were monitored for one week. Simultaneous indoor and outdoor monitoring was conducted in H01, H02 and H10 for more than six days. The air pollution was measured indoors at the dental practice (H09) and the boutique shop (H11). The boutique shop and restaurant are located on a busy low flow, low speed commercial street with lots of conflict, including roadside parking, pedestrian crossing without priority, and loading and unloading.

3.5.1 Property H01

The two storey semidetached house (H01) in Kingston Park is located to the north west of the city. Two adults and three children live in the house. The house holders do not smoke and two of them suffer from respiratory illness. One adult commutes 30 minutes by car on a typical week day and weekend day. The other adult walks for 40 minutes on a typical week day. The two children travel by a car for 20 minutes and 10 minutes on a typical weekend day and a weekday respectively. The house is fitted with gas central heating system and the windows were double glazed. The floors were carpeted in the bedrooms and lounge. There was a conservatory attached to the house with wood flooring. The kitchen is equipped with a gas hob and electrical oven.

3.5.2 Property H02

This is situated in Gosforth and is a two storey semi-detached house (H02), with a family of five living in the house. They do not smoke and they are not suffering from any respiratory illness. On a typical weekday, two adults commute for 30 minutes by metro and the other family members walk for 30 minutes for education. The family travel by car for about one hour on a typical weekend. The house is fitted with a gas central heating system and the windows are double glazed. The floors are wooden in the lounge, kitchen and two bedrooms, and carpeted in one bedroom. The kitchen is equipped with a gas hob and electrical oven and is not fitted with extractor fan. The garage is integrated in the house and it has an access door to the house though the kitchen.

3.5.3 Property H03

The three storey mid terrace house (H03) is located on Rothwell Road in Gosforth and is a quiet road. A family of two adults and three children lives in the house and one of the family members suffers from a respiratory illness, although none of the family members smoke. The male adult spends six hours driving on a typical week day and one hour driving on a typical weekend day. On a typical week day and weekend day, the female adult spends 30 minutes commuting by a car. The windows are double glazed and the house is fitted with a gas central heating system. There is an open fire place in the lounge. The floors are carpeted in the lounge, dining room and one bedroom, and wooden in three bedrooms. The kitchen is equipped with a gas hob and electric oven; however, it is not fitted with an extractor fan.

3.5.4 Property H04

House (H04) is located along a busy road near the intersection of Church road and Moor Road North. A husband, wife and son live in this two storey semi-detached house. None of the family members smoke or suffer from respiratory illness. On a typical week day, the husband, wife and son spend 30 minutes cycling, one hour driving and 20 minutes walking respectively. The wife and husband commute on a weekend, driving 20 minutes and one hour respectively. The semi-detached house was built between 1919 and 1940, is fitted with a gas central heating system and has double glazed windows. The floors are carpeted in the lounge and bedrooms. There is a gas hob and electric oven in the kitchen.

3.5.5 Property H05

Two storey mid terrace house (H05) is located beside a busy road, Salters Road, in Gosforth. The house is divided into apartments on each floor. A male and a female live in this first floor apartment (H05). The two adults do not suffer from respiratory illness and they do not smoke. The woman spends 20 minutes commuting by metro and 40 minutes walking on a typical weekday and weekend day. On a typical weekday and weekend day, the man spends 10 and 40 minutes walking respectively. The windows are double glazed and the apartment has gas central heating system. The flooring in the lounge is wood and the bedrooms have carpets. The kitchen is equipped with an extractor fan, and it is fitted with a gas hob and an electrical oven.

3.5.6 Property H06

This three storey building (H06) is located along a busy road, Station Road, in Gosforth. A single man lives in the second floor apartment (H06). He does not smoke or suffer from respiratory illness. He spends 30 minutes commuting by metro and 20 minutes walking on a typical weekday. The apartment is fitted with an electric heating system and the kitchen is fitted with an electric hob and oven. The flooring is carpet for the lounge and bedrooms, and the windows are double glazed.

3.5.7 Property H07

This property (H07) is located on Roseworth Crescent in south Gosforth. A family of two adults and two teenagers live in this three storey semi-detached house. None of the family members smoke or suffer from respiratory illness. On a typical weekday, the two adults' cycle for one hour and the two teenagers walk for forty minutes. The two adults travel by car and metro for one hour and 40 minutes on a typical weekend day respectively. On a typical weekend day, the two teenagers travel by a car for one hour. The house is fitted with a gas central heating system and most of the windows are single glazed. The floors are wooden in the lounge and dining room and carpeted in the bedrooms. A gas hob and electric oven are fitted in the kitchen.

3.5.8 Property H08

On Broadwell Court Crescent east of Gosforth, a bungalow (H08) is located on a quiet cul-de-sac. A family of two adults and one child live in the house. None of the family members smoke or suffer from respiratory illness. On a usual week day, one adult commutes by car for half hour and walks for 20 minutes. On a typical weekday, the other adult and the child travel by car for 20 minutes and walk for 15 minutes. On a typical weekend day, the family travel by a car for 30 minutes and walk for one hour, except the child who walks for 15 minutes. The house is equipped with a gas heating system and the windows are double glazed and it has a conservatory. The floors are carpeted in the lounge and bedrooms. The kitchen is equipped with an electric oven and a gas hob.

3.5.9 Property H09

The two storey mid terrace property, H09, has a dental practice located at ground floor level. It is located along a heavily used dual carriageway. The clinic is heated by gas and the windows are double glazed. The waiting room at the front of the property has wooden flooring and the reception area is carpeted. The door opens directly into the reception and patient waiting area.

3.5.10 Property H10

The two storey detached house (H10) is located in cul-de-sac, Sinderby Close, north of Gosforth. A couple, a male and a female, live in the house (H10). The female suffers from respiratory illness and the male is a smoker but only when outdoors. The male spends 30 and 10 minutes driving by car and travelling by bus respectively on a typical week day. The female travels by car and bus for 15 minutes each on a usual week day. On a typical weekend day, the two adults travel by a car for half an hour or 20 minutes mainly for shopping. The house is fitted with gas central heating system and the windows were double glazed. The floors were wooden in the lounge, conservatory and two bedrooms, and carpeted in the most frequently used bedroom. The kitchen is equipped with a gas hob and electric oven.

3.5.11 Properties H11 and H12

The boutique (H11) is a single storey mid terrace property, whilst the restaurant (H12) is a two storey mid terrace house. The two shops are in Acorn Road in Jesmond with parking located on both sides of the street. Indeed, it has very low amount of traffic that has a continually varying flow, interrupted by parking, un-parking and pedestrian movements for access to shops on both sides of the road. The boutique has air conditioning, but it was not used during the campaign when the weather was hot. Instead, the employer opened the front and back doors. The shop was heated by an electric heating system and the windows are single glazed and not opened for security reasons. The boutique shop floors are wooden. The second shop (H12) located opposite to H11 was a takeaway and restaurant on the ground floor with a kitchen and small hall on the first floor. The property was of similar build to the boutique with gas cooking, single glaze window and gas central heating system.

Table 3-1 Summary of Static Monitoring Campaign

ID	Dwelling	Micro environment	Time		Paired with during Monitoring	Campaign
			Start	End		
H01W1 L	H01	Lounge	12/07/2012	16/07/2012	H01W1 K	First
H01W1 K	H01	Kitchen	12/07/2012	16/07/2012	H01W1 L	First
H01W2 L	H01	Lounge	16/07/2012	23/07/2012	H01W2 K	First
H01W2 K	H01	Kitchen	16/07/2012	23/07/2012	H01W2 L	First
H01W3 L	H01	Lounge	23/07/2012	30/07/2012	H01W3 K	First
H01W3 K	H01	Kitchen	23/07/2012	30/07/2012	H01W3 L	First
H02W1 L	H02	Lounge	18/08/2012	25/08/2012	H02W1 K	First
H02W1 K	H02	Kitchen	18/08/2012	25/08/2012	H02W1 L	First
H03 L	H03	Lounge	03/09/2012	08/09/2012	H04 L	First
H04 L	H04	Lounge	03/09/2012	08/09/2012	H03 L	First
H05 L	H05	Lounge	11/09/2012	18/09/2012	H05 K	First
H05 K	H05	Kitchen	11/09/2012	18/09/2012	H05 L	First
H06 L	H06	Lounge	21/09/2012	28/09/2012	H07 L	First
H07 L	H07	Lounge	21/09/2012	28/09/2012	H06 L	First
H08 L	H08	Lounge	29/09/2012	06/10/2012	H08 K	First
H08 K	H08	Kitchen	29/09/2012	06/10/2012	H08 L	First
H09W1 L	H09	Lounge	22/10/2012	29/10/2012	H10W1 L	First
H10W1 L	H10	Lounge	22/10/2012	29/10/2012	H09W1 L	First
H09W2L	H09	Lounge	14/05/2013	21/05/2013	----------	Second
H01W4 L	H01	Lounge	02/06/2013	09/06/2013	H01W4 O	Second
H01W4 O	H01	Outdoor	02/06/2013	09/06/2013	H01W4 L	Second
H10W2 L	H10	Lounge	11/06/2013	17/06/2013	H10 O W2	Second
H10W2 O	H10	Outdoor	11/06/2013	17/06/2013	H10 L W2	Second
H02W2 L	H02	Lounge	08/07/2013	15/07/2013	H02W2 O	Second
H02W2 O	H02	Outdoor	08/07/2013	15/07/2013	H02W2 L	Second
H11L	H11	Lounge	19/07/2013	26/07/2013	----------	Second
H12L	H12	Lounge	27/08/2013	03/09/2013	H12 O	Second
H12O	H12	Outdoor	27/08/2013	03/09/2013	H12 L	Second

3.5.12 Overview of Properties

The twelve dwellings listed above included eight houses, one apartment, one dental practice, one boutique shop and one restaurant, and were monitored during the study in Newcastle, see Table 3-1 and Table 3-2. One house (H01) is located at Kingston Park, and the lounge and kitchen were monitored simultaneously for almost three weeks, whilst the lounge and outdoors of H01were monitored simultaneously for one week. The boutique shop and the restaurant are located north of City Centre in Jesmond. In the north of the city centre, the other houses, the apartment and the dental practice (H09) are located in Gosforth. The lounges and kitchens in three dwellings H02, H05 and H08 were monitored simultaneously for one week. In three pairs of two dwellings, the lounges were monitored simultaneously for one week. Indoor and outdoor monitoring was conducted on four dwellings and indoor monitoring performed on two residences. The monitoring was divided into two campaigns. The first campaign carried out between July and October 2012 and the second campaign conducted between May and September 2013.

Table 3-2 Description of the proprieties studied in this research

			House ID											
Category			**H01****	**H02***	**H03***	**H04***	**H05****	**H06*****	**H07***	**H08***	**H09**	**H10****	**H11**	**H12**
Household Size			5	4	5	3	2	1	4	3	-	2	-	-
Children			3	2	3	0	0	0	0	1	-	0	-	-
Teenager			0	1	0	0	0	0	2	0	-	0	-	-
Adult			2	1	2	3	2	1	2	2	-	2	-	-
Dwelling Type	House	Detached	Semi	Semi	-	Semi	-	-	Semi	Bungalow		yes		
		Terrace	-	-	Centre	-	-	-	-	-	Centre		Centre	Centre
	Flat/Level	Terrace	-	-	-	-	First/Centre	Third/Centre	-	-				
Year			-	-	-1919	1919-1940	-	1981-2000	1919-1940	-	1941-1960	1981-2000		
Gas Central Heating			Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes
Electricity Heating			No	No	No	No	No	Yes	No	No	No	No	No	No
Lounge		S/D Glazed	Double	Double	Double	Double	Double	Single	Single	Double	Single	Double	Double	Single
		# Opening	2	-	2	4	1	2	2	1	0	2	0	1
		Flooring	Carpet	Carpet	Carpet	Carpet	Wood	Carpet	Wood	Carpet	Wood	Wood	Wood	Wood
		Open Fire	Gas	-	Coal	-	No	No	Yes	Electric	No	No	No	No
Kitchen		Flooring	Vinyl		Vinyl	Laminated	Tile	Laminated	Tile	Tile	-	Tile	-	Wood
		Hob	Gas	Gas	Gas	Gas	Gas	Electric	Gas	Gas	-	Gas/Electric	-	Gas
		Oven	Electric	Electric	Electric	Electric	Electric	Electric	Electric	Gas	-	Electric	-	Gas
		Ext Fan	Yes	No	No	Yes	Yes	Yes	Yes	Yes	-	Yes	-	Yes
Location			Near a traffic light	Near a busy road	Near a quiet road	Near a major road	Near a major road	Near a major road	Near a quiet road	Near a quiet road	Near a major road	Near a quiet road	Near a busy road	Near a busy road

* The lounge is in a separate room without interconnecting door to the kitchen ** The lounge is separated by a door from to the kitchen *** Open floor plan

3.5.13 Data Handling

All logged data was downloaded using suitable software. The data were transferred into Microsoft Excel format and amalgamated into a master spread-sheet using time as a benchmarking variable to merge the data. For each monitoring period, the start and end times for using the cooker and ventilation conditions were noted. All pollutants were monitored at one minute intervals. The pollution levels were plotted with respect to time. Furthermore, the cooking activities were marked on these plots. The distribution of the PM_{10} levels in all the lounges and kitchen data of the first static campaign was calculated using 1 µg m^{-3} bin at a 1 minute interval. The distribution of the PM_{10} levels for each trial was calculated at one µg m^{-3} at a one minute interval and was then saved in a separate csv file. These data were analysed using Excel and SPSS software packages to produce descriptive statistics and finally subjected to in-depth analysis using decomposition technique.

3.6 Dynamic Monitoring Campaigns

3.6.1 First Dynamic Monitoring Campaign

The first dynamic study was conducted in Gosforth in October 2011. During this study, air pollution measurements were conducted on a selected track along the High Street, Church Road and Salters Road. A backpack fitted with DustTrak Aerosol Monitor 8534, Langan n15v and QStarz BT-Q1000XT GPS tracker, was carried along the track in thirteen runs. The surveyor walked along the track facing the traffic during the two runs. The measurements were made for PM_{10} and CO levels and GPS position. All devices were time synchronized. The QStarz BT GPS tracker data were used to divide pollution data into segments corresponding to a specific road section for the analysis.

3.6.2 Second Dynamic Monitoring Campaign

The High Street in Gosforth was chosen for the dynamic monitoring and survey campaigns which took place during five weekdays between 10^{th} and 20^{th} of June 2013 along the High Street. The back pack was carried whilst walking on the west side of the High Street, approximately one kilometre distance. Starting at the High Street and Elmfield Road intersection on the west side of the High Street, the surveyor walked northwards until Hollywood Avenue and the High Street roundabout were reached.

Then, the surveyor walked back in the opposite direction along the same footpath, and back to the position where the monitoring started. Data records at one second resolution were downloaded with bespoke software. The GPS data and PM_{10} levels were transferred into the Microsoft Excel format and amalgamated into a master spread-sheet using the time as the benchmark variable. The start and end time of each monitoring survey were recorded along with the location and time of occurrence of any pollution events, such as a bus passing or stopping, or a passer-by smoking. The data were analysed using Excel, ArcGIS and other software packages to undertake descriptive, spatial and other analysis for decomposition of pdfs.

3.7 Data Analysis Procedures for the Model

There is a number of previous research studies that have fitted a lognormal distribution model on raw data. Raabe (1971) stated that "The log-normal distribution has proved useful in many types of particle size analysis problems, including the sizing of aerosols, geological formations, and photographic emulsion grains.". Raabe (1971) fitted one log normal distribution to the data of sand particles size. Folk (1971) went one step further by describing the distribution of the particle size by multiple log normal sediment populations by classifying the data distinguishing the beach from dune sands by using grain size. Agus *et al.* (2007) stated that the lack of availability of commercial software that fitted more than one distribution to the data was the reason why this technique was not widely accepted. Hesse and McTainsh (1999) used freely available software and fitted a number of log-skew Laplace distributions to dust samples. Agus *et al.* (2007) conducted an experiment of fitting a number of log normal distributions on a particle diameter size by using the RMix program the software for which is explained in detail by Leys *et al.* (2005). The authors found this was useful to describe the interactions with different parameters of these log normal distributions. Thus it can be concluded that the decomposition technique has been proven to be useful for classifying particles sources based on its diameter size, (Leys *et al.*, 2005; Agus *et al.*, 2007). For this study a different approached was adopted for fitting the log normal distributions which was to use the decomposition technique to disaggregate the sources of the PM_{10} concentrations instead of using the particle diameter size. The reason being that the concentration increase, or decrease, is due to the pollution source and the objective of the research was to seek to identify with the pollution event the associated activity which caused it and thus to develop a model. The decomposition approach was adopted.

This section describes in detail the basic theory of the statistical technique known as *'decomposition'* which was used to reveal features in the probability density functions (pdfs) derived from both static (indoor/outdoor) and dynamic monitoring campaigns. In this study, the decomposition technique was used to characterise pollution measured statically indoors (cleaning, cooking and sleeping) and outdoors (traffic activity and street work) and dynamically outdoors (bus passing, cigarette smoking, etc.).

3.7.1 Example of the Process of Decomposition

In order to explain the statistical process of decomposition a hypothetical data set was created and plotted in Figure 3-7. Table 3-3 shows the data which contains the PM_{10} levels and the number of counts at each level and is seen to be bimodal. The first mode for the PM_{10} level is identified as 4 µg m^{-3} because it has the highest count of 800. In step 1, the estimated count is set equal to the actual count at each PM_{10} level less than or equal to the mode (4 µg m^{-3}) plus the count less than or equal to 3 µg m^{-3}.

In order to establish the estimated count for PM_{10} levels greater than the mode, the mode is used as a mirror line. Assuming the data are normally distributed when the mean, median and mode are equal and the estimated values are assumed to be same beyond the mode. The difference between the actual and the estimated counts is calculated. In the step 2, the process is repeated. The second mode for the PM_{10} level is identified as 6 µg m^{-3} which has the highest count of 335. Then, the estimated count for the second component distribution is set equal to the actual count anchored at thePM_{10} level equal to the mode 6 µg m^{-3}. PM_{10} levels greater than the mode were estimated by using the mode as a mirror line ensuring that the mode is not double counted. The difference across the whole range of data 0 to 10 µg m^{-3} is 0 thus suggesting that the two distributions are similar.

Table 3-3 Process of Decomposition

		Step 1		Step 2	
PM_{10}(µg m^{-3})	**Count**	**Estimated**	**Difference**	**Estimated**	**Difference**
0	0	0	0	0	0
1	3	3	0	0	0
2	65	65	0	0	0
3	425	425	0	0	0
4	800	800	0	0	0
5	500	425	75	75	0
6	400	65	335	335	0
7	80	3	77	75	2
8	2	0	2	0	-2
9	0	0	0	0	0
10	0	0	0	0	0

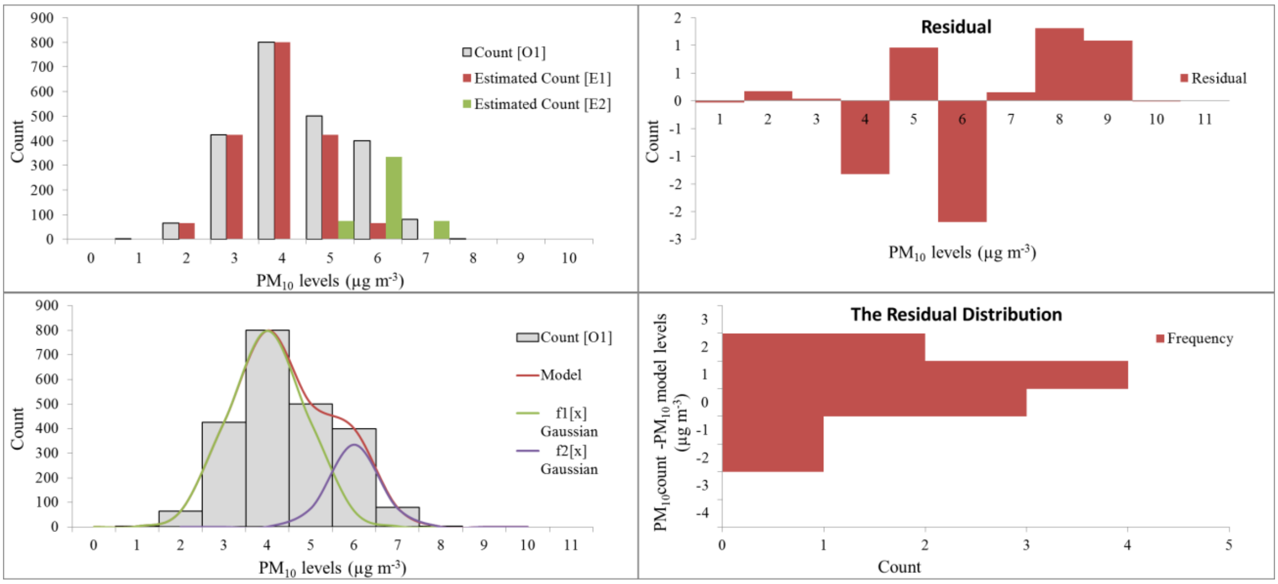


Figure 3-7 Graphs showing the distribution curve fitting the data, the residuals and the distribution of the residuals

Having demonstrated the basic process of decomposition the method of fitting a curve to the distributions is now presented. Fitting a normal distribution requires calculating the statistics namely the mean (μ) and standard deviation (σ) and using the Gaussian equation of the form

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{\left(-\frac{(x-\mu)^2}{2\sigma^2}\right)} \quad (1)$$

Calculate $f(x)$ for each x using the above example the process of decomposition was repeated and the results are presented in Table 3-4. Figure 3-7 illustrates two normal distributions fitted to the example data set. The next step is to sum up the $f(x)$ for the separate distributions to produce a theoretical predicted pdf. If this is statistically significantly similar to the actual fit ($p = 0.05$) using a χ^2 test of the distribution at a level of 95% confident then the variation in the measured pdf is explained by the two decomposed distributions. By plotting the difference between the predicted and measured pdf it can be confirmed that the distribution of the differences was not normally distributed and the median was statistically significantly differently different from zero. This suggests that there is unexplained variation prevailing in the data. It is worth highlighting that in this example, the function fitted was not optimised. The need for computer software to achieve this was recognised by Agus *et al.* (2007) who fitted only one curve to his data because of the lack of availability of commercial software to fit more than one.

Table 3-4 Process of fitting two distributions

		Step 1						Step 2								
PM_{10} ($\mu g\ m^{-3}$) (x)	**Count (O_1)**	**Estimated Count (E_1)**	**E_1 x**	**x - $\bar{x}_1$**	**$(x - \bar{x}_1)^2 E_1$**	**$f_1(x)$ Gaussian**	**Difference**	**Count (O_2)**	**Estimated Count (E_2)**	**E_2 x**	**x - $\bar{x}_2$**	**$(x - \bar{x}_2)^2 E_2$**	**$f_2(x)$ Gaussian**	**Difference**	**Model**	**Residual**
0	0	0	0	-4	0	0.0	0.0								0.0	0.0
1	3	3	3	-3	27	2.8	0.2								2.8	0.2
2	65	65	130	-2	260	65.0	0.0	0	0	0		0	0.0	0.0	65.0	0.0
3	425	425	1275	-1	425	426.3	-1.3	0	0	0		0	0.0	0.0	426.3	-1.3
4	800	800	3200	0	0	798.2	1.8	2	2	8	-2	8	0.9	1.1	799.0	1.0
5	500	425	2125	1	425	426.3	73.7	74	74	370	-1	74	75.9	-1.9	502.2	-2.2
6	400	65	390	2	260	65.0	335.0	335	335	2010	0	0	334.9	0.1	399.8	0.2
7	80	3	21	3	27	2.8	77.2	77	74	518	1	74	75.9	1.1	78.7	1.3
8	2	0	0	4	0	0.0	2.0	2	2	16	2	8	0.9	1.1	0.9	1.1
9	0	0					0.0	0	0	0	3	0	0.0	0.0	0.0	0.0
10	0	0					0.0	0	0	0	4	0	0.0	0.0	0.0	0.0
	Total	1786	7144		1424			Total	487	2922		164				
		Mean $\bar{x}_1$	4						Mean $\bar{x}_2$	6						
		St.dev	0.89						St.dev	0.58						
		St.err	0.27						St.err	0.17						

Residual		
Mean	=	0.014
SD	=	1.021
SE Mean	=	0.004
Median	=	0.03
SE Median	=	0.01

3.7.2 *Decomposition Using the Fityk Software*

The basic principle of decomposition is that there are sets of sources of data (in this application pollution building up due to emissions from different sources, whether created indoor or outdoor, and at different times over the day along with changes in rates of dispersion in the microenvironment and include cooking, shredding, overnight, etc.) which conform to the same distribution (normal, lognormal etc.); however, their statistics or parameters (for example mean, mode, median, etc.) cannot be measured independently because they are affected by dispersed emission from previous pollution events which have contributed to the ambient environment. Given the levels of the emission and the dispersion rates from source to receptor are different what is actually measured is the time dependant aggregate of concentration created by all pollution emitted and which when collated together results in a multi-polar composite pdf. When decomposition is applied to the observed distribution, it is assumed that the statistical error in the measurement, which occurs on the y coordinate, conforms to a Poisson distribution. Therefore, the standard deviation of each measurement is equal to either the highest value of the square root of the measurement value or one.

The Fityk software (Wojdyr *et al.*, 2013) was used to fit a number of distributions to the dataset. The procedure used an initial parameter of height (*h*), centre (*c*), area, half width at half maximum (*hwhm*) and width (*w* = 2**hwhm*) to fit the desired distribution

(Wojdyr *et al.*, 2013), see also Figure 3-8. A simple algorithm was employed to detect the peak (*h*) and the centre (*c*). These statistics were used to calculate the *hwhm*, *w* and *area* values. The analysis was repeated assuming different distribution functions namely Gaussian, Lorentzian, Pearson, Pseudo Voigt, Voight, Exponentially Modified Gaussian, Doniach Sunjic and Log Normal. The χ^2 test was used to assess the best fit distribution across all data sets. The distribution types considered in the research are expressed mathematically as:

Gaussian

$$f\ (x) = h\, exp\left(-In(2)\left(\frac{x-c}{hwhm}\right)^2\right) \tag{2}$$

Lorentzian

$$f\ (x) = h\,/\left(1+\left(\frac{x-c}{hwhm}\right)^2\right) \tag{3}$$

Pearson

$$f\ (x) = h\,/\left((1+\left(\frac{x-c}{hwhm}\right)^2\left(2^{\frac{1}{shape1}}-1\right)\right)^{shape1} \tag{4}$$

Where shape1=2

Pseudo Voigt

$$f\ (x) = h((1-shape2)\, exp\left(-In(2)\left(\frac{x-c}{hwhm}\right)^2\right)+\frac{shape2}{1+\left(\frac{x-c}{hwhm}\right)^2} \tag{5}$$

Where shape2=0.5

Voigt

$$f\ (x) = 0.5346\, lorentzian + \sqrt[2]{0.2166(lorentzian)^2+(Gaussian)^2} \tag{6}$$

Exponentially Modified Gaussian

$$\boldsymbol{f}\ (x) = \frac{h(hwhm)\sqrt{2\pi}}{0.16hwhm} exp(\frac{c-x}{0.08hwhm}+\frac{(0.8hwhw)^2}{2(0.08hwhm)^2})(\frac{0.08hwhm}{|0.08hwhm|}-erf\left(\left(\frac{c-x}{\sqrt{2}(0.8hwhm)}\right)+\left(\frac{0.8hwhm}{\sqrt{2}(0.08hwhm)}\right)\right) \tag{7}$$

Where erf is the error function

Doniach Sunjic

$$f\ (x) = h\, cos(0.05\pi)\frac{0.1\, tan(x-c)}{(1+(x-c)^2)^{0.45}} \tag{8}$$

Log Normal

$$\boldsymbol{f}\ (x) = h\, exp\left(-In(2)(In(\left(\frac{2ASYM(x-c)}{2hwhm}+1\right)^{ASYM})^2\right) \qquad (9)$$

Where ASYM is asymmetric

Log Normal ($assuming\ ASYM = 1$(Damgaard and Weiner, 2000))

$$\boldsymbol{f}\ (x) = h\, exp\left(-In(2)(In\left(\frac{x-c}{hwhm}+1\right))^2\right) \qquad (10)$$

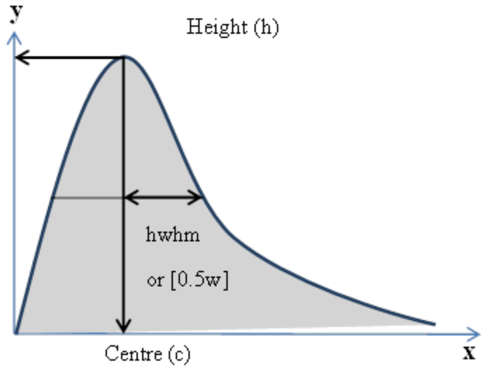


Figure 3-8 Illustration showing the statistical Parameters

In order to identify the best fit estimate nonlinear optimisation was employed (William *et al.*, 1992; Brandt, 1999). Nonlinear optimisation employs a merit function also referred to as a performance measure that evaluates the agreement between the data and the model with selected parameters. The model parameters are adjusted to reach the minimum value of the merit function. The weighted sum of squared residuals (WSSR) or the chi square (χ^2) are shown in the following equation (William *et al.*, 1992):

$$\chi^2(a) = \sum_{i=1}^{N}\left(\frac{y_i - f(x_i;a)}{\sigma_i}\right)^2 = \sum_{i=1}^{N} w_i(y_i - f(x_i;a))^2 \qquad (11)$$

Where:

χ^2 is the chi square or the weighted sum of squared residuals (WSSR)

a is adjustable parameters ($a_i, j = 1, \ldots, M$)

y_i is the actual data

$f(x;a_i)$ is the value derived from the distribution fitted by decomposition model

The weight of each point is assigned by this equation: $w_i = \frac{1}{\sigma_i^2}$

The software gives an option of using three curve fitting methods, Levenberg Marquardt, Nelder-Mead Downhill Simplex and Genetic Algorithms. All three methods aim to minimise the difference between the dataset and the distribution (chi-square) by adjusting the parameter (a) of the distribution. The Levenberg Marquardt method computes the nonlinear optimisation of curve fitting by calculating the gradient of the function and as a result, moves further downhill towards the minimum gradient = 0. The Nelder-Mead method calculates the function at N+ 1 point, where N is the dimension of the problem (Gans, 1992). This method calculates three points for a two parameter fitting. Consequently, the worst of the three points is replaced by a new point. With regards to the three points, one of the points is reflected in a line between the other two points to create a new point. The genetic algorithm attempts to mimic or evolve. It creates a population of possible solutions, and then it increases the possible solutions by trying to minimize the function.

3.7.3 Application of Decomposition to PM_{10} Concentrations

The dataset consists of the PM_{10} levels monitored indoors or outdoors as one minute averages for up to three weeks. The assumption is made that each total distribution of indoor or outdoor PM_{10} levels measured over the duration on monitoring (either 5 or 7 days) consists of several distributions, which result from activities such as cooking, smoking and others. The Levenberg Marquardt is a suitable technique to separate each dataset into the several component distributions, each associated with a particular pollutant source, which together make up the multipolar measured distribution. This method combines the inverse Hessian matrix method with the steepest descent method using lambda (λ). The model is expressed as follows along with the chi square function used to test goodness of fit:

$$f(x) = f(x;a); \quad \chi^2 = \sum_{i=1}^{N} \left(\frac{y_i - f(x_i;a)}{\sigma_i}\right)^2 \tag{12}$$

This method is a standard nonlinear least square that has to calculate the first and the second derivatives of the merit function. The first and the second derivatives are as follows:

$$\frac{\partial \chi^2}{\partial a_k} = -2\sum_{i=1}^{N} \left(\frac{y_i - f(x_i;a)}{\sigma_i^2}\right) \frac{\partial f(x_i;a)}{\partial a_k} \tag{13}$$

$$\frac{\partial^2 \chi^2}{\partial a_k \partial a_l} = 2\sum_{i=1}^{N} \frac{1}{\sigma_i^2} \left(\frac{\partial f(x_i;a)}{\partial a_k}\frac{\partial f(x_i;a)}{\partial a_l} - (y_i - f(x_i;a))\frac{\partial^2 f(x_i;a)}{\partial a_k \partial a_l}\right) \tag{14}$$

The second term of the second derivative will be dismissed in two cases, in the first the second term is set equal to zero or in the second the second term if smaller than the first term of the second derivative, it will be ignored and the second derivative will become:

$$\frac{\partial^2 \chi^2}{\partial a_k \partial a_l} = 2\sum_{i=1}^{N} \frac{1}{\sigma_i^2} \left(\frac{\partial f(x_i;a)}{\partial a_k}\frac{\partial f(x_i;a)}{\partial a_l}\right) \tag{15}$$

There are two factors introduced that are defined as:

$$\beta_k \equiv -\frac{1}{2}\frac{\partial \chi^2}{\partial a_k}, \quad \alpha_{kl} \equiv \frac{1}{2}\frac{\partial^2 \chi^2}{\partial a_k \partial a_l} \tag{16}$$

The curvature matrix (α) is equal to half of the Hessian matrix and includes two equations to solve the problem:

$$\sum_{i=1}^{M} \alpha_{kl}\delta a_l' = \beta_k \tag{17}$$

$$\delta a_l = constant \times \beta_l \tag{18}$$

The constant can be estimated to be a function of the reciprocal of the diagonal element of the curvature matrix (α) and lambda (λ).

$$\delta a_l = \frac{1}{\lambda \alpha_{ll}} \beta_l \quad or \quad \lambda\, \delta a_l \alpha_{ll} = \beta_l \tag{19}$$

From the previous equation two of them combine and a new matrix is introduced.

$$\alpha_{jj}' \equiv \alpha_{jj}[1 + \lambda] \tag{20}$$

$$\alpha_{jk}' \equiv \alpha_{jk}(j \neq k) \tag{21}$$

Then two equations will be replaced by

$$\sum_{i=1}^{M} \alpha_{kl}' \delta a_l = \beta_k \tag{22}$$

The software process has the following steps:

1. Initial parameters of the model used to compute the chi square (χ^2).
2. Assume lambda (λ) to be equal to 0.0001
3. Solve the linear equations for δa and calculate χ^2(a+δa).
4. Increase lambda (λ) by a factor of 10 if χ^2(a)≤ χ^2(a+δa).
5. Or decrease lambda (λ) by a factor of 10 when χ^2(a)>χ^2(a+δa).
6. Then the new parameter will be a+δa.
7. Repeat the calculation from step 1.
8. There are two conditions to stop the iteration:
    - When the change of chi square is smaller than the value set up by the software developer, it takes place twice in sequence. Then the iteration stops and the fit will be considered as having converged.
    - When lambda (λ) reaches 10^{15}, the iteration will stop.

The final step R^2 is computed as follows:

$$R^2 = 1 - \frac{\sum(\hat{y}_i - y_i)^2}{\sum(y_i - \bar{y}_i)^2} \tag{23}$$

The software iterates fitting the chosen distribution by selecting different values of *h* and *hwhm* appropriate for each mode characterised in the pdf.

The next step is to sum up the $f(x)$ for the separate component distributions to produce a theoretical predicted pdf. If this is a statistically significantly similar to the actual fit ($p = 0.05$) then 95% of the variation in the measured pdf is explained. By plotting the difference between the predicted and measured pdf it can be confirmed whether or not the distribution of the differences is normally distributed about the mean of zero. In this case, all the features have been explained and this residual provides an indication of the variation in the background levels synonymous with distance to the road and the amount of pollution prevailing out of doors.

3.7.4 Selection of Averaging Time and Bin Width

The PM_{10} levels were monitored at one minute intervals for static monitoring. First step was to plot the pollution levels as a time series and mark on the graph the reported event such child play, cleaning, cooking and other activities. In most cases there are two simultaneously monitored datasets e.g. the lounge and kitchen; lounges of two separate properties and indoors and outdoors. The first task was to identify the sampling average and bin width to plot the distribution, in order to ensure the character of and features in the data are preserved. Two datasets one for the lounge and the other the kitchen were created. The probability density functions (pdfs) of the PM_{10} for all the lounge and kitchen datasets were analysed using three different bin widths 1, 2 and 5 µg m^{-3} at 1 minute, 5 minutes, 15 minutes and 30 minute averaging intervals. An in-depth statistical analysis using the Fityk software and the Levenberg Marquardt method of fitting the distribution of PM_{10} levels for each lounge and kitchen dataset was analysed to establish the bin interval and averaging time most suitable to disclose features in the pdfs. This exercise is reported in chapter 6.1 and 6.2. The processed data were saved separately as a csv file and analysed using Excel and SPSS software packages.

3.7.5 Selecting the Distribution

The distributions of PM_{10} levels in each microenvironment inside each dwelling were calculated using the optimum time interval and bin. A single selected distribution was introduced to one dataset based on an initial estimate by using Fityk software. A distribution fitting for the dataset was obtained by using the Levenberg Marquardt method. Then, the R^2 value of the fitted curve was obtained. Then, two distributions were fitted to the data by using the Levenberg Marquardt method. The R^2 obtained was from these two cases of fitting one and two distributions. In this case, if the difference between the R^2 is less than 0.01, a single distribution was selected; otherwise a new distribution was added to the previous two distributions and so on, until convergence to the best fit for the measurement data. The pollution levels were plotted with respect to the time and some activities, such as cooking were marked on these plots. The interquartile range of each distribution was identified on the plot and provides a better explanation of the event associated with the distribution. The means, geometric means and geometric standard deviation were calculated as methods to compare analysis across all properties and microenvironments.

3.8 Summary

This chapter outlined the methodological approach for this study along with statistical methods for identifying the main factors affecting PM_{10} levels indoor. It started with selecting the study area, testing the equipment, designing the questionnaire forms and the procedure for data collection in the pilot study as a precursor to the main study. The statistical method for fitting the measured pdf with sub component distributions was described and illustrated by way of a simple example. This was followed by a step by step description of the theoretical principle of the Fityk software and procedure used to carry out the decomposition of the data collected. In the next chapter the results of the initial preparatory work to ensure the equipment available to the study was fit for purpose and the collection methods are appropriate to providing good quality data.

4 Equipment Testing and Pilot Study

In this chapter, the description of the equipment, how it was selected, tested and used in static and dynamic monitoring, and the results of the pilot study are presented. The work undertaken focused on CO and PM_{10} monitors, and the GPS logger. Two models of CO monitors were tested under a number of conditions, in order to select one appropriate for the study. Three GPS models were examined, in addition to two DustTraks, which were examined under different situations. The aim of the pilot study was to test the instruments, develop a methodological approach and find the key factors that affect air pollution levels. A house (H01) in Kingston Park, located in the north west of Newcastle City was monitored for the static pilot study.

4.1 Equipment Testing

The Langan, GPS and DustTrak devices were tested for their durability and accuracy. This section shows the results of the testing.

4.1.1 Langan CO Monitor

Twelve electrochemical monitors (Langan model T15v) were available at Newcastle University. Nine out of twelve were in working order, although two of the Langan monitors gave unreasonable readings. One Langan monitor recorded CO levels in excess of 200 ppm which is unrealistic in the environment monitored. The other Langan monitor gave a zero reading for three quarters of the experimental period. On 25/01/2011, seven Langan monitors, labelled A, B, D, E, H, I and J, were deployed inside the environmental chamber. The environmental chamber was programmed to have a temperature cycle of between 10°C and 30°C at three different relative humidity values. There was a linear relationship between the data of the B and D monitors, which suggest a possible linear relationship among the data of the A, B, D and J monitors see Figure 4-1. The internal battery or the memory card for the three non-working Langan monitors (C, F and G) were swapped with three new monitors and eliminated from the next experiment.

A further test was carried out using nine Langan monitors under two scenarios with a view to evaluating their comparability. The monitors were seven LanganT15v monitors and two LanganT15n monitors. The first scenario was to place all monitors in a number of microenvironments for a specific period. All the Langan monitors were measuring the CO concentrations in an office, garden and lounge for four, three and eleven hours respectively. Then, all the monitors were placed inside an environmental chamber for 60 hours in the second scenario. The environmental chamber was programmed to cycle the temperature from 10° C to 30° C and back to 10° C at three different relative humidity values (30%, 60% and 90%). Each cycle lasted for 16 hours and 40 minutes and the data was logged at 10 second intervals.

Descriptive analysis was used to examine the differences across the data from the Langan monitors and scatter plots were used to examine any possibility of a linear relationship between data set from each device. By using linear regression analysis, the comparability was investigated for the Langan monitors recording. First, the two data sets from the two new Langan monitors were compared by using scatter plots. Subsequently, the scatter plots were used to compare the data from these two new Langan monitors to the data from the seven old Langan monitors. The data from the second trial were divided into three sections based on the value of relative humidity. Table 4-1 shows some of descriptive analyses for the two scenarios for the CO concentrations that were measured by nine Langan monitors. A number of data sets were selected for further investigation and the Linear regression analysis shows that the Langan monitors R and S were well correlated during the first scenario (r^2= 90%, S = 0.19 + 0.901 R). The standard error is almost equal to 0.1892. There was a poor correlation between the Langan monitors R and S in the second trial. However, there was a strong correlation between these two Langan monitors R and S in the first and the second cycles of the second trial (r^2= 90%, S = 0.0024 + 1.02 R, r^2= 99%, S = 0.92 + 0.96 R) as shown in Figure 4-2. The two new Langan monitors R and S demonstrated a poor correlation in the last cycle of the second trial due to high humidity levels. This evaluation identified a limitation of the chemical sensors used in the Langan monitors in that their tolerance to humidity is at least 60% but caution is needed beyond. Data at 90% relative humidity and beyond is definitely not reliable.

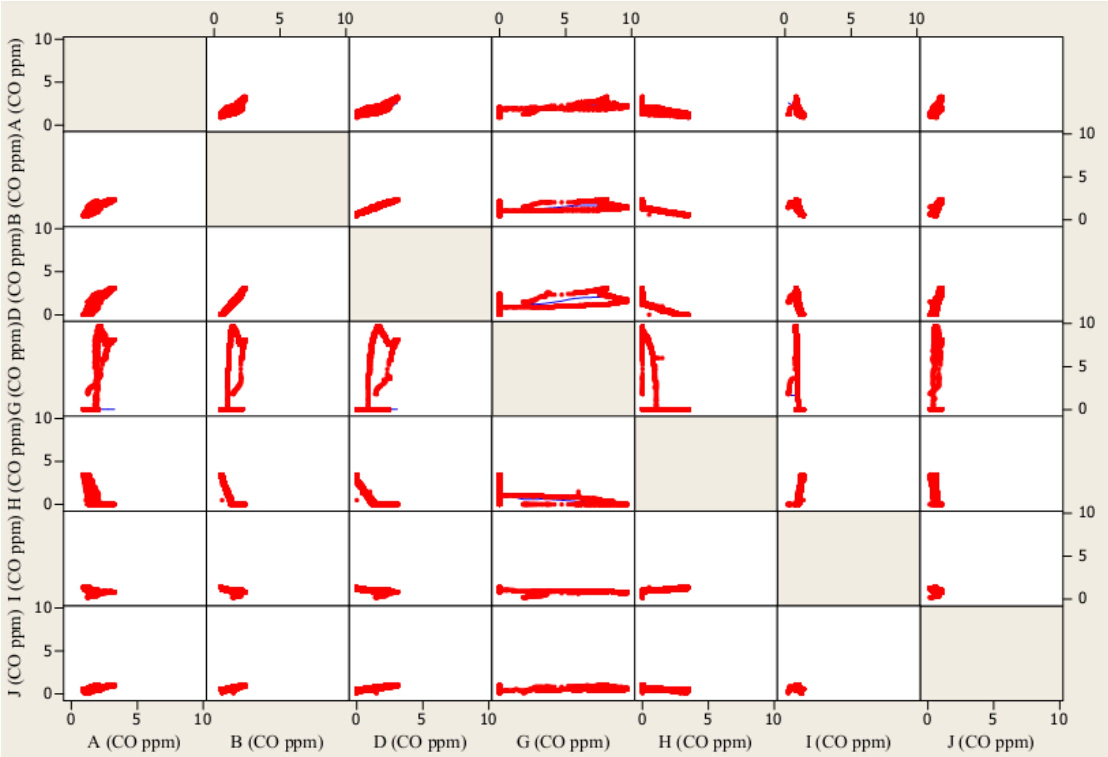


Figure 4-1 Matrix of Scatter plots of the Langan T15v test

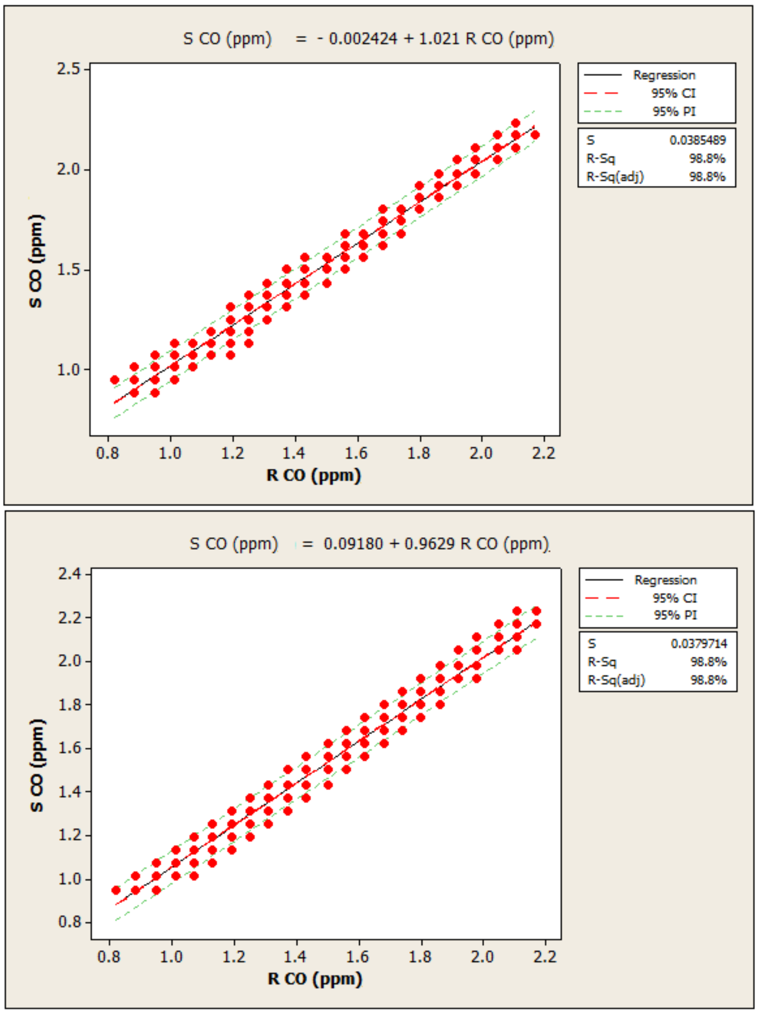


Figure 4-2 Scatter plots of Langan S vs R (first and second cycle of the second trial)

Table 4-1Statistical description of Langan data

	First Scenario	Second Scenario
Langan	**Mean (ppm)**	**Mean (ppm)**
A (T15v)	0.06205	0.14768
B (T15v)	0.09663	0.18411
D (T15v)	1.3441	1.0965
E (T15v)	0.00562	0.61057
H (T15v)	0.01022	0.00602
I (T15v)	0.04128	0.05419
J (T15v)	0.80425	0.726
R (T15n)	1.168	1.5353
S (T15n)	1.249	1.3431

This test compared the data recorded by nine Langan monitors under controlled and uncontrolled environments. The new Langan model was used as the precision equipment. The poor correlation between the new two Langan (R and S) monitors during the second trial was due to the effect of the high level of relative humidity on the electrochemical sensor during the third cycle. When the last cycle of the second trial is excluded, it can be stated that R and S Langan monitors provide the similar reading (r^2= 99%, confidence interval (CI) 95%) with a systematic error of 1 ± 0.05. The correlation in the uncontrolled environment is less than the correlation in the controlled environment for R and S Langan monitor, when the last cycle of the second trial was excluded. Prior to this test the Langan monitors A, B, D, E, H, I and J were sent to Lord Technical Shop for calibration; however, all monitors showed a poor correlation with R and S Langan monitors. It could be that the electrochemical sensors in the old Langan monitors were faulty or past their shelf life. The trial established that the Langan T15n monitors (S, R) are well correlated and the two devices were providing at the 95% level of confidence, statistically similar readings and the Langan T15v monitors (A, B, D, E, H, I, J) cannot be used in the future (the electrochemical sensors would need to be replaced)

4.1.2 GPS Devices

QStarz BT-Q1000XT, i-gotU GT-600 and three Garmin GPS devices were tested, with the aim of finding a suitable and accurate GPS device for the study. The firmware of the Garmin GPS devices was updated. QStarz BT-Q1000XT and i-gotU GT-600 GPS devices were obtained from the Human Nutrition Research Centre at Newcastle University for five days. The GPS devices were tested for two days while walking and driving to examine the reliability. The data recorder for the three Garmin GPS devices was set to log every ten seconds and every five seconds for the other two. The number of points for the Garmin 1, 2 & 3, QStarz BT-Q1000XT and i-gotU GT-600 GPS machines were 510, 562, 375, 4346 and 1162 points respectively. The Garmin GPS devices were unable to track the route as illustrated in Figure 4-3 due to signal loss. Therefore, the Garmin GPS devices were not suitable for the study. The other two GPS devices were found to be more reliable for tracking. QStarz gave more GPS points and thus, this device was selected for this study. Furthermore, the QStarz BT-Q1000XT battery life lasts longer than i-gotU GT-600.

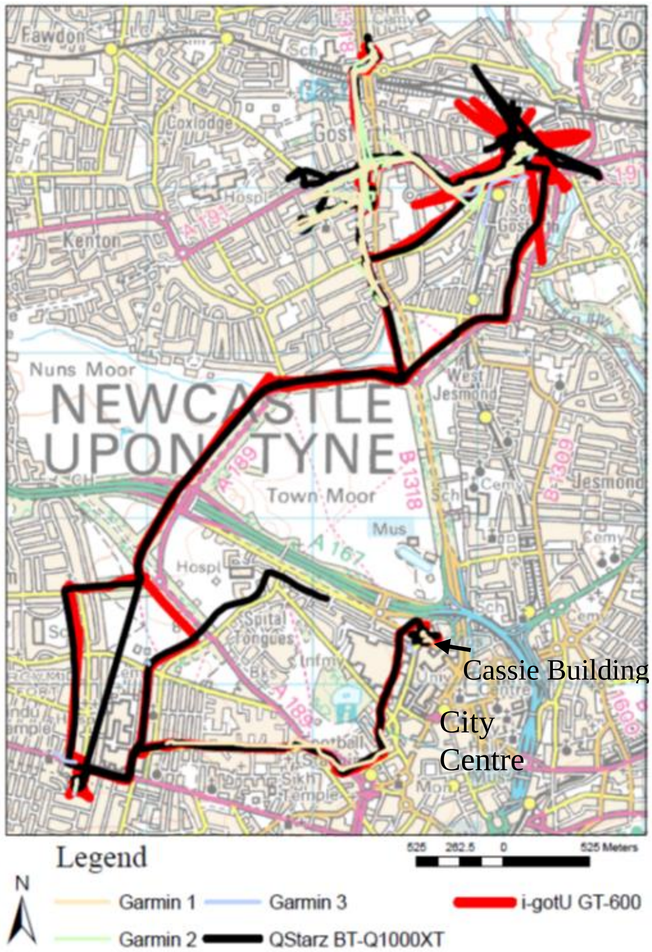


Figure 4-3 Trial routes for all GPS devices
(Source: Edina)

4.1.3 DustTrak Monitor

A TSI DustTrak 8534 monitor was used to conduct monitoring for more than an hour in several microenvironments. An individual carried the DustTrak from the Cassie Building, Newcastle University, walked towards Newcastle city centre, see Figure 4-3, and then back. Figure 4-4 shows the variation in PM_{10} in the different microenvironments, such as indoors, pavements and crossing a road during this trial.

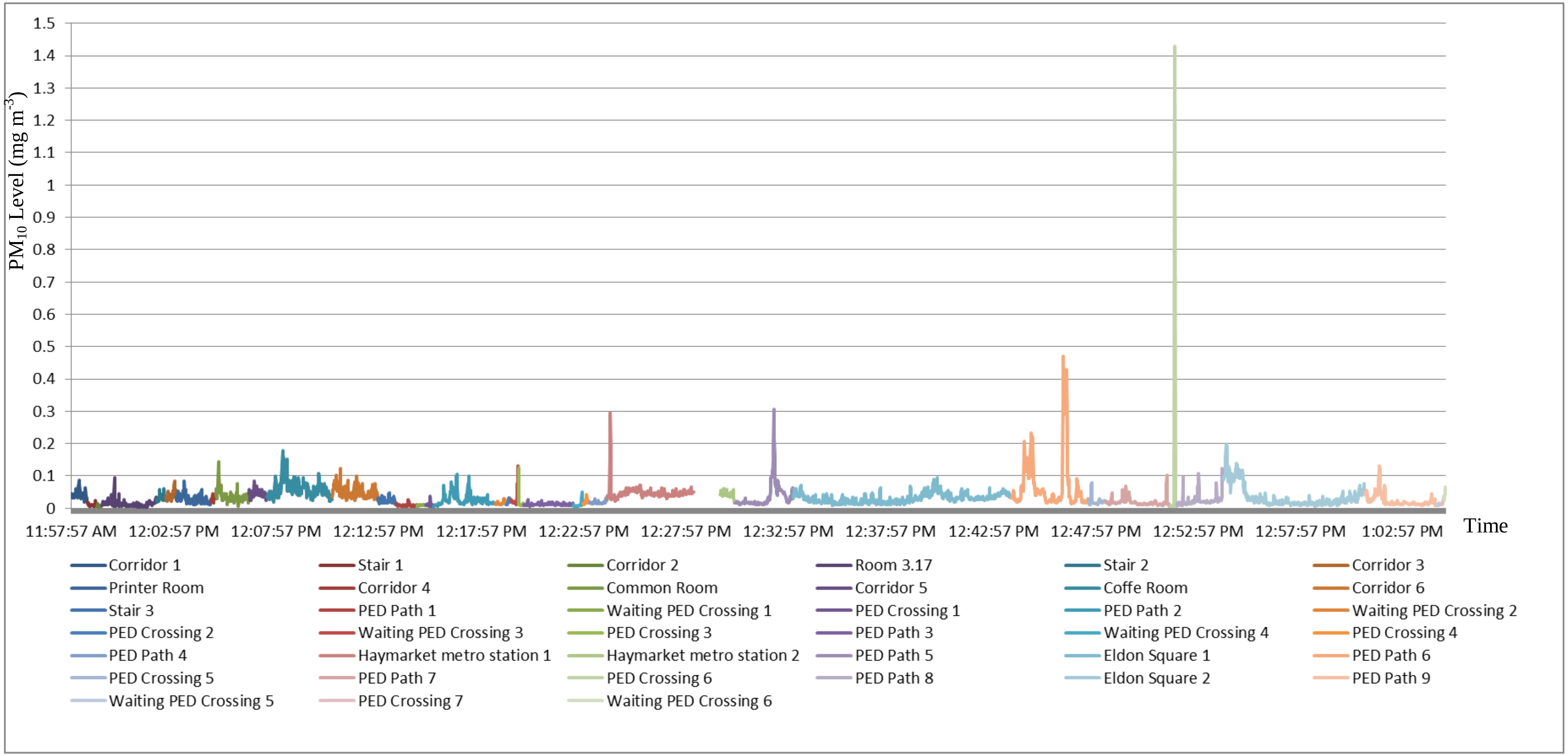


Figure 4-4 Time series plot of the first trial

The first field trial experiment was conducted at Newcastle University campus on 06/09/2011. During the experiment, the PM_{10} pedestrian exposure measurement was conducted using a particulate monitoring device (DustTrak Drx model 8534), which is manufactured by TSI Inc. The experiment consisted of six laps around the terraced houses within Newcastle University, as shown in Figure 4-5. The start and end points for the laps are the intersection of Kensington Terrace Road and Devonshire Terrace Road. The three major roads have parking spaces at both sides and a footway. The PM_{10} measurements were made at one second intervals. All manufacturer guidelines were closely followed to ensure the quality of the collected data. During sampling, the flow rate was set up to be one litre per minute (as a default) for the monitoring device, with the sampler positioned at the right hand side of the monitor. The device was used for three laps without a tube and fitted with a tube during the other three trials, see Figure 4-6. In the case of the tube, the device was held in the right hand and the tube inlet in the other hand. The data was gathered and downloaded from the DustTrak by flash memory into excel format.

Minitab 15 Statistical Software was used to analyse the data from the first field experiment and subject to statistical analysis. The PM_{10} personal exposure statistics derived from the field trials are shown in Table 4-2. The numbers of samples for each circuit without/with the tube were 276, 270, 271, 281, 276 and 271 respectively. The sampling number for each trial is the same as the time duration in the second (one second sampling integral). PM_{10} exposure varied between 0 and 87 µg m^{-3}. The mean for the PM_{10} pedestrian exposure was 12.3 µg m^{-3} (Table 4-2). Using a nonparametric test, there was a significant difference between using the DustTrak with and without a tube. Therefore, further trials were conducted.

Figure 4-5 A map of the field site showing the first field experiment route (Source: Google Map)

Figure 4-6 A DustTrak Drx8534 device (fitted without and with the tube)

Table 4-2 Statistical description of the first field experiment data

Variable	N	Mean ($\mu g\ m^{-3}$)	Minimum ($\mu g\ m^{-3}$)	Median ($\mu g\ m^{-3}$)	Maximum ($\mu g\ m^{-3}$)	Geometric Mean ($\mu g\ m^{-3}$)
without_tube_1	276	12.1	7	11	53	11.6
without_tube_2	270	11.6	7	10	87	10.6
without_tube_3	271	9.6	5	9	44	9.2
with_tube_1	281	7.8	1	8	86	2.8
with_tube_2	276	14.8	9	14.5	27	14.4
with_tube_3	271	18.1	13	18	29	17.9
all_without_tube	817	11.1	5	10	87	10.4
all_with_tube	828	13.5	1	14	86	8.9

For the second field experiment, two DustTrak 8534 monitors were used to conduct four trials. The first trial tested one of the DustTrak 8534 monitors fitted with a tube and the second test used both instruments without a tube for a short period of time. The third trial used one of them with a tube, whilst the fourth trial the tube was fitted to the other instrument. From the trials, it was concluded that there was a statistically significant difference between using the first device with a tube and using the second device without the tube when monitoring simultaneously. The devices were then sent for calibration. A third field experiment, which consisted of three tests, was conducted after the devices were returned following the calibration. The three tests were conducted on these two instruments as detailed in Table 4-3. The data was not normally distributed and hence, a nonparametric test, the Mann Whitney test, was employed to compare the medians. There was no statistically significant difference at the 95% confidence interval between the population medians (DustTrak 1 (with tube) = 3 $\mu g\ m^{-3}$, DustTrak 2 = 3 $\mu g\ m^{-3}$). Therefore, it can be concluded that there is no statistically significant difference between the population medians. The DustTrak 1 median (9 $\mu g\ m^{-3}$) is higher than DustTrak 2 (with the tube) median (8 $\mu g\ m^{-3}$) on the second test, but no statistically significant difference at a 95% confidence interval. The final test with the DustTrak 1 median (21 $\mu g\ m^{-3}$) was lower than the DustTrak 2 median (22 $\mu g\ m^{-3}$) these were statistically significantly similar at the 95% confidence interval.

Therefore, using the tube was shown to have a small effect on DustTrak measurement but differences were not statistically significantly different. In conclusion the DustTrak can be used with and without tube without correction.

The distributions of the data collected in the three field experiments are plotted in Figure 4-7. The shape of the distribution reflects the actual variation in the levels of PM_{10} measured during the field trials. In the first test the pdf (mode = 2 µg m^{-3}) exhibits a lognormal distribution. However, in the second test (mode = 5 µg m^{-3}) whilst a similar distribution is evident, it is clear that sources of higher concentrations are present. In the third test a bimodal distribution is observed reflecting the fact that the pollutant levels were measured at levels with mode = 17 µg m^{-3} and at higher level mode = 22 µg m^{-3}. These three monitoring campaigns illustrate the statistical challenges of analysing data of such variation. Lack of normality makes the averages inappropriate. The geometric mean is applicable for log normal distributions however not appropriate for multi-modal distributions. The median is appropriate for all distributions. When distributions are not Gaussian it is inappropriate to use standard statistical techniques based on the mean, therefore the nonparametric test (Mann Whitney test) was employed to compare the medians for DustTrak 1 and 2 during first, second and third tests. These were found to be statistically significantly similar at the 95% level of confidence. The means have been calculated to allow the results of this research to be compared with previous research.

Table 4-3 Statistical description for two instruments from the third field experiment

Variable		**N**	**Mean** (µg m^{-3})	**Minimum** (µg m^{-3})	**Median** (µg m^{-3})	**Maximum** (µg m^{-3})	**Geometric Mean** (µg m^{-3})
1st test	DustTrak 1 (with tube)	43195	3.91	1	3	67	3.28
	DustTrak 2	43195	4.33	1	3	86	3.27
2nd test	DustTrak 1	16430	12.09	1	9	247	9.85
	DustTrak 2 (with tube)	16430	10.17	1	8	190	8.61
3rd test	DustTrak 1	553	21.44	14	21	66	20.54
	DustTrak 2	553	22.38	15	22	71	21.49

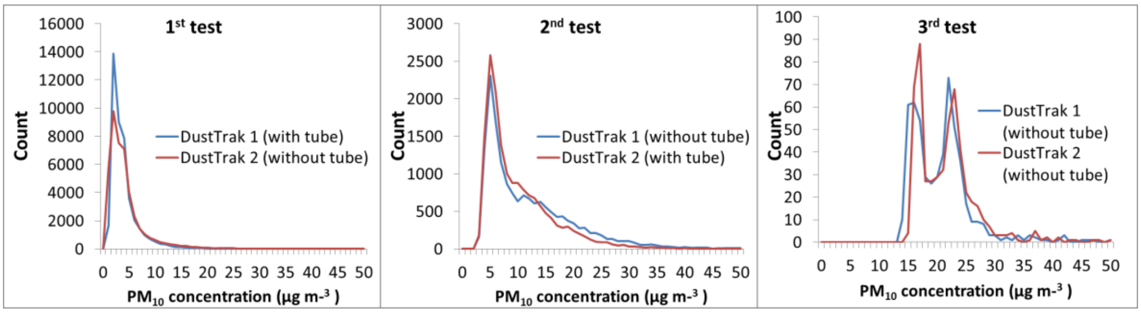


Figure 4-7 Data distributions from the three tests from the third field experiment

4.2 Static Monitoring Pilot Study

Property H01 was selected and monitored for this pilot study in Newcastle. As shown in Figure 4-8, the house (H01) is located at Kingston Park, north-west of the city centre. The kitchen, whose dimensions are shown in Figure 4-9, was monitored for four days. The kitchen was equipped with a gas hob and an electrical oven, which were located on the external wall of the kitchen, see Figure 4-9. The extractor fan was located above the gas hob and had three ventilation speeds. The ventilation in the window was located at the upper one-third. The pollutants monitored were particle matter and carbon monoxide, which were recorded at one second intervals, then averaged to one minute. Two DustTrak 8534 and three Langan T15n devices were used in this study.

Figure 4-8 Location of house H01
(Source: Google Map)

4.2.1 Static Monitoring Scenarios

A number of scenarios were tested to see if indoor pollution levels varied depending on the position of devices with respect to the source and ventilation setting (see details in Figure 4-9 and Table 4-4). In the first two scenarios, the devices were placed on the kitchen bench near to the gas cooker, although the two scenarios had different ventilation conditions. In the first scenario the extractor fan vent was on during cooking and the trickle vent was open. During the second scenario the extractor fan was not used, and the window and trickle vent were closed. The third and the fourth scenarios had similar ventilation conditions to the first scenario. In the third scenario, the devices were placed at a distance of one metre from the gas cooker, and in the fourth scenario they were placed on the opposite side of the kitchen at a distance of three metres from the cooker.

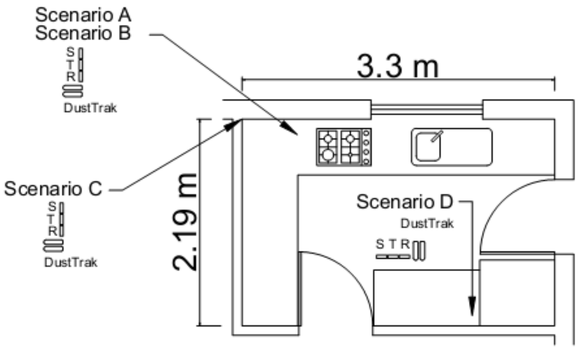


Figure 4-9 Kitchen Floor Plan and Instrument Position

Table 4-4 Scenario conditions

Scenario	**A**	**B**	**C**	**D**
Window	Closed	Closed	Closed	Closed
Extractor fan During Cooking	On	Off	On	On
Trickle Vent	Open	Close	Open	Open
Proximity with Stove	Near	Near	Far	Opposite Side

4.2.2 Data Handling

The data were transferred into the Microsoft Excel format using bespoke software. Subsequently, the data was collated into a master spread-sheet using the time as a synchronisation variable. For each scenario or case, the cooking activities and ventilation conditions were noted and the PM_{10} and CO levels were recorded at one minute intervals. These data were analysed using Excel and SPSS software packages to perform descriptive analysis.

4.2.3 *Analysis and Results*

The PM_{10} and CO were monitored under four scenarios. The first step was to plot the time series data for the PM_{10} and CO to begin to understand the temporal variation of the measured pollution. Figure 4-10 represents the PM_{10} data collected in the kitchen for each scenario. It clearly shows that the enormous variation from scenario to scenario was not simply in the magnitude of the pollution concentration, but also in the duration. The sharp spikes in level are associated with gas cooker events, in particular in the fourth scenario, which illustrated a short period spike that reached almost 2000 µg m^{-3}, which was caused by using the gas cooker. There were 56 and 59 PM_{10} pollutant events counted in all scenarios by DustTrak 1 and 2 respectively. Most of the PM_{10} pollutant events and all of the CO pollutant events were related to the use of a gas cooker or after using a gas cooker. These pollutant events were related to specific cooking activities, as revealed when cross referencing the data recorded on the logging sheets.

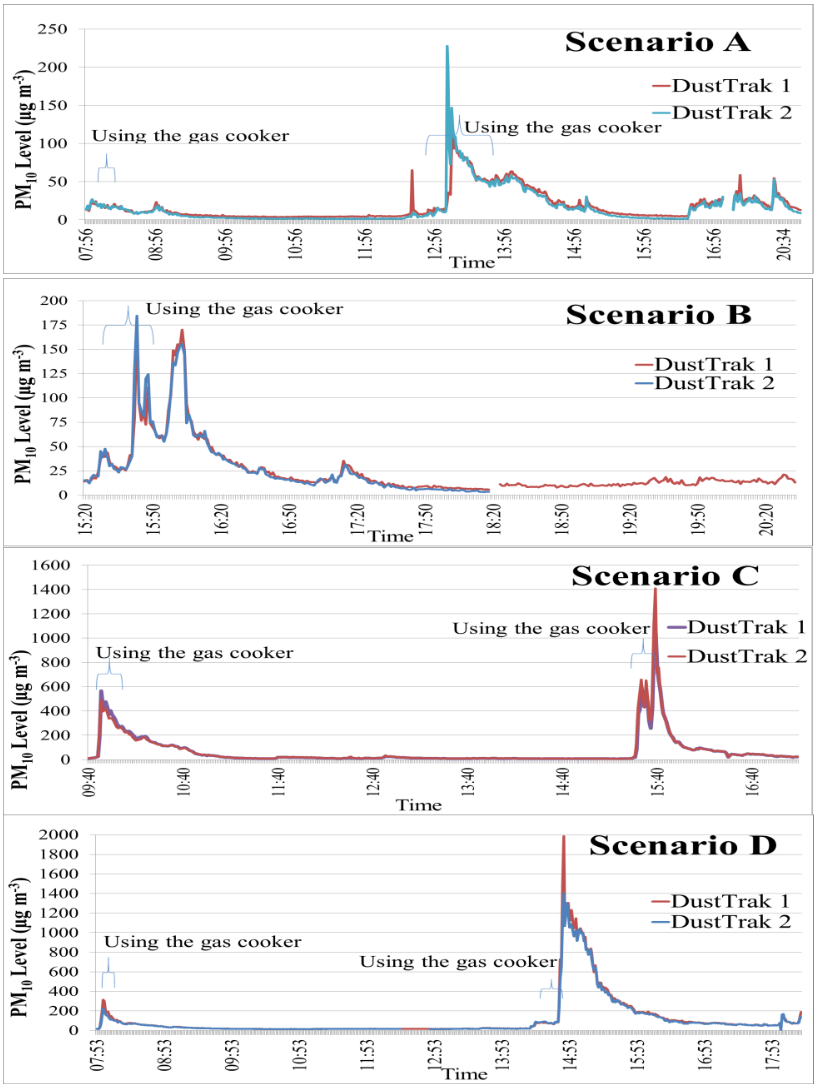


Figure 4-10 PM_{10} levels for each scenario in the static pilot study

The measured concentrations for the PM_{10} and CO were analysed and the descriptive statistics presented in Table 4-5. The PM_{10} levels varied between 3.5 and 1984.4 µg m^{-3} for DustTrak 1 and between 0.4 and 1409.3 µg m^{-3} for DustTrak 2, with the averages (medians) for DustTrak 1 and 2 being 61.7 (16.8) and 63.2 (17.0) µg m^{-3} respectively. In scenario A, PM_{10} concentrations from DustTrak 1 and 2 varied between 3.5 and 110.2 µg m^{-3} and 1.2 and 228.1 µg m^{-3} respectively. In scenario B, the PM_{10} levels varied between 5.6 and 175.6 µg m^{-3} and 3.1 and 184.6 µg m^{-3} from DustTrak 1 and 2 respectively. In scenario C, the PM_{10} ranged from 6.3to 1051.9 µg m^{-3} and 7.2 to 1409.3 µg m^{-3} from DustTrak 1 and 2 respectively. In scenario D, the PM_{10} levels from DustTrak 1 and 2 varied between 14.3 and 1984.4 µg m^{-3} and 0.4 and 1404.1 µg m^{-3} respectively. The PM_{10} means in scenarios A, B, C and D were 17.3, 23.8, 68.6 and 114.7 µg m^{-3} from DustTrak 1 and were 15.5, 31.2, 70.5 and 110.9 µg m^{-3} from DustTrak 2 respectively.

Table 4-5 Statistical description of PM_{10} (µg m^{-3}) in the static pilot study

Scenario	DustTrak	Sample Minutes	Mean	Median	Q1	Q3	Minimum	Maximum	Geometric Mean
A	1	549	17.3	8.6	4.7	19.9	3.5	110.2	10.8
	2	549	15.5	5.8	1.8	17.4	1.2	228.1	6.6
B	1	310	23.8	14.2	10.2	23.5	5.6	175.6	17
	2	179	31.2	18.4	9.5	37.2	3.1	184.6	19.2
C	1	450	68.6	15.9	8.8	67.8	6.3	1051.9	25.1
	2	450	70.5	17.5	9.9	68.0	7.2	1409.3	27
D	1	622	114.7	30.9	16.7	81.5	14.3	1984.4	45.7
	2	602	110.9	35.4	16.4	81.2	0.4	1404.1	45.4

Box plots max, min and quartiles of the data were produced and presented for PM_{10} in Figure 4-11. The PM_{10} data was not normally distributed. The medians levels of PM_{10} in scenario A for DustTrak 1 (and 2) were statistically significantly lower than in scenario B, at the 95% level of confidence (8.6 (5.8) and 14.2 (18.4) µg m^{-3} respectively). Interestingly, the medians in scenario A, B and D for DustTrak 1 and 2, at the 95% level of confidence, were statistically significantly lower than the medians in scenario D for DustTrak 1 and 2, (30.9, 35.4 µg m^{-3} respectively). In addition, the range of PM_{10} concentrations data for scenario C and D were substantially higher, and the measurements for the PM_{10} concentrations varied statistically significantly compared to scenarios A and B. For scenario A, there is a statistically significant difference between the data from two DustTraks. However, there is not a statistically significant difference for scenarios B, C and D between the data from two DustTraks at the 95% confidence interval and the p-value greater than 0.05. The readings from the two instruments were consistent in three scenarios, as shown in Figure 4-12 with R^2 greater than 0.96. Therefore, the data from both instruments were statistically significantly similar.

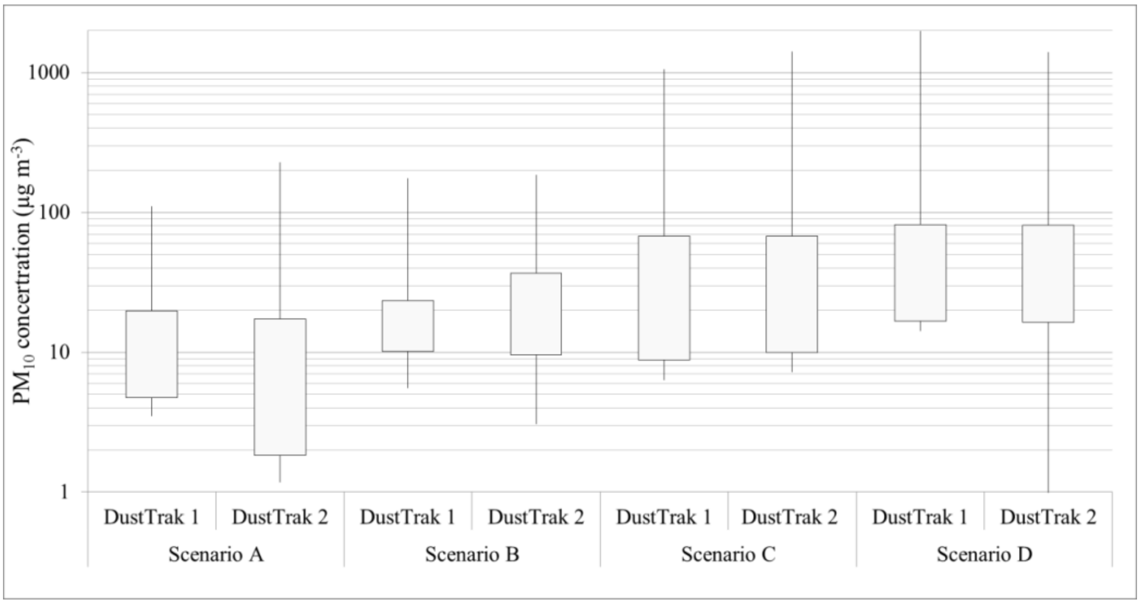


Figure 4-11 Box plot of max, min and quartiles of PM_{10} levels for scenarios A, B, C and D measured using the DustTrak 1 and 2

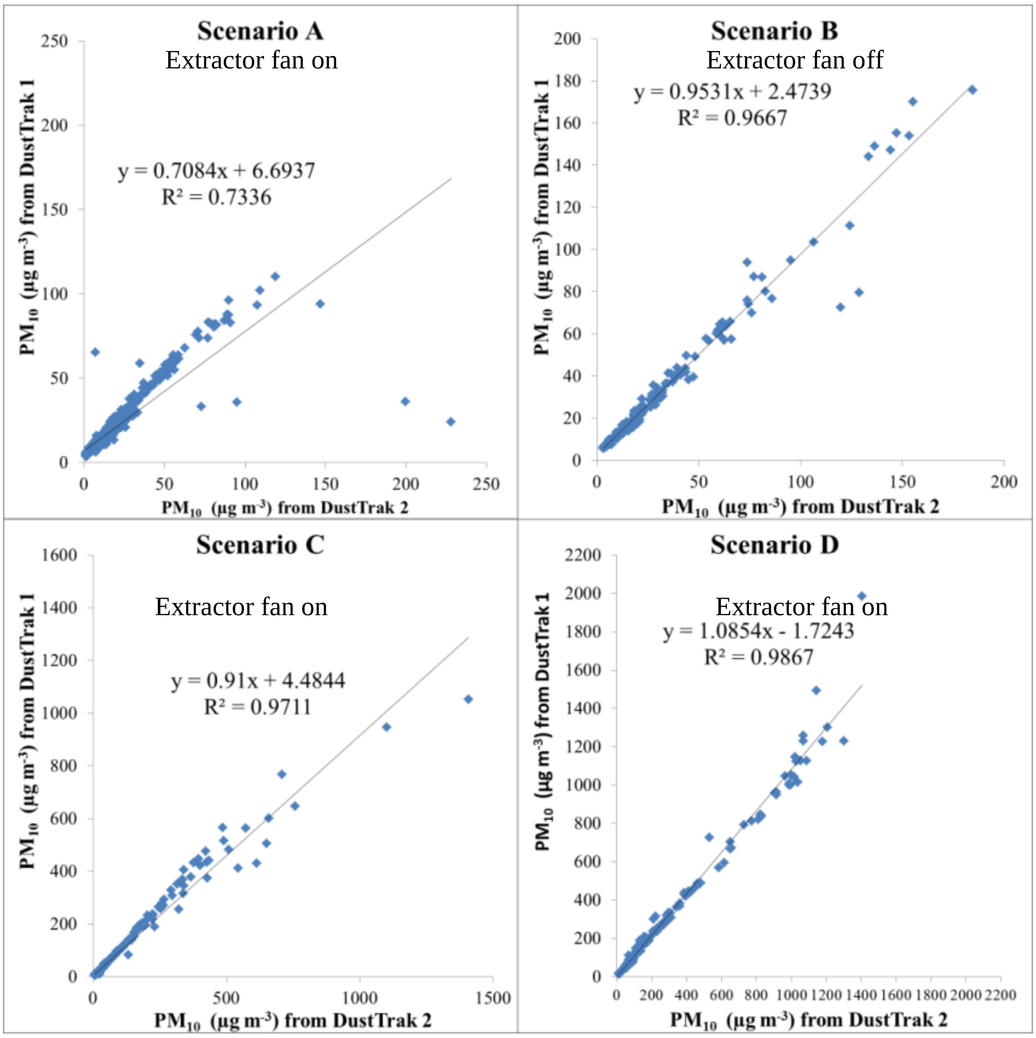


Figure 4-12 Scatter plots (DustTrak 1 vs DustTrak 2)

Table 4-6 presents the descriptive statistics data for CO. The CO levels from all devices varied between 0.03 and 4 ppm for Langan S, 0.19 and 3.43 for Langan T and 0.03 and 3.37 ppm for Langan R. The minimum (and maximum) CO concentrations for scenarios A, B, C and D recorded by the new Langan monitor (T) were 0.25 (3.43), 0.31 (2.44), 0.19 (1.80) and 0.25 (0.9) ppm and the mean (median) {geometric mean} were 0.67 (0.4) {0.5}, 0.65 (0.39) {0.51}, 0.36 (0.31) {0.34} and 0.37 (0.31) {0.35} ppm respectively. The mean CO concentration of 0.67 ppm was the highest for scenario A with the lowest mean CO concentration in scenario C with 0.36 ppm. The CO data was not normally distributed. The median levels of CO for each Langan were statistically significantly different from other Langans in each scenario, at the 95% level of statistical confidence. In addition, the range of data for CO levels in scenarios A and D were substantially higher and the measurements varied statistically significantly differently compared to the CO levels from scenarios C and D. The readings from the three Langans were not consistent, which established that these Langans were not appropriate for this study.

Table 4-6 Statistical description of CO

Scenario	Langan	Sample Minute	Mean	Median	Q1	Q3	Minimum	Maximum	Geometric Mean
A	S	350	0.20	0.03	0.03	0.03	0.03	4.00	0.05
	T	549	0.67	0.40	0.30	0.73	0.25	3.43	0.5
	R	549	0.52	0.21	0.03	0.65	0.03	3.37	0.17
B	S	-	-	-	-	-	-	-	-
	T	310	0.64	0.37	0.32	0.68	0.31	2.44	0.51
	R	310	0.66	0.39	0.28	0.76	0.14	2.39	0.48
C	S	450	0.07	0.03	0.03	0.03	0.03	1.44	0.04
	T	450	0.36	0.31	0.29	0.31	0.19	1.80	0.34
	R	450	0.167	0.09	0.05	0.10	0.03	1.88	0.09
D	S	627	0.059	0.03	0.03	0.03	0.03	0.52	0.04
	T	627	0.375	0.31	0.26	0.43	0.25	0.90	0.35
	R	627	0.168	0.06	0.03	0.27	0.03	0.77	0.09

4.2.4 Comparison with Other Studies

Table 4-7 provides a summary of the results from previous indoor measurement studies all of which used the gravimetric sampling method. As stated above in Section 3.4.5 a number of studies (Lehocky and Williams, 1996; Ramachandran *et al.*, 2000; Chang *et al.*, 2001; Chung *et al.*, 2001; R. A. Jenkins *et al.*, 2004; Zhu *et al.*, 2011) have stated that measurements of PM are overestimated by a factor of 2 to 3 when using the photometric method. On the other hand, Braniš and Kolomazníková (2010) concluded that the ratio between the DustTrak SidePak and the portable nephelometer (light scatter) measurements was approximately 3.5 and Park *et al.* (2009) stated that

DustTrak underestimated measurements by a factor of 0.48 (thus a scaling factor of 2.08 is need for comparison with gravimetric sampler methods). Therefore, in order to compare the results of this research using the DustTrak light scatter measurement with the results of the research using the gravimetric method concentrations were adjusted accordingly to give a range of values (see Table 4-5 and further details in the next paragraph). As suggested in section 4.1, the statistic chosen for use to compare results has to give due consideration to the shape of the distribution. Given the shapes of the distributions measured in this research can be log normal but are often multimodal, the median was considered the most appropriate metric. However, the mean and the geometric mean as well as the median values measured in the kitchen in this study are included in Table 4-7 to enable comparison with other research. It is worthy of note that research identified in the literature reported in this study used the mean.

This study, compared to others, found a much larger variation in PM_{10} concentrations in scenarios C and D compared to that measured in other studies, which may in part be due to the high resolution selected (one minute) but also due to the fact that within the kitchen environment during the different measurement campaigns the nature (boiling, frying, baking etc.) and duration of the cooking activity were different, sometimes there was natural and other times mechanical ventilation and the relative position of different monitors with respect to the cooker changed. This would explain the wider measured variation.

As shown in Table 4-7 the research of others all used gravimetric systems compared to this study which employed light scatter. As previous research measured an overestimation of gravimetric ranging from 2 to 3.5 times the light scatter measurements, the results of this research were scaled accordingly and thus provided an indication of the range (see brackets in Table 4-7) to allow comparison of this with previous research. Without the scaling, as shown in Table 4-7, the PM_{10} mean concentrations in this study were lower than the concentrations recorded by gravimetric measurements consistent with other studies.

However, adjusted by the scaling, the results of this study can be compared with those of others. Lawson *et al*. (2011) measured outdoor PM_{10} concentrations ranging from 22.5 μg m^{-3} (close to main roads) compared to 17.2 μg m^{-3} at a distance away. Both levels are below those measured in the kitchen in this study suggesting that pollution levels in kitchens are higher than at the roadside. The devices in scenarios A-D were all placed in the kitchen, whilst other studies pollutants were monitored in different property types (houses, flats, commercial and school premises) and therefore in different indoor microenvironments (without specific details being given) so comparison of levels is not straightforward. Stranger *et al.* (2007) gave no information concerning the activities carried out during the monitoring campaigns in his comparison of indoor exposure in residential properties compared to school premises. School children are exposed to about 50% higher pollution concentrations at school compared to at home levels. This is expected due to the large number of children present in classrooms causing re-suspension of dust particles. Levels in school were consistent with cooking activity in kitchens measured in this study. Stringer *et al.* (2007) also noted that smoking activity increased average indoor PM_{10} levels by 46%. Jones *et al.* (2000) chose his properties against a definition "a house is one adjacent to a road known to experience heavy traffic throughout the day but with increased levels at rush hours" and indicated that cooking and daily activity took place. The participants in this study noted specific types of activities during the monitoring campaigns. Flats chosen for study were on the tenth and thirteenth floor high above city centre street activity and therefore expected to have less pollution transported indoors. The highest of levels 88 $\mu g\ m^{-3}$ occurred during smoking which were typical of those highest of levels measured in Scenario D in this study. Whilst ambient levels, 15 $\mu g\ m^{-3}$ and 17 $\mu g\ m^{-3}$, at different times measured inside the flat were substantially lower that any measurements made in the current research but consistent with those indoors of rural properties monitored by Lawson *et al.* (2011). In contrast Jones *et al.* (2000) showed differences in one property in rural parts of England during a period in September, May and October typically 34 $\mu g\ m^{-3}$, 27 $\mu g\ m^{-3}$ and 45 $\mu g\ m^{-3}$ respectively. These levels are all higher than Lawson *et al.* (2011) and consistent with residential houses monitored by Stringer *et al.* (2007).

The measurements reported in Table 4-7 from this research were all within the kitchen some high PM_{10} mean concentrations can be explained by the location of the monitor with respect to the kitchen cooking appliances, the nature of the cooking activity and the type of ventilation. Interestingly the PM_{10} mean concentrations were found to be higher at further distances away from, compared to close proximity to, the cooker. Only scenario B had no ventilation creating an environment one would expect to be less variable which is not the case. In addition, the mean pollution levels of scenarios of C and D were the highest of levels measured and yet with the extractor fan on and at a further distance away from the cooker - this was unexpected.

This study has demonstrated substantial variations within the kitchen with highest levels due to frying, extractor fan on and at a distance from the cooker, whilst Jones *et al.* (2000) and Aizlewood and Dimitroulopoulou (2006) discovered that PM_{10} mean concentrations vary from house to house and measured highest levels were due to smoking indoors. Lawson *et al.* (2011) found rural homes at a distance from the road were lower than homes close to the road which was consistent with flats at greater height (tenth and thirteenth floor) above the street in city centre observed by Jones *et al.* (2000). On the other hand in some homes close to the road Jones *et al.* (2000) found levels almost twice those of Lawson *et al.* (2011).

Table 4-7 PM_{10} concentrations in other studies and this study

Study	**Sample**	**Mean PM_{10} (μg m^{-3}) (scaled x2 - x3.5)**	**Sampling Method**
Stranger *et al.* (2007)	Residential houses	39.4	Gravimetric Sampling
	Schools	60.6	
Jones *et al.* (2000)	Houses at roadside	47.8, 34.7, 16.5, 27, 20	Gravimetric Sampling
	Flat	15, 17, 88	
	Rural houses	34, 27, 45	
Aizlewood and Dimitroulopoulou (2006)	Apartment building	13.9 to 92.3	Gravimetric Sampling
	Office building	14.8 to 25.7	
Lawson *et al.* (2011)	Houses near main road	22.5	Gravimetric Sampling
	Houses far from main road	17.2	
This Study (Indoor kitchen)	Scenario A	13.1 (26 - 46)	Light Scattering
	Scenario B	20.5 (41- 72)	
	Scenario C	55.2 (110-193)	
	Scenario D	73.4 (147-257)	

Considering now measurements of CO, this study found that (ventilated) scenario D had the least variation in CO with scenarios C variations lower than scenarios A and B. The CO mean concentrations in scenarios A and B were much higher than the concentrations recorded by (Lawson *et al.*, 2011) as shown in Table 4-8. This study, similar to other UK studies, has measured CO mean concentrations well below the standard objectives, showing the influence of stricter air quality legislation and for outdoor levels cleaner vehicle technology. This study also found that the CO mean and variation is negatively correlated with the distance from the source (gas cooker). Therefore, there is a suggestion that CO concentration is inversely proportional to the distance from the source.

Table 4-8 CO concentrations in other studies and this study

Study	Sample	Mean CO (ppm)
Lawson *et al.* (2011)	Houses near main road	0.362
	Houses far from main road	0.265
This Study (Indoor kitchen)	Scenario A	0.572
	Scenario B	0.596
	Scenario C	0.334
	Scenario D	0.364

A static pilot study was conducted by using a number of devices to monitor PM_{10} and CO in a kitchen. It became clear that whether or not the room was ventilated and the cooking activities needed to be noted in detail, as the PM_{10} mean concentrations showed an increase depending on the type and duration of cooking activity that occurred. The PM_{10} means were similar or higher than other studies, and the variation in PM_{10} concentrations could be due to the position of the device or other factors such as ventilation or other activity taking place in the kitchen. The CO concentration means were similar or higher than previous studies. The cooking activity was noted for the main static monitoring campaign as the most polluting activity contributing the PM_{10} levels.

4.3 Summary

Instrument testing, fine tuning of the methodological approach and identifying the key variables affecting pollution were the main aims of the pilot study. This chapter gave a description of equipment testing and presented the pilot study results. The testing of two types of Langan monitors showed that the Langan T15n is more reliable for CO monitoring and thus this monitor was chosen for the pilot study. Comparing the data from three Langan monitors (S, T and R) showed a poor correlation among the devices and therefore CO monitoring was discontinued for the remainder of the study. The QStarz GPS monitor provided superior tracking data compared to the other GPS devices. A number of tests were carried out on two DustTraks to examine them under different situations. The data from DustTrak 1 and 2 were statistically significantly similar when using a length of tube or not, therefore it was concluded that no correction factor for attached tube was needed. For the static pilot study, the PM_{10} and CO levels were monitored using a number of devices in the kitchen of property H01 during the static pilot study. The data shows a clear and large variation from one scenario to another. This variation was not simply in the magnitude of the pollution levels, but also in their duration. The pilot study highlighted that the cooking activities needed to be noted in detail, because the results showed that the sharp spikes of pollution were associated with using gas cooker and moreover, the PM_{10} mean concentrations did not show an increase, as the distance from the gas cooker decreased. The two DustTraks were consistent in their readings. The PM_{10} levels were of similar range to other studies, as the variation in the PM_{10} could be derived from the position of the appliance or other factors. In addition, there was a poor correlation among the three Langan measurements S, T and R devices when monitoring simultaneously in the same room. Therefore, cooking activity was noted in detail in the main static monitoring campaigns. The readings from the three Langans were not consistent, which meant that these Langans were not suitable for the next stage of this study.

Comparison of the results of this preliminary with previous research has demonstrated the need to adjust the light scatter measurements before comparing the results with other studies that have used gravimetric monitoring. This is because overestimates ranging from 2 to 3.5 times have been observed. With this adjustment, the most important messages emerging from this comparison are that the microenvironments are fairly unique and the measurements are governed not only by the location of the property but also the nature of sources whether indoor or outdoor, their duration, the type of activity, whether there is ventilation as well as the type of monitoring system used.

5 Static Monitoring Campaigns

5.1 Introduction

Chapter 4 outlined the equipment testing and pilot study. The Langan CO monitors were found to be inconsistent in the measurement and therefore monitoring preceded with two DustTrak measurement systems only. The pdf were demonstrated to vary significantly in shape (single or multimodal) and at different positions in the same room. The results of the main static monitoring campaigns took place in two phases are presented in this chapter. PM_{10} measurements were conducted in the first campaign at a number of dwellings within Newcastle upon Tyne, monitoring two microenvironments simultaneously either in the lounge of two separate properties or in the lounge and kitchen of the same property for the first campaign. The statistical analysis and time series plots are presented in detail in section 5.3 and 5.4. Also, a second campaign of static monitoring was conducted to compare indoor to outdoor PM_{10} levels, the results of which are presented in section 5.5. PM_{10} measurements were conducted at a number of dwellings within Newcastle upon Tyne monitoring either at two microenvironments simultaneously in the lounge and outdoor of one property or in the lounge of two properties. Given that the second campaign was designed to measure outdoor and indoor simultaneously those properties studied in the first campaign were revisited and invited to take part in the study. However, many of the residents refused due to their experience in the first campaign of the noisy equipment therefore only four properties were common to both survey campaigns. Another difficulty encountered was that two properties, the dentist H09 and the Boutique H11 had no windows that could be opened at the front of the property, due to security issues, and in H12 the open window could not be secured overnight therefore each day the monitor's inlet tube was lifted out of doors through a window which was left open when the premises were occupied. This placed limitations on the usefulness of the data. The results of the statistical analyses are detailed in this chapter and presented, firstly the descriptive statistics in section 5.1 and secondly the time series analysis in section 5.2. Throughout this chapter discussions are in respect of the maxima, minima, medians and interquartile ranges and nonparametric tests are used throughout. This approach is taken because the pdfs are single or multimodal and do not consistently conform to specific mathematical distribution. For the measured pdf the means are calculated to allow comparison with previous research that has tended to use the means but often without comment regarding the distribution of the data measured. In addition, because the distributions are not

Gaussian it is inappropriate to use standard statistical techniques based on the mean, therefore the nonparametric test (Mann Whitney test) was employed to compare the medians or a χ^2 test for the entire distribution. For the component distributions fitted to the multi modal pdf then the geometric means are appropriate and the geometric standard deviations are an indication of the spread in the data. This approach has been adopted for the analysis of all the data collected in the survey campaigns throughout this thesis. A summary of findings is presented in section 0 at the end of this chapter.

5.2 First Campaign (Descriptive Analysis)

The PM_{10} concentrations of the first campaign were measured at ten dwellings, with four dwellings providing the data for the kitchen and lounge simultaneously and the remainder for the lounge only. The first campaign in total consisted of data collected from fourteen microenvironments for one week with two microenvironments at one dwelling being monitored during three consecutive week periods. The descriptive statistics are presented in Table 5-1. PM_{10} levels varied between minimum (maximum) 0 (4270) µg m^{-3} and for the lower (and upper) values of means, (geometric means), medians and modes were 7.2 (40.9) µg m^{-3}, 4.5 (19.7) µg m^{-3}, 5 (18) µg m^{-3} and 0 (13) µg m^{-3} respectively. Figure 5-1 shows the inter-quartiles of PM_{10} concentrations in each location for the first campaign. For clarity of interpretation the box plots of PM_{10} levels separately for the lounge and kitchens are presented in Figure 5-2 and Figure 5-3 respectively. The interquartile ranges of the first campaign varied between 2 and 29 µg m^{-3}. In H01W1, H01W3 and H02W1, the mean and median for PM_{10} in the kitchens was greater than the mean for PM_{10} in the lounges, but the reverse was true with one exception for the median of H05 the mean was the same as the median with the lounge slightly greater than the kitchen in homes H01W2, H05 and H08. In these properties the cumulative pollution levels were greater in the lounge than kitchen due to pollution generating activity that occurred at the lounge.

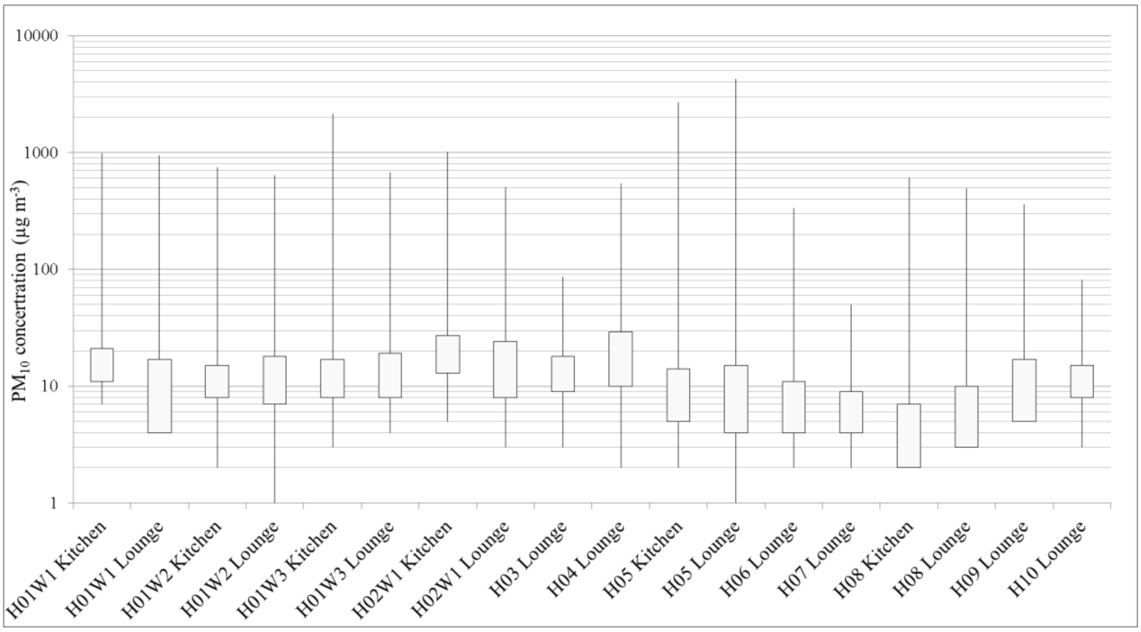


Figure 5-1 Box plot of PM_{10} Levels Static Monitoring First Campaign

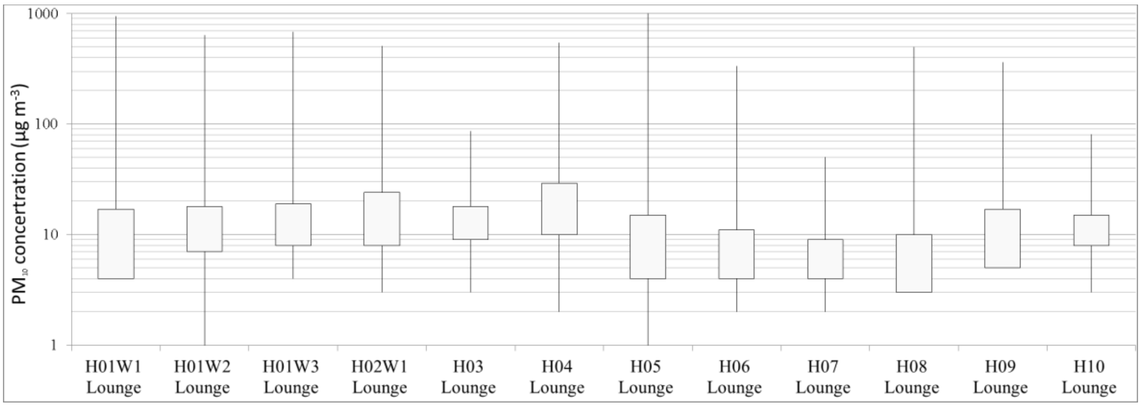


Figure 5-2 Box plot of PM_{10} Levels Static Monitoring First Campaign at the lounge

Figure 5-3 Box plot of PM_{10} Levels Static Monitoring First Campaign at the kitchen

Table 5-1 shows the descriptive statistics of the data for the first campaign. The traffic on the roads near these properties varied from very quiet to major road which was classified subjectively in the absence of measured data. The house H01 was located near a signal controlled traffic junction and PM_{10} levels varied not only from one week to another but also from the lounge and kitchen as shown in Figure 5-33. In general whilst the range of PM_{10} levels was higher in the kitchen than in the lounge the interquartile range was lower. PM_{10} minimum (maximum) levels were 0 (607) µg m^{-3} at the properties near a quiet road which were lower than at properties near a major road with PM_{10} levels 0 (4270) µg m^{-3}. On the other hand as expected PM_{10} interquartile levels 25% (75%) were lower 3 (18) µg m^{-3} at the properties near a quiet road compared to 4 (29) µg m^{-3} near a major road. Interestingly, PM_{10} median at H03 near a quiet road (13 µg m^{-3}) was higher than at properties near a major road except H04 (17 µg m^{-3}) where the median level in the kitchen was lower than in the lounge. On three occasions, PM_{10} median in the lounge was either equal to or greater than in the kitchen. In addition, PM_{10} median at properties near a major road was not always greater than those near a quiet road. In short, this analysis revealed no consistency regarding the influence of traffic flow regimes in the vicinity of each property. Furthermore, it was clear from inspection of the data that the type of activity within the microenvironment (cooking on gas/electric, hoovering, children at play etc.) that was dominating the shape and the magnitude of the peak levels measured. Therefore, time series plots were needed to further investigate the causes of the measured distribution of pollution events.

Table 5-1 Descriptive Statistics for Static Monitoring First Campaign

ID	Location in the network	Micro-environment	Time dd Hr:min	µg m^{-3}							
				Mean	GM[a]	Median	Mode	Q1	Q3	Min	Max
H01W1 **	Signalled junction	Kitchen	04 00:47	28	17.2	14	13	11	21	7	988
		Lounge	03 17:42	20.4	5.6	7	0	4	17	0	942
H01W2 **	Signalled junction	Kitchen	07 00:00	15.1	11.1	10	11	8	15	2	749
		Lounge	06 12:54	15.9	11.2	10	9	7	18	1	638
H01W3 **	Signalled junction	Kitchen	06 23:56	21.2	12.9	12	7	8	17	3	2150
		Lounge	04 11:44	19	12.6	11	9	8	19	4	678
H02W1 *	Busy road	Kitchen	07 00:00	24.5	19.7	18	12	13	27	5	1010
		Lounge	07 00:00	20.2	14.6	14	6	8	24	3	507
H03*	Quiet road	Lounge	07 00:00	15.3	13.5	13	9	9	18	3	86
H04*	Major road	Lounge	07 00:00	24.9	17.4	17	9	10	29	2	541
H05 **	Major road	Kitchen	07 00:00	32.6	9.6	7	5	5	14	2	2680
		Lounge	07 00:00	40.9	9	7	3	4	15	1	4270
H06***	Major road	Lounge	07 00:00	14.7	7.2	6	3	4	11	2	336
H07*	Quiet road	Lounge	07 00:00	7.2	5.9	5	4	4	9	2	50
H08*	Quiet road	Kitchen	07 00:00	7.8	4.5	5	2	2	7	0	607
		Lounge	07 00:00	10.1	5.6	6	3	3	10	0	495
H09	Major road	Lounge	07 00:00	12.7	8.9	11	5	5	17	0	360
H10**	Quiet road	Lounge	07 00:00	13	11.4	11	8	8	15	3	81

* The lounge is in a separate room without interconnecting door to the kitchen ** The lounge is separated by a door from to the kitchen *** Open floor plan [a] Geometric mean

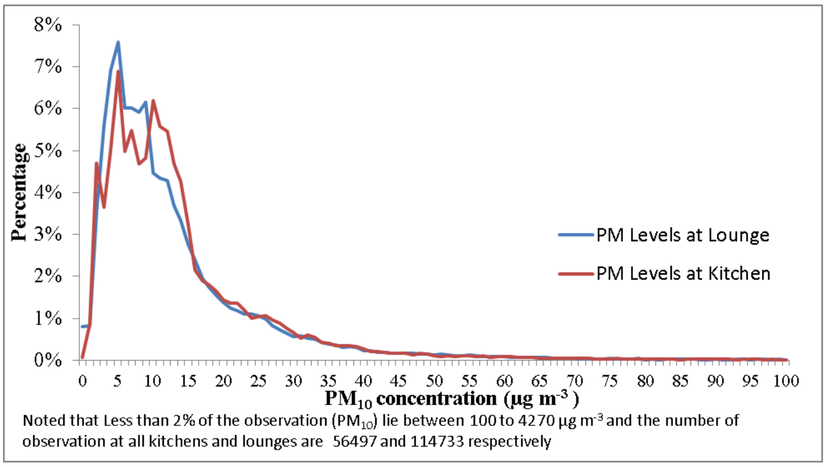


Figure 5-4 PM_{10} Distribution at two microenvironments, the lounge and the kitchen across all properties monitored for the first campaign

Distributions of PM_{10} levels for the first campaign data were drawn and plotted for all data sets separately for the lounge and kitchen using 1µg m^{-3} bin at 1 minute sample averaging interval. Given extremely long tail the distribution is cut at 100 m^{-3} in plotting the distributions. Figure 5-4 provides an example of the data gathered and it is very clear that the data is not normally distributed. Also, the two datasets were quite different in shape. One noticeable fact was that not only was the distribution in the kitchen quite different in shape to that of the lounge the number of spikes observed was up to three times higher. Interestingly, a great deal of structure was evident in both distributions all of which exhibited the “long tails”.

When convenient, householders were asked to record particular events such as cooking, cleaning and give an indication of the time of occurrence and duration of such activity. These were noted on the time series plots. Two participants did not record the activities namely at houses H03 and H05. But, the participant in (H03) retrospectively gave indication of some of the activities and their duration. Therefore, this analysis only was not possible for the H05 dwelling as they did not complete the dairies. In the analysis of the total data set the long tail embraced specific activities, such as cooking and vacuuming. In other cases, whether in the kitchen or lounge the high levels of measured pollution coincided with an unrecorded or unknown event. Therefore, it became necessary to subject the data to further more detailed analysis. There were twelve plots for PM_{10} in all, in some cases for both the lounge and kitchen and for others just the lounge, including three campaign weeks at one dwelling (H01). The results are shown in Figure 5-5 through to Figure 5-16. The lounges of six dwellings (H03, H04, H06, H07, H09 and H10) were monitored for one week and the pollution levels measured simultaneously in the kitchen and lounge at each of the three dwellings (H02, H05 and H08) for one week and (H01) for three weeks.

5.3 Time series plots (First Campaign)

The time series plots for PM_{10} were examined to provide a better understanding of the temporal variation and in particular the features in the PM_{10} measured indoors. The monitoring began on different days of the week and at different times of the day and depended solely on the availability of the householder to be at the property to install the monitors. However, irrespective of the start time, monitoring continued for a full week. Households were encouraged to report their activity for at least one week day and one weekend day and subsequently these were marked on the time series plot for each household for each monitoring period and microenvironment.

Please note that for consistency and ease of comparison of measurements gathered from different microenvironments in different properties the time series are plotted starting at Sunday though to midnight Saturday. This means that if monitoring began on a Tuesday the Sunday and Monday will be measurements made the following week. All statistical tests were carried out using the Mann Whitney test to compare medians because the data are not normally distributed.

5.3.1 Property H01

The PM_{10} mean levels at the house (H01) in the kitchen and (lounge) for each of three weeks at H01W1, H01W2 and H01W3 were 28 (20.4), 15.1 (15.9) and 21.2 (19) µg m^{-3} respectively. The medians for the kitchen (lounge) for each of three weeks revealed similar results with the first week having a larger difference between the kitchen and (lounge) 14 (7) µg m^{-3} (statistically significantly different and higher with p=0.000). The PM_{10} levels were statistically significantly similar during the second week 10 (10) µg m^{-3} (p=0.5385) and marginally different in the third week 11 (12) µg m^{-3} (p=0.000). This demonstrates the importance of activities on indoor microenvironments as the activities were different from one week to another. The main difference here was Ramadan in the second week which coincided also with the school holiday from the Friday in the second week and throughout the third week. The consistency throughout all three weeks of the mean values being substantially higher than the medians, suggests non-normality of the data with a long tail. This is confirmed by the measured range in levels of PM_{10} which varied between 7 and 988 µg m^{-3}, 2 and 749 µg m^{-3} and 3 and

2150 μg m^{-3} in the kitchen during the first (H01W1K), second (H01W2K) and third week (H01W3K) respectively. The range of PM_{10} measured in the lounge (H01W1 L, H01W2 L and H01W3 L) were 0 and 942 μg m^{-3}, 1 and 638 μg m^{-3}, 4 and 678 μg m^{-3} respectively. Interestingly, the maximum level in the lounge compared to the kitchen in week three were very much lower than in the other two weeks which can be explained by the fact that much cooking activity in preparation for Ramadan occurred but after the first week festivities activities settle down and less cooking takes place.

Figure 5-5 to Figure 5-7 show the time series of PM_{10} concentrations in the kitchen and lounge plotted with the specific activities reported by the householder marked appropriately. The graphs clearly show that most of the pollutant events were associated with cooking. Furthermore, it was established that some of the spikes in PM_{10} levels were associated with specific other activity events, in particular in the H01W1 trial, Figure 5-5 which illustrates several spikes for short periods that exceeded 100 μg m^{-3} but were not recorded as cooking events see 16:00 hrs on Friday. However, there was no reported activity so it could not be explained. In general the gas hob activity had a lower peak compared to the electric oven. Moreover, other spikes that occurred were not recorded as being associated with a specific activity due to unacceptable imposition on the householder time to record all events. However, the characteristic shape of other peaks was consistent with known recorded activity. As expected the pollution events occurring in the lounge usually followed the similar trend to those in the kitchen but at a lower level due to dispersion. This is particularly prominent for the ambient pollution levels overnight when there is no activity when the family members are asleep.

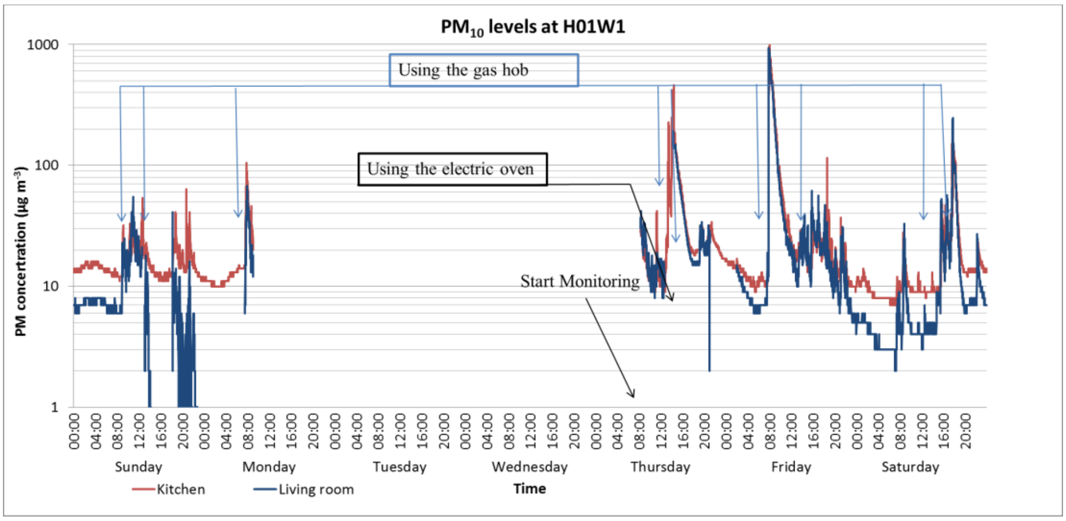


Figure 5-5 PM_{10} Levels at H01W1

Figure 5-6 and Figure 5-7 display measurements made in the same household as Figure 5-5, but during different weeks. Figure 5-5 represents a school term week, Figure 5-6 a period of Ramadan during the school term and the third week Ramadan and school holiday (Figure 5-7). During the first days of Ramadan, the cooking activity was different than a normal day as it involved frying and boiling in preparation for Ramadan and then during Ramadan food was prepared mainly in the late evening. This caused high pollution levels at night time as illustrated in the second and third weeks. However, cooking activity reduced as the days passed compared to the first week of Ramadan into the second week as noted above. As the number of occupants in the house was higher and for longer periods during school holiday this led to an increase of re-suspended particles. The PM_{10} concentrations varied in shape and pattern from one day to another as illustrated by the time series measured in H01 during the three monitoring periods.

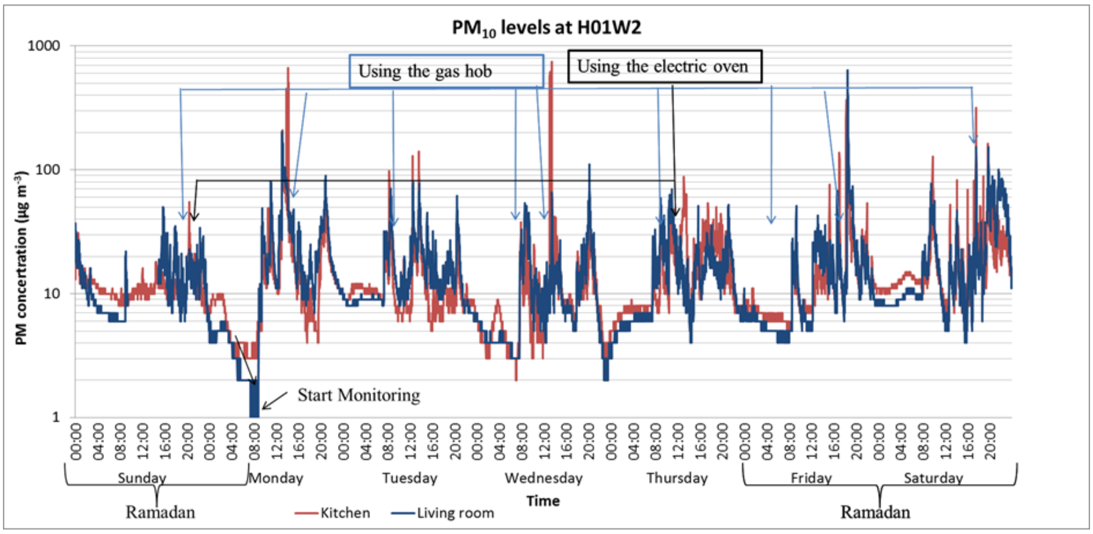


Figure 5-6 PM_{10} Levels at H01W2

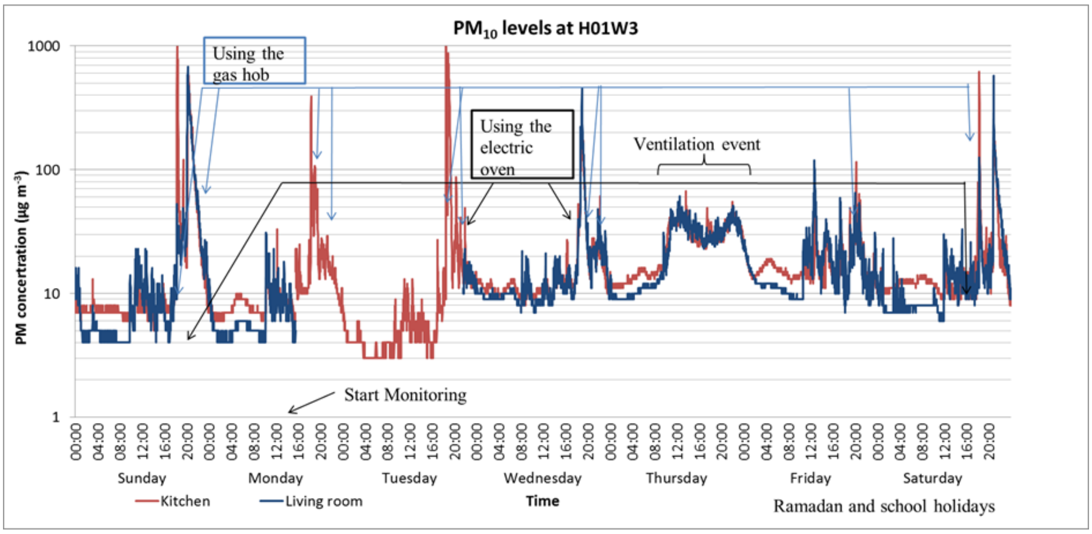


Figure 5-7 PM_{10} Levels at H01W3

The most striking week to week difference is in the ambient levels overnight in the kitchen whilst always higher than in the lounge the differences were much smaller especially in the second week. This could be explained by the fact there was much more activity and cooking taking place between dawn and dusk during Ramadan. The rather atypical profile observed on the Thursday of the third week trial (H01W3) was probably due to the fact that the windows were opened during this day. This will be considered further in chapter 6 section 6.3. This three weeks measurement campaign in one house shows clearly how the microenvironment is very much governed by the activities within and whether the oven or gas hob was used for cooking with a window open or not substantially influencing overall levels as well as characteristic shape of these resulting pdf.

5.3.2 Property H02

The PM_{10} mean (and median) at the house (H02W1) in the kitchen and lounge were 24.5 (18) µg m^{-3} and 20.2 (14) µg m^{-3} respectively. The median for the kitchen was statistically significantly higher than in the lounge ($p = 0.000$). Consistent with H01W1 the distribution was non-normal and whilst mean levels were more aligned with the medians they were much larger than in property H01. The range for PM_{10} levels from 5 to 1010 µg m^{-3} in the kitchen H02W1K and in the lounge H02W1L between 3 and 507 µg m^{-3} were not as high as H01W2. This suggested more frequent or longer periods of PM_{10} levels above the median borne out by the higher upper quartile, Q3, value. Figure 5-8 shows the time series for PM_{10} in the kitchen and lounge. There were more than fifteen pollution events, that exceeded 100 µg m^{-3}, and some of these events were associated with nine recorded cooking events and responsible for the high Q3 value. Other similar spikes occurred which were not associated with a specific event recorded (because activities were noted only for one week and one weekend day) but were likely to be cooking events. Some cooking events caused several spikes for short periods as illustrated in the Figure 5-8. PM_{10} concentrations in the lounge overnight were generally much lower and follow the time series trend for the PM_{10} levels in the kitchen throughout the day. Figure 5-8 illustrates similar (Sunday, Monday and Tuesday) levels and patterns of PM_{10} concentrations from one day to another reflecting mainly the cooking activity. Friday is quite different and to some extent reveals a similar pattern to Thursday in H01W3 when the windows were recorded open. Therefore, it is suggested that this is likely to be the cause.

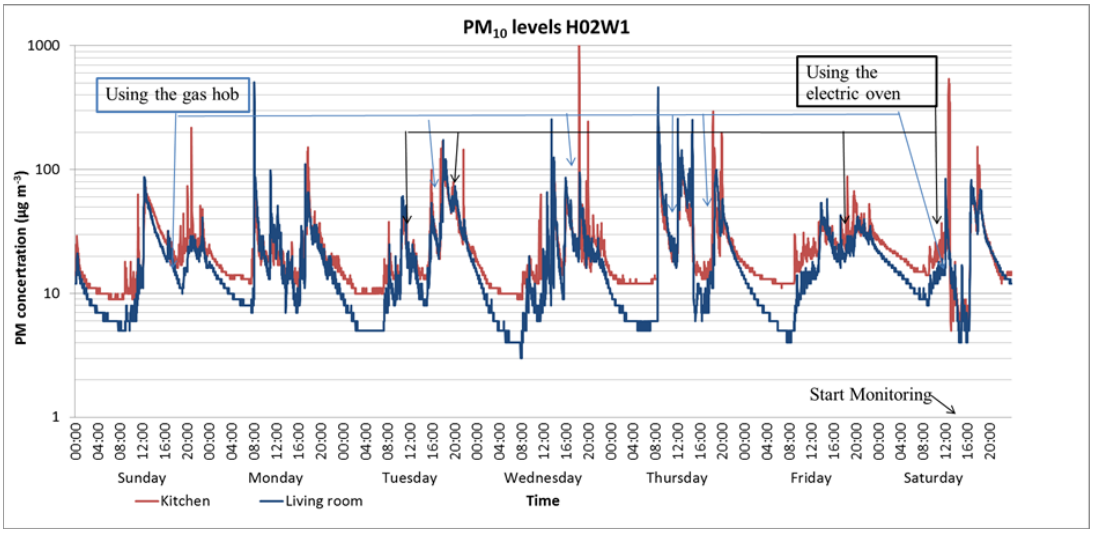


Figure 5-8 PM_{10} Levels at H02W1 with lounge separated from the kitchen by a hallway

5.3.3 Properties H03 and H04 Simultaneous Monitoring

The lounges of H03 and H04 were monitored simultaneously during September 2012. Property H03 is located along a quiet low traffic flow road and H04 located alongside a busy road. The minimum (and maximum) PM_{10} concentrations at H03 and H04 were 3 (86) and 2 (541) µg m^{-3} respectively. The PM_{10} median (13 µg m^{-3}) at H03 was statistically significantly lower (p=0.000) than at H04 (17 µg m^{-3}), also the PM_{10} mean (15.3 µg m^{-3}) at H03 was noted to be much lower than at H04 (24.9 µg m^{-3}). The lounge of H03 was not used frequently by the household occupants which was not the case for the property H04 which was used with high frequency. Unfortunately, the participant of H03 did not record activity in the lounge. However, the participant (H03) gave an indication of some of the activities and their duration retrospectively, therefore Figure 5-9 indicates activities based on recollection rather than recorded at the time of occurrence. The PM_{10} spikes again are likely due to activity in lounge but their magnitude and pattern were conducive to the periods of reported sitting and the more active playing of a young child was coincident with the higher PM_{10} levels.

In stark contrast, there were several pollution events that occurred in property H04 as illustrated in Figure 5-10. Some of these events measured were associated with cooking activity in the kitchen which was responsible for several characteristic short duration spikes that exceeded 50 µg m^{-3} as illustrated in the Figure 5-10. As before, other spikes occurred which were not associated with a specific recorded event, therefore no further comment can be made. PM_{10} concentrations in the lounge of H04 were characterised by both cooking as well as in-lounge activity such as playing and people movement. This was despite the lounge being in a separate room without an interconnecting door to the kitchen. However, the reception area between was small (about three square metres and both kitchen and lounge doors remained open. On the other hand in property H03 PM_{10} levels reflect only the activity in the lounge given that the kitchen is in a separate room without an interconnecting door separated by a long (3.5m) hall and both kitchen and lounge doors remained closed most of the time. Also, cooking activity duration was less at H03. Time series in H03L was less consistent than for H04L from day to day. H03L exhibited a pattern more consistent with lounge activity observed in other properties.

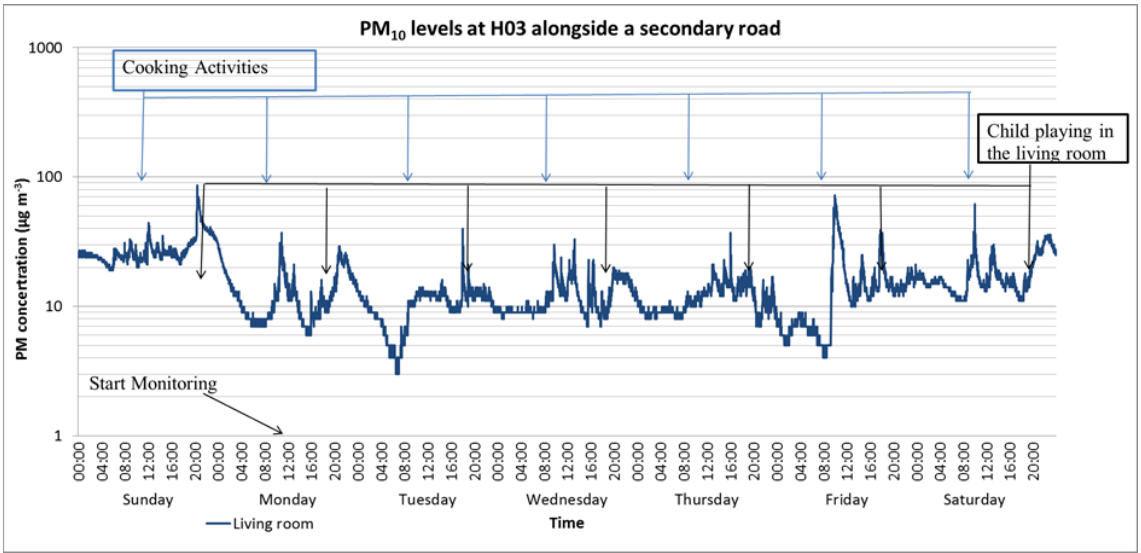


Figure 5-9 PM_{10} Levels at H03 with lounge separated from the kitchen by a hallway

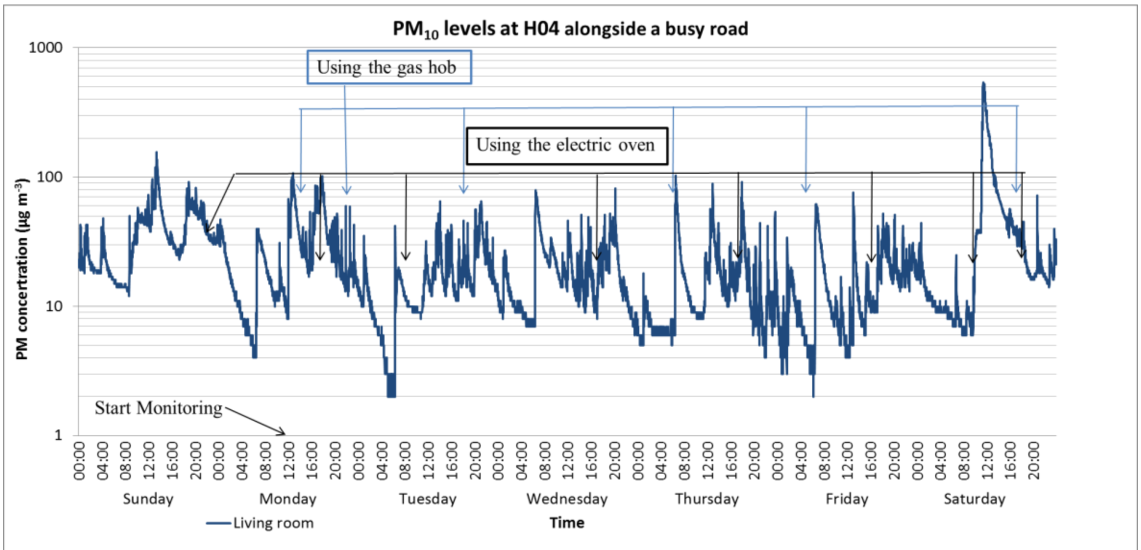


Figure 5-10 PM_{10} Levels at H04 with lounge separated from the kitchen by a hallway

5.3.4 Property H05

Property H05 is located along a busy road and as before the lounge and the kitchen of H05 were monitored simultaneously for one week. The PM_{10} concentrations in the kitchen and lounge ranged from 2 to 2680 µg m^{-3} and from 1 to 4270 µg m^{-3} respectively. The PM_{10} averages (and median) at the kitchen and lounge were 32.6 (7) and 40.9 (7) µg m^{-3} respectively. However, in contrast to properties H01 during the first and third week and H02 both the mean and the median PM_{10} levels were lower in the kitchen compared to the lounge. The participants of H05 did not record their activities, therefore the pollution events could not be explained specifically. However, there were quite different features monitored in H05 compared to H01 and H02 as shown in Figure 5-11, and there was a high pollution event which lasted for several hours that occurred from 20:00 on Monday to 04:00 Tuesday and continuously exceeded 2000 µg m^{-3} which could not be explained due to lack of diary data available. PM_{10} levels in H05, when compared to H01 and H02, exhibited longer durations of the lowest levels with less consistency from day to day. The difference in levels between kitchen and lounge were the smallest of all properties commensurate with only a door separating the lounge and kitchen. Given the absence of an activity diary the PM_{10} time series plot was not so useful to improve our understanding of the temporal variation in H05.

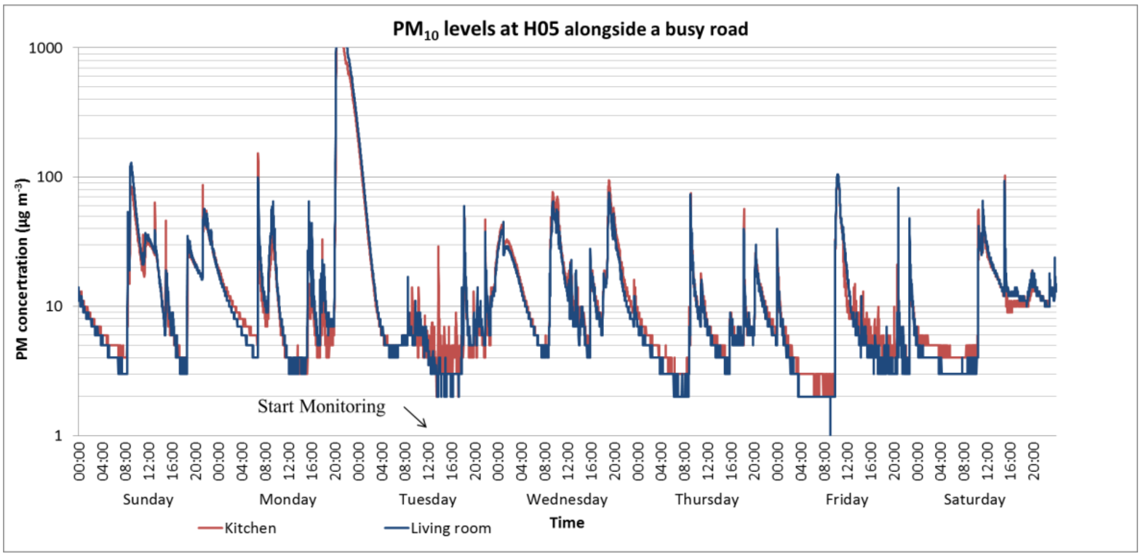


Figure 5-11 PM_{10} Levels at H05

5.3.5 Properties H06 and H07 Simultaneous Monitoring

H06 and H07 were monitored simultaneously in the lounge for one week. H06 was an apartment located alongside a busy trafficked road. Whilst property H07 was located alongside a quiet secondary road it had two lounges one used infrequently. The latter was the one chosen for the study to give a new insight into pollution levels with less time occupied by residents. The mean (median), minimum (and maximum) of the monitored PM_{10} concentrations at H06 and H07 were 14.7 (6), 2, (336) and 7.2 (5), 2 (50) µg m^{-3} respectively. The PM_{10} median at H06 was statistically significantly higher than at H07 (p=0.000). Figure 5-12 shows several pollution events which varied in magnitude pattern and duration. On Sunday evening, two pollution events occurred the first was linked to cooking activity in the kitchen but the second pollution event exceeded 100 µg m^{-3} for 35 minutes at 22:39 hrs. Another unrecorded event exceeding 100 µg m^{-3} over the period 20:25 hrs to 23:49 hrs occurred on Thursday. Activity during the day, except for Monday, was fairly consistent for Tuesday through to Friday with cooking activity at 08:00 hrs and 20:00 hrs evident. Activity during Monday throughout the day with overnight was very different from the other days. The absence of activity as expected resulted in lower levels of PM_{10} without spikes in the time series when the property was reported to be vacant on Saturday and Sunday. The limited information available on activities prevents further comment. There were nine pollution events that occurred in property H06 exceeding 50 µg m^{-3} five of which were pollution events hypothesised as cooking events based on the data provided by the participant. Reported activity watching TV was mostly consistent with low levels of pollution.

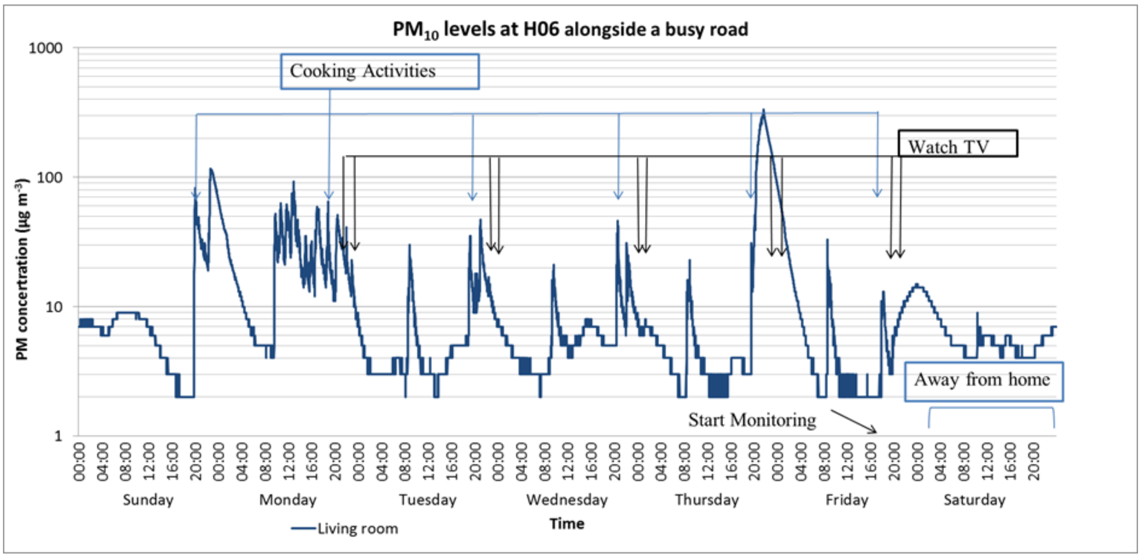


Figure 5-12 PM_{10} Levels at H06

In property H07 see Figure 5-13, peak levels were much lower than those measured in other properties and loosely associated with cooking activity, but levels were strongly associated with occupant activity in the lounge as recorded by householder. Levels in property H07 were lower than those of H06 with means (median), minimum (maximum) respectively 7.2 (5), 2 (50) µg m^{-3} and 14.7 (6), 2, (336) µg m^{-3} respectively. This is consistent with the lounge not separated from the kitchen in H06 whilst it was separated with a hall in the other property H07. As with other properties, due to the separation from the kitchen, PM_{10} levels overall were lower in the lounge.

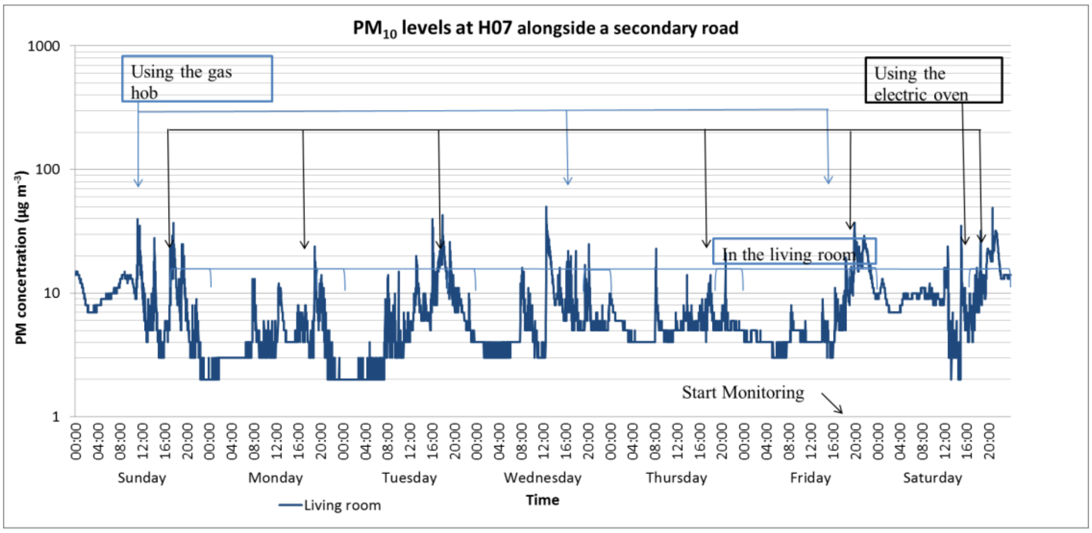


Figure 5-13 PM_{10} Levels at H07

5.3.6 Property H08

H08 was located on a low traffic road with the lounge separated by a hall from the kitchen. The levels of PM_{10} were measured simultaneously in the lounge and the kitchen for one week. The average (and median) PM_{10} concentration in the kitchen and lounge were 7.8 (5) and 10.1 (6) µg m^{-3} respectively. The PM_{10} median in the kitchen was statistically significantly lower than in the lounge (p=0.000). However, the difference was not marked as those observed in other properties (H02) which is consistent with this property having the hall separating the lounge from kitchen. The minimum to maximum PM_{10} concentrations in the kitchen ranged from 0 to 607 µg m^{-3} and in the lounge from 0 to 495 µg m^{-3}. The PM_{10} variations in the two microenvironments in Figure 5-14 showed less consistency from day to day and the pollution trend was different from one day to another. There were seven pollution events which exceeded 50 µg m^{-3} in the lounge. Four coincident with cooking events but the others that occurred were not associated with recorded events. Some of PM_{10} peaks occurred when it was known that occupants were in the lounge but the presence of people in the room was not always associated with “peaks”. The PM_{10} levels overnight, when activities were absent, in this property were similar in the kitchen and lounge as was the case also for H01W2 and H05. But, it is difficult to explain the reason for similarity in pollution levels rather than just trends in the kitchen and lounge overnight for H07 and H05 compared to the different levels and similar trends observed in H01W2 because the characteristics of these properties are quite different. H01W2 kitchen was separated from lounge by a door only as was the case in property H05, however this was not the case for H08.

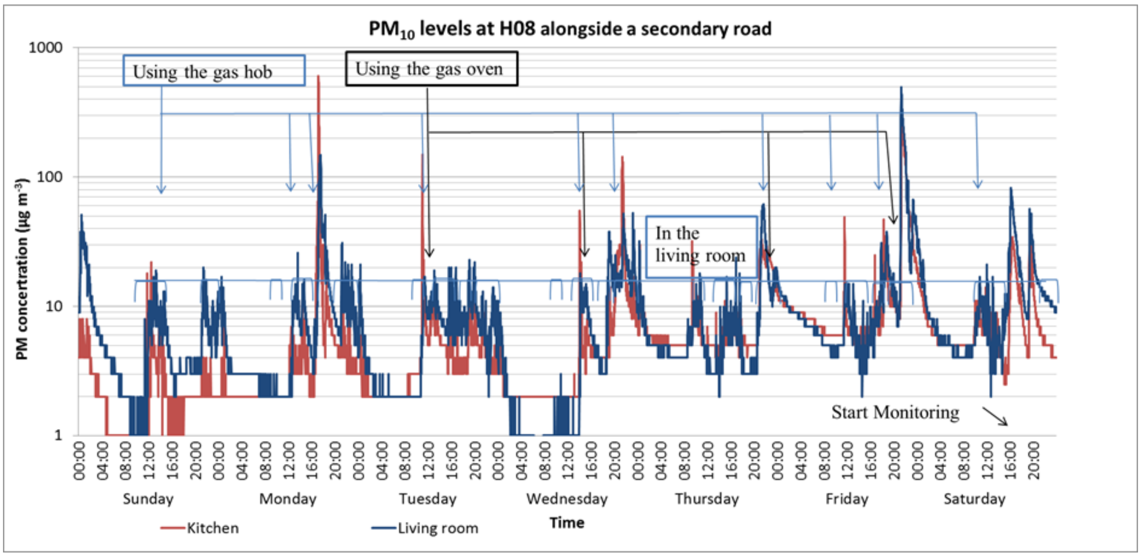


Figure 5-14 PM_{10} Levels at H08

5.3.7 Properties H09 and H10 Simultaneous Monitoring

H09 is located alongside a busy trafficked road whilst H10 is located in a cul-de-sac. The property H09 was a terraced two storey building from which a dentist operated its business. Property H10, a two storey detached private home was some 0.5 km distant to the nearest busy trafficked road. The lounge of H10 and the reception room of H09 were monitored for one week simultaneously. The measured concentration of PM_{10} was analysed and the descriptive statistics presented in Table 5-1. The mean (and median), minimum (maximum) PM_{10} concentration levels in the dental practice (H09) and for the private home (H10) were 12.7 (11), 0 (360) µg m^{-3} and 13 (11), 3 (81) µg m^{-3} respectively.

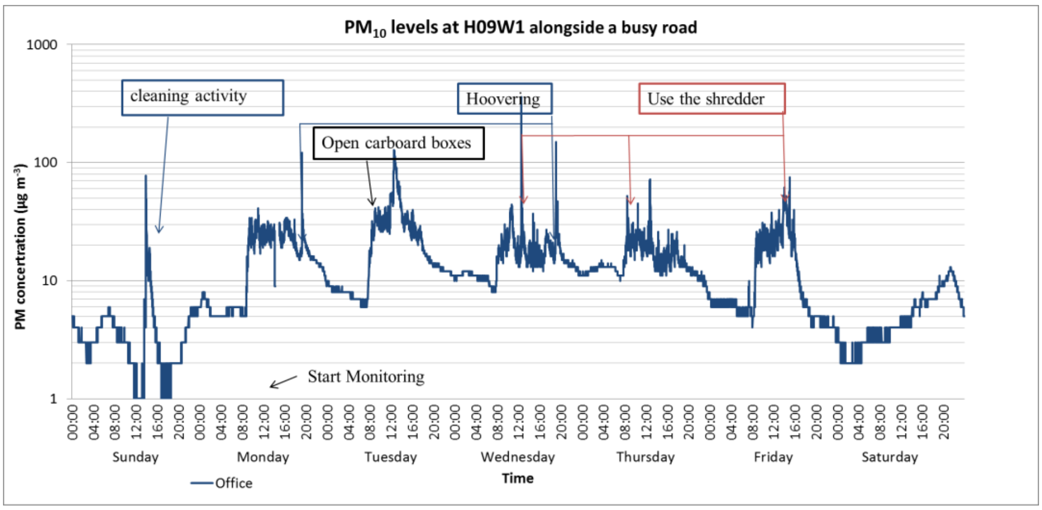


Figure 5-15 PM_{10} Levels at H09

Activities were recorded in both properties. Known activities are marked on the time series plot for the dentist H09 and private home H10 respectively in Figure 5-15 and Figure 5-16. The data shows large variation within days with little consistency from day to day in H09 and not simply in the magnitude of the concentration of pollution but also, in the duration of the level. There were high PM_{10} levels during opening hours possibly caused by a combination of activity of the staff and the high frequency of the main door opening and closing directly into the reception room as patients arrived for, and departed having received, dental treatment. It was established that some of the spikes in levels were associated with specific pollution events, as shown in Figure 5-15. This figure illustrates eight spikes that exceeded 50 µg m^{-3} for short periods. Two of them were caused by hoovering and other three due to using the shredder. Three other spikes could be associated with a specific event but because of work pressures of staff, time spent recording events was limited. One of three spikes occurred during closing time (weekend) which may have been caused by an outdoor event, but following an enquiry it was established to be due to cleaning activity on Sunday.

Figure 5-16 represents the data collected from the lounge of H10. There were five peaks exceeding 50 µg m^{-3}. Cooking activity was responsible for two of the peaks but an outdoor event was the cause of the peak measured during the morning of Wednesday as reported by the householder. The peak on the Saturday afternoon was unpacking luggage and doing laundry having arrived back home from business and a specific cause of the other peaks was not reported.

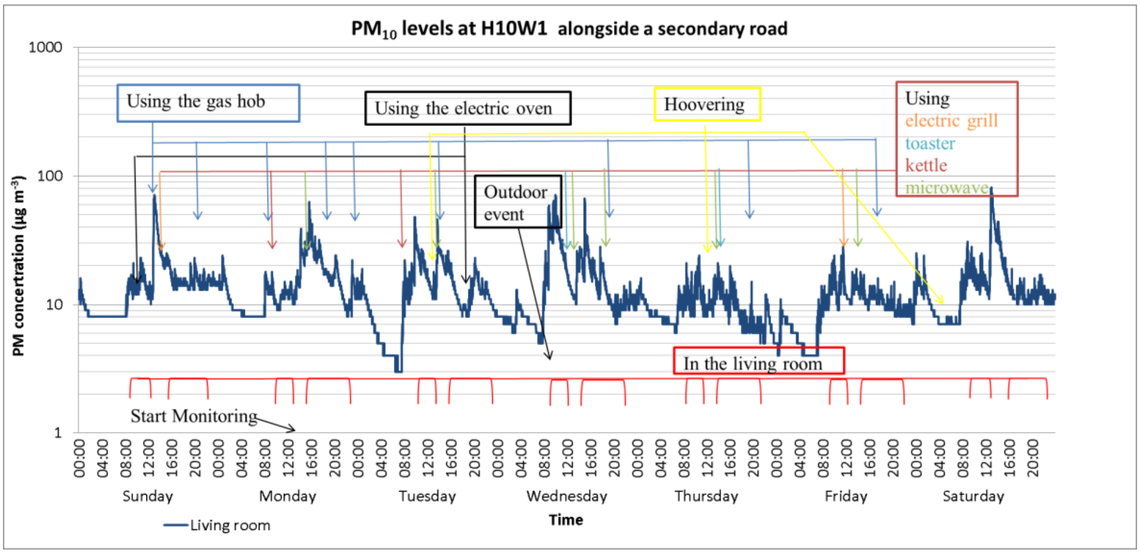


Figure 5-16 PM_{10} Levels at H10

5.4 Lounge vs. Kitchen (First Campaign)

The detailed analysis of time series plots for PM_{10} presented in the previous section has been used to gain a better understanding of the temporal variation in the measured pollution and have enabled fundamental understanding of the cause of reported indoor pollution such as cooking. The analysis revealed considerable variation in the PM_{10} levels with some indication of replication of the trajectory in the lounge compared to the kitchen suggesting a degree of dispersion away from the source. This association was stronger when the lounge was separated only by a door which was usually left open. Evidence of dispersion from kitchen to the lounge was studied further by using regression analysis of data simultaneously monitored in the kitchen and lounge of three properties H01, H02 and H08. The measured PM_{10} in the lounge was plotted on the y axis against the independent level recorded in the kitchen on the x axes to investigate the effect of the dispersion for different conditions namely non-cooking, using gas hob or oven and after cooking activity. The regression statistics are given in Table 5-2 and Figure 5-17 to Figure 5-21 present all the data collected from the kitchen and lounge simultaneously at each house. These clearly illustrate the huge variation between kitchen and lounge for different properties and activity not only in respect of the magnitude of the pollution concentration but also in its duration. These graphs now are discussed in turn.

Table 5-2 P value kitchen vs lounge at different activities

Site	Category	Kitchen Median (μg m^{-3})	Lounge Median (μg m^{-3})	Count	Statistical Significant Difference	p-value of the difference	R^2 Values
H01W1	After	124	118.	222	none	0.0873	0.7
	Non Cooking	13	7	5073	PM kitchen higher than PM lounge	0.0000	0.79
	Using Gas	22	18	78	PM kitchen higher than PM lounge	0.002	0.86
	Using Oven	381	157	9	PM kitchen higher than PM lounge	0.0000	0.01
H01W2	After	23	17	246	PM kitchen higher than PM lounge	0.0002	0.03
	Non Cooking	10	10	8867	none	0.3721	0.08
	Using Gas	27	29	573	none	0.3526	0.38
	Using Oven	32	15	31	PM kitchen higher than PM lounge	0.0000	0.19
H01W3	After	68	62	205	none	0.2213	0.00
	Non Cooking	12	10	7712	PM kitchen higher than PM lounge	0.0000	0.87
	Using Gas	29	24	330	PM kitchen higher than PM lounge	0.0000	0.51
	Using Oven	15	10.5	30	PM kitchen higher than PM lounge	0.0000	0.01
H02W1	After	30	26	247	none	0.1041	0.23
	Non Cooking	17	13	9427	PM kitchen higher than PM lounge	0.0000	0.56
	Using Gas	30	23	265	PM kitchen higher than PM lounge	.0018	0.01
	Using Oven	32	24.5	60	PM kitchen higher than PM lounge	0.0000	0.38
H08	After	12	23	255	PM lounge higher than PM kitchen	0.0000	0.34
	Non Cooking	5	5	9708	PM lounge higher than PM kitchen	0.0000	0.76
	Using Gas	23	15	268	PM kitchen higher than PM lounge	0.0000	0.11
	Using Oven	15	10	25	PM kitchen higher than PM lounge	0.0208	0.14

5.4.1 Property H01

Figure 5-17 to Figure 5-19 present the scatter plots showing the correlation between PM_{10} at the lounge with the kitchen at H01 during three consecutive week periods with the data separated depending on the activity during periods of (a) non cooking event, (b) using the gas hob, (c) cooking in the oven and finally (d) after cooking. There was a positive correlation between PM_{10} at the lounge and kitchen for non-cooking, using the gas hob and after cooking during the first week as shown in Figure 5-17. For non-cooking activities the correlation was not so strong due to groups of "outlier" points which suggest other (unknown) non-cooking activities either in the kitchen or lounge see points marked (A) and (B) respectively in Figure 5-17. For the other three activities there were differences depending on the activity type. However, there was no statistically significant difference at the 95% confidence level between PM_{10} at the lounge and the kitchen (p-value = 0.0873) for the after cooking activities during the first week even though PM_{10} levels in the lounge were lower than in the kitchen by about 5%. For one day on 13/07/2012, both lounge and kitchen microenvironments were higher during and after grilling and cooking during the first week. On the few occasions when the electric oven was used there appeared to be a nine times increase in ambient emissions in the lounge. However, given a range of PM_{10} levels (279 – 421 µg m^{-3}) in the kitchen with relatively few events of cooking in the oven statistical significance could not be reached.

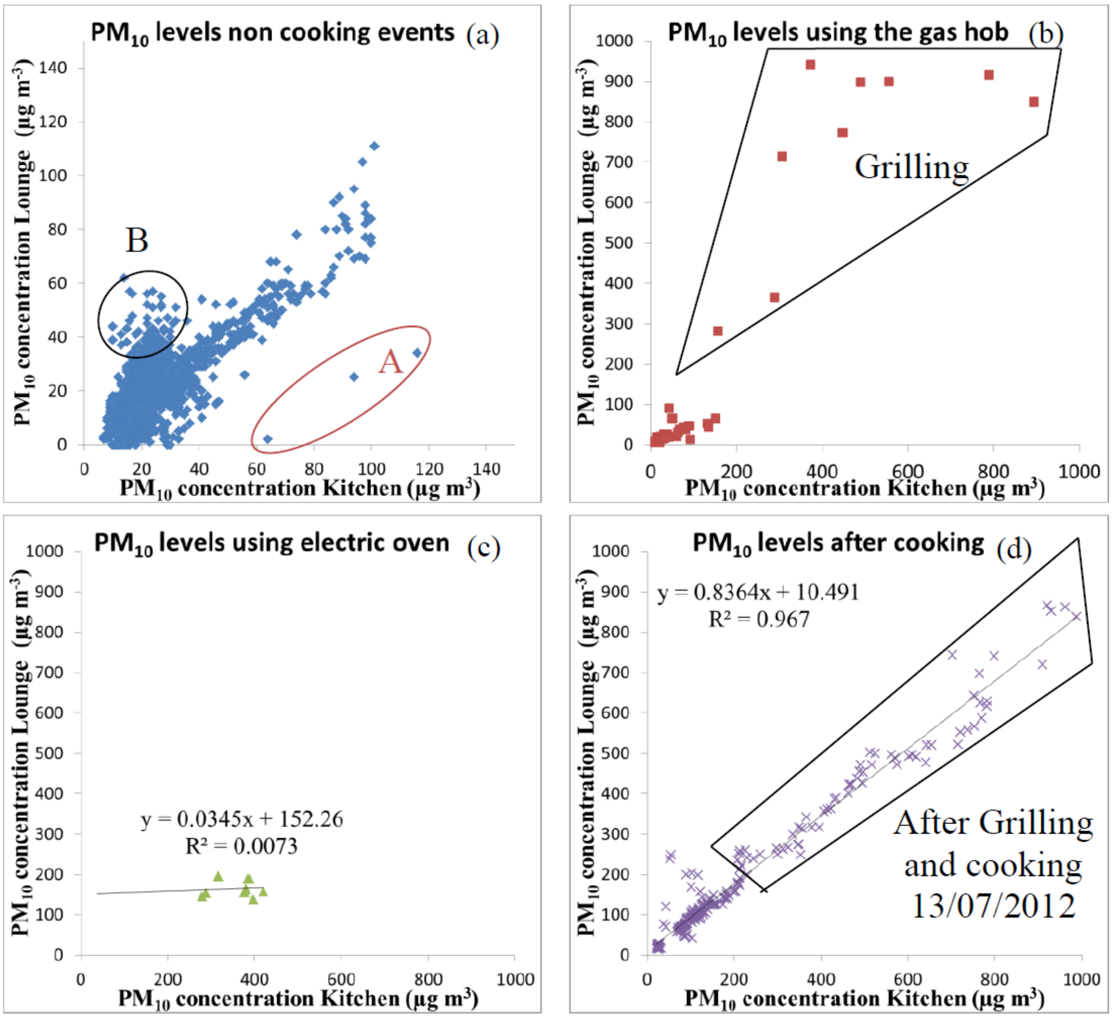


Figure 5-17 Scatter plots (Lounge vs Kitchen) H01W1

For H01W2, there was poor correlation between PM_{10} in the lounge and kitchen for all four activity types, see Figure 5-18. There was no statistically significant difference between PM_{10} measured in the lounge compared to the kitchen for non-cooking (p-value = 0.3721) and using the gas hob activity (p-value = 0.3526) during the second week. However, PM_{10} in the kitchen was statistically significantly higher than PM_{10} measured in the lounge after cooking and when using the oven at H01W2. During week two in H01, when using the gas hob, PM_{10} levels either in the lounge or kitchen were high when boiling and grilling see Figure 5-18. A striking difference in PM_{10} levels in the lounge occurred during the day of 19/07/2012 when the door between the kitchen and the lounge was closed when access was not required. The lounge levels were significantly lower and without an extractor fan and kitchen door closed those in the kitchen increased. Another one day event when the reverse was true, lounge levels were more than double those in the kitchen and were due to cleaning activity which occurred after the night meal finished.

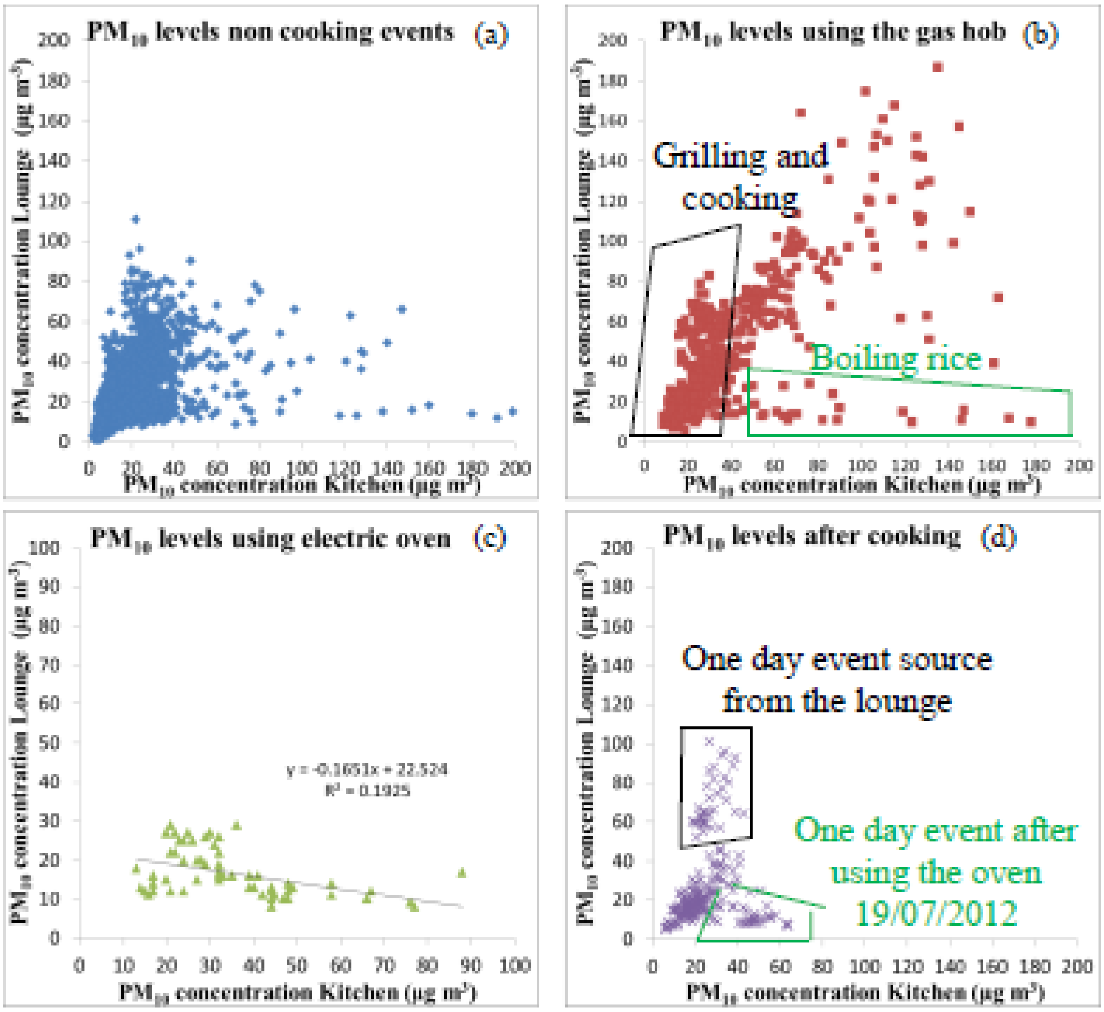


Figure 5-18 Scatter plots (Lounge vs Kitchen) H01W2

Turning now to the third week of monitoring in H01, Figure 5-19 reveals patterns in the data that were consistent to events observed in either or both of the previous two weeks. There was no correlation between PM_{10} in the lounge and kitchen when using gas hob and oven conditions for H01W3, see Figure 5-19. However, there was a degree of correlation between PM_{10} in the lounge and the kitchen for non-cooking and after cooking. There was no statistically significant difference between PM_{10} measured in the lounge compared to the kitchen (p-value = 0.2213) for after cooking condition during the third week. The scatter graphs revealed interesting features which in all cases were caused by specific one day events. In both microenvironments, there were high PM_{10} levels that occurred for one day during non-cooking on 28/07/2012 due to an unrecorded event, using gas hob (25/07/2012) both of which manifested themselves in high levels on those two days (25/07/2012 and 29/07/2012) during the 'after cooking' event. As throughout this third week the children were not at school and Ramadan continued these features were associated with specific daily activity which dominated the PM_{10} levels sourced either in the lounge or in the kitchen.

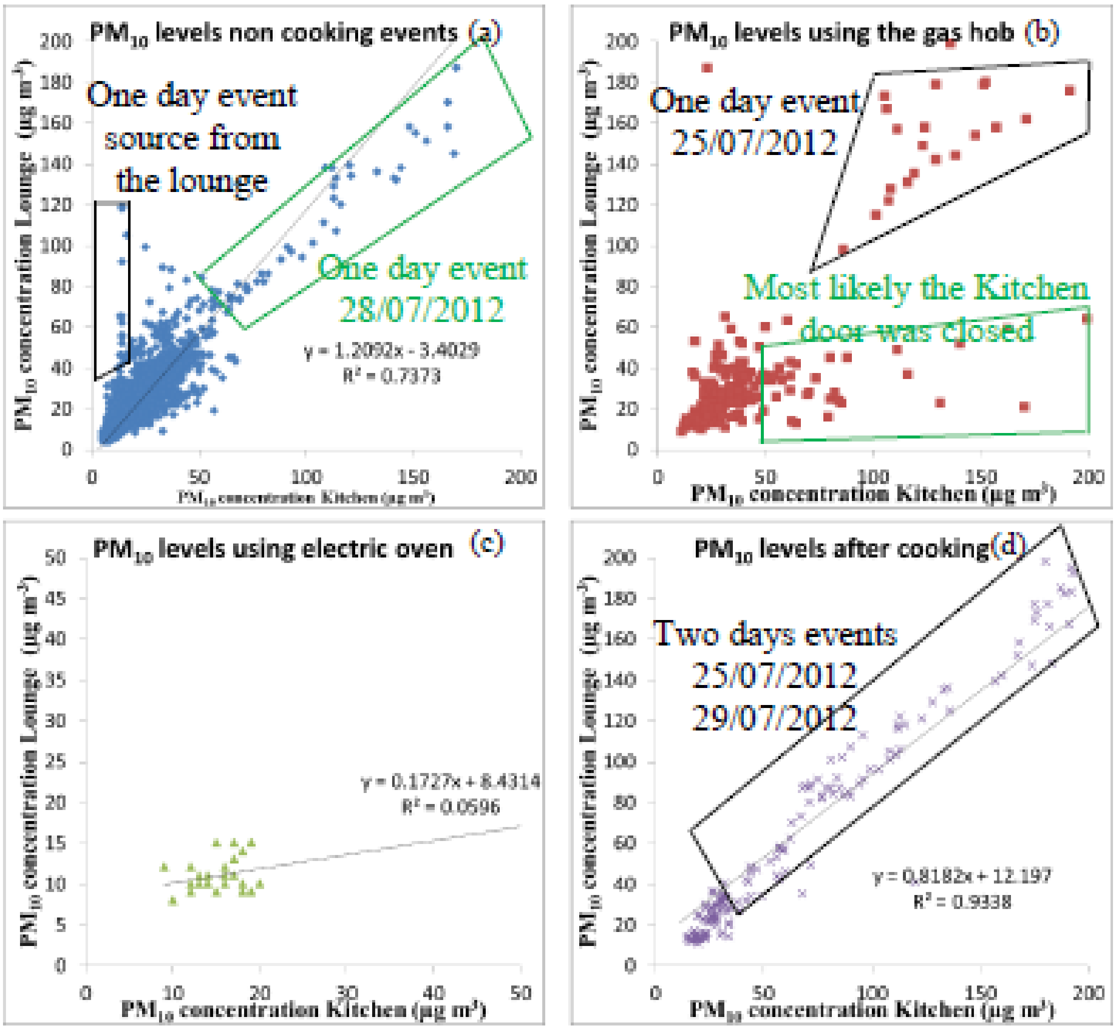


Figure 5-19 Scatter plots (Lounge vs Kitchen) H01W3

5.4.2 Property H02W1and H08

The scatter plots, see Figure 5-20 and Figure 5-21, show the correlation between PM_{10} at the lounge and the kitchen as measured at properties H02W1 and H08 respectively. The graphs reveal clusters consistent with those observed in property H01. Given that recorded levels identified clusters with similar characteristics to other properties adds credibility to the interpretation of levels not recorded. As before underlying correlations between the levels of pollution in the kitchen and lounge were evident suggesting the dispersion effects that occur between two rooms Figure 5-20. There was no significant difference between PM_{10} levels measured in the lounge compared to the kitchen for after cooking condition for H02W1 (p-value = 0.1041). However, PM_{10} in the kitchen was statistically significantly higher than PM_{10} in the lounge for the other three conditions during first week p-value =0.0000, p-value =0.0018 and p-value = 0.0000 respectively. Indeed, high PM_{10} levels occurred for one day only in the kitchen as a result of closing the kitchen door at H02W1. For H02, there were high PM_{10} levels that occurred on 23/08/2012 which appeared to be sourced both in the kitchen and the lounge. The effect of closing the door whilst cooking on the 22/08/2012 was responsible for an increase in levels of PM_{10} in kitchen and decrease in the lounge.

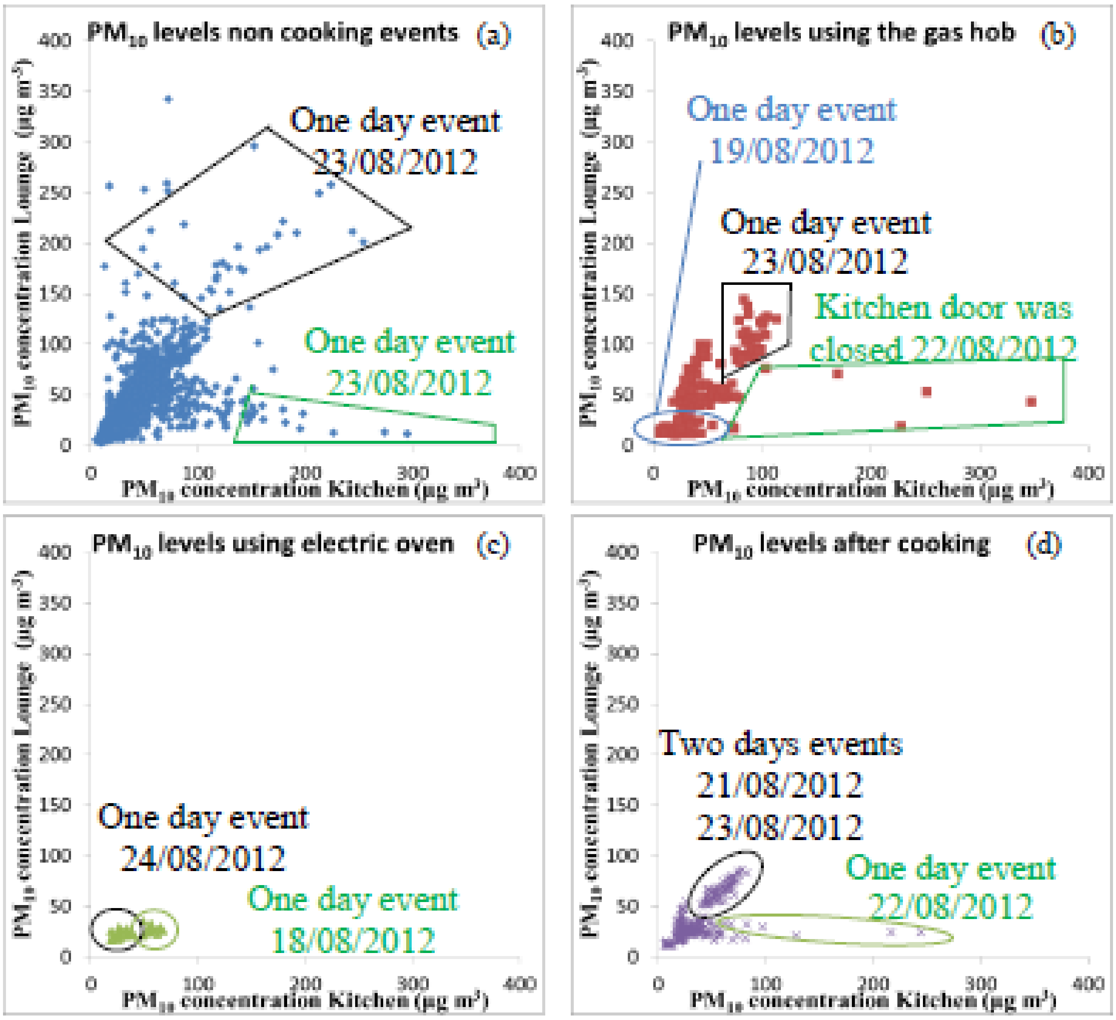


Figure 5-20 Scatter plots (Lounge vs Kitchen) H02W1

At H08, similar features to H01 and H02 are revealed. There was correlation between PM_{10} lounge and kitchen for non-cooking condition except for one day event on 05/10/2012 which was due to unrecorded activity. PM_{10} in the lounge was statistically significantly higher than PM_{10} in the kitchen for after cooking and non-cooking conditions at H08 p-value =0.0000 and p-value = 0.0000 respectively. On the other hand, PM_{10} in the lounge was statistically significantly lower than PM_{10} in the kitchen for using the gas hob and the electric oven at H08. The characteristics effects of the use of the electric oven on the levels of PM_{10} in the lounge are clearly evident in Figure 5-20 (c) where two clusters related to the use of the oven on 18/08/2012 and 24/08/2012 are quite distinct.

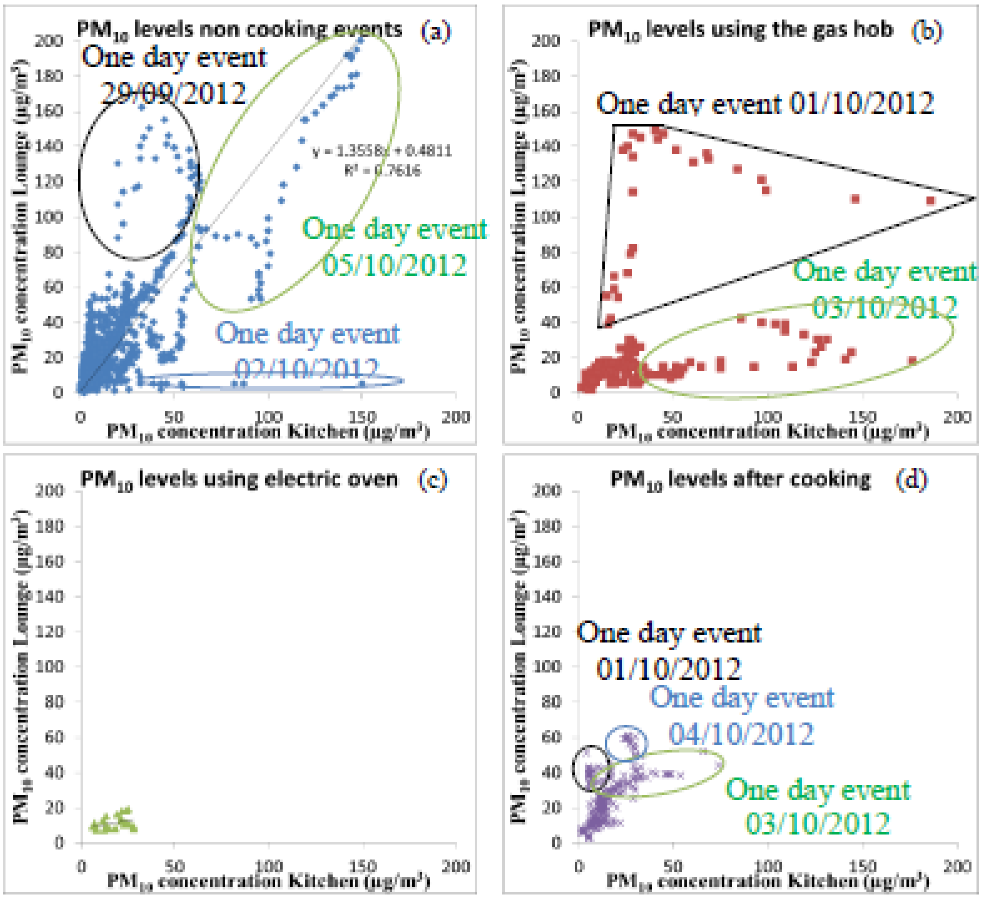


Figure 5-21 Scatter plots (Lounge vs Kitchen) H08

This detailed analysis of the data collected over the three weeks has demonstrated the complexity of source emission indoors and the huge challenge faced when trying to prove the impact of the traffic related pollution on indoor levels. The analysis in property H01 week one illustrated that PM_{10} sourced in the kitchen disperses into the lounge when the access door between the rooms is left open. However, the reverse was not generally true in the sense that emissions sourced in the lounge were not necessarily correlated with a specific consequential change in levels in the kitchen when the access door was open unless the source levels were substantial. Given that the weeks two and three in property H01 coincided with Ramadan the shift in eating time to late evening and the associated change in food preparation and cooking times was clearly evident. As Ramadan is a period of celebration there is additional activity during the day with more time spent preparing food. Also given that, week three in property H01 coincided with school holidays, this led to additional activity with children creating more activity in the lounge which has had an effect on pollution levels and responsible for the increased variation and less correlation between PM_{10} levels at kitchen and lounge. This is evident in the raw data. Despite this variation, there is consistency in the understanding of the features in the time series throughout the three weeks.

5.5 Second Campaign (Descriptive Analysis)

The first campaign of data collected indoor was carried out and detailed the results were presented in the previous sub section. Huge variations of PM_{10} levels were demonstrated in the time series data from property to property consistent with (Stranger *et al.*, 2009; Lawson *et al.*, 2011), also week to week and from day to day in any one week in one property. The second campaign was launched and PM_{10} concentrations were measured at six dwellings, four dwellings with simultaneous measurements in the lounge and outdoor and the other two in the lounge only. The second campaign in total consisted of data collected from ten microenvironments monitored for at least five days. The descriptive statistics are presented in Table 5-3. The statistics for PM_{10} levels varied greatly with minimum (maximum) values 0 (5330) µg m^{-3} and means, geometric means, medians and modes are 15.1 (110.7) µg m^{-3}, 5.9 (36.4) µg m^{-3}, 3 (31.5) µg m^{-3} and 2 (23) µg m^{-3} respectively. Figure 5-22 shows the interquartile of PM_{10} concentrations in each location for the second campaign. The interquartile range of the second campaign varied between 2 and 138 µg m^{-3}. Given that for all microenvironments means were greater than the medians their distributions were not Gaussian. Interestingly in H01W4 and H12, the mean for PM_{10} in the lounge was greater than the mean for PM_{10} outdoor, but the reverse was true in homes H02W2 and H10W2. The cumulative pollution levels were higher at the lounge for H09W2 and H12 due to pollution events that occurred either indoors or outdoors.

Table 5-3 Descriptive Statistics for Static Monitoring Second Campaign

ID	Location in the network	Micro-environment	Time dd Hr:min	µg m^{-3}							
				Mean	GM[a]	Median	Mode	Q1	Q3	Min	Max
H01W4 **	Signalled junction	Outdoor	07 00:00	25.5	22.1	23	21	15	30	4	104
		Indoor	07 00:00	28.4	19.4	16	13	13	26	4	809
H02W2 **	Busy road	Outdoor	05 23:30	34.1	30.9	31.5	23	23	43	9	111
		Indoor	07 00:00	26.7	24.0	24	22	19	30	9	582
H09W2	Major road	Indoor	07 00:00	42.2	13.5	15	3	7	22	1	3550
H10W2 **	Near a quiet road cul-de-sac	Outdoor	05 23:30	20.3	13.2	10	6	7	24	3	122
		Indoor	05 23:30	15.1	5.9	3	2	2	22	1	264
H11	Busy road	Indoor	06 09:11	31.4	27.4	27	21	20	37	8	198
H12**	Busy road	Outdoor	07 00:00	55.9	19.8	14	8	7	50	3	1830
		Indoor	07 00:00	110.7	36.4	18	11	11	138	7	5330

* The lounge is in a separate room without interconnecting door to the kitchen

** The lounge is separated by a door from to the kitchen

[a] Geometric mean

The box plot of PM_{10} levels monitored in the lounge and outdoor is presented in Figure 5-22. For clarity and to assist with interpretation the box plots of PM_{10} levels are presented separately for the indoor and outdoor in Figure 5-23 and Figure 5-24 respectively. Table 5-3 shows the descriptive statistics data of the second campaign. The road traffic near these properties ranged from quiet to congested. In general, outdoor levels were higher compared to indoor with less difference in the interquartile range except for the property H12 which was rather unique. This was due to the fact that property H12 is a fast food and small restaurant business. The house H01 was located near a signal controlled junction and PM_{10} levels varied not only from one day to another but also between outdoor and indoor. The measured PM_{10} minimum (maximum) was higher indoor and the interquartile range generally was higher than outdoor see Figure 5-22. Indoor PM_{10} levels varied 1 (264) µg m^{-3} at the property H10 located in a quiet road and it was even lower at H11 with 8 (198) µg m^{-3} whilst H12 in a very busy retail street indoor PM_{10} levels varied from 1 (5330) µg m^{-3}. Outdoor PM_{10} levels varied 3 (1830) µg m^{-3} at the H12 property in a very busy retail street whilst property H10 in a quiet cul-de-sac was 3 (122) µg m^{-3} experienced levels that in fact were similar to other properties on busy roads H01 4 (104) µg m^{-3} and H02 PM_{10} levels varied 9 (111) µg m^{-3}. These statistics alone are indicating that there are a number of sources and physical processes that are coming into play and influencing pollutant levels outdoors as well as indoors. Referring to the indoor PM_{10} interquartile ranges lower (upper) quartiles varied from 2 (22) µg m^{-3} at H10 the property near a quiet road, which measured a larger range compared to H09 on a main road 7 (22) µg m^{-3}. These were different to properties near a major or busy road with interquartile ranges varying for H01 near to a traffic signal control junction 12 (26) µg m^{-3}. On a busy road H02, 19 (30) µg m^{-3} is similar to H11, 20 (37) µg m^{-3} but property H12 was quite a lot higher, 11 (138) µg m^{-3} clearly suggesting that local factors affecting individual property microenvironments. When choosing a different metric, for example the median level of PM_{10} at H10W2 located in a quiet road indoor (outdoor) 3 (10) µg m^{-3} was lower than at other properties near a major or busy roads. In all properties PM_{10} median indoor were not greater than outdoor except for H12. In addition, outdoor and indoor PM_{10} medians at properties near a major or busy road were greater than those near a quiet road except for H12 property which shows very different characteristics to all others warranting more in depth analysis. Therefore, the time series plots were created to investigate the causes of the observed pollutant events.

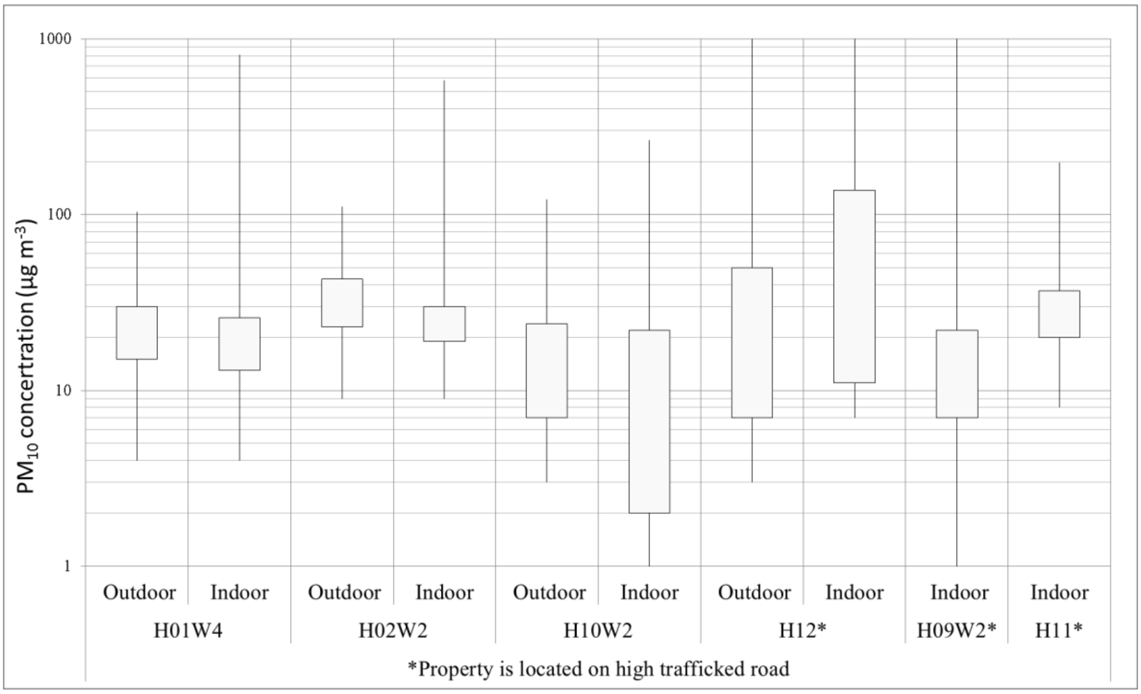


Figure 5-22 Box plot of PM_{10} Levels Static Monitoring Second Campaign

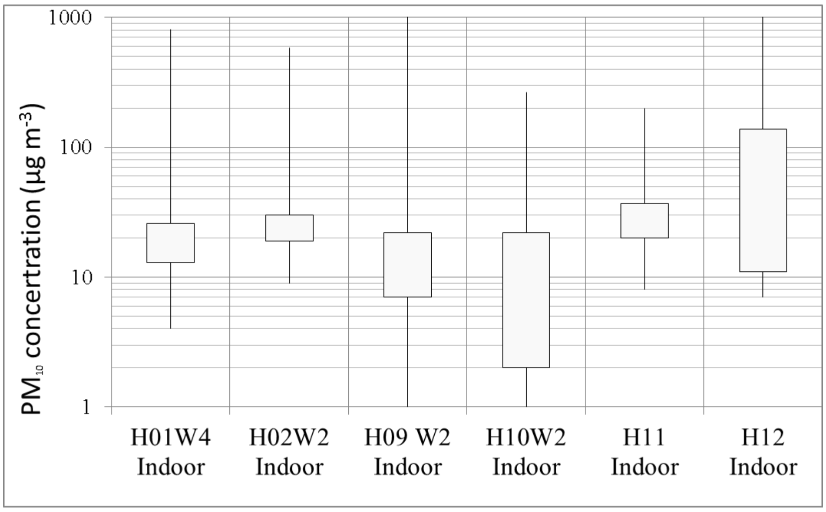


Figure 5-23 Box plot of PM_{10} Levels Static Monitoring Second Campaign at the lounge

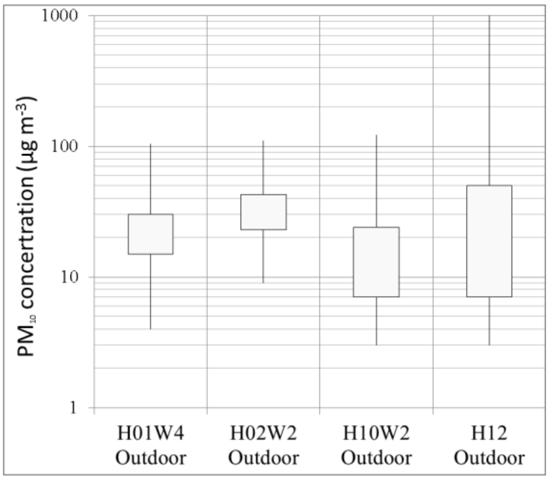


Figure 5-24 Box plot of PM_{10} Levels Static Monitoring Second Campaign outdoor

The householders were asked to record particular events such as cooking, cleaning and give an indication of the time of occurrence and duration when it was convenient for them to do so. These were noted on the time series plots. One participant did not record the activities at property H12. Unfortunately this detailed analysis was not possible for the H12 property, which exhibited characteristics that were inconsistent with other properties. However, as a fast food and restaurant the time series can be interpreted by inference. Simultaneous monitoring indoor and outdoor were carried out at each of the four dwellings (H01, H02, H10 and H12) for more than five days giving four time series graphs for PM_{10} for both the indoor and outdoor, see Figure 5-25, Figure 5-26, Figure 5-27 and Figure 5-28, and for the indoor of two dwellings (H09 and H11) see Figure 5-29 and Figure 5-32. The next section will consider each property separately.

5.6 Time Series Plots (Second Campaign)

The time series plots for PM_{10} were examined to provide a better understanding of the temporal variation in the indoor PM_{10} measurement. The start of the monitoring differed from one property to another due to the need to accommodate households' and shop owner's availability to gain access to the property. In each case, an appointment was made to enable monitor installation at the beginning and decommissioning at the end. For consistency graphs were plotted Sunday to Saturday and comments on the data from the household were added as available. The start of monitoring was indicated on each time series plot for each property as before.

5.6.1 Property H01

As property H01 was monitored for three weeks in the first campaign this property is labelled H01W4 for consistency. The PM_{10} mean levels at the house (H01W4) indoors, in the lounge and outdoor were 28.4 and 25.5 µg m^{-3} respectively. The median indoor (outdoor) for H01W4 revealed statistically significant difference 16 (23) µg m^{-3} ($p = 0.000$). Throughout the mean values were substantially higher than the medians suggesting non-normality of the data with a long tail. This is confirmed by the measured range in levels of PM_{10} which varied between 4 and 809 µg m^{-3} indoors during the fourth week (H01W4L). This clearly demonstrates the importance of activities on indoor microenvironments. The range of outdoor PM_{10} measured (H01W4O) was 4 and 104 µg m^{-3}.

Figure 5-25 shows the time series of PM_{10} concentrations indoor in the lounge and outdoor plotted together with specific activities as reported by the householder marked appropriately. The graph clearly shows that, most of the indoor pollutant events were associated with cooking. Furthermore, it was established that some of the spikes in indoor PM_{10} levels were associated with specific other activities such as cleaning and children playing. This figure illustrates several spikes indoor for short periods that exceeded 50 µg m^{-3} and 11 spikes were caused by a cooking event. Moreover, spikes which were unrecorded events on occasions exhibited the characteristic shape of peaks that were consistent with previously recorded cooking activity. The pollution events occurring indoors were not associated with outdoor spikes. PM_{10} concentrations indoor did not follow the same trend as the PM_{10} concentrations outdoor from one day to another day the PM_{10} levels outdoor and indoor varied in shape and pattern and therefore it can be concluded that they have different source origins.

Although, PM_{10} concentrations varied in shape and pattern from one day to another day as illustrated by the time series measured in H01W4, the most striking difference was in the ambient levels overnight which were always higher outdoor compared to indoors in the lounge. This could be explained by the fact that there is no activity when the family members are asleep and outdoor levels of pollution emitted and re-suspended during the day begin to settle overnight with the occasional pass by of a vehicle. The rather atypical profiles observed on specific days Tuesday, Wednesday and Thursday clearly illustrate how the microenvironment is very much governed by the activities within.

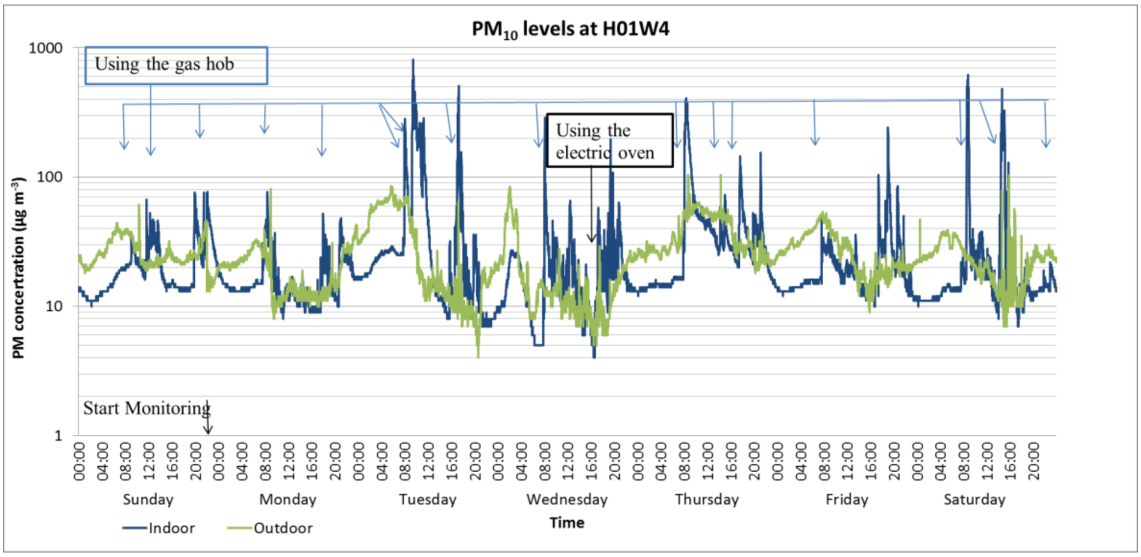


Figure 5-25 PM_{10} Levels at H01W4

5.6.2 *Property H02*

At house (H02W2), outdoor and indoor PM_{10} levels were monitored for one week. Outdoor and indoor PM_{10} means were 34.1 and 26.7 μg m^{-3} respectively with the mean for PM_{10} outdoor greater than indoor. The PM_{10} levels outdoor and indoor ranged from 9 to 111 μg m^{-3} and from 9 to 582 μg m^{-3} respectively with peak levels higher indoor due to cooking. Outdoor and indoor variations are illustrated in Figure 5-26. Twelve pollution spikes occurred indoor, six were caused by a cooking events with pollution spikes for short periods that exceeded 50 μg m^{-3} illustrated in Figure 5-26. Moreover, there was no association between the other spikes and specific known events because they were unrecorded. Outdoor and indoor PM_{10} concentrations varied in levels and pattern from one day to another.

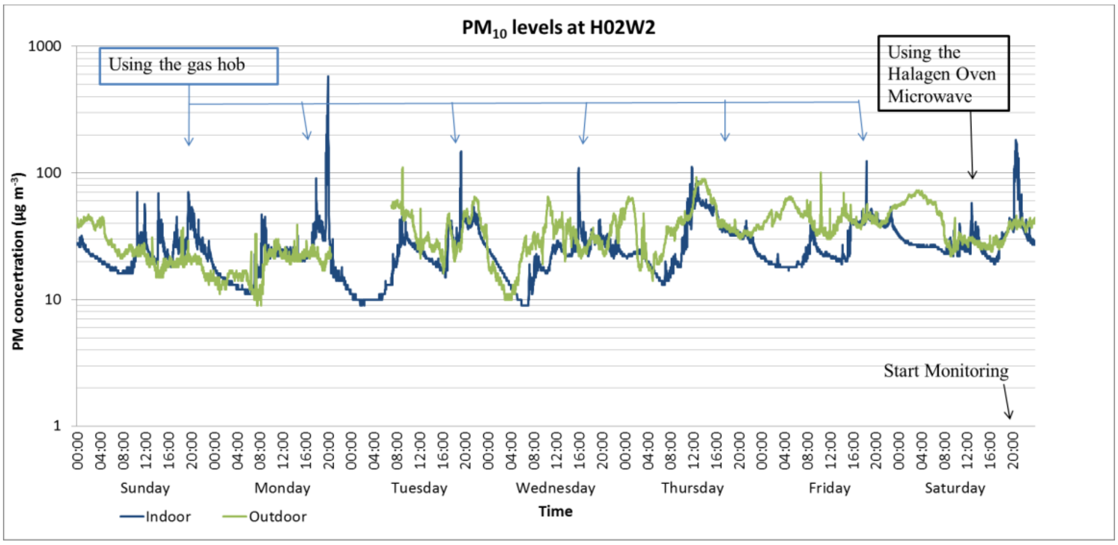


Figure 5-26 PM_{10} Levels at H02W2

The PM_{10} mean (and median) at the house (H02W2) indoors in the lounge and outdoor were 26.7 (24) μg m^{-3} and 34.1 (31.5) μg m^{-3} respectively indicating non normality of the distribution. The median for the lounge was statistically significantly lower outdoor compared to indoor ($p = 0.000$). The mean levels in the lounge of H02W2 were more in line with H01W4, the median was much higher than in property H01W4 and the range for PM_{10} levels from 9 to 582 μg m^{-3} indoor in the lounge H02W2L was not as high as H01W4L from 4 to 809 μg m^{-3}. The outdoor H02W2O range for PM_{10} levels between 9 and 111 was similar to H01W4O from 4 to 104 μg m^{-3}. Figure 5-26 shows the time series for PM_{10} indoor in the lounge and outdoor. There were twelve pollution events and some of these events were associated with six recorded cooking event although others could be assumed to be cooking events by inference. Some cooking events caused several spikes for short periods that exceeded 50 μg m^{-3} as illustrated in

Figure 5-26. Moreover, other spikes occurred which could be associated with outdoor pollution spikes and therefore could be caused by outdoor event as observed on Tuesday and Thursday. PM_{10} concentrations in the lounge overnight were generally similar or much lower and followed the time series trend for outdoor PM_{10} levels throughout the day much more than property H01W4. Figure 5-26 illustrates this similarity in levels and shape of PM_{10} concentrations on Sunday, Monday and Tuesday however early hours on Friday and Saturday, and to lesser extent Sunday, reveal much higher levels of PM_{10} when indoor activity is really low as people sleep in the night.

5.6.3 Property H10

H10 is located in a cul-de-sac. The property, a two storey detached private home some 0.5 km distant to the nearest busy trafficked road namely Great North Road. The lounge of H10 was monitored for five days during a period when the property was vacant. Monitors were set up to simultaneously measure pollutant levels inside in the lounge and outside the window of an upstairs bedroom using a tube which was slipped through a very slightly open window. A bedroom on the first floor was used due to the security risk of leaving a window open overnight and when the property was vacant. The measured concentration of PM_{10} was analysed and the descriptive statistics presented in Table 5-3. The mean (and median), minimum (maximum) PM_{10} concentration levels measured outdoor and indoor in the lounge at the private home (H10) were 20.3 (10), 3 (122) µg m^{-3} and 15.1 (3), 1 (264) respectively. Given the means were greater than the medians the data were not normally distributed either outdoor or indoor. Levels of pollution monitored outdoor were consistently higher than indoor when the house was vacant.

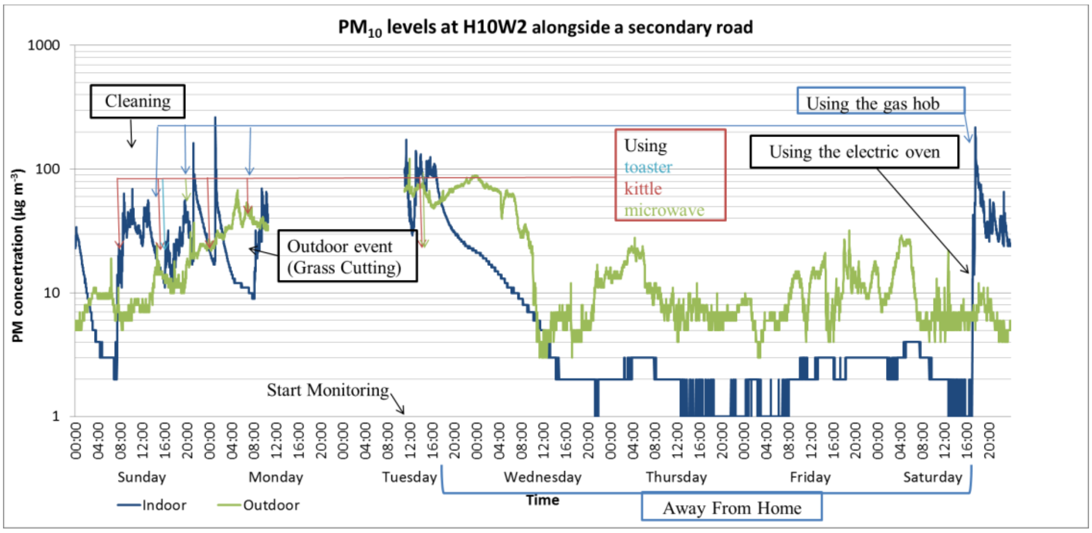


Figure 5-27 PM_{10} Levels at H10W2

The first stage was to plot the time series data for PM_{10} in order to begin to understand the temporal variation of measured pollution with regards to the activities. Activities were noted on the time series plot for the private home H10 in Figure 5-27 for the short period prior to vacating the property and on return following the short business trip. The data clearly show the gradual fall in PM_{10} levels after the property was vacated after 17:00 hrs on Tuesday. The ambient background levels in the home dropped to below 3 µg m^{-3} throughout the period of absence with a hint that levels indoor increased with levels outdoor but not statistically significantly. Outdoor levels varied from 3 µg m^{-3} to 20 µg m^{-3} reaching higher levels been 20:00 hrs and 06:00 hrs overnight. There was no day to day consistency of PM_{10} levels throughout the period the householders were away from the property. When the householders were resident in H10 the data shows large variation within days with little consistency from day to day not simply in the magnitude of the concentration of pollution but also, in the duration of the level. There were several peaks exceeding 50 µg m^{-3} indoors. Cooking activity was responsible for two of the peaks and cleaning activity for the other. There was a peak on Tuesday morning which coincided with the householders preparing for travel and packing and moving luggage. The peak on the Saturday afternoon was unpacking luggage and dealing with the laundry, having arrived back home from business, which caused re-suspension of particles. PM_{10} time series plot and activities diary gave a better understanding of the temporal variation.

5.6.4 Property H12 Restaurant in a Low Traffic Flow but High Activity Street

The air pollution levels were monitored inside the restaurant on the first floor and outdoor simultaneously during the time when staff were on the premises. This was because of the security risk leaving open the window on the latch. Two DustTrak devices were used to monitor outdoor and indoor PM_{10} levels for a week employing a tube to take air from the outside and the monitor left on the window ledge indoors. PM_{10} concentrations outdoor and indoor at the restaurant (H12) varied between 7 and 5330 µg m^{-3} and 3 and 1830 µg m^{-3} with the averages (median) being 110.7 (18) and 55.9 (14) µg m^{-3} respectively. Figure 5-28 illustrates the data collected from the restaurant, but there was not any record of the activities. However, the data clearly shows the huge variation in pollutant levels during opening hours, the times when cooking occurred continuously. Although a degree of consistency in the PM_{10} levels between indoor and outdoor during cooking there were differences in recorded levels from one day to another, not simply in the magnitude of the concentration of pollution but also, in the duration of the variations. Figure 5-28 illustrates these differences from morning to night times and from day to day. Given that there was a great deal of consistency of the outdoor and indoor measurement during opening hours when levels inside were mostly slightly greater or equal to those outside, suggests that what was actually being measured outdoor was the pollution from indoors due to the close proximity of the inlet to the polluting indoor environment with the window open. During closing hours the monitor was actually measuring indoor on the first floor. Again the PM_{10} levels mostly track the restaurant levels except for Tuesday and Wednesday evening when they were statistically similar. This microenvironment is the highest with greatest variation of all properties studied. Also the analysis outdoor and indoor of the restaurant has revealed the challenges faced in collection of data given security and business pressures preventing diaries being kept.

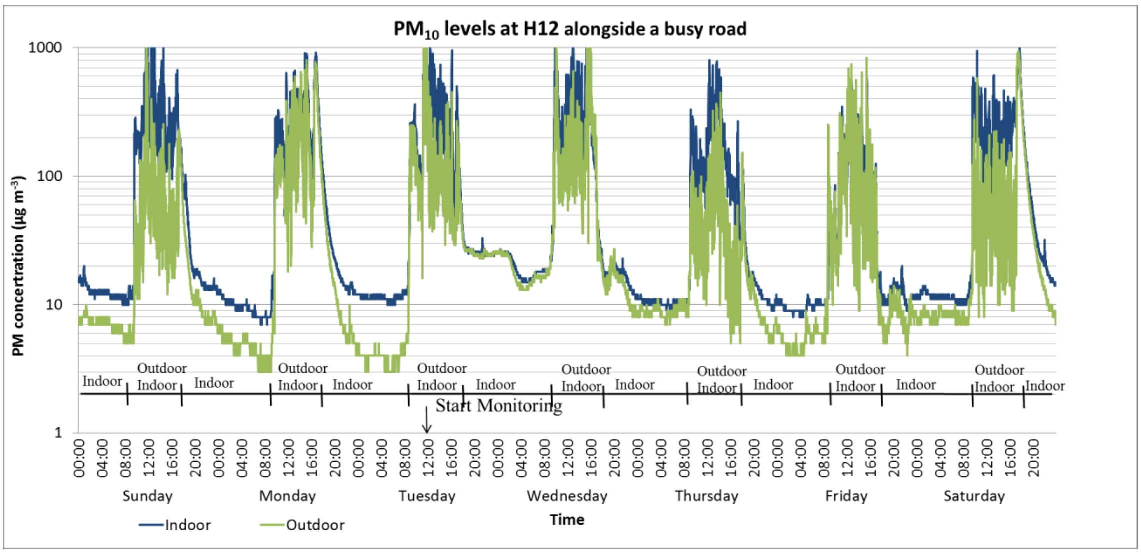


Figure 5-28 PM_{10} Levels at H12

5.6.5 Property H09 on Vary Busy Heavily Traffic Dual Carriageway

H09 is located alongside a very busy trafficked road which is on the Great North Road a main radial out of Newcastle city which joins the A1(M) north of Newcastle towards Scotland. The property H09 is a terraced two storey building from which a dentist operated his/her business. The area behind the reception desk in the waiting area of H09 was monitored for one week. The waiting area was next to the door that opens directly onto a car parking area between the road and façade of the building. The measured concentration of PM_{10} was analysed and the descriptive statistics presented in Table 5-3. The mean (and median), minimum (maximum) PM_{10} concentration levels in the dental practice (H09) were 42.19 (15), 1 (3550) µg m^{-3} respectively.

In order to begin to understand the temporal variation of measured pollution, the activities were noted on the time series plot for the dentist H09 in Figure 5-29. The data shows large variation within days with little consistency from day to day in H09 and not just in the magnitude of the concentration of pollution but also, in the duration of the level. There were high PM_{10} levels during opening hours possibly caused by a combination of activity of the staff but also by the high frequency of opening and closing of the main door as patients arrived for and departed after dental treatment. It was established that some of the spikes in levels were associated with specific pollution events, as shown in Figure 5-29 indicating eight spikes for short periods that exceeded 50 µg m^{-3}. Two of them were due to laying of tiles outdoor at the façade on Monday and Tuesday see Figure 5-29 and photograph in Figure 5-30. The other four spikes were caused by cleaning activity and using the shredder. Specific cause of the other peaks was not reported. The dental practice (H09) was open on Saturday so that the PM_{10} levels were of a similar pattern to the morning open hours during the week. However, PM_{10} levels were still high during closing time on Saturday and enquiries at a later date revealed that this would have been be due to cleaning carried out at the weekend.

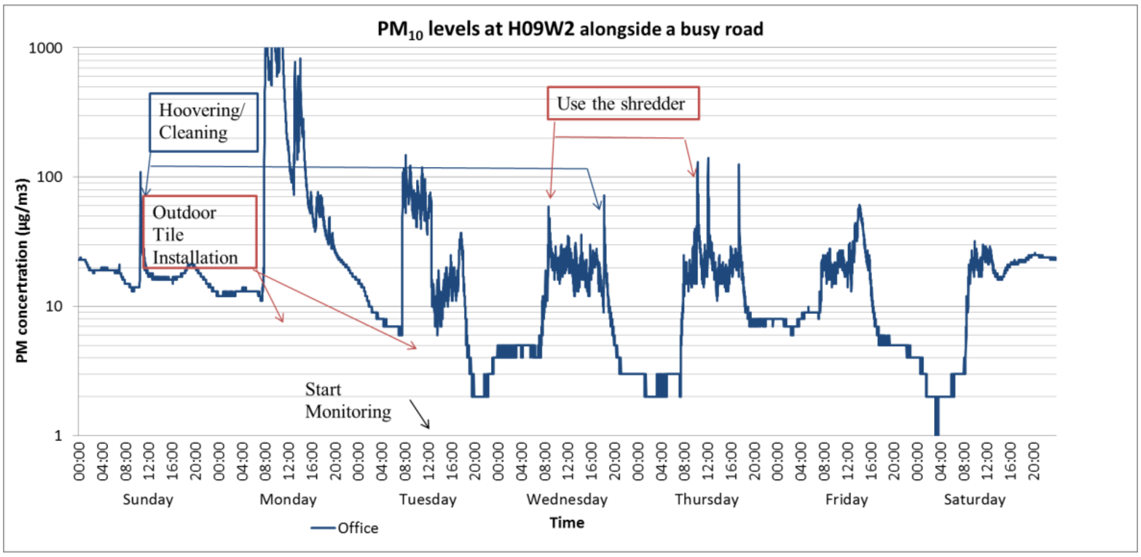


Figure 5-29 PM_{10} Levels at H09W2

Figure 5-30 The ramp at H09

5.6.6 Property H11Boutique Shop in Low Flow but High Activity Street

The air pollution levels (PM_{10}) were monitored in the boutique (H11) on July 2013. A DustTrak was used to monitor PM_{10} at the boutique (H11) for one week see Figure 5-31. PM_{10} levels in the boutique (H11) varied between 8 and 198 µg m^{-3} with the average of 31.4 µg m^{-3}. The time series plots were produced based on PM_{10} and activities diaries record in order to understand the temporal variation of measured pollution. The monitoring took place in July in a week during a hot spell and the door was left open for a high proportion of the opening hours. The door opening periods and cleaning events were noted on the time series plot, see Figure 5-32, which is the data collected from the boutique. PM_{10} levels during opening hours were higher than PM_{10} levels during the night. Given constraints on time serving customers diary records were incomplete but some of the spikes in levels recorded were associated with specific pollution events such as moving around garments and customers walking around the shop. Figure 5-32 illustrates several spikes that prevailed for both short and long periods and exceeded 50 µg m^{-3}. Some of them were caused by cleaning activities and others were caused by outdoor events as both doors were opened throughout the day. The time series plots for PM_{10} were used to gain a better understanding of the temporal variation in the measured pollution and to inform the sources of the pollution in the decomposition analysis

Figure 5-31 DustTrak in the Boutique Shop

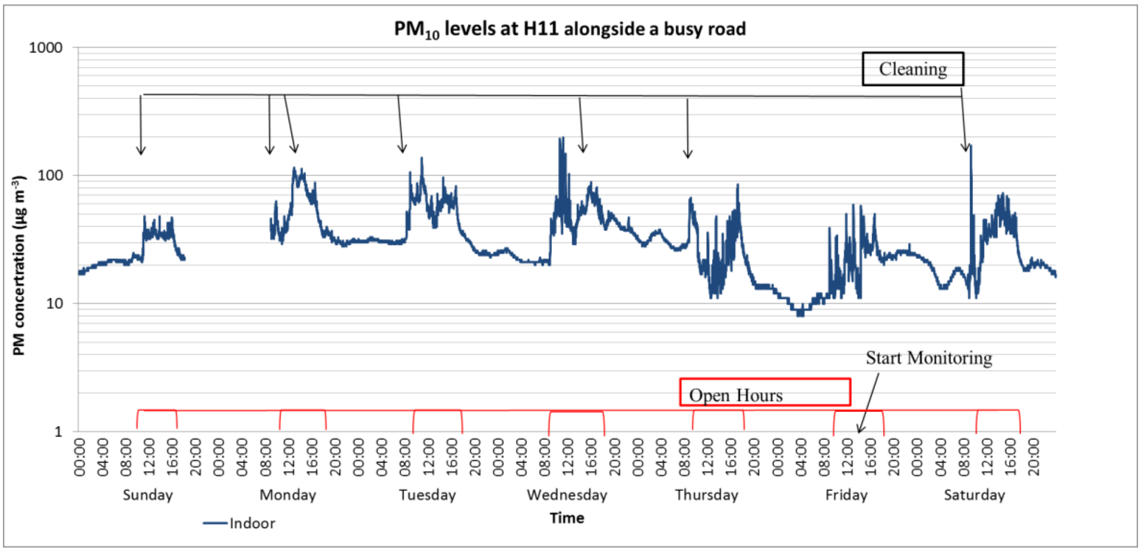


Figure 5-32 PM_{10} Levels at H11

5.6.7 Overview of time series for all properties

In this section the details of the analysis of the time series of simultaneous outdoor and indoor measurements again has revealed enormous variation in microenvironments. In addition, several inconsistences were revealed: when outdoor measurements were sometimes higher and often lower irrespective of whether levels were measured during the day or night. This suggests that local sources irrespective of whether monitored indoor or outdoor are very important highlighting the benefit of householders completing diaries. This analysis has provided an understanding of many of the features in the time series data and this knowledge will be used in the next section to investigate the component distributions of the pdf.

5.7 Meteorological and PM_{10} Outdoor Data (Second Campaign)

Meteorological data, wind speed (ms^{-1}), wind direction (^{o}) and temperature (^{o}C) were obtained from AQMS at Cradlewell, Newcastle for use in this study. The data used were recorded in Newcastle. Although, the use of meteorological data collected from a single point in Newcastle was not ideal nor considered truly representative of the meteorological conditions immediately within the vicinity of the monitoring sites nevertheless is provided an indication of the magnitude of the prevailing wind, temperature and wind speed. However, meteorological data at one minute resolution was not available at the Cradlewell site for use in this research. Also, meteorological station a central location on roof of a university building in Newcastle was not available at the time of research. Therefore, the data from the AQMS at Cradlewell was used for this study. Table 5-4 present a summary of PM_{10} levels and meteorological data at the outdoor monitoring of four sites during the second static monitoring campaign. Property locations with respect to the road are shown in Figure 5-33 to Figure 5-36 along with outdoor PM_{10} roses were plotted and showed PM_{10} levels and wind direction and these will be discussed in more detail in this chapter. It is not possible to compare the daily averages of the outdoor pollution levels at the monitoring sites at H01W4, H02W2 and H10W2 with the annual limit specified in the EU and UK (e.g. for PM_{10} it is 40 µg m^{-3}) because the monitoring campaign was not conducted for the whole period of one year and the limit value is based on an annual average. However, the levels can be compared to the 24 hourly limit of 50 µg m^{-3} that should not be exceeded more than 35 times a year. The site H12 exceeded this limits only three times. Table 5-5 shows the conversion of 24 hrs values into the Air Quality Bands specified by DEFRA (DEFRA, 2014b) and it can be seen that most of the sites fall in the low band with the index between 1 and 3. Only one site (H12) fell in the Moderate to high bands with Indexes 4 and 7. Indeed in Newcastle AQMAs for example the one studied in Gosforth High Street were all declared due to nitrogen dioxide exceedances and not for particles.

Table 5-4 Summary of PM_{10} levels and meteorological data (Second Campaign)

	H01W4					H02W2					H10W2					H12				
	$PM_{10\ Outdoor}$ µg m^{-3}	$PM_{10\ Lounge}$ µg m^{-3}	Wind Speed (ms^{-1})	Tem (C°)	AQMS µg m^{-3}	$PM_{10\ Outdoor}$ µg m^{-3}	$PM_{10\ Lounge}$ µg m^{-3}	Wind Speed (ms^{-1})	Tem (C°)	AQMS µg m^{-3}	$PM_{10\ Outdoor}$ µg m^{-3}	$PM_{10\ Lounge}$ µg m^{-3}	Wind Speed (ms^{-1})	Tem (C°)	AQMS µg m^{-3}	$PM_{10\ Outdoor}$ µg m^{-3}	$PM_{10\ Lounge}$ µg m^{-3}	Wind Speed (ms^{-1})	Tem (C°)	AQMS µg m^{-3}
Mean	25.5	28.4	9.9	15.0	12.0	34.1	26.7	9.4	19.8	16.0	20.3	15.1	10.9	15.2	11.8	55.9	110.7	5.8	17.1	16.1
Max	104	809	22.5	25	36.1	111	582	20.2	33	45.3	122	264	25.1	24	35.8	1830	5330	15.6	27	38.2
Min	4	4	0.3	7	0	9	9	0.3	13	0	3	1	0.1	9	1.9	3	7	0.3	9	0.3
Median	23	16	7.9		19	31.5	24	14.2		13.6	10	3	10.7		10.7	14	18	8.3		17.3

Table 5-5 Outdoor PM_{10} levels ($\mu g\ m^{-3}$) according to the UK standard index

	H01W4	H02W2	H10W2	H12
Day	Outdoor	Outdoor	Outdoor	Outdoor
Sunday	*	25.1	11.4	37.6
Monday	19.0	18.7	*	76.5
Tuesday	31.0	38.1	*	*
Wednesday	17.3	28.2	28.1	79.0
Thursday	35.9	41.8	10.2	25.8
Friday	26.8	44.6	10.0	45.8
Saturday	22.7	*	9.2	59.5

* incomplete 24 hrs data

PM_{10} levels Low Index 1 (UK)	0-16 $\mu g\ m^{-3}$
PM_{10} levels Low Index 2 (UK)	17-33 $\mu g\ m^{-3}$
PM_{10} levels Low Index 3 (UK)	34-50 $\mu g\ m^{-3}$
PM_{10} levels Moderate Index 4 (UK)	51-58 $\mu g\ m^{-3}$
PM_{10} levels Moderate Index 5 (UK)	59-66 $\mu g\ m^{-3}$
PM_{10} levels Moderate Index 6 (UK)	67-75 $\mu g\ m^{-3}$
PM_{10} levels High Index 7 (UK)	76-83 $\mu g\ m^{-3}$

Table 5-4 shows the mean PM_{10} concentrations for outdoor and indoor, wind speed and temperature. All sites had a data capture period of more than five days. In general, the monitoring sites H12 recorded the highest PM_{10} concentrations outdoor and indoor. The H10W2 site, which was in a cul-de-sac location at a distance of 0.5 km from the nearest high trafficked road, recorded the lowest PM_{10} concentration values outdoor and indoor. Mean PM_{10} level outdoor at H02W2 was higher than mean PM_{10} level outdoor at H01W4. However, the mean (median) PM_{10} level indoor at H02W2 was lower (lower) than mean (median) PM_{10} level outdoor at H01W4.

There is a main intersection located south west of property H01 separated by open green space from H01 as shown in Figure 5-33. The wind direction was mainly from the south west to east south east which coincide with the aspect of the open space therefore enabling the pollution from the street to easily reach the property H01W4. Indoor mean (median) PM_{10} was higher (lower) than outdoor mean (median) PM_{10} due to indoor activity. H02W2 property on the other hand is located on a busy trafficked road with traffic calming. This property is located in a shallow street canyon approximately perpendicular to the prevailing wind and is vulnerable to build up of pollution within the street. This is borne out by the fact that pollution came mainly from the leeward and windward sides depend on the wind direction. Also, the concentrations in this street are compounded by the traffic calming which increases acceleration related emission with a road hump just outside property. Outdoor PM_{10} mean was greater than indoor PM_{10} mean for H02W2.

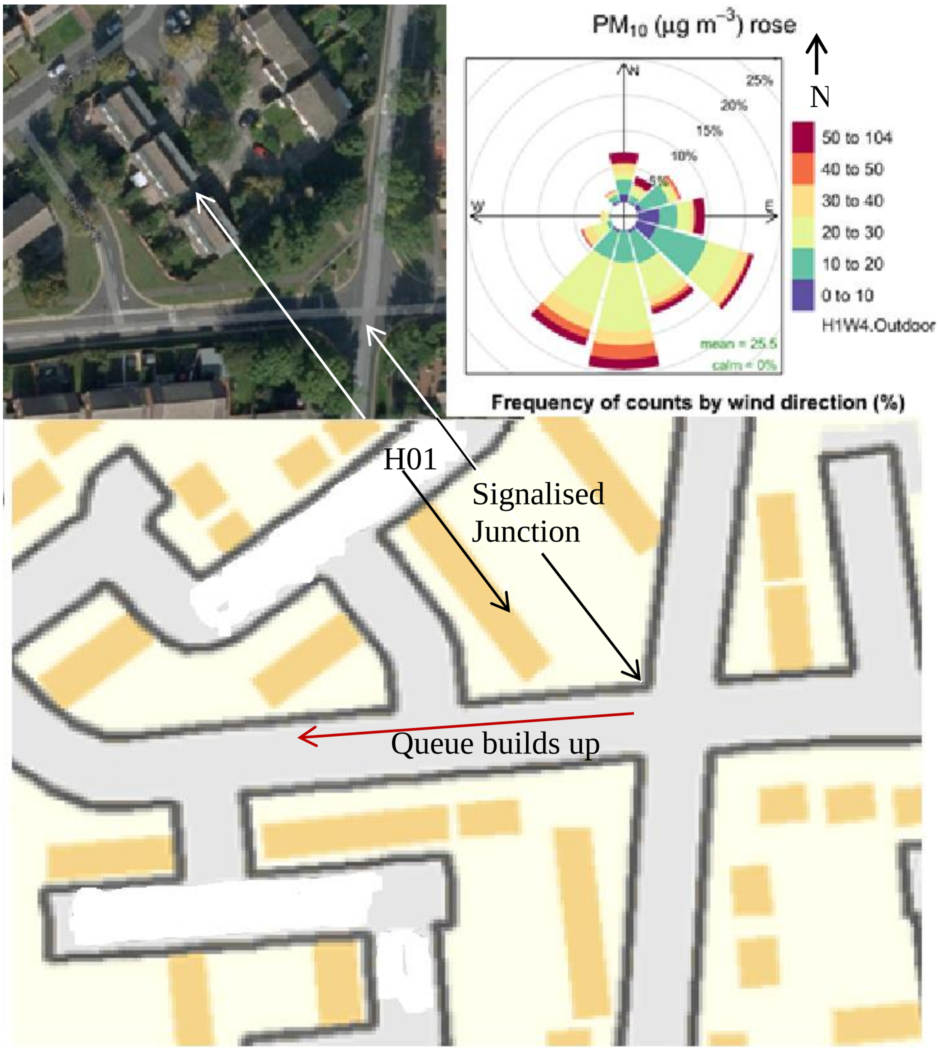


Figure 5-33 H01 location and outdoor PM_{10} rose
(Source: Streetmap, Google Earth)

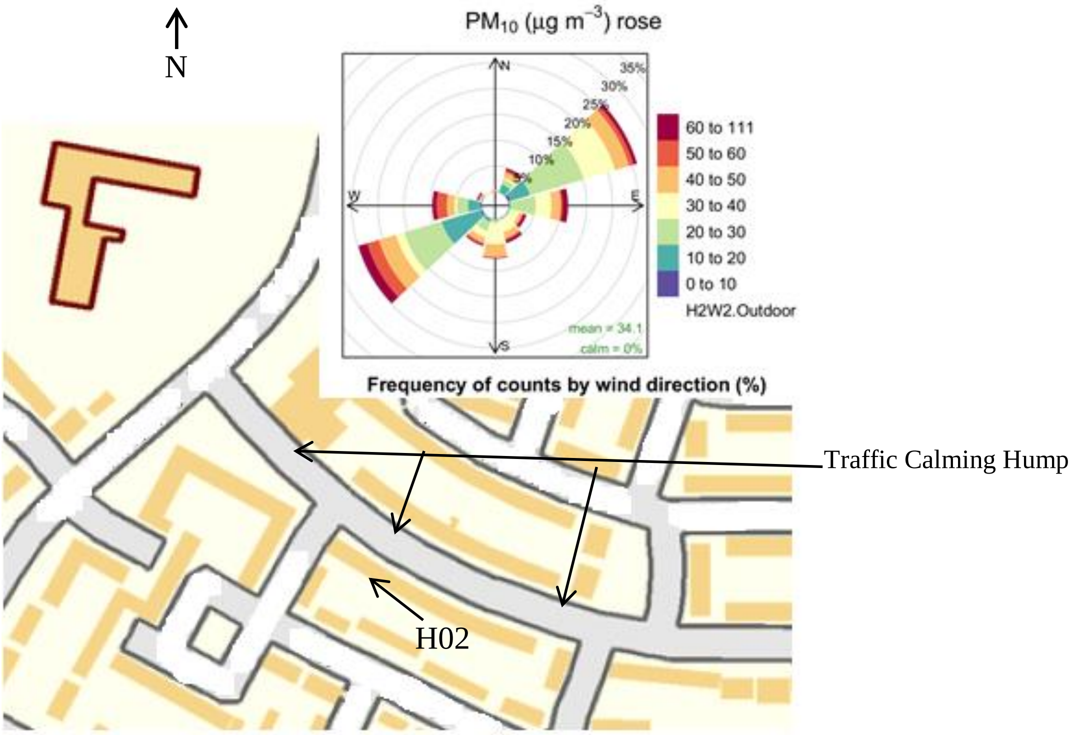


Figure 5-34 H02 location and outdoor PM_{10} rose
(Source: Streetmap)

South and west is the main wind direction at H10W2, which is located in a quiet cul-de-sac in a relatively small housing estate with little traffic. PM_{10} mean outdoor was the lowest of all outdoor levels measured at other properties but it was higher than indoor. This property is on the leeward side of the canyon and considering the dominant wind direction receives pollution also from the west which is the shortest distance from the main Great North Road, see Figure 5-35.

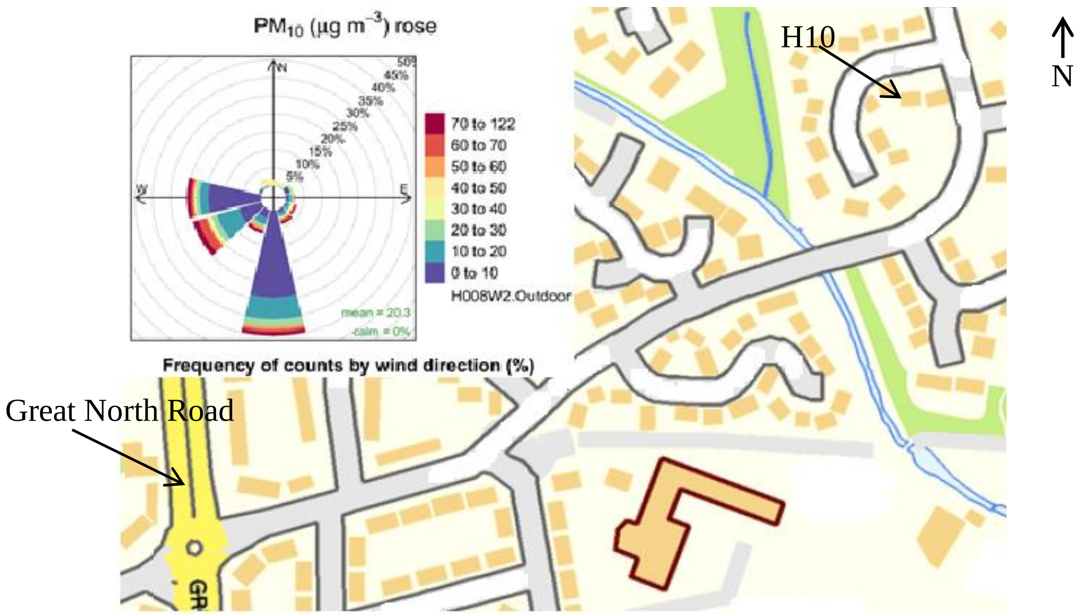


Figure 5-35 H10 location and outdoor PM_{10} rose
(Source: Streetmap)

H12 was in Acorn Road in Jesmond. Shops with parking are located on both sides of Acorn Road although flow levels are very low, traffic is continually interrupted by parking, un-parking and pedestrian movements gaining access to shops on both sides of the road. The wind direction was mainly from the south see Figure 5-36 and it has the highest outdoor PM_{10} mean compared the means outdoor levels in other properties, which was probably mainly due to the indoor PM_{10}, given that cooking activities are the main source of pollution in the takeaway and restaurant. This property is on the ventilated side of narrow street canyon.

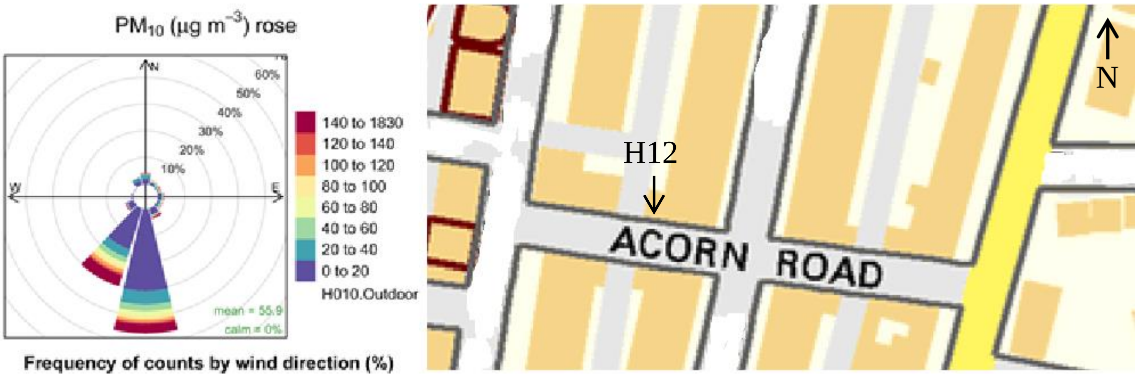


Figure 5-36 H12 location and outdoor PM_{10} rose
(Source: Streetmap)

5.8 Summary

The PM_{10} levels were recorded inside ten dwellings within Newcastle upon Tyne, six of which measured levels in the lounge of two properties simultaneously and four in the kitchen and lounge in the same property during first campaign. Fourteen microenvironments were monitored during the first campaign including repeated measurements in the same two microenvironments over three consecutive weekly periods at one dwelling. The range over all PM_{10} concentrations measured was between 0 and 4270 µg m^{-3}. The PM_{10} means, medians and modes of all trials ranged from 7.2 through to 40.9 µg m^{-3}, 5 to 18 µg m^{-3} and 0 to 13 µg m^{-3} respectively. The interquartiles of PM_{10} concentrations for all microenvironment ranged from 2 to 29 µg m^{-3}. These descriptive statistics clearly suggested distributions that were not normally distributed and exhibited multiple peaks and long tails revealing different characteristics of the sources of PM_{10} in the individual microenvironments monitored.

By plotting the distributions of PM_{10} levels from the first campaign using 1 µg m^{-3} bin at 1 minute interval when meta data recorded by householders was available the “long tails" were matched in some cases with specific activities including grilling. Generally kitchen PM_{10} levels were higher than those measured in lounges consistent with dispersion effect between the two. Homes with a hall separating the kitchen from the lounge experienced the lowest levels. Also, there was a suggestion that the use of an extractor fan reduced pollution in kitchens and on the two occasions when the window was opened pollution levels were higher indoor compared to outdoor. On a few occasions, in the absence of meta data, there was opportunity to ask householders to recall specific activities and their duration. The data clearly illustrated huge variation from one dwelling to another consistent with Stranger *et al.* (2009) but not simply in the magnitude of the concentration of pollution but also, in the duration and the extent to which levels dispersed from one room to another. Short period spikes typically exceeded 100 µg m^{-3} were associated with cooking, cleaning and shredding paper. However, some of them were associated with isolated events. For example, at property H05 a high pollution event was recorded on the Monday night early hours Tuesday morning and lasted for several hours and exceeded 2000 µg m^{-3}. This could not be explained as no record was made by the householder. The lack of meta data was a limitation of this study but requesting such information was found to be an unacceptable imposition on some householders. The time series plots for PM_{10} presented here were used to gain a better understanding of the temporal variation in the measured pollution and despite unrecorded events have provided knowledge to inform the next stage of this research.

During the second campaign, the PM_{10} levels were recorded at six dwellings, four dwellings with simultaneous measurements indoors in the lounge or retail area and outdoor and two dwellings indoors either lounge or shop only. Ten microenvironments were monitored for at least five days in the second campaign. The range over all PM_{10} concentrations measured was between 0 and 5330 µg m^{-3}. The PM_{10} means, medians and modes of all trials ranged from 15.1 to 110.7 µg m^{-3}, 3 to 31.5 µg m^{-3} and 2 to 23 µg m^{-3} respectively. The interquartiles of PM_{10} concentrations for all microenvironments of the second campaign ranged from 2 to 138 µg m^{-3}. Given that for all microenvironments the mean was greater than the median their distributions were not Gaussian and exhibited long tails with multiple modes revealing different characteristics within the individual microenvironment monitored.

This chapter has revealed complexity in the time series of PM_{10} levels measured inside or outside properties whether on main, minor or residential roads. In addition, pollutant levels are dominated by the sources whether it is cooking in the kitchen; children playing in the lounge or shredding paper in the dentist. The detailed analysis of the time series of simultaneous outdoor and indoor measurements again has revealed enormous variation in microenvironments. Furthermore, there were several inconsistences that emerged when outdoor measurements were sometimes higher and often lower irrespective of whether levels were measured during the day or night. This pattern suggests that local sources irrespective of whether monitored indoor or outdoor are responsible highlighting the importance of householder's completing diaries. An important contribution to knowledge relevant to this this research is that the characteristics of the recorded activity, cooking, cleaning, shredding, window open etc. do have similar influences on the PM_{10} levels monitored which means that "families" or "clusters" exist in the overall data sets and are responsible for the multiple peaks observed in the pdf. The analysis of time series plots has added credibility to the interpretation of the sources of pollution whether from cooking or day to day activity in the lounge. This analysis forms a sound basis for the decomposition analysis presented in the next chapter which investigates in detail the indoor-outdoor pollution measurements. In order to address the key research question as to whether there is a measureable change in ambient pollution inside a building due to traffic related pollution is necessary to separate the "families" of data which govern the features (peaks) evident in the pdf. Therefore, further statistical analysis was carried out, using the technique of decomposition. The next chapter presents the result of the decomposition analysis.

6 Static Campaigns Modelling

The previous chapter whilst demonstrating huge variations in the PM_{10} time series data from day to day in any one week and from week to week within rooms in one property, also revealed huge variations from property to property. However, a degree of consistency did emerge in that specific activity influenced the relationship between PM_{10} levels measured in the lounge and the kitchen. The characteristics of the PM_{10} trajectories were similar in the different properties and were observed to have substantial influence on the overall pdf. In this chapter the technique of decomposition is used to explore the characteristics of the multimodal pdf which were found to typify the microenvironments monitored in the properties. In the next section 6.1 the method used to select a distribution will be presented followed in section 6.2, by an investigation of the sensitivity of the results to different levels of aggregation of the PM_{10} data. Section 6.3 presents the main analysis of the first campaign. Section 6.4 presents the results of the decomposition analysis before a summary of findings is presented in Section 6.5.

6.1 Select a Distribution

Section 3.7 explained the method of decomposition and the fitting of a distribution employed in this research. For efficiency of carrying out the analysis, the Fityk software was used with the Levenberg Marquardt nonlinear optimisation analysis method. The best fit distribution sufficiently generic to be applicable to all individual data sets was identified by aggregating all the data representative of similar microenvironments, namely kitchens separate from lounges. By fitting several different distributions including the Gaussian, Lorentzian, Pearson, Pseudo-Voigt, Voigt, EMG, Doniach-Sunjic and Lognormal in turn the best fit to each of the two microenvironments was investigated as shown in Table 6-1. The R^2 values for all trials varied from 0.79 to 0.99. The distribution that was found most suitable to explain the PM_{10} levels in all kitchens was found to be the Doniach-Sunjic distribution with R^2 value equal to 0.96 whilst for the lounges the best fit was lognormal R^2 value 0.99. Given the highest R^2 value for the two distributions overall was given by the lognormal, and this distribution is consistent with previous research findings that PM_{10} distribution is lognormal (Raabe, 1971; Mahmood, 1973; Lai *et al.*, 2004; Cassidy *et al.*, 2007; Nethery *et al.*, 2008; Roosbroeck *et al.*, 2008; Wang *et al.*, 2013), the lognormal distribution was adopted for all further analyses.

Table 6-1 R^2 when fitting one distribution type to the pdf separately for the kitchen and lounge

Distribution Type	R^2	
	Kitchen	Lounge
Gaussian	0.862	0.878
Lorentzian	0.835	0.914
Pearson	0.835	0.914
Pseudo-Voigt	0.810	0.914
Voigt	0.788	0.911
EMG	0.942	0.988
Doniach-Sunjic	0.958	0.984
Lognormal	0.949	0.992

6.2 Sensitivity to Level of Aggregation

The kitchen and lounge data were averaged over different time intervals namely 1, 5, 15 and 30 minutes and aggregated into 1 µg m^{-3}, 2 µg m^{-3} and 5 µg m^{-3} bin widths. Each resulting pdf was fitted with one lognormal distribution using Levenberg Marquardt method and the centre parameter for the model was not fixed in the first but fixed in the second analysis.

Table 6-2 R^2 value in fitting one lognormal distribution assuming different time intervals for averaging and collating data into different bin widths

Time Interval (minutes)	Bin Width (µg m^{-3})	R^2			
		Centre* Not Fixed		Centre Fixed	
		Lounge	Kitchen	Lounge	Kitchen
1	1	0.992	0.949	0.991	0.948
	2	0.997	0.960	0.983	0.961
	5	0.998	0.978	0.729	0.791
5	1	0.992	0.941	0.992	0.936
	2	0.996	0.951	0.991	0.954
	5	0.946	0.971	0.766	0.818
15	1	0.993	0.929	0.991	0.922
	2	0.995	0.951	0.993	0.954
	5	0.932	0.967	0.782	0.824
30	1	0.991	0.920	0.987	0.910
	2	0.994	0.938	0.995	0.565
	5	0.922	0.962	0.714	0.833

*Centre is highest frequent concentration of the distribution see section 3.7.2 for more details

Table 6-2 illustrates the result and shows consistently that based on the R^2 statistic when the centre of the distribution (mode) was not fixed the model performance was much better than when the centre was fixed. Also, the shorter averaged time intervals (1 and 5 minutes) generally exhibited higher R^2 than for the longer time intervals but not substantially and on the whole for the shorter time interval average, there was little difference across the bin width 1, 2 and 5 µg m^{-3}. However, the maximum structure in the pdfs was evident at 1 minute sample averaging over 1 µg m^{-3} bin widths and offered the best chance to observe any consistency in patterns in the pdf. Therefore, this sampling regime was adopted and maintained throughout the rest of the analysis of the static and dynamic campaigns reported in this thesis.

6.3 First campaign Data Analysis

The Fityk software was used systematically to decompose the pdf of each microenvironment separately fitting up to five lognormal distributions based on the condition that made no further improvement in the R^2 value, see section 3.7.5. Property H01W3 K has five component distributions, H01W1 L, H01W3 L, H03 L and H04 L have four and all others have three. The statistical parameters, namely height, width and centre, geometric mean and standard deviation for each component distribution are presented in Table 6-3. The interquartile range for each component distribution and the R^2 for the fitting of the curve were all extracted from the software and reported in the table. All R^2 values were greater than 0.94.

The interquartile pollution levels, as a measure of the spread of each distribution, was identified on the time series plot. The characteristics, cooking, night time and day time were used to associate a component distribution of the total pdf with an activity or event. For example, Figure 6-1 illustrates the time series plot for H01W3 for the lounge and it indicates the interquartile ranges of the four lognormal component distributions. The interquartile of the first distribution is at the bottom of the figure and coincides with the night time levels. The next highest component distribution has an interquartile range that matches levels observed during the day time when most household low activity takes place. The next two lognormal distributions overlapped. The third component distribution was associated with cooking and other unknown activity and the fourth distribution was explained by a ventilation event. This represents a subjective explanation of the model output. Never the less, the technique was helpful to identify component distributions for night time, during the morning and cooking as well as, in most cases other defined activities. On a few occasions, it was not possible to classify the distribution due to the limited data that was recorded by the householder or the distributions were overlapping which make it difficult to classify. Also, the classification was subjective which need to be verified by comparing them to the actual data that corresponded to the event or classification after it has been extracted from the dataset. Nevertheless, the method was demonstrated to be helpful tool to classifying the component distributions in a generic way.

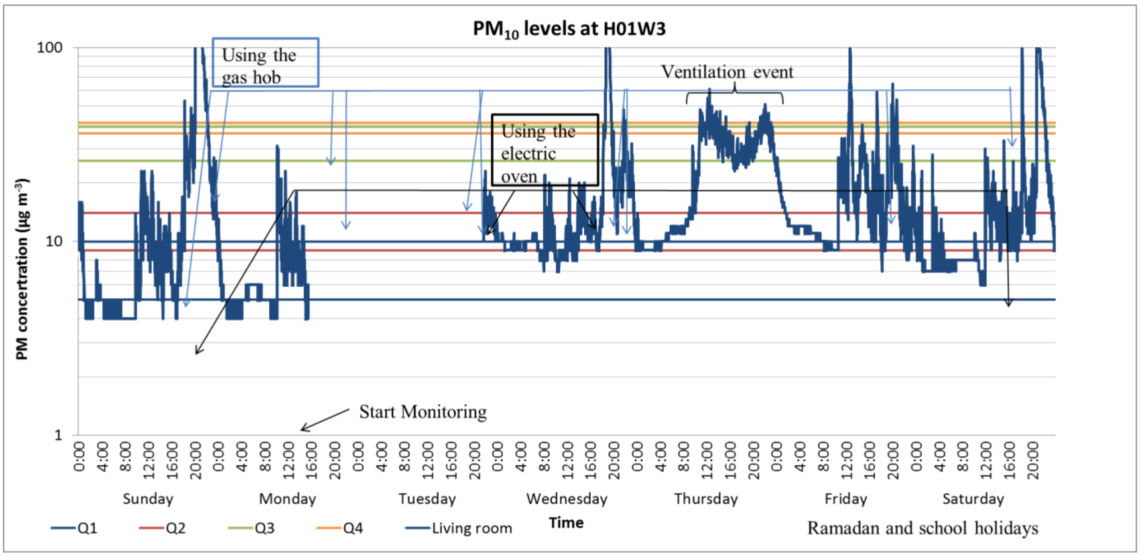


Figure 6-1 PM_{10} levels with indicate the interquartile ranges of the distributions models

The pdfs were plotted for each microenvironment showing the three, four or five lognormal distributions as illustrated in Figure 6-2, Figure 6-3 and Figure 6-4. Each figure presents the analysis for the same property but for data measured respectively in three consecutive weeks. The graphs on the right are for the two microenvironments monitored simultaneously namely kitchen (top) and lounge (bottom). They illustrate the component lognormal distributions and the overall best fit pdf (which is the summation of the individual components) and includes the observed pdf. These distributions are presented as line graphs for clarity. More than 92% and up to 98% of the variation in the pdf (see Table 6-3) could be explained, demonstrating the appropriateness of this method in classifying the distributions in a generic way. Furthermore, by cross referencing the centre and interquartile of the components distributions against the time series and the reported events by the householder, associations could be made. These are recorded in the events column in Table 6-3. The graphs on the left show the differences between the measured data and the predicted value based on the decomposition technique. These represent the residuals and can be associated with the unexplained data synonymous with “error”. If the distribution of the residuals is normally distributed and the average not significantly different from the zero then all the variation in the pdf is explained by the identified indoor activity with statistical significance. Given that the analysis was repeated systematically for each property and microenvironment the remainder of this section will be devoted to a discussion of the characteristics of the measured pdf for each property in turn.

Table 6-3 R^2 by fitting a number lognormal distributions (First Campaign)

Dwelling ID	Height[a] μg m^{-3}	Centre[b] μg m^{-3}	Width[c] μg m^{-3}	R^2	Event	Q1[d]	Q3[e]	% explained by each component distribution[f]	Total of overall pdf explained[g]	GM[h]	GSD[i]
H01 W1 K	436.9	10.0	6.8	0.99	Mix (activities +night)	10	19	78%	93%	15.0	1.5
	274.5	12.6	1.5		Unclear	12	14	10%		14.1	1.2
	45.3	20.0	3.9		Cooking	20	25	5%		23.5	1.2
H01 W1 L	787.5	0.1	0.4	0.96	Sunday night	0	1	13%	92%	0.2	2.8
	329.4	3.8	4.5		Mix (activities + night)	4	10	42%		6.7	1.9
	796.1	6.4	0.8		Unclear	7	8	12%		7.5	1.1
	79.1	15.6	11.1		Cooking	16	30	25%		23.3	1.6
H01 W2 K	432.6	4.5	5.3	0.97	Night	4	12	35%	96%	8.2	1.8
	772.5	8.4	4.8		Activity	8	15	56%		11.7	1.5
	32.8	25.3	10.5		Cooking	25	39	5%		32.5	1.4
H01 W2 L	250.9	2.3	1.3	0.99	Some of night	2	4	6%	97%	2.6	2.1
	715.1	6.2	7.5		Mix (activities + night)	7	16	83%		9.4	2.0
	25.5	19.4	20.7		Cooking	21	47	8%		30.3	1.8
H01 W3 K	759.4	3.3	0.9	0.98	Early Tuesday morning	3	5	9%	97%	4.1	1.4
	912.5	6.8	2.3		Night	6	10	32%		8.5	1.3
	743.8	11.2	4.0		Activity	11	16	45%		14.1	1.4
	55.7	26.6	10.4		Cooking	26	40	9%		34.7	1.3
	49.2	36.8	2.4		Ventilation	37	40	2%		38.7	1.1
H01 W3 L	536.2	4.5	3.1	0.99	Night	5	10	30%	97%	6.6	1.6
	679.0	9.1	4.0		Activity	9	14	50%		12.1	1.4
	68.8	25.2	10.5		Cooking + other events	26	39	13%		32.8	1.4
	30.9	36.2	3.6		Ventilation	36	41	4%		38.8	1.1
H02 W1 K	1207.0	9.4	0.9	0.99	Night	9	11	12%	95%	10.2	1.1
	749.8	12.7	4.3		Activities	12	18	48%		16.3	1.4
	179.1	21.8	13.0		Cooking + other events	22	39	35%		31.2	1.5
H02 W1 L	764.4	5.2	3.3	0.99	Night	5	9	39%	99%	7.7	1.5
	209.9	9.0	4.4		Mix (activities + night)	9	19	14%		12.9	1.5
	201.7	15.5	15.0		Cooking + other events	16	35	46%		25.9	1.7
H03 L	272.1	6.1	5.8	0.94	Night	6	13	23%	98%	9.6	1.7
	715.4	9.8	5.8		Unrecorded events	10	17	62%		12.6	1.5
	170.8	12.3	1.9		Unrecorded events	12	14	5%		13.8	1.2
	238.8	24.6	2.1		Unrecorded events	25	27	8%		26.4	1.1
H04 L	160.3	2.4	0.9	0.98	Night	2	3	2%	98%	3.1	1.4
	462.4	9.0	12.4		Mix (activities + night)	9	25	87%		15.6	2.0
	147.1	18.3	1.0		Unclear	18	19	3%		19.1	1.1
	32.3	33.3	12.2		Cooking + other events	34	49	6%		41.9	1.3
H05 K	1341.5	4.1	3.7	0.98	Mix (activities + night)	4	9	74%	94%	6.9	1.6
	173.0	10.1	2.7		Unrecorded events	10	14	7%		12.2	1.3
	53.8	21.4	16.7		Unrecorded events	23	43	13%		32.6	1.6
H05 L	1317.1	3.3	3.8	0.99	Mix (activities + night)	3	8	75%	95%	5.9	1.8
	197.9	11.7	2.2		Unrecorded events	12	14	6%		13.3	1.2
	56.7	21.7	16.6		Unrecorded events	22	43	14%		32.4	1.6
H06 L	1392.7	2.8	3.2	0.99	Mix (activities + night)	3	6	67%	96%	5.3	1.8
	575.6	4.8	1.7		Activities	5	7	14%		6.1	1.3
	47.3	18.6	20.8		Cooking	20	37	15%		30.9	1.8
H07 L	2002.6	3.8	2.5	0.94	Away from home +	4	6	75%	92%	5.7	1.5
	278.8	9.2	3.5		Activities	9	14	15%		11.7	1.4
	44.7	21.6	2.7		Cooking	22	25	2%		23.7	1.1
H08 K	5973.7	1.3	0.7	0.99	Away from home +	1	3	41%	97%	2.2	1.5
	1647.7	4.7	2.1		Activities	5	7	52%		6.9	1.4
	30.6	21.3	8.6		Cooking	22	33	4%		28.3	1.3
H08 L	1207.0	2.5	4.9	0.99	Away from home +	2	8	88%	97%	5.5	2.2
	173.8	8.6	2.5		Activity	9	11	7%		10.5	1.3
	8.3	32.5	17.4		Cooking	33	55	2%		42.9	1.4

Continue Table 6-3

Dwelling ID	Height[a] µg m-3	Centre[b] µg m-3	Width[c] µg m-3	R^2	Event	Q1[d]	Q3[e]	% explained by each component distribution[f]	Total of overall pdf explained[g]	GM[h]	GSD[i]
H09 L	724.4	3.3	5.8	0.96	Close	3	11	64%	96%	6.6	2.3
	365.0	11.8	3.8		Tuesday, Wednesday	12	16	21%		16.3	1.4
	108.5	20.6	6.7		Open Hour	21	29	11%		27.8	1.3
H10 L	285.2	4.2	3.1	0.98	Night	4	8	13%	98%	7.1	1.6
	911.9	8.3	5.5		Mix (activities +night)	9	15	75%		12.8	1.5
	260.3	12.6	2.4		Cooking	13	15	10%		14.4	1.2

[a] The most frequent or highest count of the distribution see section 3.7.2 for more details
[b] The highest frequent concentration (mode) of the component distribution see section 3.7.2 for more details
[c] The widths of the component distribution at the half height at the at centre see section 3.7.2 for more details
[d] The lower quartile of the component distribution which was calculated (µg m^{-3})
[e] The upper quartile of the component distribution which was calculated (µg m^{-3})
[f] The ratio of the component distribution and the observed data expressed as a percentage
[g] the difference between the sum of each component distribution and the observed data relative to the observed data expressed as a percentage
[h] Geometric mean
[i] Geometric standard deviation

On all occasions these graphs are produced in the text plotted up to 100 µg m^{-3} so that the features are more easily interpreted. The full data sets are plotted on the log scale in Appendix V to Appendix DD for completeness. All curve fitting and statistical tests have been carried out on the complete range of data throughout the thesis.

6.3.1 Property H01 Semidetached Close to Busy Intersection

Cooking activity as expected was associated with high geometric means of PM_{10} in the kitchen compared to the (lounge) 23.8 (23.3), 32.5 (30.7) and 34.7 (32.8) µg m^{-3} for week one, two and three respectively. Also, the reported differences in cooking activity in the household from week to week (being less in week one during school term time compared to week 2 Ramadan and school term, and week 3 Ramadan and school holiday) resulted in different geometric means of PM_{10} 23.5 compared to 32.5 and 34.7 µg m^{-3} with greater variation and pervading for longer periods and geometric standard deviation (width) 1.2 (3.9) compared to 1.4 (10.5) and 1.3 (10.4) respectively as shown in Figure 6-6. In week 2 and 3 compared with week 1 there also was more activity in the lounge due to school holiday geometric mean (geometric standard deviation) 9.4 (2.0), 12.1 (1.4) and 6.7 (1.9) µg m^{-3} respectively, see Figure 6-5. In week 2 and 3 compared with week 1, night time levels were consistently lower than day time activities with Sunday night time being substantially (40 times) lower (geometric mean 0.2 µg m^{-3}) than other periods and there was not any explanation for this extremely low level. The most interesting result was when the back door and windows of the property were left open for ventilation when the geometric means reached their highest 38.7 and 38.8 µg m^{-3} for in the kitchen and lounge respectively with least geometric standard deviation 1.1 and 1.1 respectively. The lowest geometric standard deviation implies that PM_{10} levels were fairly well mixed across kitchen and lounge. The higher geometric means can be explained as due to outdoor pollution being higher than indoor levels. This was investigated further by analysing the pollution concentration from AURN site in Newcastle and the results are shown in Figure 6-7. This graph clearly shows that background levels on this day (Thursday) were higher compared to all other days monitored that week. Also, the wind speed during the period, when the windows and door were open, was 2.3 ms^{-1} and did not exceed 4 ms^{-1}. The wind direction on the date of occurrence also suggests that the local junction may be a contributory factor, see Figure 6-8.

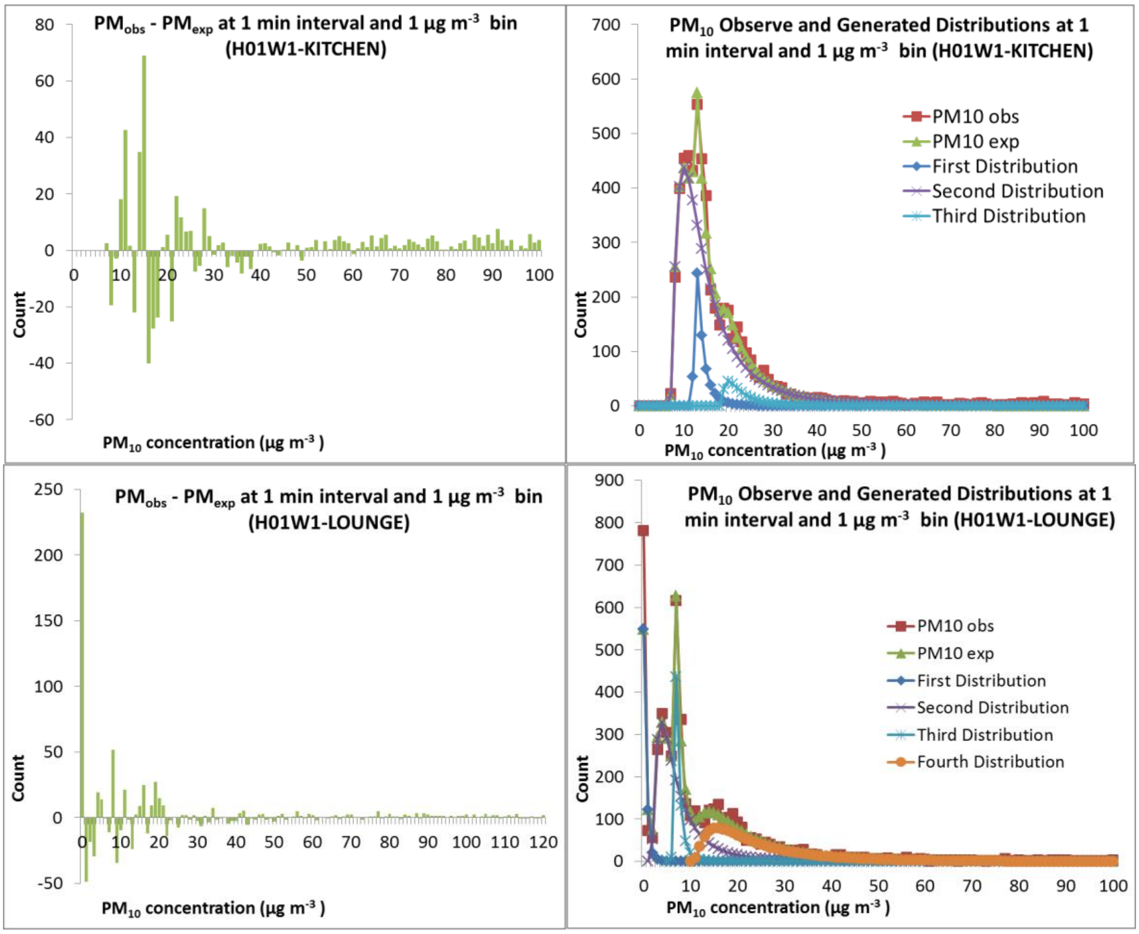


Figure 6-2 PM_{10} Distributions at H01W1 (Monitored, Modelled and Residuals)

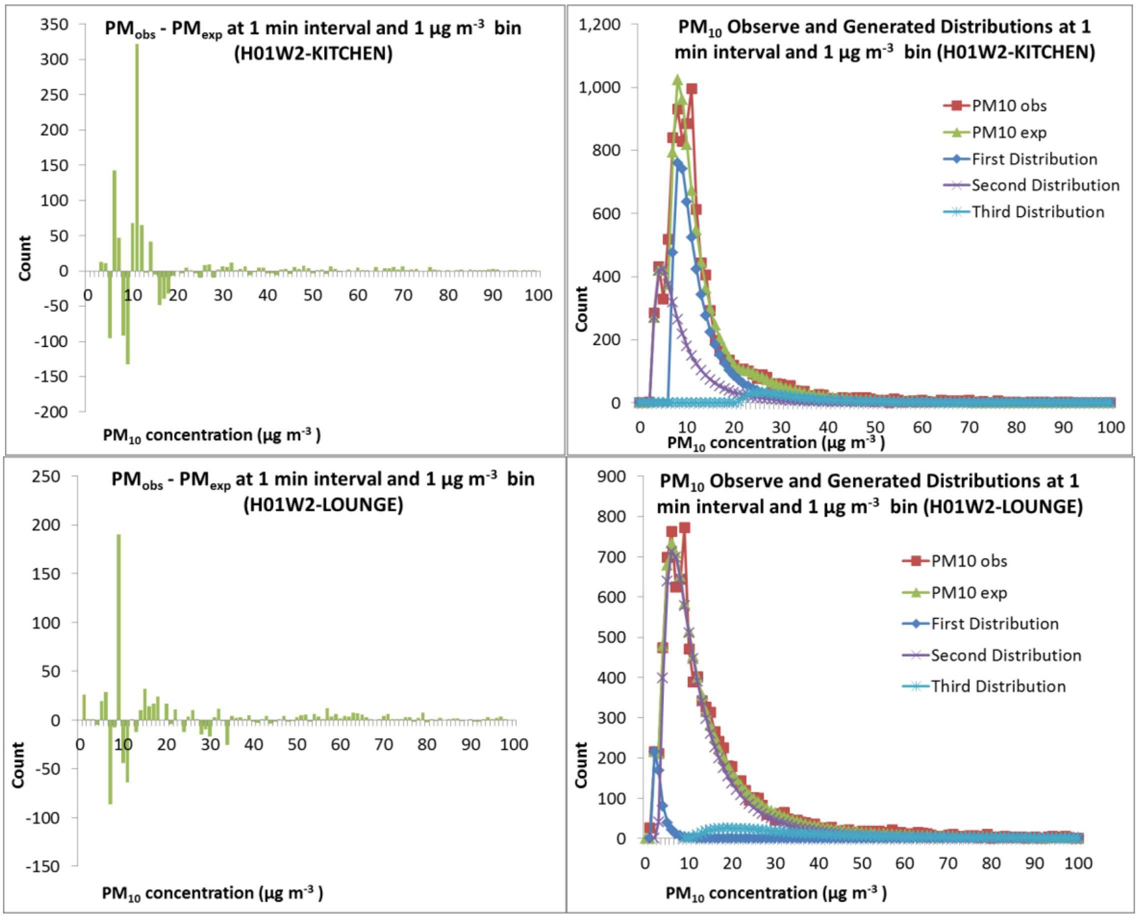


Figure 6-3 PM_{10} Distributions at H01W2 (Monitored, Modelled and Residuals)

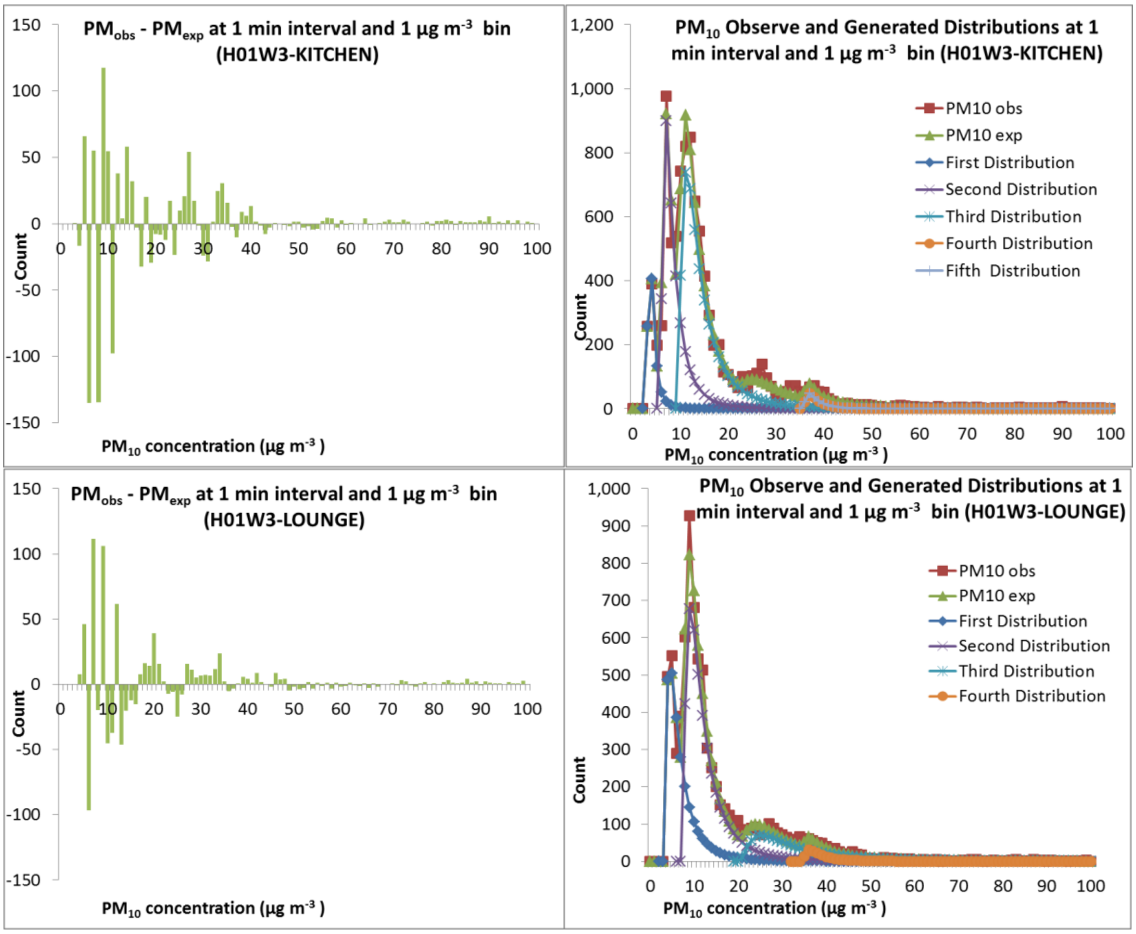


Figure 6-4 PM_{10} Distributions at H01W3 (Monitored, Modelled and Residuals)

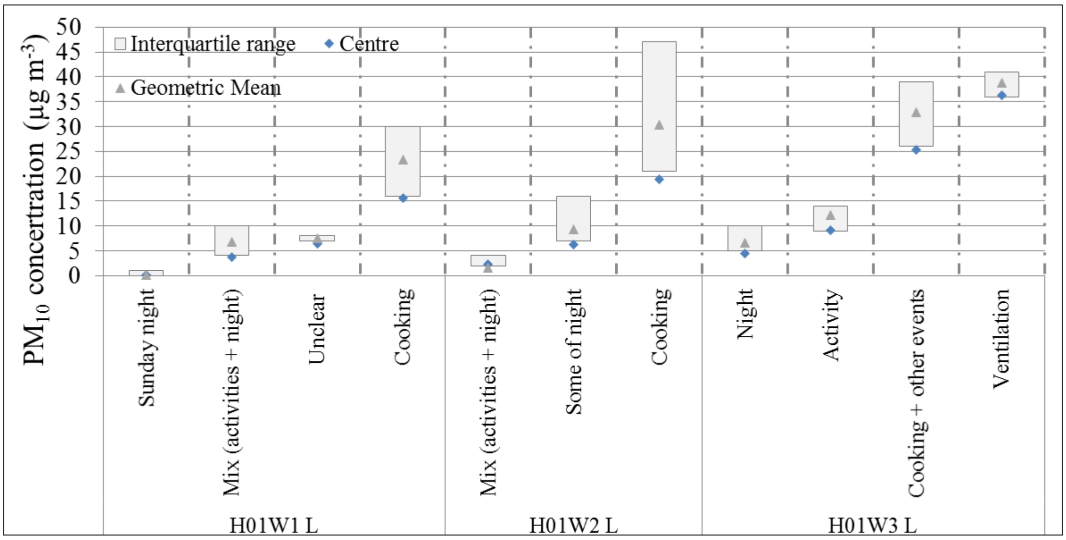


Figure 6-5 Statistics of 1st 2nd and 3rd week for H01 lounge (centre/geometric/interquartile)

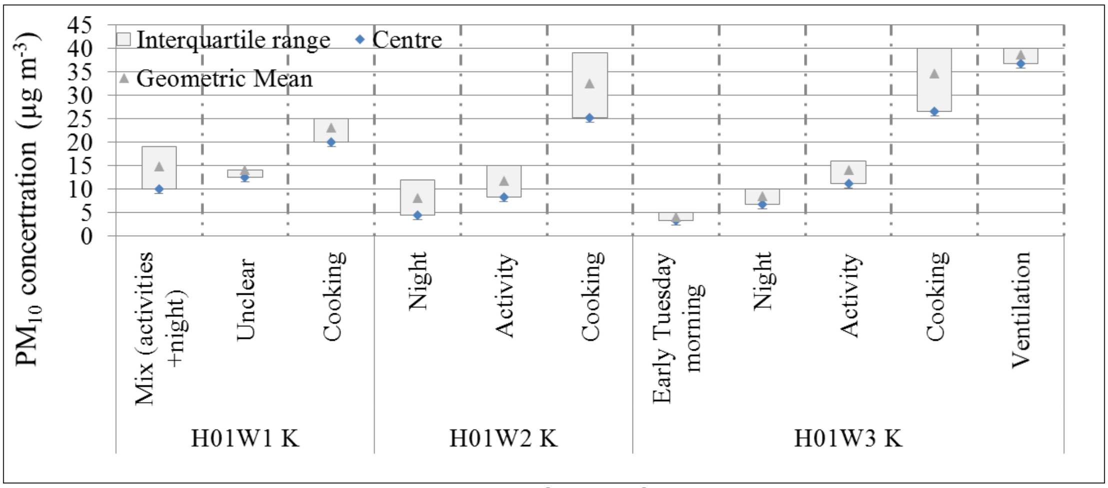


Figure 6-6 Statistics of 1st 2nd and 3rd week for H01 kitchen (centre/geometric/interquartile)

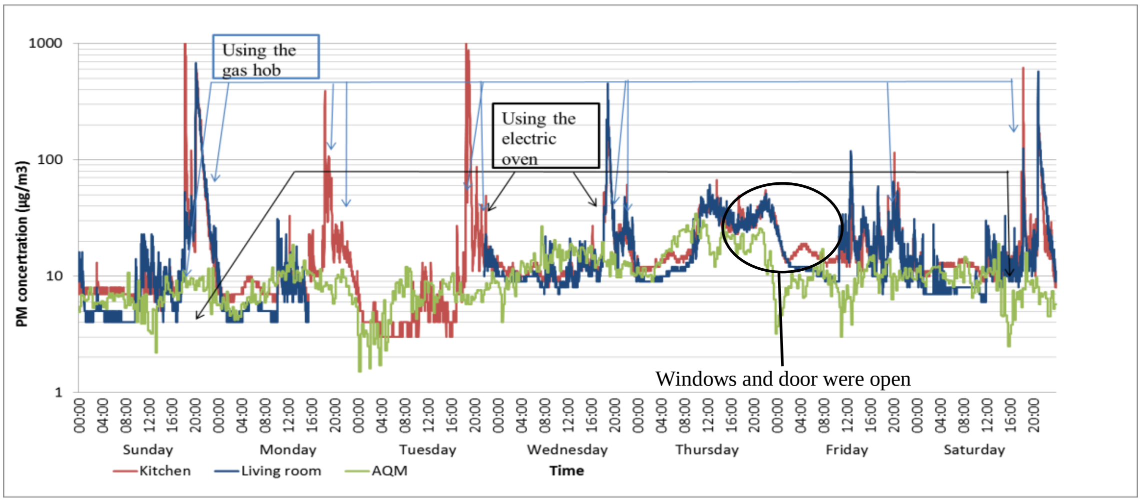


Figure 6-7 PM$_{10}$ Levels at H01W3

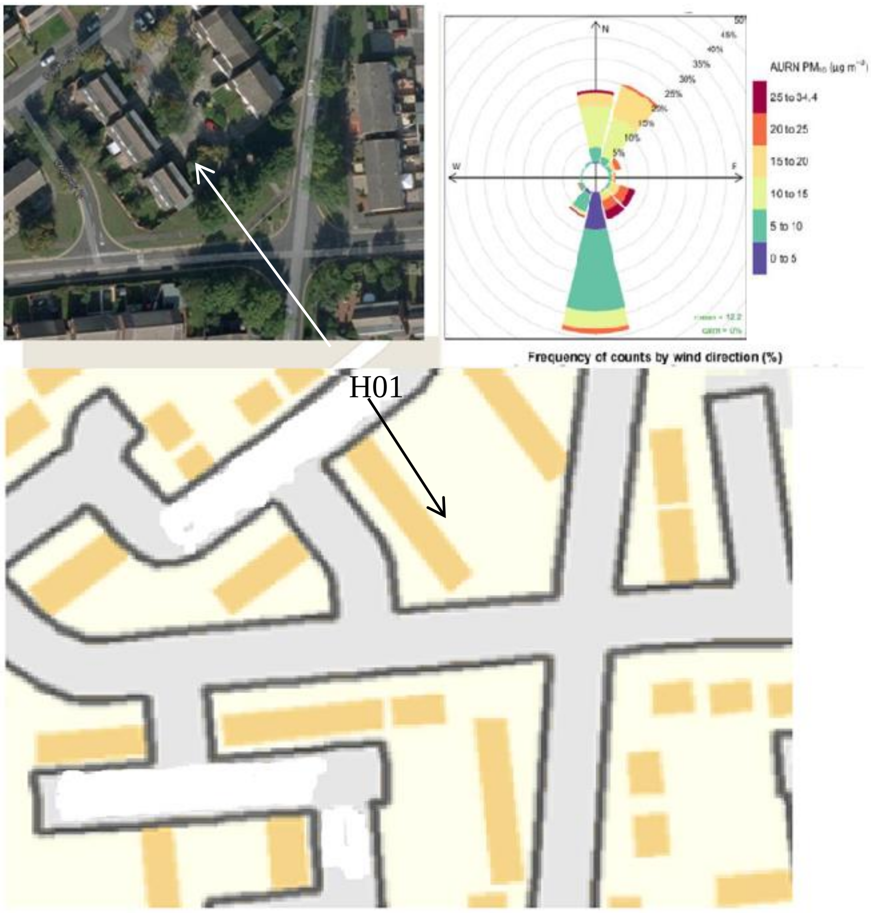


Figure 6-8 H01W3 location and AURN PM_{10} rose
(Source: Streetmap, Google Earth)

The component distributions fitted to the actual data statistically significantly explained for kitchen (lounge) 93% (92%), 96% (97%) and 97% (97%) for week 1, 2 and 3 respectively see Table 6-3. The analysis of the residuals (see Figure 6-9) demonstrated that their distributions were not normally distributed therefore non parametric statistical tests were carried out. The one sample Wilcoxon test was used to test whether the median values were statistically significantly different from zero. The results showed that for the kitchen (lounge) respectively for each of the three weeks median were 0 (0), 0 (0) and 0 (0) μg m^{-3} were statistically significantly different from zero except for H01W2L as shown in Table 6-4.

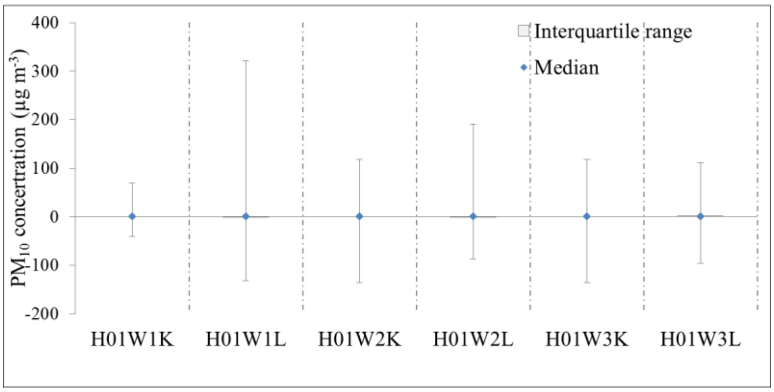


Figure 6-9 Residuals of H01 kitchen and lounge week 1, 2 and 3 (median/interquartile)

Table 6-4 One sample Wilcoxon test result for the residuals

ID	Total Count	Number for Test	Wilcoxon Statistic	Estimated P value	Estimated Median	Statistically Significantly Different from 0
H01W1K	989	290	36397.5	0	0.0000	Yes
H01W1L	943	309	35973	0	0.0000	Yes
H01W2K	750	242	20726	0	0.0000	Yes
H01W2L	943	383	35922	0.697	0.0000	No
H01W3K	2151	307	38086.5	0	0.0000	Yes
H01W3L	679	284	30268.5	0	0.0000	Yes
H02W1K	1011	348	36891	0.001	0.0000	Yes
H02W1L	508	382	36038.5	0.803	-0.0050	No
H03L	87	84	1794.5	0.968	0.0000	No
H04L	542	393	44418	0.011	0.0000	Yes
H05K	2681	499	95496	0	0.0000	Yes
H05L	4271	528	111388	0	0.0000	Yes
H06L	337	334	39446	0	0.4850	Yes
H07L	51	49	687	0.462	0.4650	No
H08K	2681	316	44209.5	0	0.0000	Yes
H08L	496	280	26173.5	0	0.0000	Yes
H09W1L	361	200	9742	0.708	0.0000	No
H10W1L	82	79	1847.5	0.192	0.7450	No

6.3.2 Property H02 Semidetached Close to Busy Road

Consistent with property H01 the cooking activity was associated with high PM_{10} geometric means in the kitchen (31.2 µg m^{-3}) compared to the lounge (25.9 µg m^{-3}) see Figure 6-11. Also, the cooking activity resulted in elevated slightly more variable levels over longer periods in the kitchen compared to the lounge (geometric standard deviation 1.5 and 1.7 respectively). Night time levels in the kitchen geometric mean (geometric standard deviation) 10.2 (1.1) µg m^{-3} were consistently higher than the lounge 7.7 (1.5) µg m^{-3} but with less variation. The most interesting result in this property was that the kitchen and lounge were separated by a small hall. Therefore, the difference between kitchen and those measured in the lounge were not as large as was expected. However, the doors generally were left open and separated by a distance of only about 2.5 metres. Also, during cooking people passed from one room to another and, as reported by the householder, other activity including children playing took place whilst cooking. These are evident from the pdfs showing very small peaks above 20 μg m^{-3} in Figure 6-10 for both the kitchen and the lounge. Instead these events, along with other reported activity, are responsible for the larger width of the component distributions explaining 35% and 46% for kitchen and lounge respectively compared to property H01 with 5%, 5%, 9% and 25%, 8%, 13% for week 1, 2 and 3 respectively. The residuals were found not to be normally distributed, however, there was no statistically significant difference between the median and zero for H02W1L and there was a statistically significant difference between the median and zero for H02W1K.

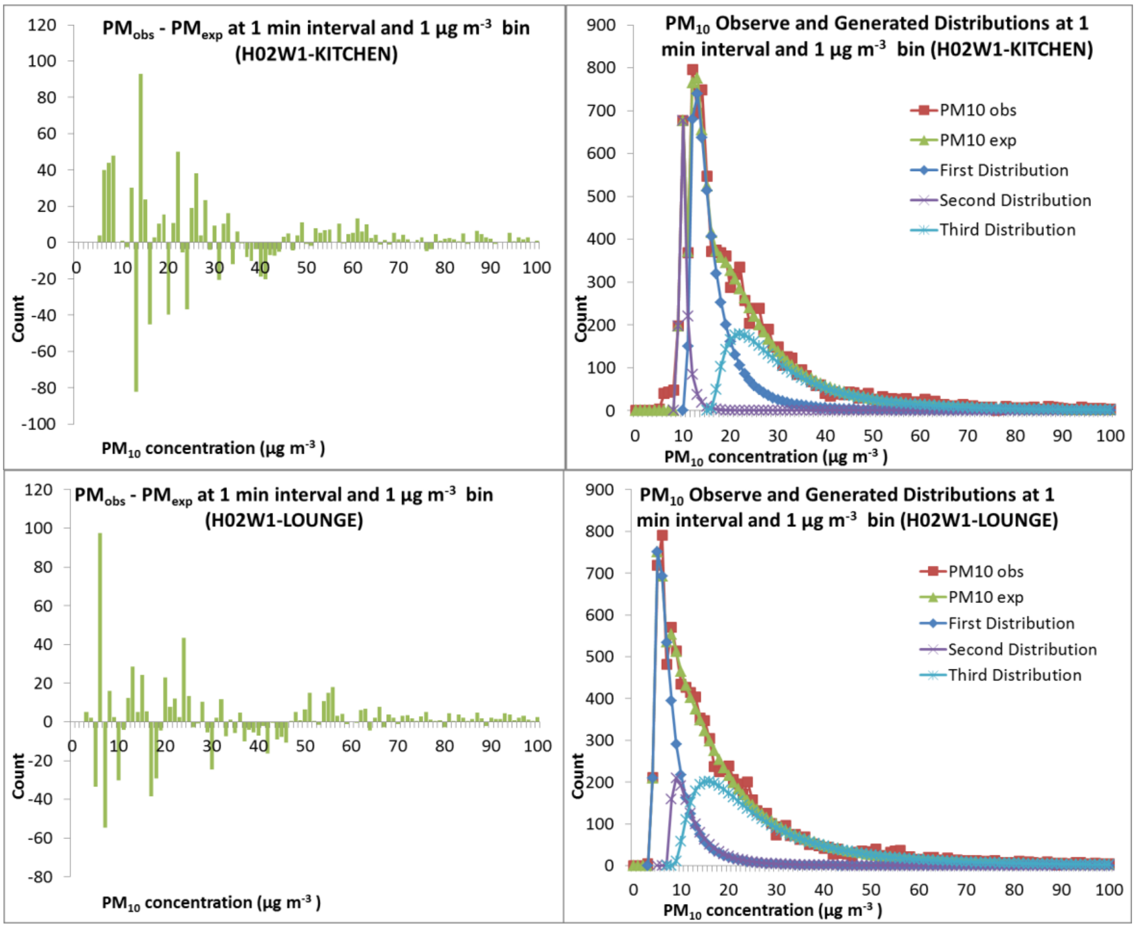


Figure 6-10 PM_{10} Distributions at H02W1 (Monitored, Modelled and Residuals)

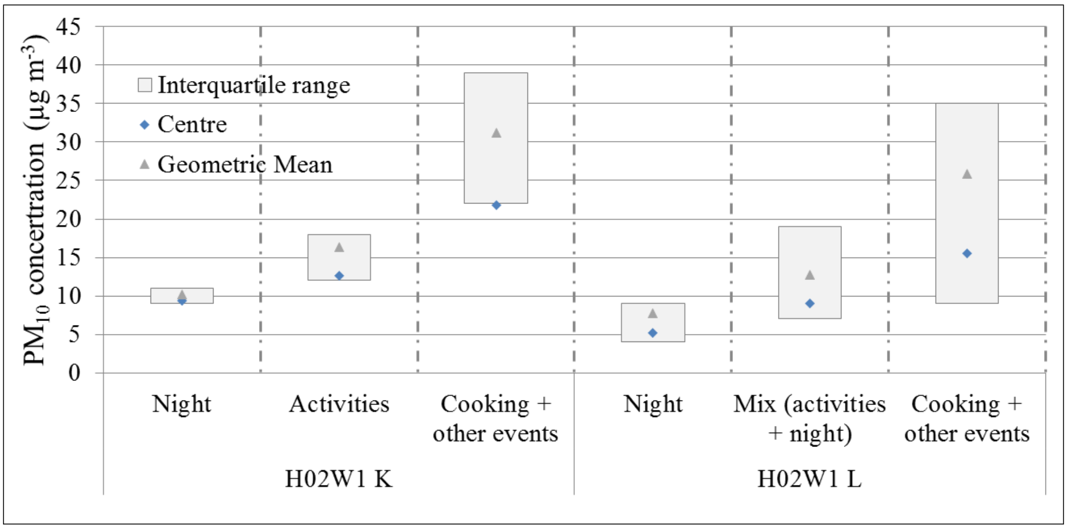


Figure 6-11 Statistics for H02W1 kitchen and lounge (centre/geometric/interquartile)

6.3.3 Properties H03 Alongside Quiet Road and H04 Alongside Busy Road

Four component lognormal distributions were fitted to each of the properties H03 L and H04 L PM_{10} as shown in Figure 6-12. Unfortunately, the participant of H03 did not record activity, therefore the distributions could not be explained by activities. Specific distribution was inferred because it occurred during the night time geometric mean (geometric standard deviation), 9.6 (1.7) µg m^{-3} which was indicated on the time series plot Figure 5-9. Whilst, the other distributions could not be explained precisely, however, due to the regular recurrence day to day it is suggested that the sub component distributions are consistent with cooking and activity in the lounge.

For H04, some of distributions were explained using time series plot and activity diary, see Figure 5-10. In property H04, night time levels were consistently lower than day time activities geometric mean (geometric standard deviation), 3.1 (1.4) and 15.6 (2.0) µg m^{-3} respectively and less spread see Figure 6-13. Also, compared to day time activity and during cooking PM_{10} levels are higher often with a larger width indicating more variation and much higher than at night time as shown in Figure 6-13. Consistent with other properties, day time activity levels in both properties H03 and H04 geometric mean (geometric standard deviation) 13.6 (1.5) and 15.6 (2.0) µg m^{-3} were lower than cooking 26.4 (1.1) and 41.9 (1.3) µg m^{-3} respectively.

The lounge of H03 was not used frequently by the household occupants. Therefore, the spread of the component distributions of H03 is less than that measured in H04 where the lounge was used with high frequency. Cooking levels in the lounge at H04 were characterised with higher geometric means and (geometric standard deviation) than

H03, 41.9 (1.3) µg m^{-3} compared to 26.4 (1.1) µg m^{-3}. This is possibly due to the reception area between the two being small (about three square metre) and both kitchen and lounge doors remained open in property H04 whilst the kitchen of H03 is in a separate room without an interconnecting door separated by a long (3.5m) hall and both kitchen and lounge doors remained closed most of the time. An interesting feature in property H04 was an isolated event, that could not be explained, which occurred at a mode of 19.1 µg m^{-3} geometric mean and 1.1 geometric standard deviation. Levels in property H03 generally were more consistent with H01 during the first and second week whilst H04 was more in line with the higher levels measured in H01 in the third week when more activity was recorded by the householder. In all 95% and 98% of the total variation was explained for properties H03 and H04 respectively. The residuals for H03 and H04 were not normally distributed and the median for H03 was not statistically significantly different from the zero whilst H04 was statistically significantly different from zero.

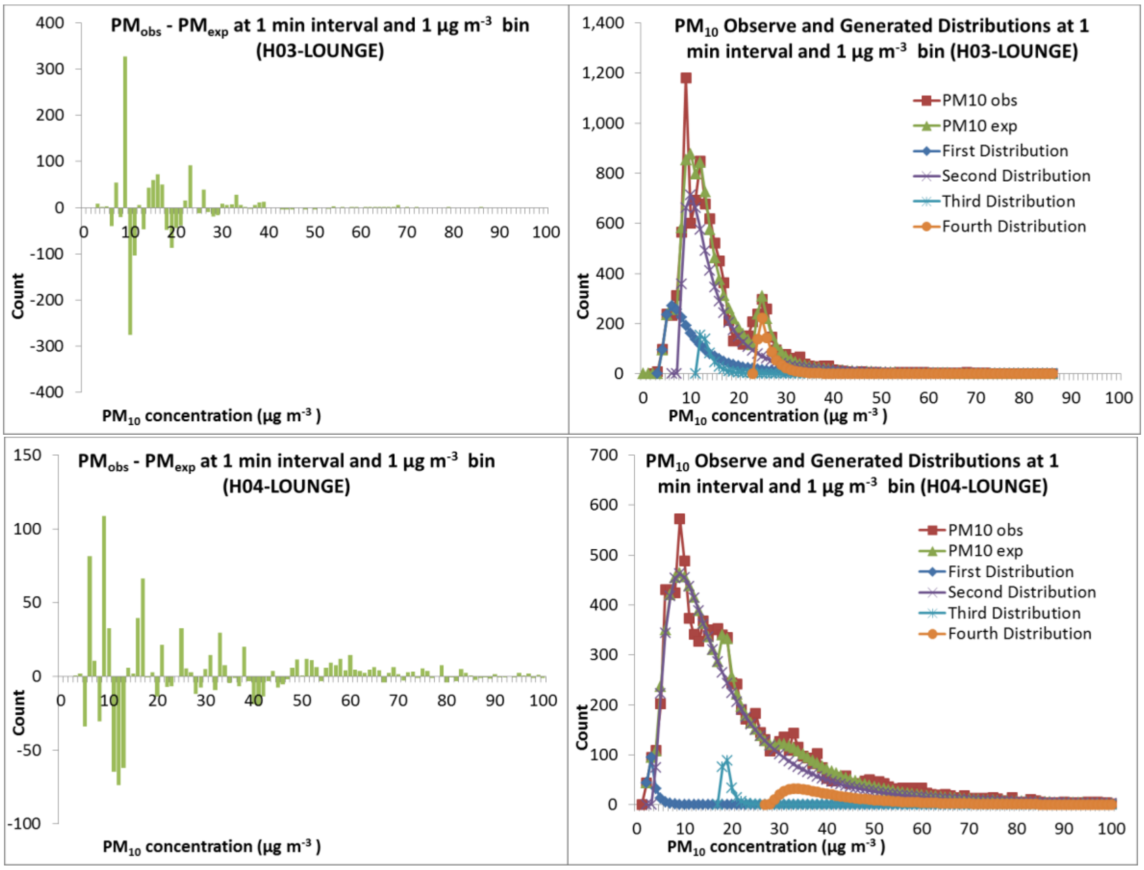


Figure 6-12 PM$_{10}$ Distributions at H03 and H04 (Monitored, Modelled and Residuals)

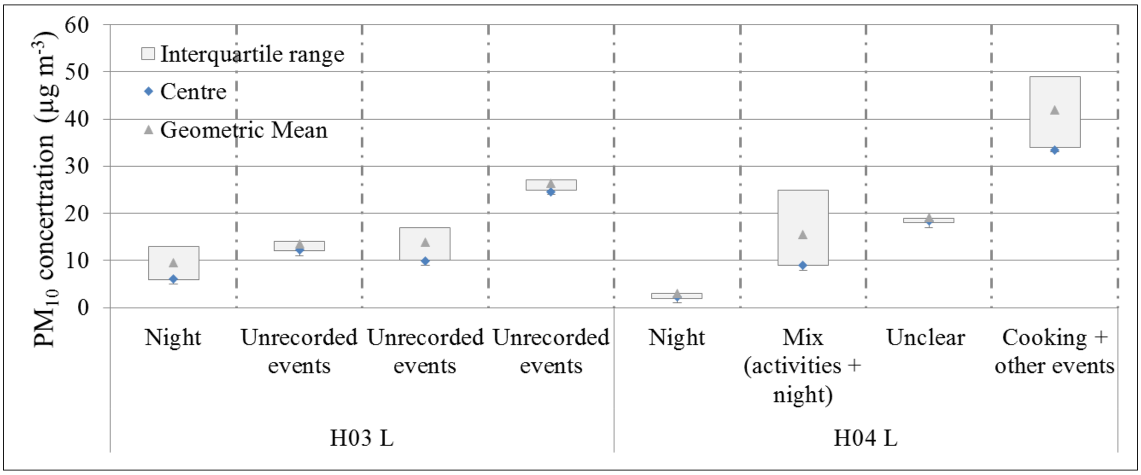


Figure 6-13 Statistics for H03 and H04 (centre/geometric/interquartile)

6.3.4 Property H05 Alongside Busy Road

The participants of H05 did not record their activities, therefore the component distributions of the pdf see Figure 6-15 could not be identified. Three component distributions were fitted to both kitchen and lounge, see Figure 6-15. Only one distribution was explained as this occurred during the night time which was indicated on the time series plot Figure 5-11. Night time, as expected, was associated with low geometric means in the kitchen and the (lounge) 6.9 (5.9) µg m^{-3} respectively, see Table 6-3. In property H05, there was no statistically significant differences between the kitchen and the lounge with geometric means and (geometric standard deviation) 6.9 (1.6), 12.2 (1.3), 32.6 (1.6) µg m^{-3} and 5.9 (1.8), 13.3 (1.2), and 32.4 (1.6) µg m^{-3} for each component distribution respectively, see Figure 6-15. This can be due to there being a door only separating the kitchen from the lounge which was left open. Given the width of the component distribution with the highest geometric mean is greater than the other two distributions is assumed to be associated with cooking. The residuals were not normally distributed and the medians for kitchen and lounge were both statistically significantly different from zero.

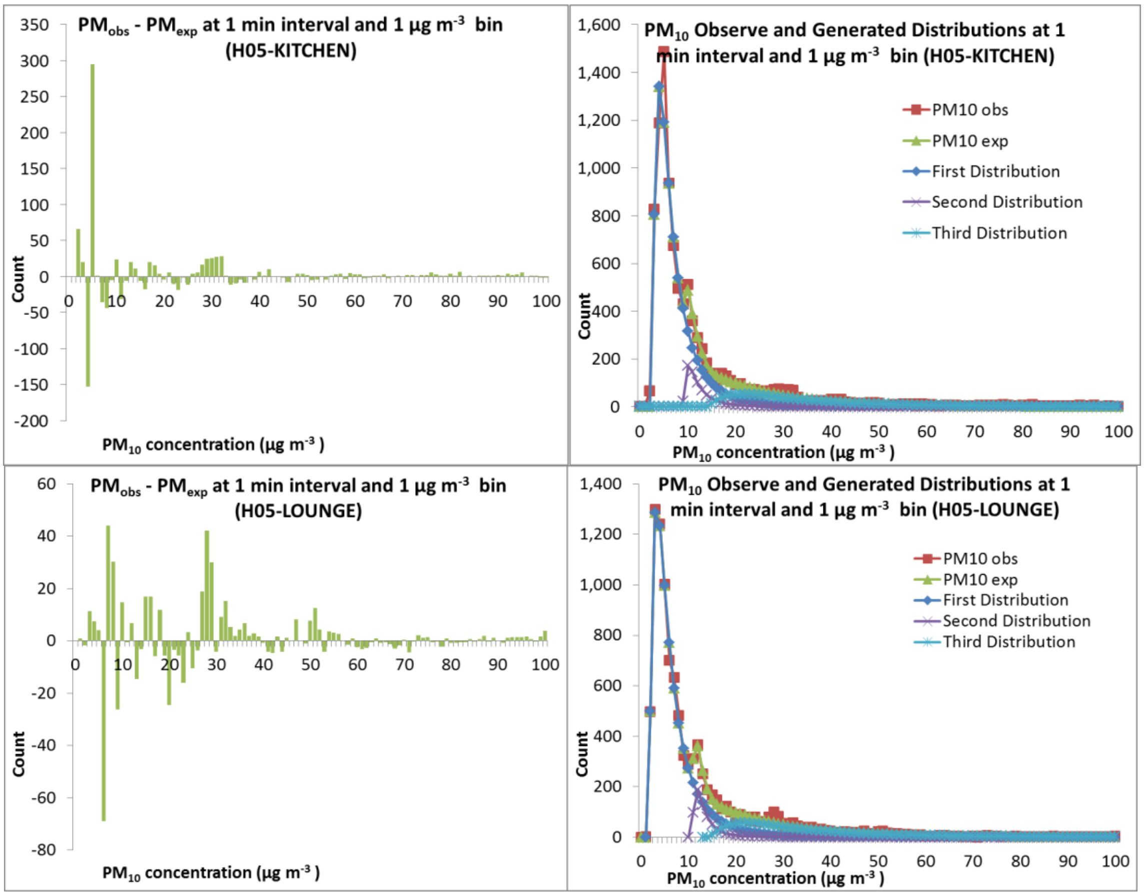


Figure 6-14 PM_{10} Distributions at H05 (Monitored, Modelled and Residuals)

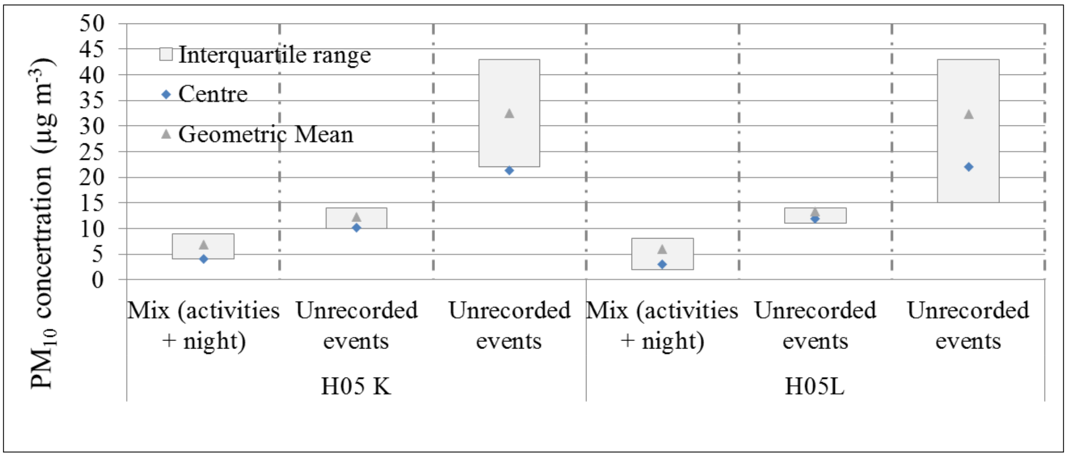


Figure 6-15 Statistics for H05 kitchen and lounge (centre/geometric/interquartile)

6.3.5 Properties H06 Open Plan and H07 Hallway Separation

Figure 6-16 illustrates three lognormal distributions fitted to the pdf for the lounge of property H06 measured simultaneously with property H07. Cooking activity was associated with high geometric means in the lounge of 30.9 and 23.7 µg m^{-3} for H06 and H07 respectively. However, the geometric standard deviation of cooking activity is higher at H06, 1.8, compared to property H07, 1.1, see Table 6-3 and Figure 6-17. This can be explained as the kitchen is integrated with lounge at H06 whilst a hall was between them in property H07. Night time geometric means were consistently lower than day time activities for both H06 and H07. Day time activities geometric means and (geometric standard deviation) for H07 of 11.7 (1.4) µg m^{-3} were higher than H06 of 6.1 (1.3) µg m^{-3} consistent with property H06 having single occupant compared to four occupants on H007. However, there appears to be a conflict in that one would have expected more cooking for four people in H07 but it is concluded that this is due to the kitchen being integrated rather than separated from the lounge. The three component distributions fitted to the pdf explained 96% and 92% of the variation for property H06 and H07 respectively. The residuals were not normally distributed and the median was not statistically significantly different from the zero for H06 yet it was statistically significantly different from zero for H07.

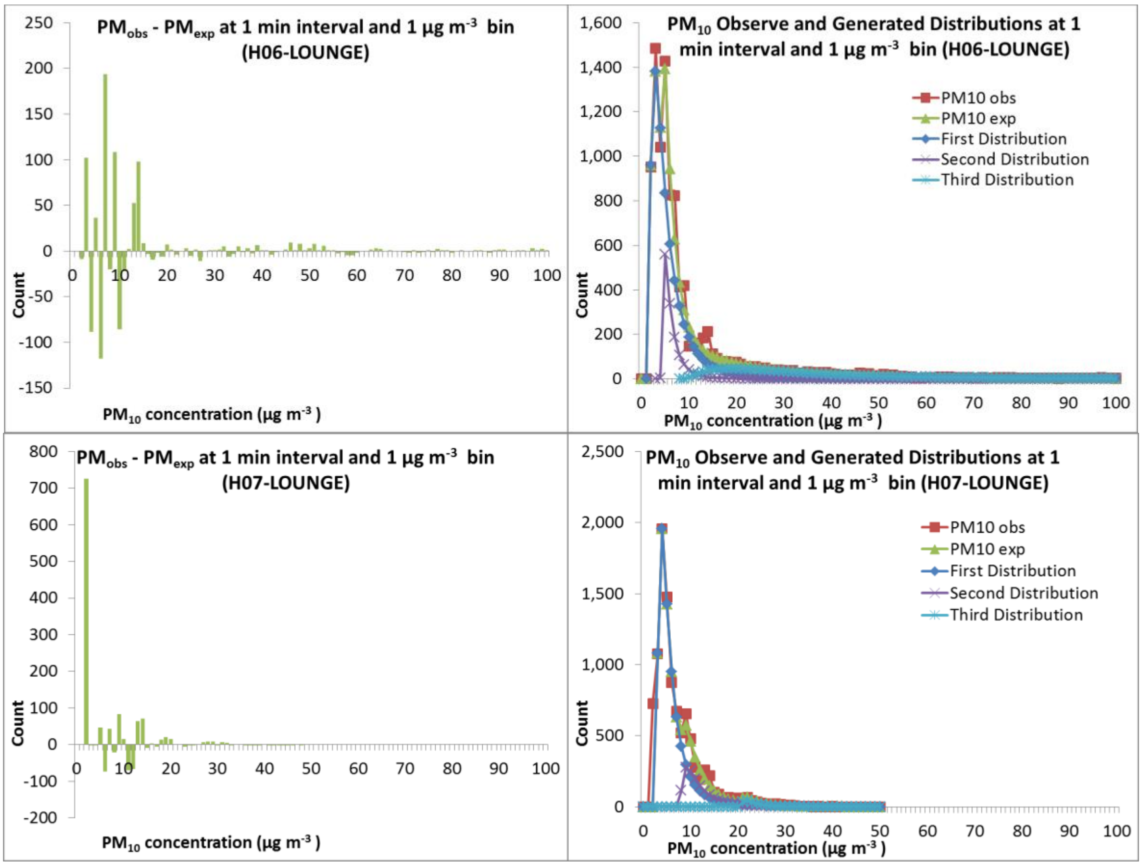


Figure 6-16 PM_{10} Distributions at H06 and H07 (Monitored, Modelled and Residuals)

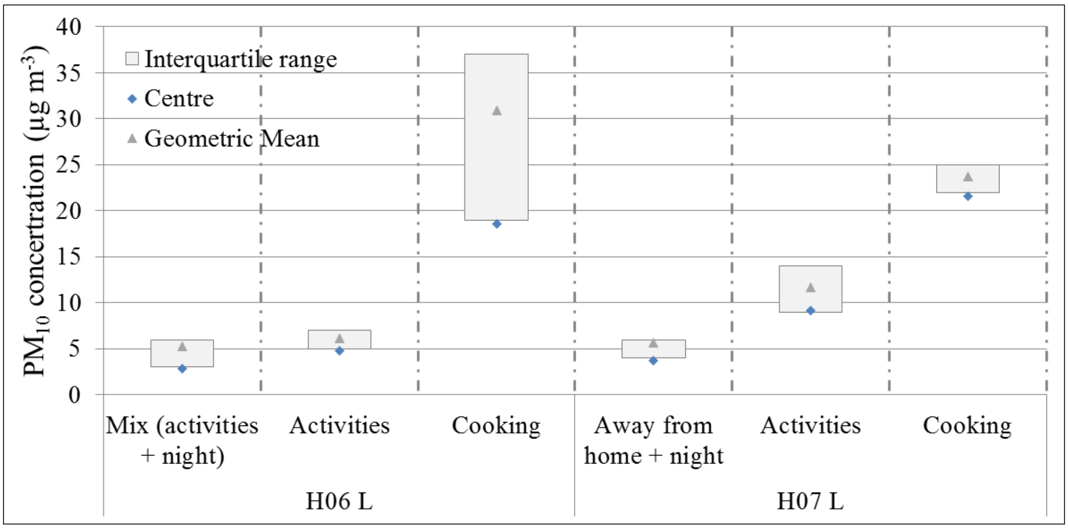


Figure 6-17 Statistics for H06 and H07 (centre/geometric/interquartile)

6.3.6 Property H08 Detached Alongside Quiet Road

Figure 6-18 provides the pdf for the kitchen and lounge monitored simultaneously in property H08. Relative to other properties levels measured were lower. The structure in the pdf was explained to 97% for both kitchen and lounge with three component lognormal distributions. It was unexpected that cooking activity was associated with higher levels with similar variation in the lounge compared to the kitchen geometric mean (geometric standard deviation) 42.9 (1.4) and 28.3 (1.3) µg m^{-3} respectively. Night time and away from home, and within day activity geometric means and (geometric standard deviation) respectively in the kitchen 2.2 (1.5), 6.9 (1.4) µg m^{-3} were less than in the lounge 5.5 (2.2), 10.5 (1.3) µg m^{-3} as shown in Figure 6-19. This contradicts the finding from the other properties. However, this can be explained by the fact that in the property H08 PM_{10} levels reflect only the activity in the lounge, given that the kitchen is in a separate room without an interconnecting door and separated by a long (3m) hall and both kitchen and lounge doors remained closed most of the time. Also, daytime activity levels were higher in the lounge than in the kitchen. An interesting observation in H08 was that during the period when no one was in the home the geometric mean was lower in the kitchen than in the lounge. This observation also suggests that there is more pollution activity generally in the lounge than in the kitchen and with doors closed less opportunity for dispersion. The residuals were not normally distributed and the medians were statistically significantly different from zero.

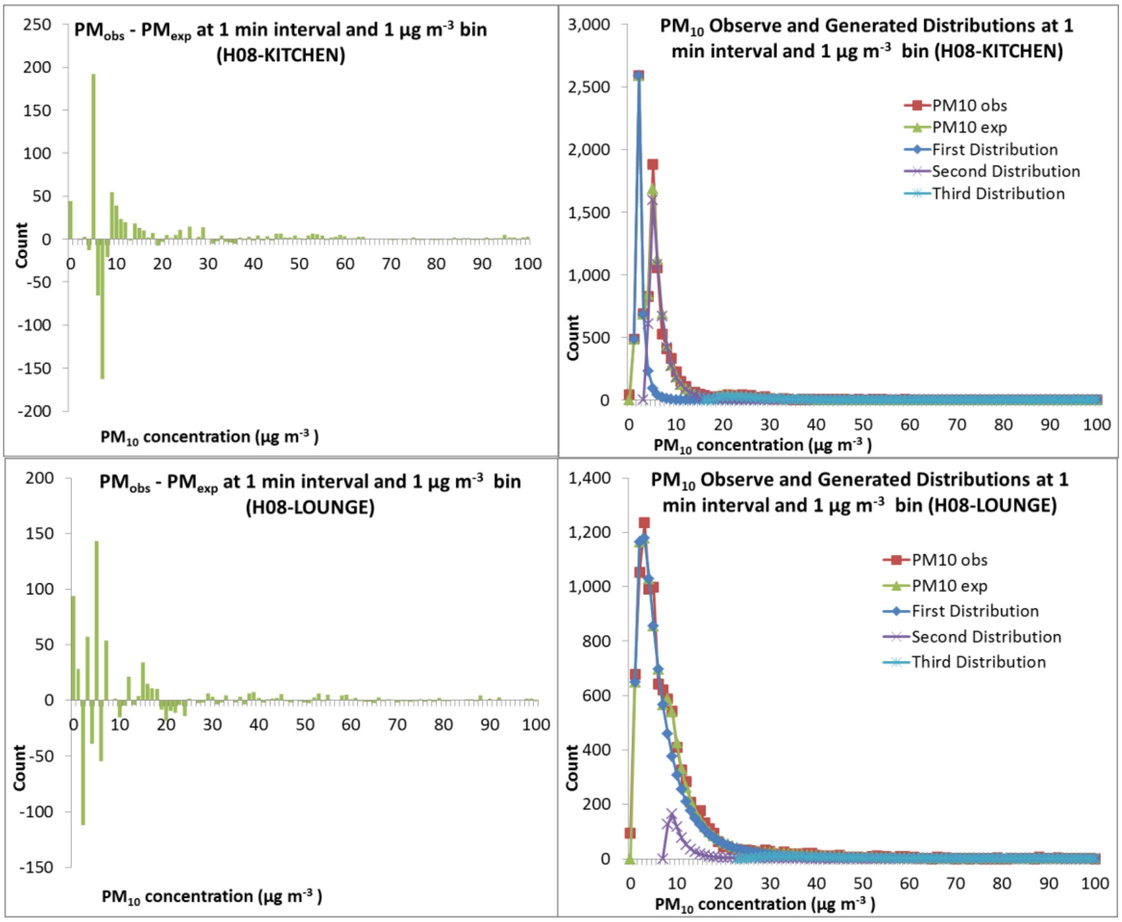


Figure 6-18 PM_{10} Distributions at H08 (Monitored, Modelled and Residuals)

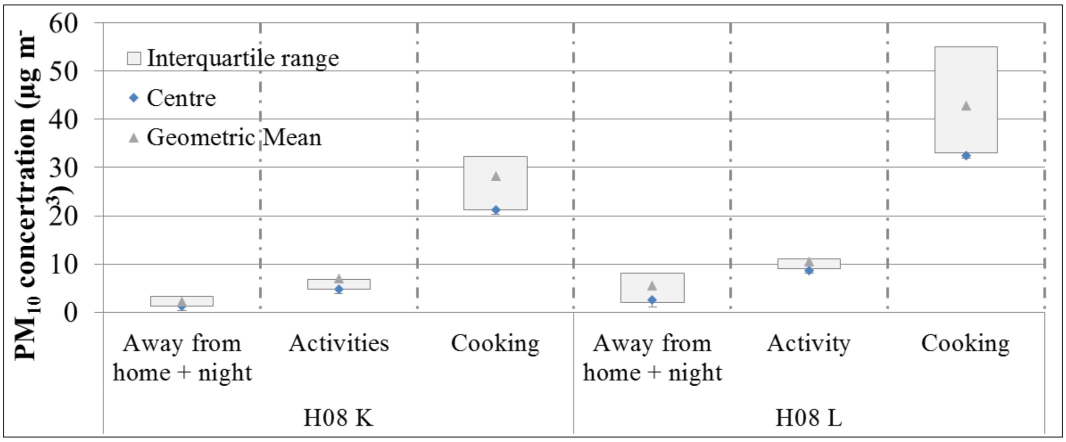


Figure 6-19 Statistics for H08 kitchen and lounge (centre/geometric/interquartile)

6.3.7 Properties H09 and H10

Figure 6-20 illustrates three component lognormal distributions fitted to the data from the lounge of properties H09 and H10. H09 is the dental practice and by cross referencing of reported activity in the time series the distributions were characterised as opening hours, closing and some nights. Closing time levels and variation were consistently lower than opening hours see Figure 6-21 with geometric mean and (geometric standard deviation) values of 6.6 (2.3) µg m^{-3} and 27.8 (1.3) µg m^{-3}

respectively. Cooking activity in property H10 as expected was associated with high geometric mean (geometric standard deviation) 14.4 (1.2) μg m^{-3} in the lounge compared to night time 7.1 (1.6) μg m^{-3} and day time activity 12.8 (1.5) μg m^{-3}. The three component distributions explained 96% and 98% of the monitored pdf in the properties H09 and H10 respectively. The residuals were not normally distributed and the medians were not statistically significantly different from zero.

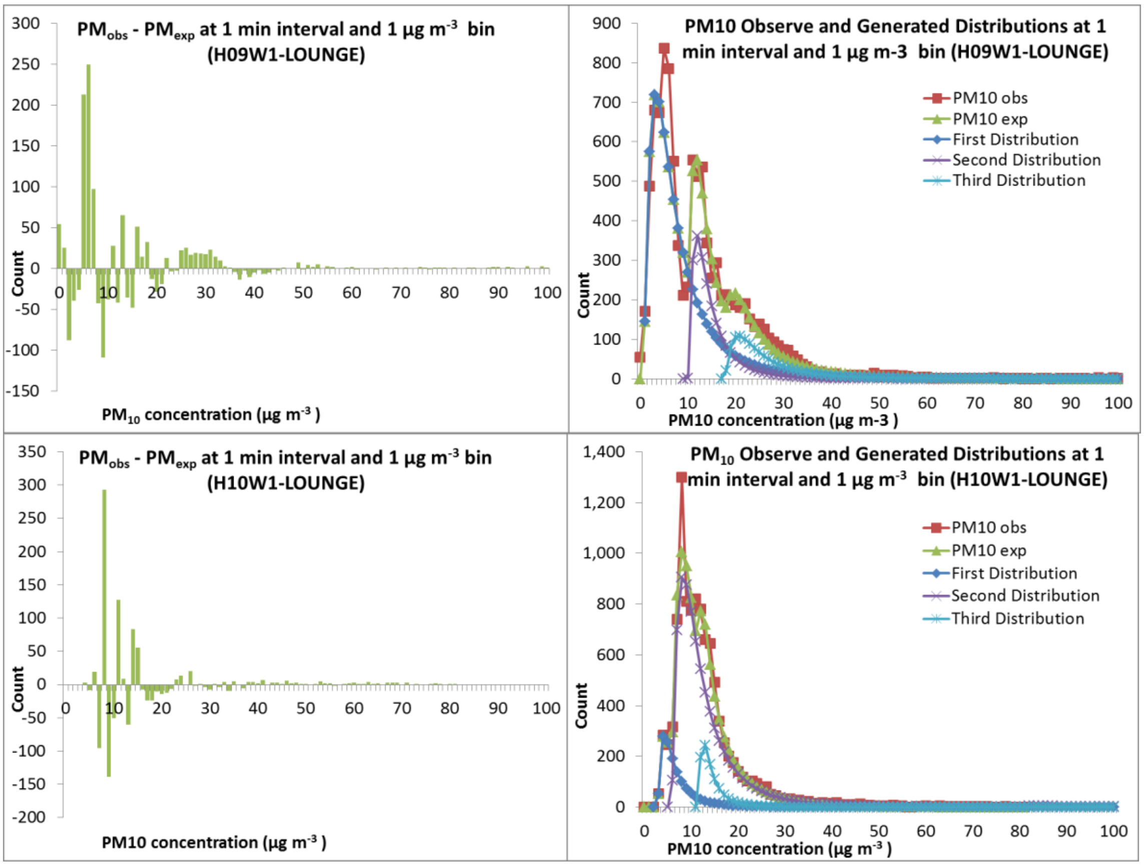


Figure 6-20 PM_{10} Distributions at H09 and H10 during first week (Monitored, Modelled and Residuals)

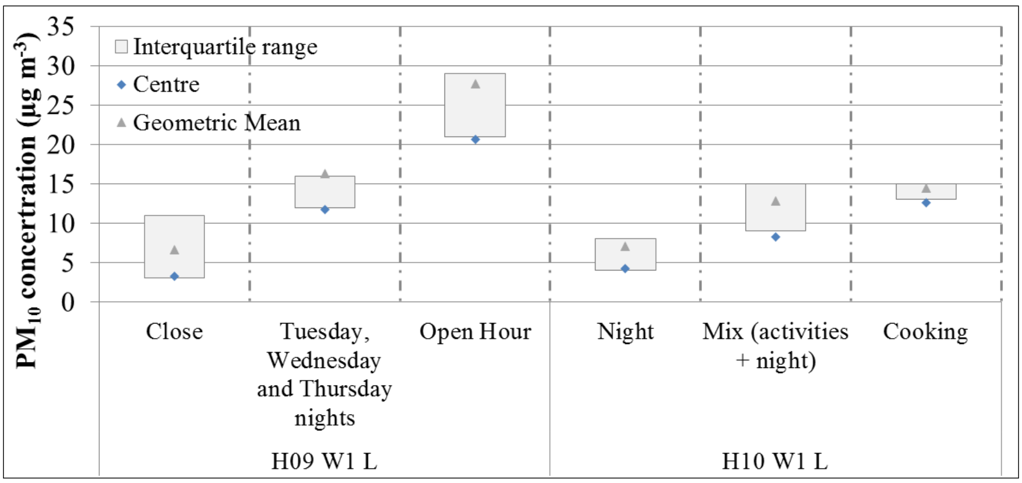


Figure 6-21 Statistics for H09W1 and H10W1 (centre/geometric/interquartile)

6.3.8 Day to Day Variation in Activities

The decomposition of a full week of data collected in each property in the first campaign demonstrated that there were huge differences between kitchen and lounge in some properties but not in others and depended a great deal on the nature of activity whether cooking, cleaning, shredding, sleeping, away on vacation; whether the window and door in the kitchen was open or closed and whether there was physical separation between kitchen and lounge. So far, the analysis carried out has been for the entire data set and typically 92% up to 98% of the measured pdf was explained. In this section the decomposition analysis is repeated taking the minute by minute data independently over each day separately for Monday through to Sunday for properties H09 and H10 to establish whether more variation is explained by decomposition analysis for which the participants provided the activities dairies in much more detail.

The distributions of PM_{10} levels for H09 and H10 were divided into each day at 1 µg m^{-3} bin width at a one minute averaging interval. Up to four lognormal distributions were fitted to each dataset and the results are shown in Table 6-5 and Table 6-6. As before, the tables show the parameters as height, width and centre, the interquartile range and percentage of pdf explained of each distribution the geometric mean and standard deviation. Modelled and residual plots are given in Appendix J to Appendix U. The technique, as before, disaggregated the data identifying specific activities which occurred on that particular day. However, in most cases much less of the pdf was explained ranging from 61% to 94% except for two days Monday and Saturday in property H10L which was 97%. This was mainly due to the elapse times between the events in a particular day when dispersion is taking place and is not being accounted for as a component of the “event” or longer periods of inactivity such as on Sunday in the dentist or when the members of the household were away. This is illustrated by the residuals plot in Figure 6-22 where the lowest levels of pollution are not being explained. This analysis of the dental practice microenvironment seems to suggest that the pollution from low levels of activity may be better described by a normal rather than a lognormal distribution. This means that the decomposition as a technique is valid but the fundamental distribution fitted needs to be different. Investigating this further is out of scope of this but a topic for further research.

For property H09 when the dental practice was closed, one distribution dominated geometric means and (geometric standard deviation) 3.9 (1.3) µg m^{-3} however, the cleaning event 13.9 (1.3) µg m^{-3} was identified. On Monday, there were two distributions for opening hour the early morning levels geometric means and (geometric standard deviation) 17.9 (1.2) µg m^{-3} being lower than the afternoon 25.0 (1.2) µg m^{-3} which suggests that following the dispersion and ventilation effects of the unoccupied building over the weekend the pollution generating activity builds up during the day. However, this observation needs to be viewed with caution because the Monday morning corresponded to the period of measurement at the end of monitoring campaign and the Monday afternoon was data recorded at the start of the monitoring campaign, therefore each of them is corresponding to a different Monday of consecutive weeks.

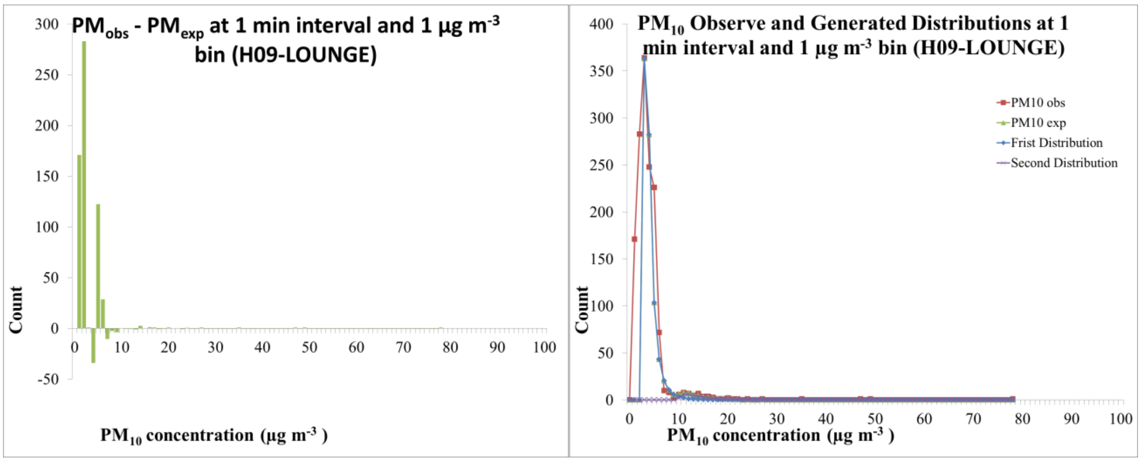


Figure 6-22 PM_{10} Distributions at H09 on Sunday (Monitored, Modelled and Residuals)

Table 6-5 R^2 value by fitting a number of lognormal distributions on H09 data

Dwelling ID	Height	Centre	Width	R^2	Event	Q1	Q3	Total of overall pdf explained	GM[a]	GSD[b]
H09 L Sunday	513.1 6.3	3.2 11.5	1 4.3	0.62	Weekend Cleaning	3 12	4 17	61%	3.9 13.9	1.3 1.3
H09 L Monday	536.1 63.6 64.0	5.2 15.7 22.1	0.7 2.7 3.6	0.96	Night Day (morning) Day (afternoon)	5 16 22	6 19 27	83 %	5.7 17.9 25.0	1.2 1.2 1.2
H09 L Tuesday	159.2 78.0 43.5 3.3	6.7 12.1 27.4 50.0	2.0 2.9 5.0 11.1	0.84	Night After closing Opening hours Unrecorded	7 12 28 51	9 16 34 64	85%	8.3 14.4 31.3 56.1	1.3 1.2 1.2 1.1
H09 L Wednesday	231.6 81.3	10.8 16.1	2.1 4.3	0.92	After closing Opening hours	11 16	14 22	87%	12.5 19.4	1.2 1.3
H09 L Thursday	35.6 455.2 57.4	9.6 12.3 18.2	6.2 1.0 3.0	0.87	After closing Night Opening hours	10 12 18	18 14 22	88%	13.7 13.2 20.6	1.5 1.1 1.2
H09 L Friday	406.1 35.1	4.5 17.7	1.3 6.9	0.81	Night Opening hours	5 18	6 27	80%	5.5 22.6	1.3 1.3
H09 L Saturday	363.0 127.3	2.6 6.4	1.8 1.5	0.91	Weekend Weekend night	3 7	5 8	91%	3.7 7.4	1.6 1.2

[a] Geometric mean
[b] Geometric standard deviation

Activity in H09 related mainly to people moving about, sitting down standing up with continual opening and closing of the outside door directly into the room creating a more diffuse pollution microenvironment. On the other hand, property H10 was a dwelling with regular and more discrete activity prevailing for longer resulting in features that were decomposed with much higher R^2 values. Table 6-6 illustrates these observations well where the three distributions are fitted to each day (Saturday through to Wednesday) with night, day and cooking following similar patterns with geometric means and (geometric standard deviation) similar. However, Thursday and Friday were different and fitted with only two component distributions for night and day with the absence of the "cooking". With reference to Figure 5-16 the peaks associated with cooking are absent. However, they do exhibit a pattern consistent with opening of a window or a door as observed in property H01W3. The diary completed by the householder was consulted and a note had been made that on these two days the extractor fan was used. This adds credibility to the use of decomposition to reveal similar features in pollution microenvironments.

Table 6-6 R^2 value by fitting a number of lognormal distributions on H10 data

Dwelling ID	Height	Centre	Width	R^2	Event	Q1	Q3	Total of overall pdf explained	GM[a]	GSD[b]
H10 L Sunday	393.0 168.0 10.6	7.900 13.000 20.400	0.5 2.8 3.1	0.91	Night Day Cooking	8 13 21	8 17 25	85%	8.2 15.3 22.7	1.1 1.2 1.1
H10 L Monday	247.7 90.5 17.5	8.100 12.300 24.200	1.6 4.6 4.1	0.99	Night Day Cooking	8 13 24	10 18 29	97%	9.4 15.8 27.1	1.2 1.3 1.2
H10 L Tuesday	150.1 112.6 19.3	3.561 9.857 19.580	1.6 5.3 2.1	0.89	Night Day Cooking	4 10 20	6 17 22	91%	4.8 13.5 21.1	1.4 1.4 1.1
H10 L Wednesday	185.3 20.5 6.0	7.337 18.100 38.600	3.6 9.2 4.0	0.96	Night Day Outdoor event	8 19 39	12 30 44	94%	10.0 24.3 41.1	1.4 1.4 1.1
H10 L Thursday	287.2 128.2	6.716 10.1	2.4 1.5	0.97	Night Day	7 10	10 12	93%	8.4 11.2	1.3 1.2
H10 L Friday	142.2 201.8	4.1 8.9	2.4 2.7	0.92	Night Day	4 9	7 12	93%	10.9 6.0	1.3 1.5
H10 L Saturday	360.2 195.4 2.3	6.4 11.2 33.1	0.8 3.4 14.2	0.99	Night Day Cooking	7 11 34	8 16 49	97%	7.6 13.9 39.7	1.1 1.3 1.2

[a] Geometric mean
[b] Geometric standard deviation

This section has delved more deeply into the usefulness of the decomposition technique to identify within the day events. This analysis of H10, an event-dominated microenvironment, has demonstrated that the technique is a valuable tool that disaggregates the sources of pollution over shorter time periods. However, it is important that the correct distribution is fitted at the first step of the decomposition process. This analysis has shown that lognormal performs well with event driven environments whilst a different, possibly the Gaussian better fits more diffuse environments. All R^2 values were greater than 0.8 apart from H09 L Sunday with R^2 value of 0.62. This analysis explained more than 79% of observed data except H09 L Sunday. The method was showed promise in classifying and characterising the feature in the distributions.

6.4 Explaining PM_{10} Levels (Second Campaign)

Consistent with the analysis of the first campaign the Fityk software was used to systematically decompose the pdf of each microenvironment separately, fitting up to five lognormal distributions based on the improvement of R^2 as explained in section 3.7.5. The properties are dealt with systematically in the same order as in the previous chapter. First the descriptive statistics are presented followed by the decomposition analysis.

6.4.1 Descriptive Statistics

The statistical parameters, namely height, width and centre, of each distribution are presented in Table 6-7. The interquartile range for each distribution and the R^2 for the fitted distribution were obtained from the software and reported along with the geometric mean and standard deviation. All R^2 values were greater than 0.89 suggesting that at least 89% of the variation in the pdf was explained. The interquartile range of each component distribution was identified and plotted to allow comparison across microenvironments. The characteristics such as cooking, night time and day time were used to associate a component distribution of the total pdf. The technique was able to identify component distributions for night time, during the morning and cooking as well as other activities which in most cases could be identified when diary data were available. This method was demonstrated to be successful in classifying the distributions in a generic way.

Table 6-7 R^2 by fitting a number lognormal distributions (Second Campaign)

Dwelling ID	Height[a] μg m^{-3}	Centre[b] μg m^{-3}	Width[c] μg m^{-3}	R^2	Event	Q1[d]	Q3[e]	% explained by each component distribution[f]	Total of overall pdf explained[g]	GM[h]	GSD[i]
H01 W4 O	349.9	10.9	10.0	0.96	Afternoon	12	24	53%	95%	19.6	1.7
	352.7	21.7	6.9		Other times of the day	22	31	37%		27.5	1.3
	41.5	48.5	7.0		Outdoor event Thursday	49	58	4%		54.1	1.2
	46.4	62.5	1.9		Bin collection Tuesday	61	65	1%		64.2	1.0
H01 W4 L	359.1	11.7	11.7	0.97	Activity	13	27	64%	92%	19.2	1.7
	776.8	12.9	2.2		Some of nights	13	16	24%		15.4	1.2
	123.3	25.7	2.2		Cooking	26	28	4%		27.3	1.1
H02 W2 O	156.5	14.1	11.4	0.96	Night time	15	29	29%	98%	22.3	1.7
	259.3	22.9	10.4		Day time	24	36	43%		30.2	1.4
	83.4	33.7	1.9		Tuesday night	33	36	2%		35.8	1.1
	190.0	39.5	7.0		Outdoor events	40	49	21%		45.0	1.2
	56.8	57	3.6		Some morning and noon of some days	56	62	3%		60.2	1.1
H02 W2 L	248.6	12.1	8.6	0.94	Night time	13	24	32%	93%	18.0	1.6
	466.0	21.0	8.2		Activity	22	32	58%		26.9	1.4
	67.5	38.6	2.6		Cooking	39	42	3%		40.6	1.1
H09 W2 L	680.6	2.3	2.9	0.89	Close (some night)	3	6	29%	83%	5.0	1.7
	275.2	7.5	3.0		Mondays and Thursday nights	8	11	12%		9.4	1.4
	454.6	16.9	5.3		Sunday and opening hours	17	24	37%		21.4	1.3
	13.1	53.4	23.6		Outdoor event	55	85	5%		69.3	1.3
H10 W2 O	899.7	5.7	4.6	0.95	Other days	6	12	73%	91%	9.2	1.7
	41.4	26.0	16.3		Outdoor events	27	47	12%		37.8	1.5
	58.9	67.0	5.7		Outdoor events Tuesday	67	74	6%		71.9	1.1
H10 W2 L	3356.	1.4	1.0	0.94	Away from home + night	2	3	55%	92%	3.0	1.6
	155.6	10.9	3.5		Other night	11	16	10%		15.1	1.3
	88.5	22.0	16.4		Cooking + activities	23	44	26%		33.7	1.6
	11.9	92.2	5.6		Packing activities	93	100	1%		98.2	1.1
H11 L	184.5	12.6	10.9	0.94	Thursday night and morning opening hours and Friday morning	13	27	33%	92%	19.5	1.7
	327.1	20.9	5.4		Saturday and Wednesday nights and Friday	21	28	29%		25.8	1.3
	338.5	29.9	2.3		Sunday opening hours and Monday night	30	33	12%		32.0	1.1
	76.1	37.2	10.5		Other opening hours	38	51	13%		45.0	1.3
	23.9	57.0	13.6		Cleaning events	58	75	5%		66.9	1.2
H12 O	710.4	4.9	5.1	0.89	Night	5	12	55%	91%	8.0	1.8
	182.9	16.2	0.7		Wednesday night	16	17	2%		16.8	1.1
	303.6	24.4	1.1		Tuesday night	24	26	5%		25.5	1.1
	26.9	39.7	71.3		Opening hours	45	134	29%		76.3	2.1
H12 I	10555	10.2	3.3	.96	Night	10	15	53%	89%	13.2	1.3
	254.0	25.1	1.0		Tuesday night	25	26	4%		25.8	1.1
	12.4	80.7	169.4		Opening hours	94	305	32%		162.1	2.3

[a] The most frequent or highest count of the distribution see section 3.7.2 for more details
[b] The highest frequent concentration (mode) of the component distribution see section 3.7.2 for more details
[c] The widths of the component distribution at the half height at the at centre see section 3.7.2 for more details
[d] The lower quartile of the component distribution which was calculated (μg m^{-3})
[e] The upper quartile of the component distribution which was calculated (μg m^{-3})
[f] The ratio of the component distribution and the observed data expressed as a percentage
[g] the difference between the sum of each component distribution and the observed data relative to the observed data expressed as a percentage
[h] Geometric mean,
[i] Geometric standard deviation

The pdfs were plotted for each microenvironment showing the three, four or five lognormal distributions as illustrated in Figure 6-23, Figure 6-26, Figure 6-29 and Figure 6-31. Each figure presents analysis for each property for simultaneously monitoring outdoor and indoor PM_{10} concentration levels. The graphs on the right are the pdfs for the two microenvironments monitored simultaneously namely outdoor (top) and indoor (bottom). They illustrate the component lognormal distributions and the overall best fit pdf (which is the summation of the individual component distribution) including the observed pdf. These distributions are presented as line graphs for clarity. More than 86% and up to 96% of the variation in the pdf could be explained by the component distribution demonstrating the appropriateness of this method in classifying the distributions in a generic way.

On all occasions these graphs are produced in the text plotted up to 100 µg m^{-3} on the x axis so that the features are more easily interpreted. The full data sets are plotted on the log scale in Appendix EE to Appendix JJ for completeness. All curve fitting and non-parametric statistical tests were carried out on the complete range of data throughout the thesis when distributions were found not to be normally distributed

6.4.2 Property H01 Semidetached Close to Busy Intersection

Figure 6-23 illustrates four and three component distributions to outdoor and lounge respectively and Figure 6-24 shows the centre of each distribution and interquartile ranges. The outdoor pdf exhibited four component distributions. The largest of geometric mean (geometric standard deviation) 64.2 (1.0) µg m^{-3} on Tuesday coincided with refuse collection. This suggested that pollution caused by refuse collecting activity, the loading and unloading, stopping and starting of a large truck contributes significantly to outdoor concentrations. Specifically PM_{10} levels and variation within the day, and from day to day, increased during the day and were lower overnight. Interestingly, the diurnal peak levels were not always measured during the day time but sometimes overnight as seen on Tuesday, Wednesday and Thursday. Figure 6-25 shows the AURN (Gosforth) and wind speed data analysis can be seen in Figure 3-2 along with outdoor and indoor PM_{10} levels. The geometric mean (geometric standard deviation) 54.1 (1.2) µg m^{-3} occurred from midnight to 04:00 hrs on three consecutive nights Tuesday, Wednesday and Thursday periods and coincided with higher levels of outdoor PM_{10} at H01W4 which is inconsistent with the AURN. In fact on all other days pollution overnight were always systematically higher than the AURN but consistent with the lower component distribution 19.6 (1.7) µg m^{-3}. Furthermore with reference to Figure 6-25, there is no consistency between the wind speed and elevated levels, given on Tuesday and Saturday PM_{10} levels are higher, wind speeds low and vice versa on other days. Cooking activity was associated with high levels in the lounge with geometric mean (geometric standard deviation) 27.3 (1.1) μg m^{-3}. The night time levels were similar to day time activities but lower geometric mean (geometric standard deviation) 15.4 (1.2) and 19.2 (1.7) μg m^{-3} respectively. The residuals were not normally distributed and the indoor residual median was significantly different from zero and outdoor residual median was not statistically significantly different from the zero. This suggests that indoors there is a component of the distribution not explained (for example continuous background level) on the other hand all features within the pdfs were explained by the sub components.

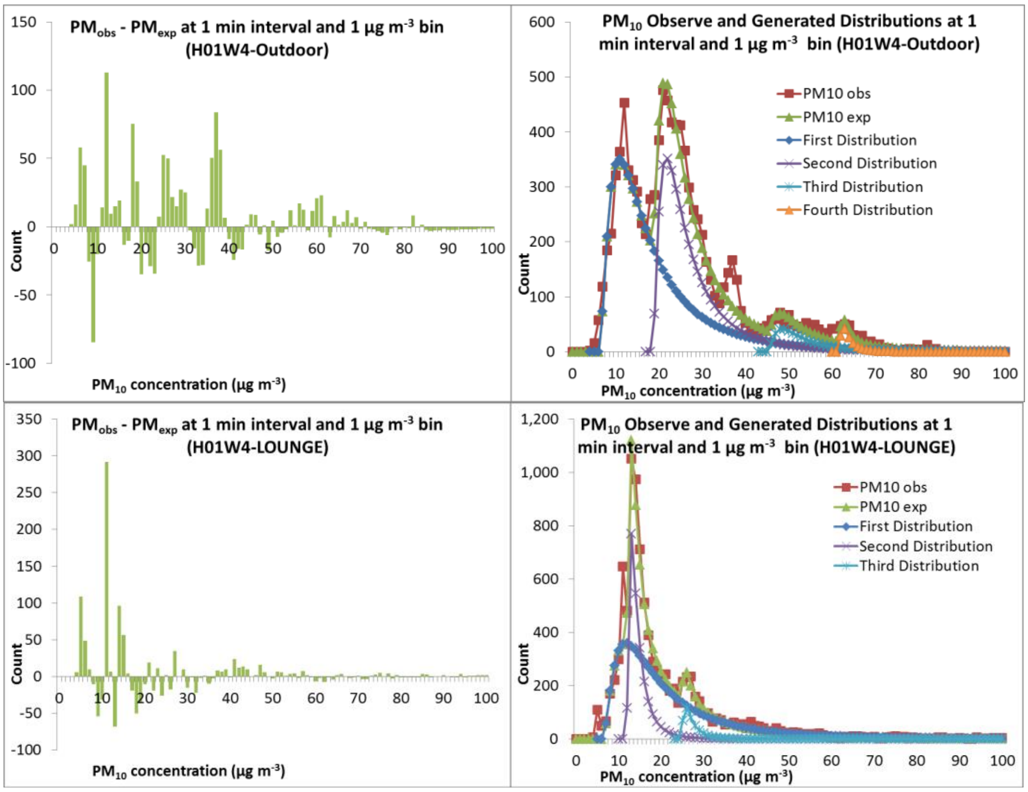


Figure 6-23 PM$_{10}$ Distributions at H01W4 (Monitored, Modelled and Residuals)

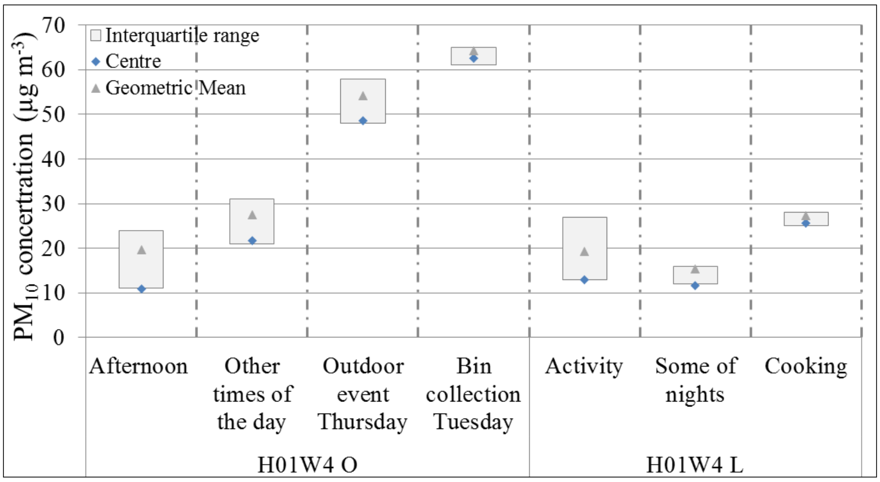


Figure 6-24 PM$_{10}$ component distributions at H01W4 outdoor and indoor (centre/geometric/interquartile)

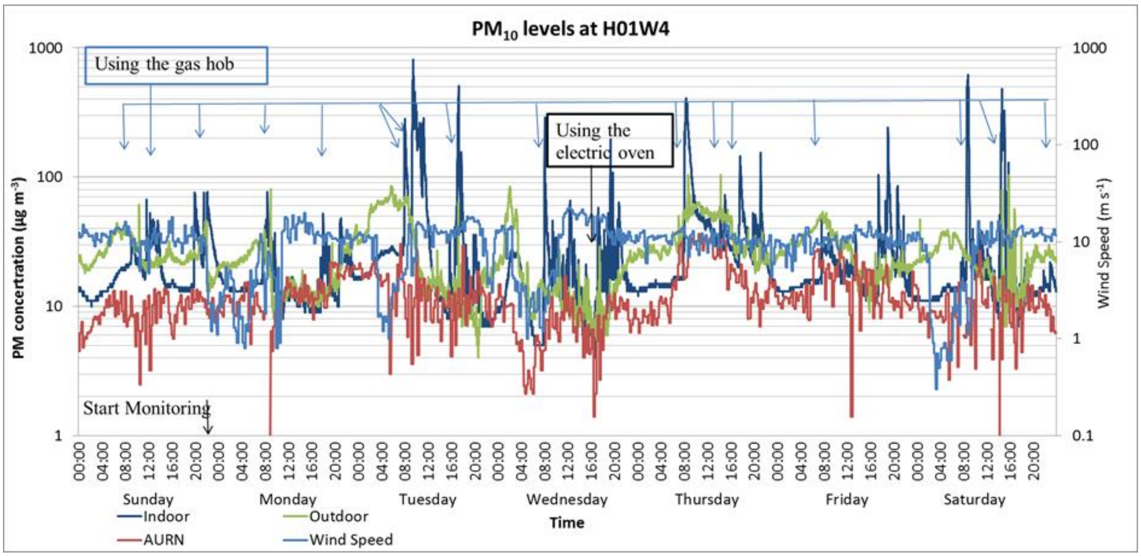


Figure 6-25 PM_{10} time series of H01W4 and AURN and wind speed

6.4.3 Property H02 Semidetached Close to Busy Road

Figure 6-26 illustrates the component distributions fitted to outdoor and indoor for actual and modelled pdf (right of figure) along with the residuals calculated as the difference between the two (left of figure). The outdoor levels were fitted with four component distributions to achieve the highest R^2 although a fifth between 60 and 70 µg m^{-3} was evident and therefore fitted accepting slightly lower R^2. However, the data explained by a fifth distribution was not sufficiently large to avoid a significant contribution to the general "error". Property H02 outdoor levels very closely tracked indoor levels for the period 20:00 hrs to 04:00 hrs on Saturday/Sunday, Wednesday/Thursday and Friday/Saturday when outdoor levels were substantially higher. This pattern was consistent with features observed at H01 and can be explained in terms the absence of pollutant sources indoor. As expected, cooking activity was associated with high PM levels in the lounge geometric mean (geometric standard deviation) 40.6 (1.1) µg m^{-3}. Night time geometric mean (geometric standard deviation) 18.0 (1.6) µg m^{-3} were lower than day time activities 26.9 (1.4) µg m^{-3} and slightly lower geometric standard deviation. The geometric mean (geometric standard deviation) overnight time in the lounge were lower than outdoors with values 18.0 (1.6) and 22.3 (1.6) µg m^{-3} respectively. Also, a similar pattern emerged when comparing day time activity in the lounge geometric mean (geometric standard deviation) 26.9 (1.4) µg m^{-3} with outdoor values 30.2 (1.4) µg m^{-3}. This suggested that outdoor pollution was being transported to indoors at this property. The residuals were not normally distributed and the medians of the residuals were not statistically significantly different from the zero.

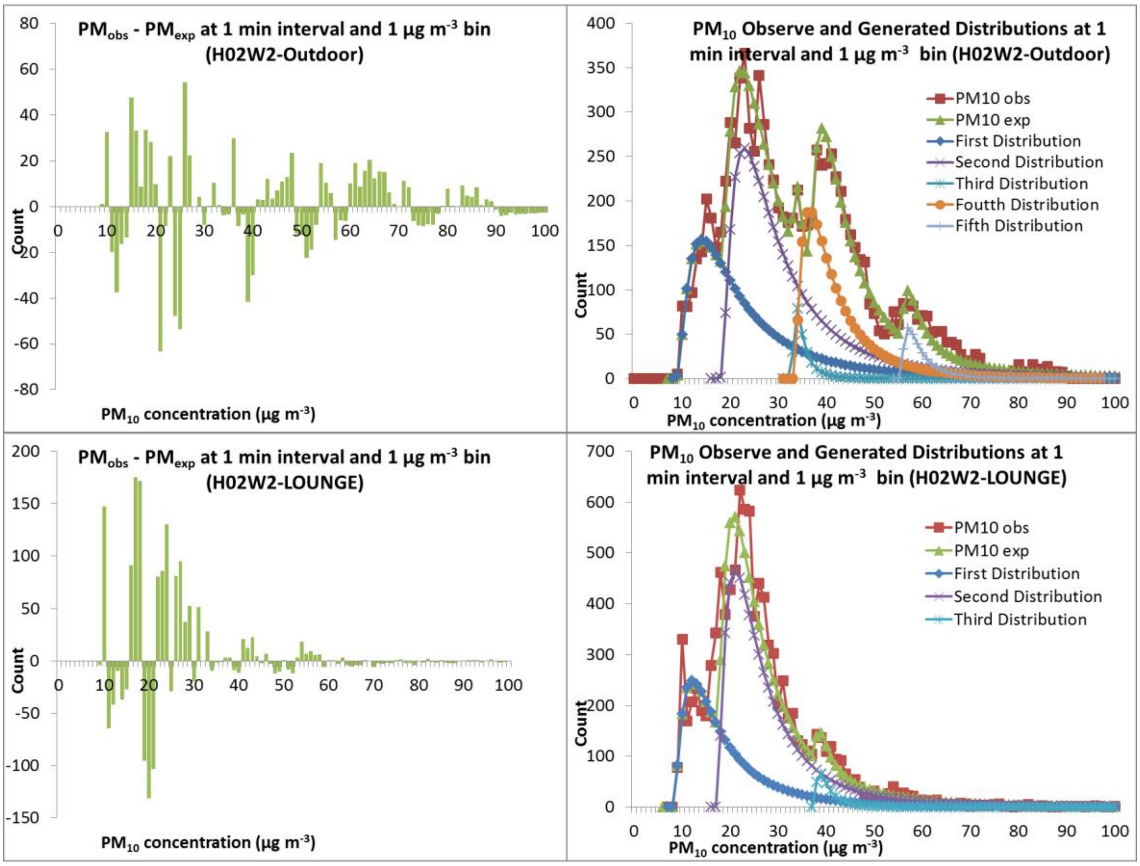


Figure 6-26 PM_{10} Distributions at H02W1 (Monitored, Modelled and Residuals)

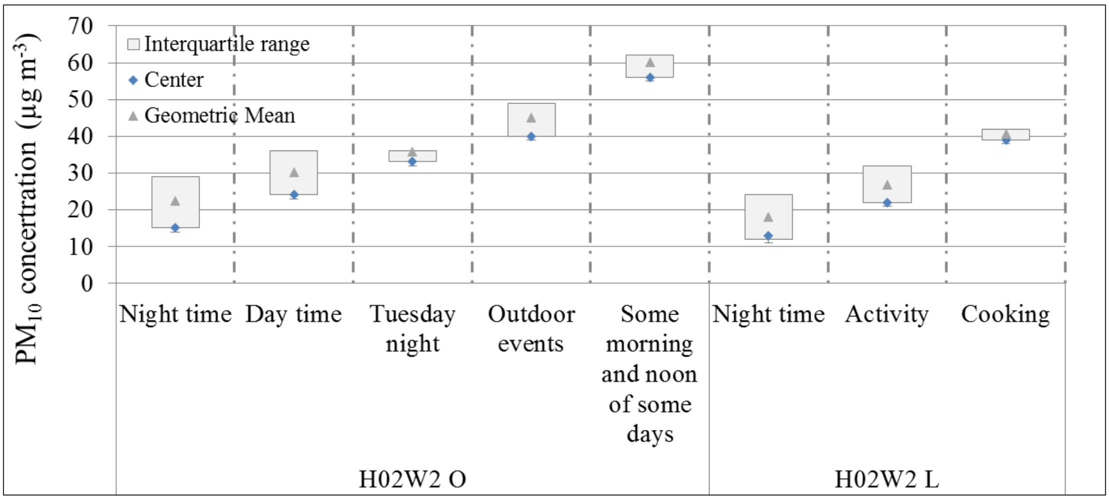


Figure 6-27 PM_{10} component distributions at H02W2 outdoor and indoor (centre/geometric/interquartile)

6.4.4 Property H10 Near a Quiet Road

Respectively four and three lognormal distributions were fitted to the outdoor (H10W2 O) and indoor in the lounge (H10W2 L) dataset as shown in Figure 6-29. The second campaign of monitoring at this property was arranged at a time when the occupants were planning not to be at the property for a few days. This was so that there would be no indoor activity (cooking, cleaning, watching television etc.) for that period. The refuse collection took place just after the monitoring began and when luggage was finally packed the householders cooked a light meal before departure late afternoon about 16:00 hrs. On returning to the property on Saturday evening, unpacking to deal with laundry took place and day to day activity resumed. Outdoor levels were very variable with little consistency from day to day. There was a suggestion that outdoor levels were highest over the day and between about midnight and 06:00 hrs (but not on Thursday and monitoring did not take place Tuesday) levels dropped substantially. Pollutant emissions on Tuesday due to refuse collection seemed to have prevailed all day with geometric mean (geometric standard deviation) 71.9 (1.1) µg m^{-3} and grass cutting early, at 08:00 hrs, on Monday morning prolonged the higher levels over a longer period: geometric mean (geometric standard deviation) 37.8 (1.5) µg m^{-3}. The packing activity prior to departure also was associated with the high levels in the lounge just as the monitoring commenced with geometric mean (geometric standard deviation) 98.2 (1.1) µg m^{-3} followed by cooking activity 33.7 (1.6) µg m^{-3}. The majority of time was spent away from the home and levels during the day were geometric mean (geometric standard deviation) of 3.0 (1.6) µg m^{-3} being lower than during the night time 15.1 (1.3) µg m^{-3} respectively as shown in Figure 6-28. The most interesting result was the rise of indoor PM_{10} on Sunday and dramatic fall on Wednesday lunch time, this coincided with much activity cleaning, cooking and doing the laundry creating high levels of PM on Sunday rendering levels similar indoor and outdoor. The residuals were not normally distributed and the median of indoor residuals was not statistically significantly different from the zero and median of outdoor residual was statistically significantly different from the zero.

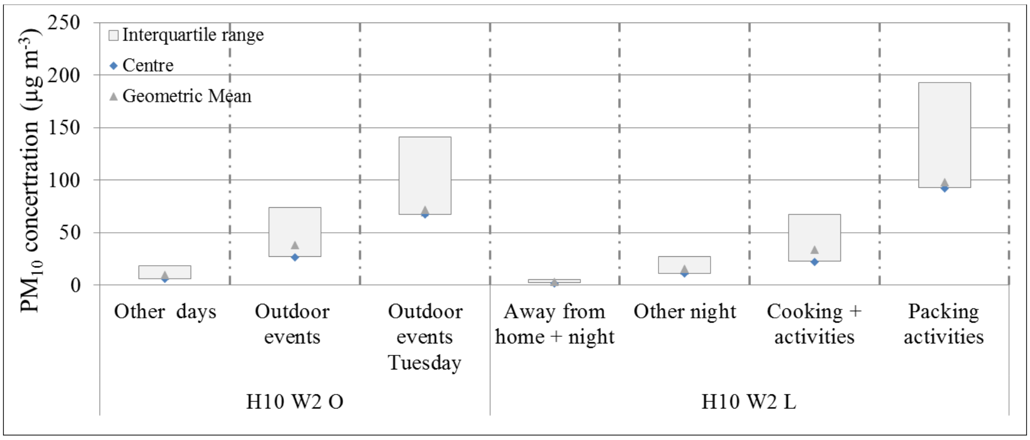


Figure 6-28 PM_{10} component distributions at H10W2 outdoor and indoor (centre/geometric/interquartile)

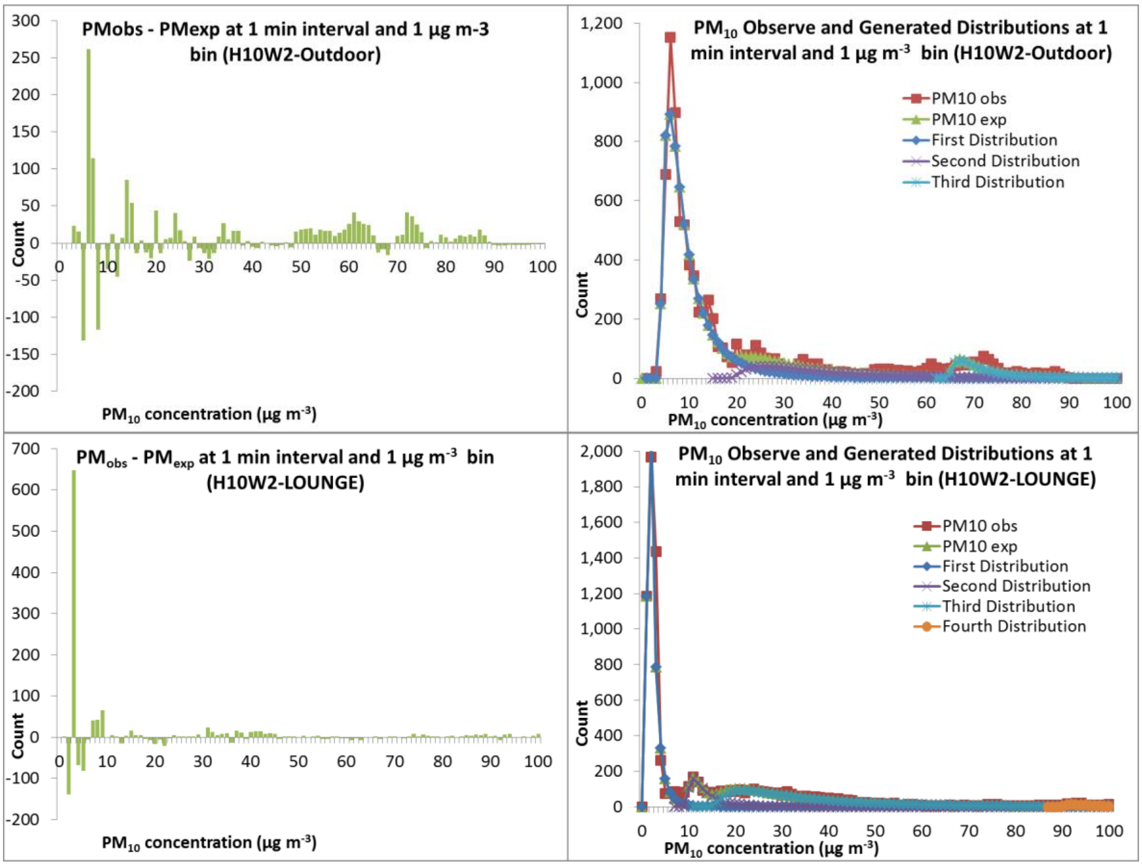


Figure 6-29 PM_{10} Distributions at H10W2 (Monitored, Modelled and Residuals)

6.4.5 Property H12 Alongside Commercial Road

Figure 6-31 shows the four and three component lognormal distributions fitted to each dataset outdoor and indoor respectively. During opening hours PM_{10} geometric means were consistently higher and with more variation than when closed 162.1 (2.3) µg m^{-3} and 13.2 (1.3) µg m^{-3} respectively. During opening hours there was a cooking activity which was continuous and responsible for the elevated levels. In fact, monitoring inside a restaurant has endorsed the exposure risk presented by cooking activity. Another important observation was the similarity in the outdoor and indoor pdf which was due to two reasons. The first was that the monitoring tube was only placed outdoor when the window was open during restaurant opening hours due to security risk. Secondly overnight the monitors were on the first floor and although at slightly different positions and heights from the floor they were exposed to PM_{10} from cooking which pervaded the whole property explaining why as if overnight "outdoor" and indoor component distributions are statistically significantly similar. Given the tube was positioned so close to the window which remained slightly open and the pollution levels indoor were so high, the outdoor levels measured were largely influenced by indoor rather than sources outdoor. Night time geometric means were consistently lower than during opening hours in the day as shown in Figure 6-30. The residuals were not normally distributed and the median residual of outdoor was not statistically significantly different from the zero and the median residual of indoor was statistically significantly different from the zero.

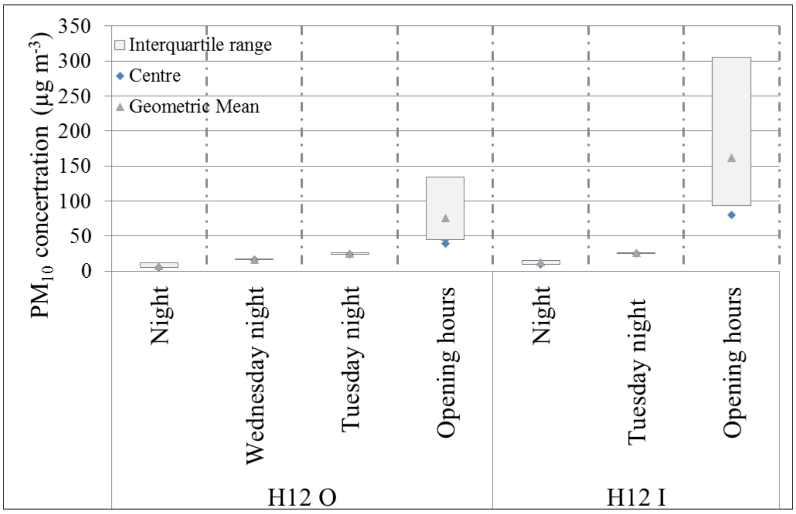


Figure 6-30 PM_{10} component distributions at H12 outdoor and indoor (centre/geometric/interquartile)

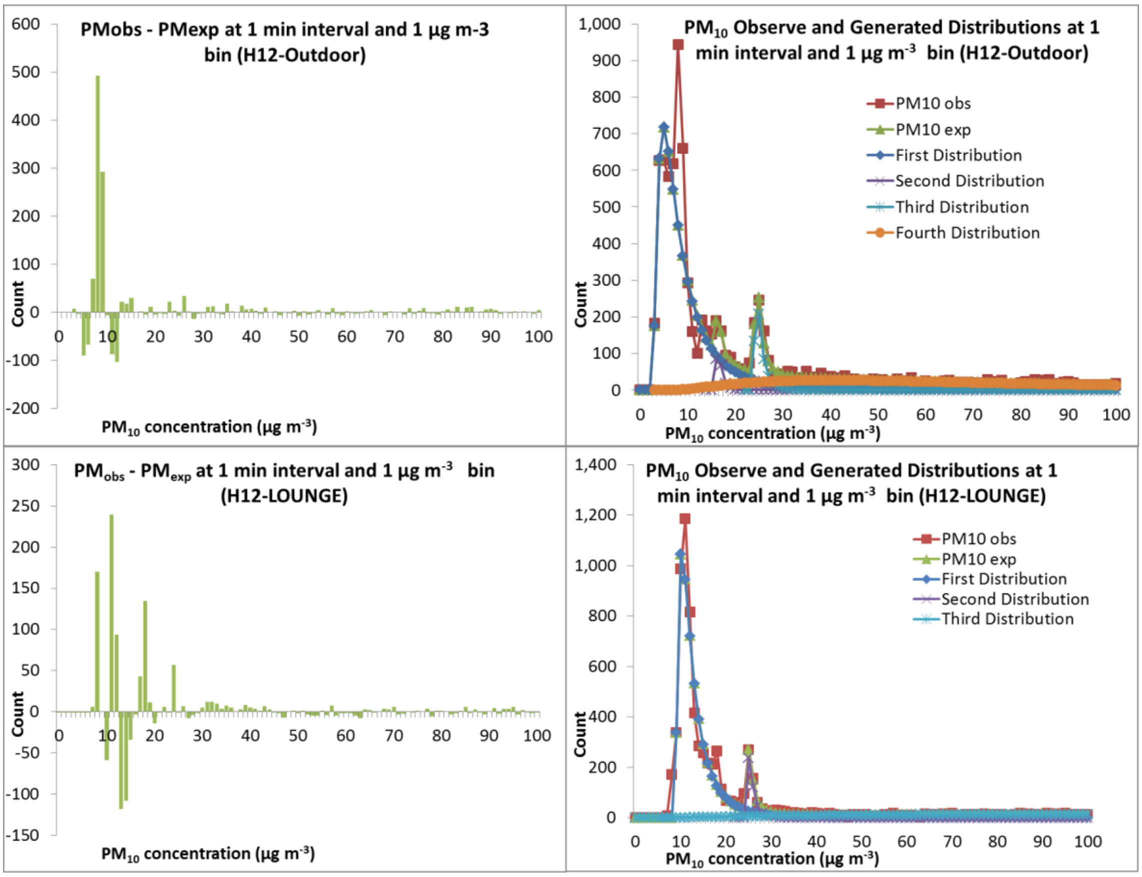


Figure 6-31 PM_{10} Distributions at H12 (Monitored, Modelled and Residuals)

6.4.6 Property H09 Alongside Main Road

Figure 6-32 shows the pdf of the data collected which has four component distributions. The more passive nature of the activity in the dentist resulted in lower levels and widths of component distributions compared with other properties of the second campaign and cleaning and shredding events created separate high level exposure events which were of such short duration that they contributed to the tails of the pdf. One outdoor event occurred during two days which caused elevated indoor levels geometric mean (geometric standard deviation) 69.3 (1.3) µg m^{-3}. This event was construction work at the façade which produced a lot of dust that became transported indoors as patient accessed the dental practice. Opening time was associated with high levels indoors: geometric mean (geometric standard deviation) 21.4 (1.3) µg m^{-3} but was not higher than outdoor events: geometric mean (geometric standard deviation) 69.3 (1.3) µg m^{-3}. Figure 6-33 illustrates closing hours for some nights: geometric mean (geometric standard deviation) 5.0 (1.7) µg m^{-3} were lower than Monday and Thursday nights 9.4 (1.4) µg m^{-3} but with similar width. On Sunday pollution levels were higher than typical night time which was likely caused by cleaning activity which took place earlier in the day on the Sunday. The residuals were not normally distributed and the median was statistically significantly different from zero.

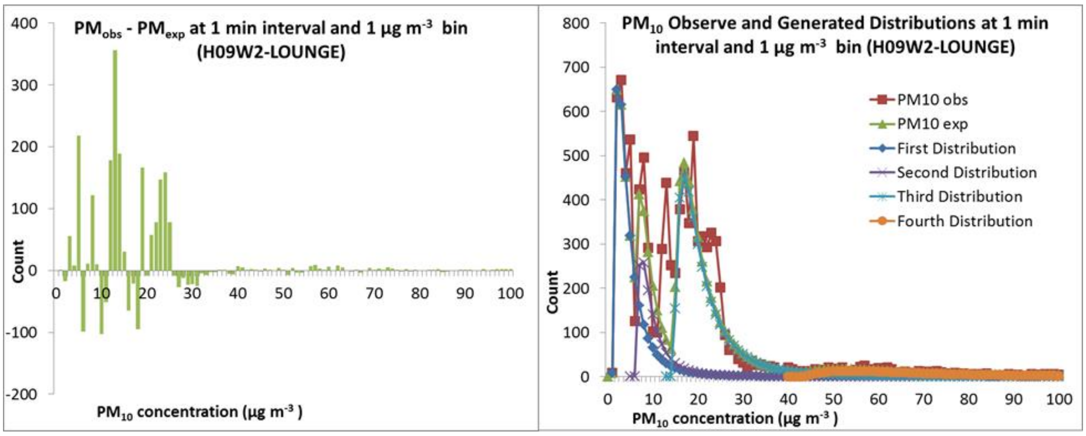


Figure 6-32 PM_{10} Distributions at H09W2 (Monitored, Modelled and Residuals)

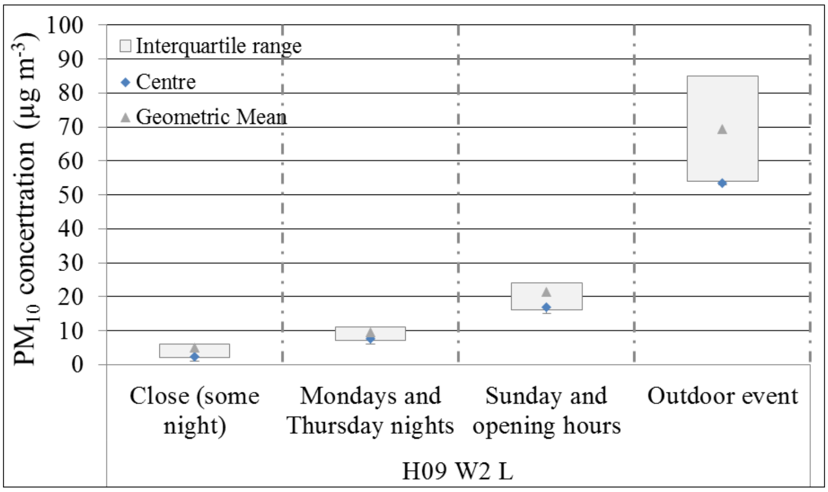


Figure 6-33 PM_{10} component distributions at H09W2 indoor (centre/geometric/interquartile)

6.4.7 Property H11 Alongside Commercial Road

There was no window available to feed through the tube to be able to measure pollution outdoor and indoor simultaneously and the door to the boutique remained open for much of the time due to the high outdoor temperatures at the time of the survey. H11 dataset was fitted with five component distributions as shown in Figure 6-34. Opening hours, as expected, were associated with high levels indoor. Also, there was a difference during opening hours on Monday to Wednesday compared to Thursday to Sunday. Night time geometric mean was consistently lower than opening hours as shown in Figure 6-35 except on Thursday and Friday opening hours. Events occurred which caused elevation and increased variation of indoor levels: geometric mean (geometric standard deviation) 66.9 (1.2) µg m^{-3}. These events were cleaning events which re-suspended particles indoors. Other opening hours were associated with high levels indoor geometric mean (geometric standard deviation) 45.0 (1.3) µg m^{-3} but were not high as during the periods when cleaning events took place. The first three distributions illustrate a mix of closing time and opening hours. These have not been investigated further due to the diary records were not completed. The residuals were not normally distributed and the median was not statistically significantly different from the zero.

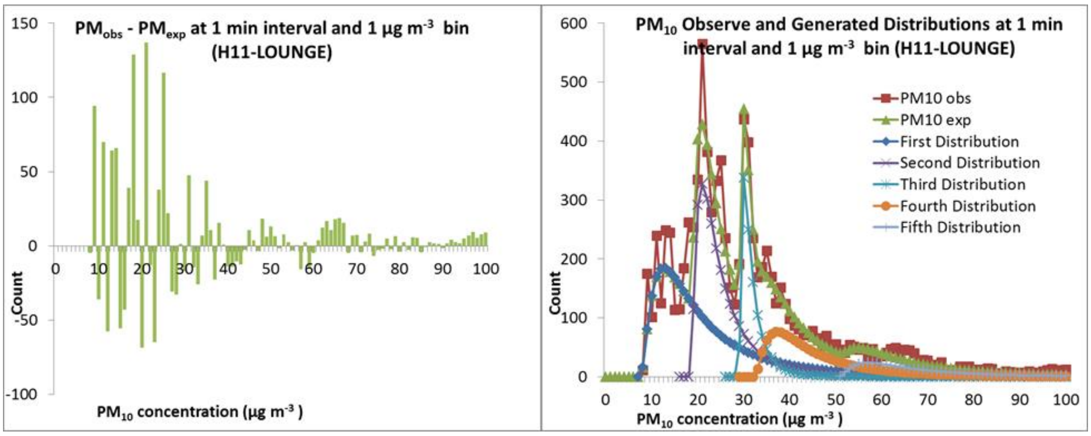


Figure 6-34 PM$_{10}$ Distributions at H11 (Monitored, Modelled and Residuals)

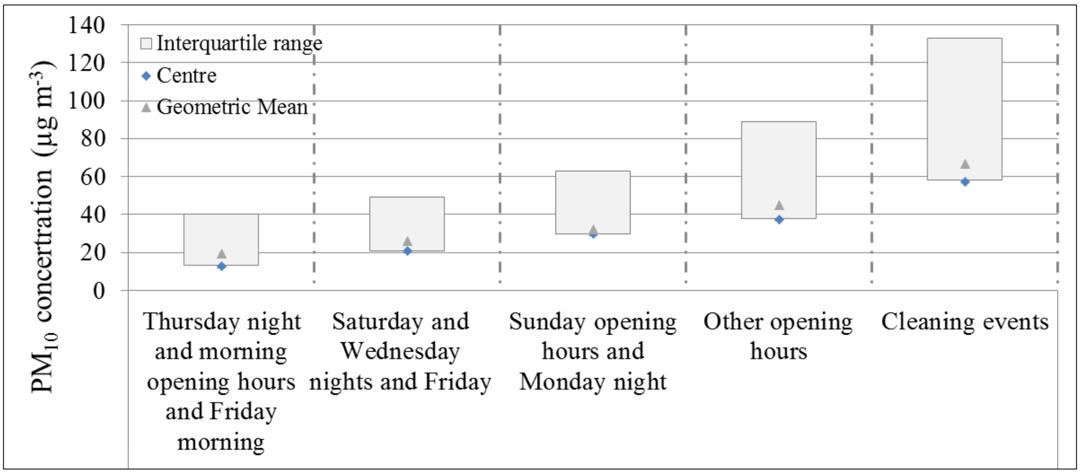


Figure 6-35 PM$_{10}$ Distributions models at H11 indoor (centre/geometric/interquartile)

6.5 Summary

The technique of decomposition was used to explore the characteristics of the multimodal pdf which were found to typify the activity (cooking, cleaning, shredding etc.) taking place in these properties. The Fityk software was used with the Levenberg Marquardt nonlinear optimisation analysis method to fit the component distributions. The best fit distribution which was to be sufficiently generic to be applicable to the all individual data sets was identified by aggregating all the data representative of similar microenvironments, namely kitchens separate from lounges. The lognormal distribution was found to be the most appropriate distribution for the PM$_{10}$ levels measured when considering distributions aggregated over the entire week of measurement. However, the day to day analysis indicated that when activity was more diffuse without regular high polluting events for example as in the reception area of a dental practice, the analysis of data on the day by day time scale suggested that a Gaussian distribution may be more appropriate. Proof that this was the case is considered outside the scope of this research and a research gap that has been identified for future work. One minute sample averaging over 1 µg m^{-3} bin widths offered the best chance to observe consistency in data patterns in the pdfs. Therefore, this sampling regime was adopted and maintained throughout the analysis of the static campaigns reported in this thesis.

The pdf of each microenvironment of the first static campaign was separately fitted with up to five component lognormal distributions by systematically applying the decomposition technique with the use of Fityk software. Table 6-3 and Table 6-7 present the statistical parameters of each distribution, including height, width and centre, the R^2 value of the curve fitting, the interquartile range of each distribution, the percentage of the data explained and the geometric mean and standard deviation for the first and second campaigns respectively. More than 92% of the variation in the measured pdf was explained by the sum of the decomposition component distributions for the first campaign. For the second campaign, high values of all R^2 of the fitting of the cumulative component distributions to the raw data were reported to be greater than 0.89. For each microenvironment, the time series plot was used to display the interquartile range of each component distribution. A component distribution of the total pdf was associated with characteristics, such as cooking, overnight and during the day. This technique was found to be promising for classifying the component distributions into night time, during the morning and cooking as well as in most cases other activities. On two occasions, it was not possible to identify precisely the distribution characteristic due to the limited data that was recorded by the householder, however given the activity pattern sometimes noted on one week day and weekend day made inferences possible. Decomposition was demonstrated to be useful in classifying the distributions in a generic way.

Cooking activity was associated with the high levels observed both in the kitchen and the lounge during the first campaign, the former being higher than the latter across properties H01, H02 and H05 where the kitchen was separated from the lounge by a door only. This suggested that pollution was being dispersed and brought into the lounge from the kitchen. However, it was not the case for property H08 where cooking activity was not associated with the much higher levels in the lounge but instead due to people movements. H08 kitchen is in a separate room without an interconnecting door separated by a long (3m) hall and both kitchen and lounge doors remained closed most of the time. Therefore, it is even more surprising the levels are higher in the lounge. However, the lounge has a door into a conservatory with doors used frequently to access the garden which may be influencing levels. The reported differences in activity in H01 with more cooking to prepare for Ramadan resulted in elevated levels over longer periods. Night time levels were consistently lower than day time activities in all properties. The most interesting result in H01W3 was when the back door access to into the kitchen and windows were left open the geometric means were high and similar level in the kitchen and lounge with lower geometric standard deviation. This suggested that pollution was being brought into the property from outside and rendered levels fairly evenly within both the kitchen and lounge. This was found to coincide with a pollution episode registered by AURN measurements some distance away in Gosforth, Newcastle. The residuals were not normally distributed and the medians not significantly different from the zero except for H02W1L, H03L, H07L, H09W1L and H108W1L. These will be discussed further in chapter 8.

During the first campaign, when property pdf of H09 and H10 were divided into each day of the week before the decomposition analysis was performed assuming the lognormal distribution as before, it was clear that the decomposition technique with reference to the time series plots was able to characterise specific events occurring in the 24 hour periods and revealed further features such as in H09. The opening hours were disaggregated into an AM and PM period although the AM of the Monday corresponded to a different day to the PM because monitoring started on the afternoon of the previous week. This makes it difficult to explain this AM, PM difference with any confidence. In addition, decomposition was able to detect an outdoor event at property H08 which was generated by cavity wall insulation installation at a property nearby.

Specific outdoor events were associated with high levels outdoor across the properties H01, H02, H09 and H10 during the second campaign. This suggested that outdoor pollution sources included refuse collection and grass cutting activities which contributed significantly to outdoor background levels. Specifically, in general PM_{10} levels outdoor were higher and varied more from day to day during the day and were lower and less variable overnight. But this was not found to be the case on some days. Property H02 outdoor levels very closely tracked indoor levels and this pattern was consistent with features observed at H01 and can be explained in terms the absence of pollutant sources indoor. This suggested that outdoor pollution was being transported indoor at property H02. Cooking activity, as expected, was associated with high levels in the lounge across properties H01, H02 and H12 but it was not the case in property H10 due to indoor generated event of packing and moving luggage in advance of departure for a period away from home. The night time levels were lower than day time activities or during opening hours across all properties except H11 which could not be investigated further due to diary records being incomplete. For property H10, the majority of the time was spent away from the home and was the lowest due to the absence of indoor sources. Due consideration of the prevailing wind direction in relation to each property is consistent with the finding of the decomposition in that H01, H02 and H10 are most vulnerable to outdoor traffic related pollution but the extremely high levels indoor H12 dominate. In the next chapter a much more detailed comparison across all properties for each microenvironment studied namely inside kitchen, lounge/shop and outdoor will be presented along with the residuals of the modelled and measured pdfs.

7 Dynamic Monitoring Studies

7.1 Introduction

Given confidence in the usefulness of the decomposition analysis technique and that the methodology for the static monitoring campaigns provided sufficient data to produce statistical confidence in the results the question was raised as to whether the decomposition technique was also applicable to dynamic data. Therefore, this chapter describes and presents the analysis and results from two dynamic monitoring campaigns. The aim of the first dynamic campaign carried out was to test the instruments and find the key factors that affect air pollution levels in a trafficked street canyon. The campaign was conducted on a major road in Gosforth, Newcastle upon Tyne. The second dynamic campaign conducted between the 10th and 20th of June 2013 aimed to test out the decomposition analysis approach and investigate the key influences on personal exposure in street canyons using the decomposition technique. PM_{10} measurements were conducted for a number of days whilst walking along High Street in Gosforth, Newcastle upon Tyne. The next section 7.2 presents the result of the first dynamic monitoring campaign. In section 7.3 the statistical analyses of dynamic monitoring of the second campaign are presented in detail. The same analysis procedures employing the decomposition technique was applied. The summary of the finding is presented in section 7.4.

7.2 Dynamic Monitoring of the First Campaign

7.2.1 Overview

The first campaign of the dynamic monitoring was conducted along the High Street Figure 7-1 between the 13th and 20th of October 2011. The back pack carrier walked facing the traffic on both sides of the road. A back pack fitted with a DustTrak Aerosol Monitor 8534 and QStarz BT-Q1000XT GPS tracker. The carrier started the journey from the Salters Road and High Street intersection on the west side of the High Street and walked towards the south along the High Street until the pedestrian traffic lights on Causey Street was reached. Subsequently, the carrier crossed the road and walked back to the intersection on the east side of the High street. The run was repeated 13 times. The distance between the intersection and the pedestrian traffic lights was approximately 0.5 km. The average distance for these runs was 1.0 km.

The meteorological data for the parameters wind speed (ms^{-1}) and wind direction during this study were provided by Newcastle University. All logged data from this pilot study was downloaded using appropriate software. The data was transferred into the Microsoft Excel format and amalgamated into a master spread-sheet using the time as a benchmarking variable. The data was analysed using Excel and SPSS software packages to carry out descriptive analysis. For each run, the start and end time were noted, along with the location of any directly observed pollution event such as cigarette smoking and presence or passing of any gross emitting vehicles e.g. smoke. The GPS data and PM_{10} were monitored every second. The GPS data was used to divide pollution data into segments corresponding to a specific road section.

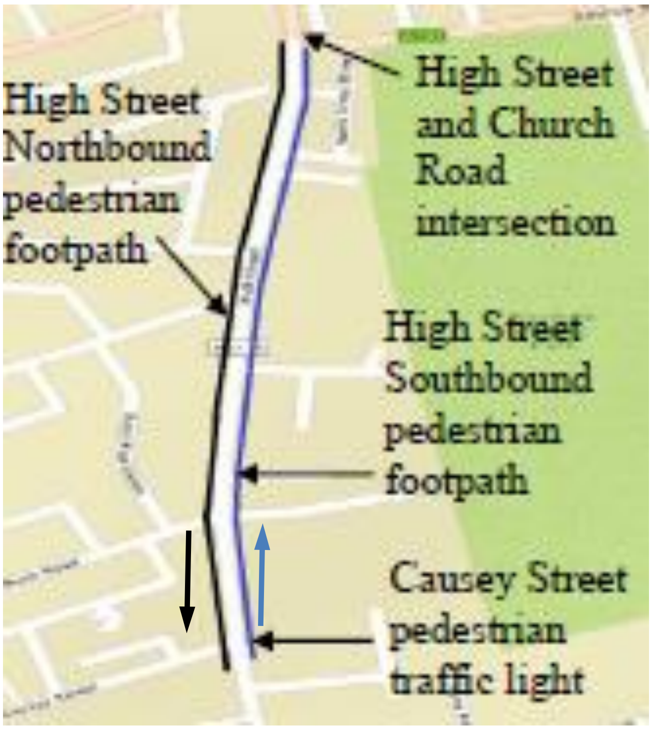


Figure 7-1 Field site showing route traversed during the dynamic monitoring pilot study (Source: Google Map)

7.2.2 Results and Discussion

Out of thirteen runs conducted for PM_{10}, two runs were eliminated due to power loss and malfunction of the equipment. Table 7-1 demonstrates the duration and the date of each run. Each run is divided into northbound and southbound based on the location of the surveyor. The first step was to plot the time series for the PM_{10} to understand the spatial and temporal variation of the measured pollution (Figure 7-2). Figure 7-3 represents all the data collected for each run at the northbound side of the road. It clearly shows the huge variation from run to run, not simply in the magnitude of the pollution concentration, but also the variations along the length of the road. The sharp spikes in level are associated with specific pollution events, in particular during the evening run 10, which illustrates a short period spike that reached approximately 800 µg m^{-3}. As shown in Figure 7-2 and Figure 7-3, this was caused by traffic congestion, as recorded by the surveyor in his log book, on a stretch of road which has a canyon effect.

Table 7-1 Duration and date of each run for dynamic pilot study

Run ID	Duration (sec)	Date
Afternoon Run 1	797	13/10/2011
Afternoon Run 2	811	13/10/2011
Morning Run 3	803	18/10/2011
Morning Run 4	808	18/10/2011
Evening Run 5	830	18/10/2011
Evening Run 6	851	18/10/2011
Morning Run 7	767	19/10/2011
Afternoon Run 8	790	19/10/2011
Evening Run 9	851	19/10/2011
Evening Run 10	804	19/10/2011
Morning Run 11	813	20/10/2011

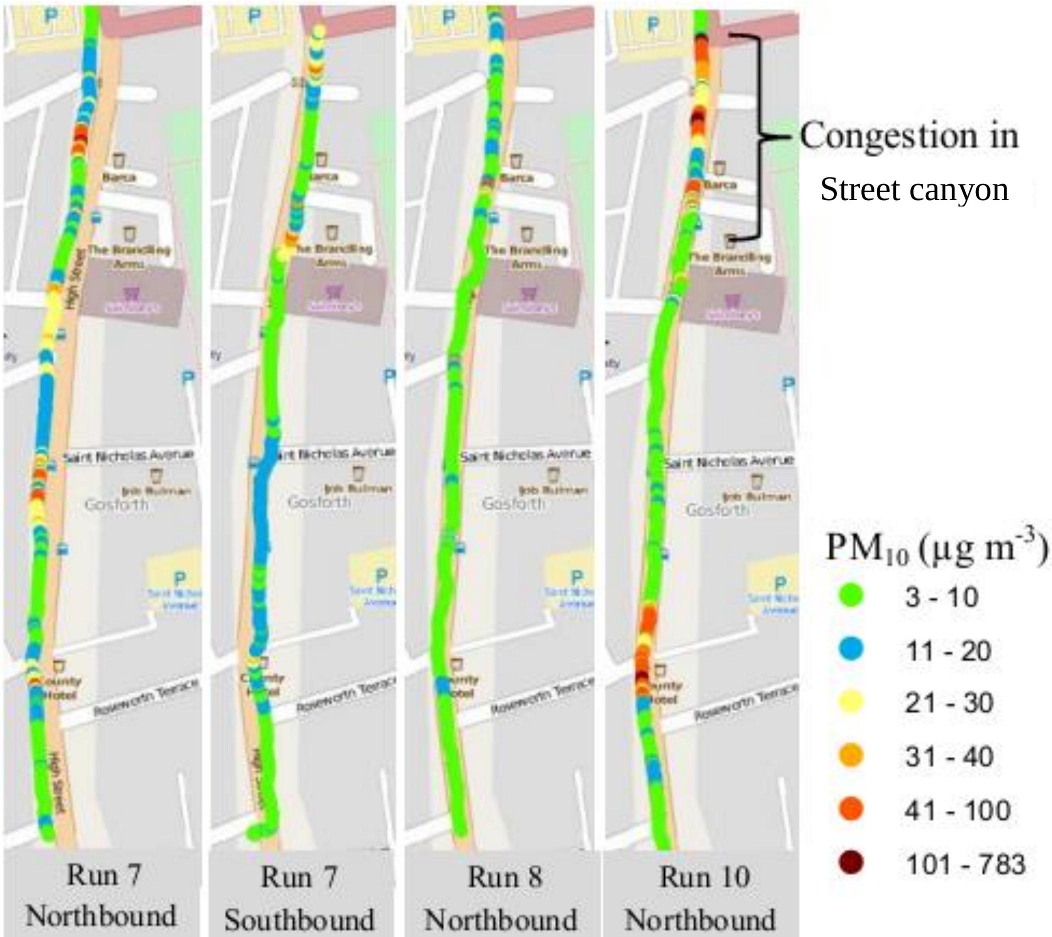


Figure 7-2 Spatial variation of PM_{10} during dynamic pilot study
(Source: Google Map)

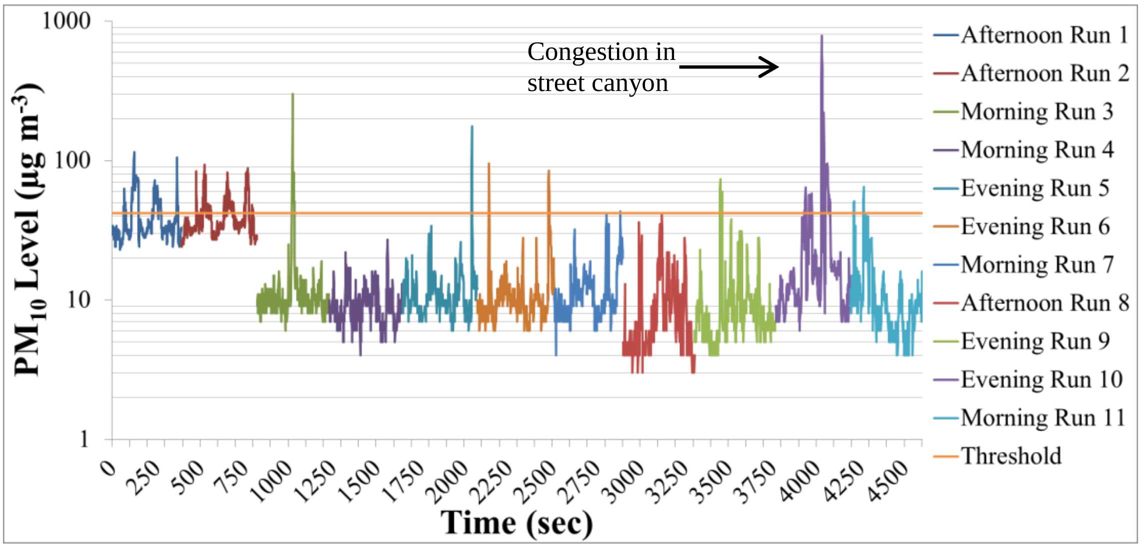


Figure 7-3 The PM_{10} levels from northbound side for each run

As shown in Figure 7-3, PM_{10} levels of run 1 and run 2 were statistically significantly higher than other runs and will be discussed later. The measured concentrations of PM_{10} and CO were analysed and the descriptive statistics are presented in Table 7-2. The PM_{10} varied between 3 and 783 µg m^{-3} whilst the average was 18.0 µg m^{-3}. During the morning runs the PM_{10} concentrations varied between 4 and 489 µg m^{-3}; in the afternoon runs, between 3 and 189 µg m^{-3}; and between 4 and 783 µg m^{-3} throughout the evening runs. The averages (geometric means) for the morning, afternoon and evening runs were 14.6 (11.7), 26.7 (20.2) and 15.1 (11.0) µg m^{-3} respectively. As for the static monitoring, the pdf were not normally distributed therefore nonparametric test on the median was carried out and geometric mean used as a basis for discussion.

Box plots for the PM_{10} data have been produced and presented in Figure 7-4. The median levels of PM_{10} in the morning and the evening were at the 95 per cent level of confidence statistically significantly similar (10, 10 µg m^{-3} respectively). Interestingly, these two medians were, at the 95% level of confidence, statistically significantly lower than the median for the afternoon PM_{10} levels (27 µg m^{-3}). However, the range of data for the morning and evening PM_{10} concentrations were substantially higher and the measurements varied significantly compared to the PM_{10} concentration during the afternoon.

Table 7-2 Descriptive statistics of PM_{10} (µg m^{-3}) for the dynamics runs

Dynamic Run ID	**Number of sample (sec)**	**Mean**	**Median**	**Min**	**Max**	**Geometric mean**	**Geometric StDev**
All Runs	8925	18.0	11	3	783	13.2	2.1
Morning Runs	3191	14.6	10	4	489	11.7	1.7
Afternoon	2398	26.7	27	3	189	20.2	2.3
Evening Runs	3336	15.1	10	4	783	11.0	1.8

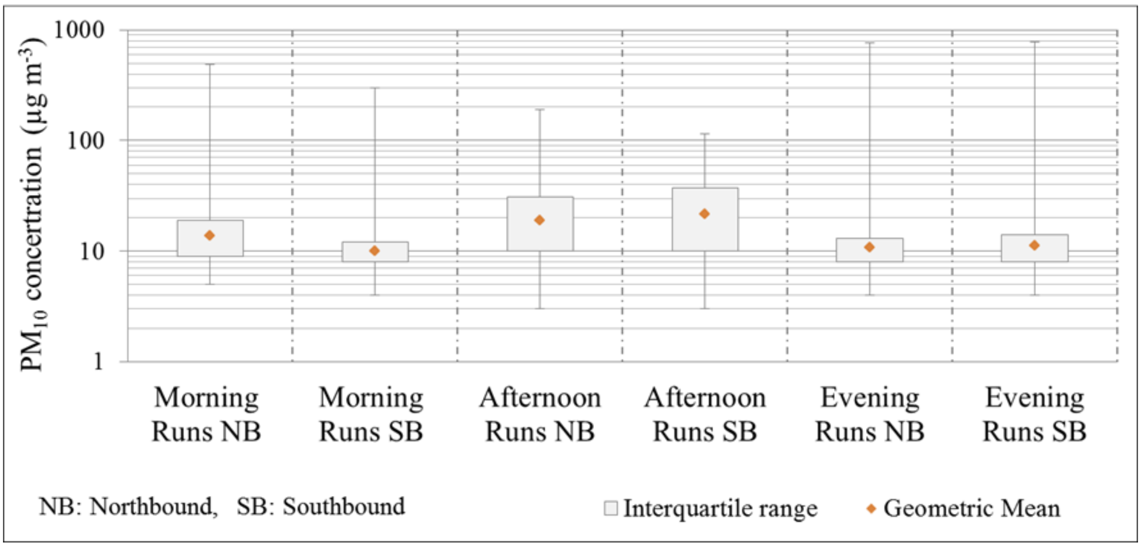


Figure 7-4 Box plot of runs based on time and side of the road

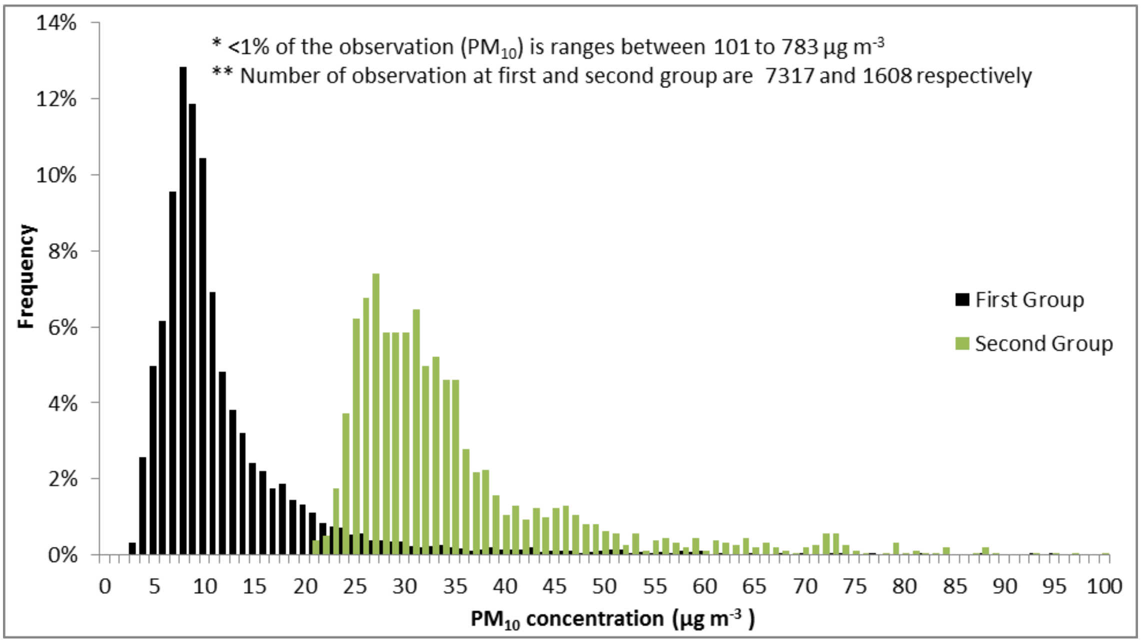


Figure 7-5 Distribution of the two groups

It is clear from Figure 7-5 that the data are not normally distributed. Therefore, it was analysed further. These runs were divided into two groups as they were found to be statistically significantly different. The first group consisted of the data collected from the 18th to 20th October 2011 (Run 3 to run 11) and the second group was the data collected on 13th October 2011 (Run 1 and Run 2). The data from the first and second groups were collated and the distribution plotted for PM_{10} measurements in Figure 7-5. Interestingly, a great deal of structure is evident in the distributions. Firstly the data in the *"long tails"* were matched against the pollution events recorded, and in all but about 10% of cases, whether in the first or the second group, the high levels of measured pollution coincided with either one or more incidences of smokers, HGVs or buses passing by. A striking result is the fact that not only is the second group distribution quite different in shape to the first group (with two possibly three nested distributions), the magnitude of the pollution levels in second group were three to four times higher compared to first group. Furthermore, the PM_{10} levels were in the region of 14-24 µg m^{-3} for the first group and 36-48 µg m^{-3} in the second group as shown in the Figure 7-5. The component distributions were often associated with the traffic flow regimes, which ranged from congested and free flow traffic at a higher speed.

There were sixteen pollutant events counted in the first group of campaigns. Half of the pollutant events from the first group were related to steady free flow traffic when a bus or HGV was passing. In the second group, 71 pollution events occurred, of which 56% coincided with a bus or HGV passing by or stopping, irrespective of traffic levels. The rest of the data set did not show any obvious reasons or particular patterns in the occurrence of the event. These will be resolved in future research following further data collection campaigns, by increasing the sample size, and performing more in-depth statistical analysis.

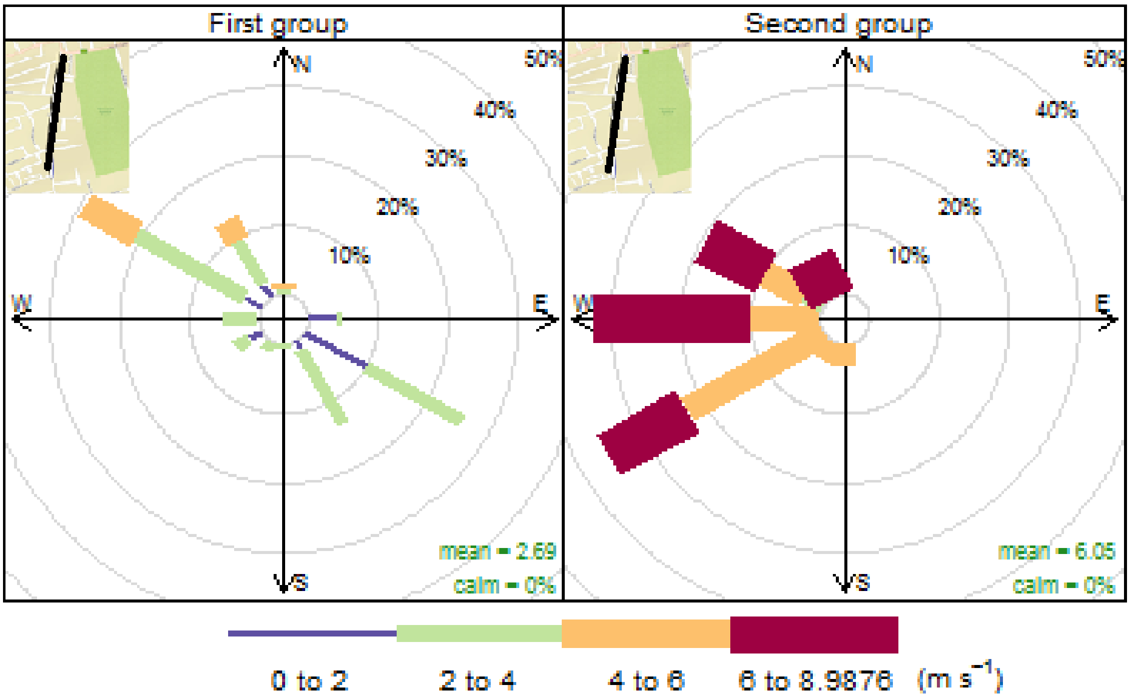


Figure 7-6 Wind rose diagram for the two groups

Another contributing factor to the measured difference compared to the peak is that the wind speed was much higher, 6 ms^{-1}, during the second survey group, compared with the first, where the wind speed was 2 ms^{-1} (Figure 7-6). Also, the direction of the prevailing wind was different during first compared to the second group (Figure 7-6), being throughout perpendicular to the street orientation and in spite of the higher wind speed caused a canyon effect. It is likely that dust re-suspension is a contributing factor to the elevated PM_{10} levels in the off peak. Other analysis gave statistically significant evidence, at a 95% level of confidence, that the median PM_{10} level was different on the two sides of the road and was lower on the side sheltered from the wind (the leeward side).

7.2.3 Comparison with Other Studies

Previous researchers have used similar detection method (light scattering) as this research so direct comparison of the results is straightforward. In general, this study found much larger variations in PM_{10} concentration compared to those measured in other studies which may be due in part to the high resolution selected (one second) for sampling. On the other hand, the PM_{10} mean concentrations in this study were much lower than the concentrations recorded by other studies, as shown in Table 7-3. In comparison with other studies, Martin (2006) found the PM_{10} mean concentration in the morning was less than in the evening, which was different to the findings in this study. The traffic pattern was expected to peak in the morning and the evening. Therefore, it was anticipated that the PM_{10} concentration would follow the same trend. However, it was established that the PM_{10} mean concentration in the afternoon was the highest when the average wind speed was also at its highest which may suggest that the re-suspension of dust from the road surface plays a part. In general the off peak periods across the studies were higher probably due to the higher speeds because traffic flows tend to be lower. Heavy traffic and congested traffic are associated with higher concentration levels measured by Buonnao *et al.* (2011) in Cassino, Central Italy, Gulliver and Briggs (2007) in Leicester, UK and Martin (2006) in Prague, Czech Republic. The lower peak period values in this study are due mainly because, relatively flows in Newcastle are substantially lower.

Buonanno *et al.* (2011) found that one side of the road had a higher PM_{10} concentration than the other side depending on the street configuration and metrological condition. The leeward side was found to have statistically significantly higher PM_{10} concentration compared the windward during six runs in this study. On the other hand, PM_{10} concentrations on the leeward side were statistically significantly lower than the PM_{10} concentration on the side from where the wind was blowing (the windward side) on two runs. On two runs, there was a statistically significant difference between PM_{10} concentrations on both sides of the street, when the wind blew parallel to it. However, one run showed a statistically significantly similarity between PM_{10} concentrations on both sides of the street when the wind blew parallel to it. This study did not confirm that one side of the road had higher PM_{10} concentrations than the other side of the road due to the wind direction.

Table 7-3 PM_{10} concentrations in other studies and first campaign

Study	Sample	Mean PM_{10} (μg m^{-3})	Sampling Method
Buonanno *et al.* (2011)	Street A (congested)	43.6	Light Scattering
	Street B (slow traffic)	30	
	Street C (free flow traffic)	53.1	
	Street D (heavy traffic)	72.9	
Gulliver and Briggs (2007)		35.8	Light Scattering
Martin (2006)	Morning	64.9	Light Scattering
	Evening	86	
Gulliver and Briggs (2004)		38.18	Light Scattering
First Campaign - this study.	Morning Runs NB[a]	17.81	Light Scattering
	Morning Runs SB[b]	11.48	
	Afternoon Runs NB[a]	24.05	
	Afternoon Runs SB[b]	29.2	
	Evening Runs NB[a]	14.59	
	Evening Runs SB[b]	15.64	

[a] High Street Northbound pedestrian footpath (NB)
[b] High Street Southbound pedestrian footpath (SB)

7.2.4 Summary

Dynamic monitoring was conducted using a backpack fitted with devices to monitor PM_{10} and location. The GPs data was used to divide the data into road sections. Thirteen runs up and down the street were collected for PM_{10}. Two runs were eliminated due to power loss and equipment malfunction. The mean PM_{10} concentration in the second group was the highest. This was probably due to the higher (6 ms^{-1}) winds measured during the afternoon, re-suspending more of the pollution, compared with the wind speeds (2 ms^{-1}) measured during the first group. The PM_{10} means were lower than other studies possibly due to the huge variation in emission sources creating peaks in PM_{10} concentrations which were sampled at a much higher frequency and therefore picked up the transient spikes in pollution.

7.3 Dynamic Monitoring Second Campaign

7.3.1 Descriptive Analysis of Dynamic Monitoring Along High Street

PM_{10} levels were collected during 24 dynamic monitoring runs, see section 3.6.2 for more details. The first step was to plot the time series data for PM_{10} to begin to understand the temporal variation of measured pollution. Figure 7-7 represents all the data collected at the High Street during the monitoring campaign. It clearly shows the huge variation from trial to trial not simply in the magnitude of the pollution concentration but also in the variations along the length of the road. The sharp spikes in PM_{10} levels are associated with specific pollution events, in particular run number 10 illustrates 34 short period spikes which reached PM_{10} levels exceeding 100 µg m^{-3} which general were caused by traffic idling and stop-start characteristic of congestion in a stretch of road with canyon effect or a smoker passing-by.

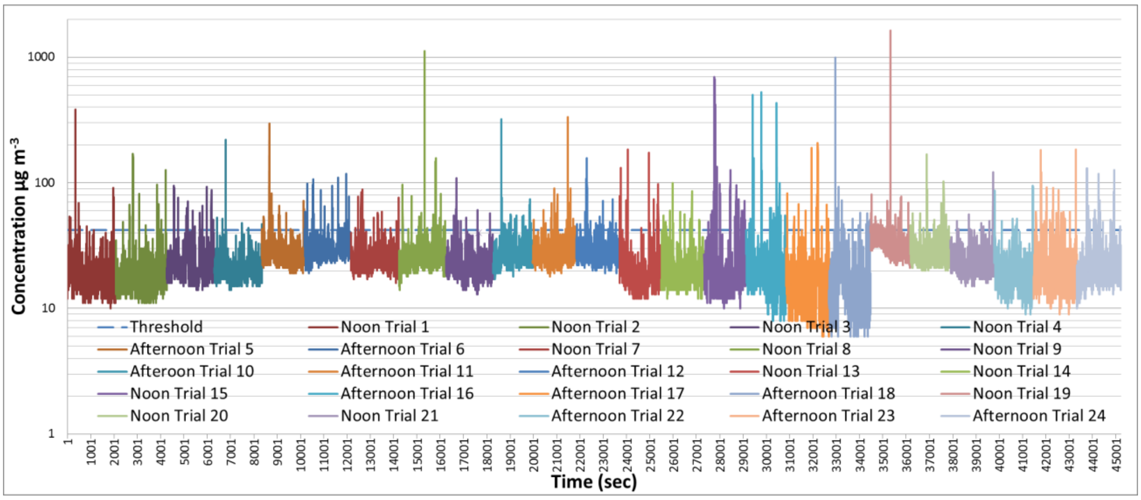


Figure 7-7 The PM_{10} levels from dynamic monitoring runs

The measured concentrations of PM_{10} and were analysed and the descriptive statistics are presented in Table 7-4. There was a varying number of pollutant events observed in the campaign. Total PM_{10} levels varied between 6 and 1630 µg m^{-3} and the average (geometric mean) was 23.6 (21.5) µg m^{-3}. Noon and afternoon PM_{10} concentrations varied between 10 and 1630 µg m^{-3} and 6 and 993 µg m^{-3} and the averages (geometric mean) were 23.3 (21.5) and 23.8 (21.4) µg m^{-3} respectively. Box plots of the data were produced and presented for the PM_{10} in Figure 7-8. The median level of PM_{10} summed over the noon campaigns was, at the 95 per cent level of confidence, statistically significantly lower than the median level of PM_{10} across those carried out in the afternoon (23.3, 23.8 µg m^{-3} respectively). Interestingly, the range of data for the noon PM_{10} concentrations was substantially higher and lower geometric standard deviation in the noon campaigns being 1.4 µg m^{-3} compared to the afternoon PM_{10} concentration with 1.6 µg m^{-3}.

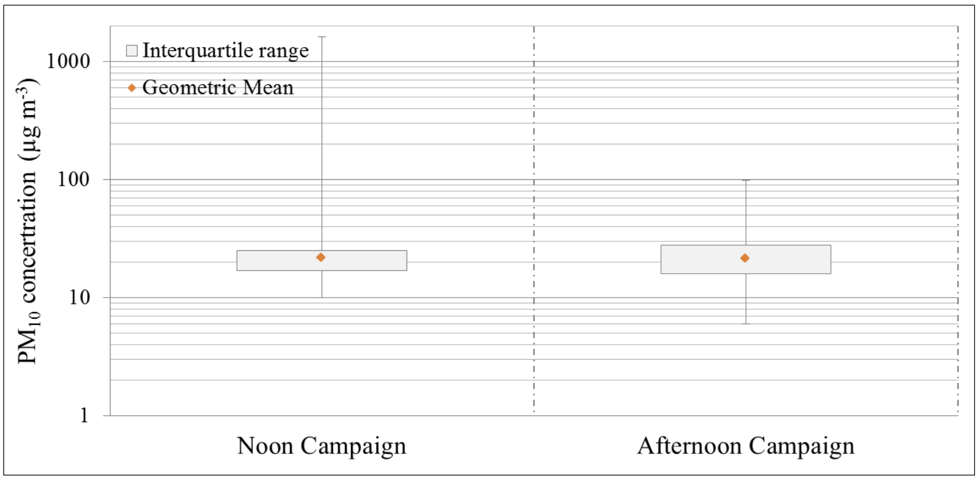


Figure 7-8 Boxplot of trials based on time and road side

Table 7-4 The mean concentration of PM_{10}

Variable	Time second	Mean µg m^{-3}	Median µg m^{-3}	Q1 µg m^{-3}	Q3 µg m^{-3}	Min µg m^{-3}	Max µg m^{-3}	Geometric mean	Geometric StDev
Noon	25194	23.3	21	17	25	10	1630	21.5	1.4
Afternoon	20030	23.8	23	16	28	6	993	21.4	1.6

7.3.2 Comparison with Other Studies

Research carried out in previous studies used similar detection method (light scattering) as used in the current study making direct comparison straightforward. This study found in general a much larger variation in PM_{10} concentration compared to those measured in other studies, which may be due in part to the high sampling resolution selected (one second). On the other hand, the PM_{10} mean concentrations in this study were lower than the concentration recorded by other studies, as shown in Table 7-5. In comparison to other studies, Martin (2006) found PM_{10} mean concentrations in the morning were less than in the evening as expected given the association with traffic patterns. Therefore, it was anticipated that the PM_{10} concentration would follow the same trend. However, this was not the case because this study showed that PM_{10} concentrations at noon were statistically significantly (three times) lower than PM_{10} concentrations during the afternoon for High Street measurements. Buonanno *et al.* (2011) found that one side of the road had a higher PM_{10} concentration than the other side depending on the street configuration and meteorological condition. However, this study carried out dynamic monitoring on one side of the street only, therefore the difference between PM_{10} concentrations on both sides of the road was not investigated. Buonanno *et al.* (2011) illustrated the large differences in levels of pollution depending on road hierarchy. Even the lowest level measured, 30 µg m^{-3}, was higher than the High Street. Gulliver and Briggs (2004) and Gulliver and Briggs (2007) recorded PM_{10} levels in

Northampton at 38.2 and 35.8 µg m^{-3} which were both similar and higher than for low traffic and lower than congested observed in the Buonanno *et al.* (2011) study. In this study high activity levels in Gosforth High Street (namely pedestrians crossing, high frequency of bus services with many bus stops, loading and unloading and heavy vehicles gaining access to city) caused much congestion, stop-start, idling and acceleration away from bus stops, pedestrian crossings and junctions. This results in huge variations not only along the street but at different times of the day. It is clear from this analysis and that of previous research that exposure levels are variable and most probably unique to the location, time and weather conditions at the time of the study.

Table 7-5 PM_{10} concentrations in other studies and this study

Study	**Sample**	**Mean PM_{10} (µg m^{-3})**	**Sampling Method**
Buonanno *et al.* (2011)	Street A (congested)	43.6	Light Scattering
	Street B (slow traffic)	30	
	Street C (free flow)	53.1	
	Street D (heavy traffic)	72.9	
Gulliver and Briggs (2007)		35.8	Light Scattering
Martin (2006)	Morning	64.9	Light Scattering
	Evening	86	
Peters *et al.* (2013)	Antwerp, Belgium	97	Light Scattering
	Mol, Belgium	45	
Gulliver and Briggs (2004)		38.18	Light Scattering
Current Study (Dynamic Monitoring along High Street)	Noon Trials PM_{10}	23.3	
	Afternoon Trials PM_{10}	23.8	

7.3.3 Model PM_{10} Levels

This section attempts to explore whether the technique of decomposition is applicable to dynamic as well as static monitoring. The statistical analyses are presented in detail following the same analysis procedures adopted in chapters 7 and 8. The dynamic monitoring data was averaged over one minute interval and aggregated into 1 µg m^{-3} bin widths. The Fityk software was used systematically to decompose the pdf of dynamic monitoring data into its components fitting three lognormal distributions. The pdfs were plotted for dynamic monitoring data showing three lognormal distributions as shown in Figure 7-9. The graph on the right is for the dynamic data. It illustrates the component lognormal distributions and the overall best fit pdf (which is the summation of the individual component distributions) and includes the observed pdf. These distributions are presented as line graphs for clarity. The graph on the left shows the residuals which are the differences between the measured data and the predicted value based on the decomposition technique. About 88% of the variation in the pdf (see

Table 7-6) could be explained demonstrating the appropriateness of this method in classifying the distributions in a generic way.

Furthermore, by cross referencing the interquartile of the component distributions against the traffic log of events made by the surveyor and Arc GIS plots, associations could be made between the component distributions and activity on the street respectively. These are recorded in the event column in Table 7-6. The statistical parameters, namely height, width, centre and geometric mean and geometric standard deviation, of each distribution are presented in Table 7-6. The interquartile range for each component distribution and the R^2 for the fitting of the curve were obtained and reported. The R^2 value was 0.88. The pollution events, which were recorded such as smoking, heavy goods vehicles or buses passing by, were associated with a component distribution of the total pdf. High levels, which were greater than the interquartile range of each component distribution, of measured pollution were consistently coincident with either one or more incidences of smoking or heavy goods vehicles or a bus passing by. The technique was able to identify component distributions which could be associated with a traffic related characteristic other than the smoking, heavy goods vehicles or bus passing by events. The highest levels associated with the pass by of specific vehicles (hgv or buses) do not occur sufficiently frequently during the survey campaigns to emerge as a separate component distribution with statistical significance. However, as anticipated, the decomposition was able to successfully classify the distributions of dynamic monitoring in a generic way and interestingly for the pollution events (rather than the 'ambient background') with a lognormal distribution consistent with the static measurements. A comparison of the statistics of the dynamic with the static component distributions allowed differences and similarities in the levels measured to be explored.

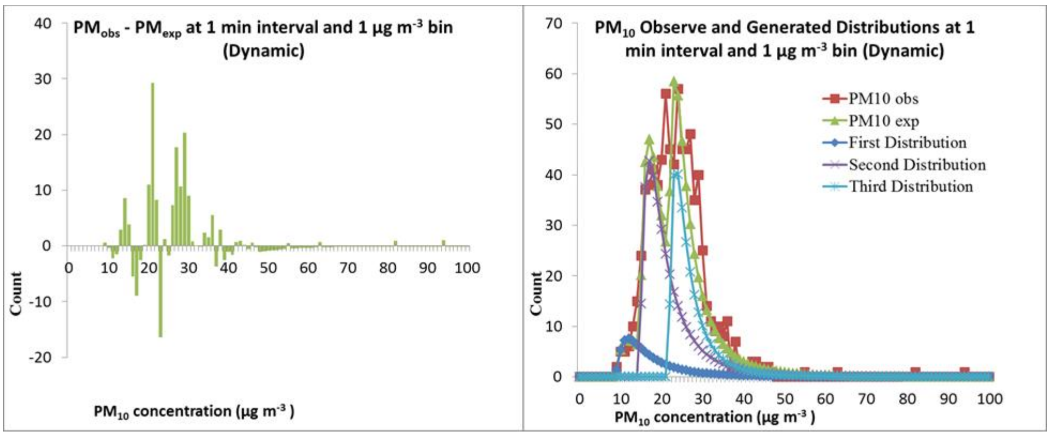


Figure 7-9 PM_{10} Distributions of Dynamic Campaign (Monitored, Modelled and Residuals)

Table 7-6 R^2 by fitting three lognormal distributions (dynamic monitoring campaign)

Height	Centre	Width	R^2	Event	Q1	Q3	% explained by each component distribution	Total of overall pdf explained	GM[a]	GSD[b]
7.6	11.8	7.1		Light free flow	12	21	10%		15.9	1.4
42.7	17.0	5.5	0.90	Steady free flow	17	24	45%	88%	21.0	1.3
41.6	23.5	4.1		Heavy start/ stop	24	29	33%		26.7	1.2

[a] Geometric mean
[b] Geometric standard deviation

With reference to Figure 7-9 and the time series plot in Figure 7-7 the three sub component distributions were seen to be associated with light or free flowing traffic the statistics are: centre (geometric mean), 11.8 (15.9) µg m^{-3}; for smooth free flow (higher traffic volume travelling at a slower speed) 17.0 (21.0) µg m^{-3} and finally for heavy stop/start traffic PM_{10} levels are even higher 23.5 (26.7) µg m^{-3}. As expected the variation width (geometric standard deviation) for the three sub components was different being higher 7.1 (1.4) µg m^{-3} for the light free flow traffic, compared with the high volume traffic state 5.5 (1.3) µg m^{-3}. The heavily congested stop-start traffic exhibited the least variation 4.1 (1.2) µg m^{-3}.

7.4 Summary

The results of the dynamic monitoring campaigns were presented in this chapter. Instrument testing and identifying the key variables were the main aims of the first campaign. During the first dynamic study, a back pack fitted with a number of instruments was carried along a specific track. The dynamic monitoring of the first campaign measured the PM_{10} levels and GPS location and the traffic conditions were noted. The GPS data was used to divide the pollution and traffic data into road sections. It established that the pollution medians were highest during the second group. This can be explained, as result of the high wind speed and direction measured creating a canyon effect during the afternoon measurement of the first campaign. The first campaign identified the importance of local source emission as well as the wind condition. Therefore, the level of information relating to HGV and buses, and smoking activity was increased in the second campaign. The dynamic measurements of the second campaign were subject to an in depth analysis and shown not to be normally distributed so non parametric tests were employed. The pdfs were disaggregated using lognormal distributions and found to be composed of three component distributions using decomposition. The PM_{10} means of the two campaigns were lower than previous studies. The results suggest that whilst the most prevalent sources of pollution (traffic volumes whether in a saturated and unsaturated state) conform well to log normal distributions the ambient background may better conform to a Normal distribution. In addition, the very high transient polluting events, such as heavy goods vehicles, buses and smokers passing by, whilst in themselves an important contributor to personal exposure they did not occur with sufficient frequency during the survey campaign to render a statistically significant component distribution. For this reason less of the overall pdf was explained resulting in a lower R^2 compared to the static environments. The next chapter will bring together the results of the static and the dynamic data collection campaigns and discuss the relevance of these findings in the policy context.

8 Discussion of Static Monitoring and Dynamic Monitoring

8.1 Introduction

The previous chapter detailed the full analysis of the first and second campaigns of data collected indoor and outdoor. Huge variations in the PM_{10} time series data from day to day across all properties whether on main, minor or residential roads were discovered and detailed in previous chapters. Furthermore, there were several inconsistences revealed, such as outdoor measurements were often lower but sometimes higher irrespective of whether the levels were measured during the day or over the night. This pattern suggested that local sources are mainly responsible for exposures, irrespective of whether monitored indoor or outdoor, highlighting the importance for householders completing diaries. The results of the technique of decomposition used to explore the characteristics of the multimodal pdf demonstrated that component distributions which explain the sources within the microenvironments in the properties could be found for both the static and dynamic monitoring survey campaigns. In this chapter the results of the analysis from both campaigns are compared to each other to address whether there is any statistical evidence that properties in busy rather than low traffic activity roads experience different levels of pollution due to the ingress of pollution from outdoors to indoors. Section 8.2 presents an overview of the main analysis of the static monitoring, in sections 8.3 and 8.4 a discussion of model residuals and model validation are given and finally the summary in section 8.5. Throughout this chapter, the mean values of the distributions are quoted to allow direct comparison with results of other research.

8.2 Overview of the Static First and Second Campaigns

The PM_{10} concentrations of the raw data measured for at least five days during the first and the second campaigns combined were compared. Measurements were made at twelve dwellings, with four dwellings providing the data for the kitchen and lounge simultaneously, providing the data for outdoor and lounge/indoor business premise simultaneously and the remainder for the business (dental office, Boutique and restaurant) indoor only. The first and second campaigns in total consisted of data collected from twenty microenvironments with five microenvironments at four dwellings being monitored for more than a one week period. The descriptive statistics are presented in Table 8-1, Table 8-3 and Table 8-4 for each week of data lounge/business, kitchen and outdoor respectively. For clarity of interpretation the box plots of PM_{10} levels are presented separately for the lounge indoor business, kitchen and outdoor in Figure 8-1, Figure 8-2 and Figure 8-3 respectively.

8.2.1 Indoor of Properties Lounge or Business

The road traffic in the vicinity of these properties varied from quiet to congested states. PM_{10} levels in the lounge varied between 0 (5330) µg m^{-3}, with lower (and upper) values of means, geometric means, medians and modes 7.2 (110.7) µg m^{-3}, 5.6 (36.4) µg m^{-3}, 5 (27) µg m^{-3} and 0 (22) µg m^{-3} respectively across all properties. Figure 8-1 shows for each location the median, interquartile range and the mean and geometric means of PM_{10} concentrations, median and modes minimum (maximum) varied between 3 (27) µg m^{-3} and 0 (22) µg m^{-3} lower quartile 2 (20) µg m^{-3} upper quartile 9 (138) µg m^{-3} and mean 7.2 (110.7) µg m^{-3} and geometric means 5.6 (36.4) µg m^{-3}. Given the mean in all cases is at the upper edge or higher than the upper quartile these distributions are not normally distributed. Two properties H10W2L and H12L are clear outliers. The former on a quiet road has a low concentration median (3 µg m^{-3}) due to property being vacated, also large interquartile range 2 to 22 µg m^{-3} due the property being both vacant and occupied for part of the monitoring period. The other outlier H12L median 18 µg m^{-3} also has a very high interquartile range (11 to 138 µg m^{-3}) due to the cooking activity in the restaurant. The other properties fall into three clusters. These have medians below 10 µg m^{-3} (H01W1, H05, H06, H07 and H08), above 10 µg m^{-3} and below 20 µg m^{-3} (H01W2, H01W3, H02W1, H03, H04, H09W1, H10W1, H01W4 and H09W2) and above 20 µg m^{-3} (H02W2 and H011).

Levels monitored inside properties were caused predominantly by indoor pollution sources. Also, in H05 and H09W2, the PM_{10} means, geometric means in the lounge (40.9 and 42.2 µg m^{-3}, 9 and 13.5 µg m^{-3} respectively) were high compared to the other means, geometric means across all lounges except H12L which is the restaurant. This was due to an unrecorded event and construction work respectively. For the properties adjacent to a quiet road, the means for PM_{10} in the lounge were lower than the other properties except for H09W1 which is located alongside a busy road. However, the house H01 was located in the vicinity of a signal controlled traffic junction and PM_{10} levels varied substantially from one week to another. This was identified as being caused by the changing activities from week to week indoors during the survey period of Ramadan coinciding with the school holidays as well as those out of doors due to the location of the signalised junction with respect to the property and the prevailing meteorological conditions.

PM_{10} minimum (maximum) levels were 0 (809) µg m^{-3} at the properties near a quiet road which were lower than at properties near a major road with PM_{10} levels 0 (5330) µg m^{-3}. On the other hand as expected PM_{10} interquartile levels were lower 3 (24) µg m^{-3} at the properties near a quiet road compared to 4 (138) µg m^{-3} near a busy or a major road. Interestingly, PM_{10} median at H03 near a quiet road (13 µg m^{-3}) was higher than at properties near a busy or a major road except H04, H2W2, H09W2, H11 and H12 (17, 24, 15, 27 and 18 µg m^{-3} respectively). In addition, PM_{10} median at properties near a major road was not always greater than those near a quiet road. In short, this analysis revealed inconsistency in the influence of traffic flow regimes in the vicinity of each property. Furthermore, it is clear that the type of activity is dominating both the shape of the pdf and the magnitude of the levels measured.

Table 8-1 Descriptive statistics for static monitoring indoors in lounge/business

ID	**Location in the network**	**Time** dd Hr:min	**µg m^{-3}**							
			Mean	**Median**	**Mode**	**Q1**	**Q3**	**Min**	**Max**	**GM[a]**
H01W1**	Signalled junction	03 17:42	20.4	7	0	4	17	0	942	5.6
H01W2**	Signalled junction	06 12:54	15.9	10	9	7	18	1	638	11.2
H01W3**	Signalled junction	04 11:44	19.0	11	9	8	19	4	678	12.6
H02W1*	Busy road	07 00:00	20.2	14	6	8	24	3	507	14.6
H03*	Quiet road	07 00:00	15.3	13	9	9	18	3	86	13.5
H04*	Major road	07 00:00	24.9	17	9	10	29	2	541	17.4
H05**	Major road	07 00:00	40.9	7	3	4	15	1	4270	9
H06***	Major road	07 00:00	14.7	6	3	4	11	2	336	7.2
H07*	Quiet road	07 00:00	7.2	5	4	4	9	2	50	5.9
H08*	Quiet road	07 00:00	10.1	6	3	3	10	0	495	5.6
H09W1	Major road	07 00:00	12.7	11	5	5	17	0	360	8.9
H10W1**	Quiet road	07 00:00	13.0	11	8	8	15	3	81	11.4
H01W4**	Traffic signal	07 00:00	28.4	16	13	13	26	4	809	19.4
H02W2**	Busy road	07 00:00	26.7	24	22	19	30	9	582	24
H09W2	Major road	07 00:00	42.2	15	3	7	22	1	3550	13.5
H10W2**	Quiet road	05 23:30	15.1	3	2	2	22	1	264	5.9
H11	Busy road	06 09:11	31.4	27	21	20	37	8	198	27.4
H12**	Busy road	07 00:00	110.7	18	11	11	138	7	5330	36.4

* The lounge is in a separate room without interconnecting door to the kitchen, ** the lounge is separated by a door only and *** open floor plan Geometric mean

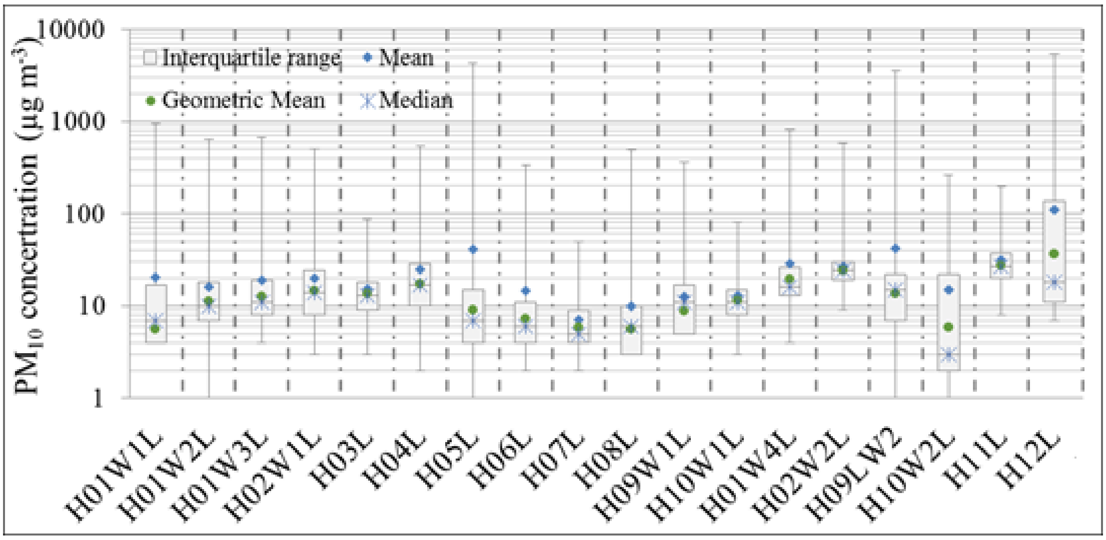


Figure 8-1 Box plot of PM_{10} levels static monitoring lounge

8.2.2 Comparison with Other Studies

Table 8-2 provides an overview of the results of previous studies of microenvironments which mainly used gravimetric sampling method compared with this research which used light scattering method. As explained in section 3.4.5 because gravimetric methods overestimate particulate levels by factors ranging from x2 to x3.5 the light scattering estimates are scaled accordingly to provide a range of levels to enable comparisons to be made. With reference to Table 8-2, this study found a much larger variation in PM_{10} concentrations across properties irrespective whether located on a quiet or heavily trafficked road and although the measured values suggested that indoor levels were higher on main compared to quiet roads they were not significant. Instead levels were dominated by internal activity for example in H12 compared to those measured in most previous studies, levels were high due to the prolonged periods of cooking as it was a restaurant and takeaway. In comparison to other studies, Lawson *et al.* (2011) and Fischer *et al.* (2000) found that the PM_{10} mean concentrations in houses near a main road were higher than at houses far from a main road which was consistent with Jones *et al.* (2000) who found flats on the tenth and thirteenth floor were lower than properties at street level. However, the study reported in this thesis did not find that the dwellings near to a major road always had higher PM_{10} levels than the ones near to a quiet road. This was due to the fact that the decomposition technique demonstrated that PM_{10} levels were dominated by specific source/activity events in the microenvironment whether originating indoor or outdoor. Indoor levels for example were found in this study to substantially be due to cooking activities especially in H12, a fast food and restaurant and refuse collection was shown to influence indoor levels in several properties. However, in the dentist reception, H09W2 due to the construction work at the façade of the property and given the high frequency with which the main door opened and closed directly into the reception room as patients arrived for, and departed having received, dental treatment did contribute significantly to indoor levels. Diapouli et al. (2011) in a study of concentrations in three flats monitored during summer and winter observed that *"elevated indoor concentrations were recorded, caused by increased ambient aerosol penetration, air penetration in the indoor microenvironments and/or indoor particle generation".* Indeed, in H09W2, there was no suggestion that the ambient background concentrations in the dentist were elevated due specifically from the heavily trafficked road. However, this was due to one outdoor event which occurred during two days which caused elevated indoor levels. Stringer *et al.* (2007), Jones *et al.* (2000) and Aizlewood and Dimitroulopoulou (2006) found that PM_{10} mean concentrations vary from house to house due to indoor activities including movement, Ch Monn *et al.* (1997), and that levels can vary significantly from one week to another, these observations are consistent with this study as seen in the Table 8-2. Ch Monn *et al.* (1997) showed that indoor pollution levels would be lower than outdoor in the absence of indoor sources and without high level of human activity. This was consistent with Custódio et al. (2014) who studied an unoccupied property and the measurements in this study in property H10 during periods when the occupants were away a similar fall in concentrations was measured.

Table 8-2 PM_{10} concentrations in other studies on this study

Study	Sample	Mean PM_{10} (µg m^{-3}) (scaled x2 - x3.5)	Sampling Method
Stranger *et al.* (2007)	Residential houses	39.4	Gravimetric Sampling
	Schools	60.6	
Jones *et al.* (2000)	Houses at roadside	47.8, 34.7, 16.5, 27, 20	Gravimetric Sampling
	Flat	15, 17, 88	
	Rural houses	34, 27, 45	
Aizlewood and Dimitroulopoulou (2006)	Apartment building	13.9 to 92.3	Gravimetric Sampling
	Office building	14.8 to 25.7	
Lawson *et al.* (2011)	Houses near main road	22.5	Gravimetric Sampling
	Houses far from main road	17.2	
Ch Monn *et al.* (1997)	Low Indoor Activity	10.8	Gravimetric Sampling
	Normal Indoor Activity	32.8	
	Indoor smokers	26.9	
Fischer et al. (2000)	Along High Traffic Street	37	Gravimetric Sampling
	Along Low Traffic Street	22	
Diapouli et al. (2011)	During Warm Period	35	Gravimetric Sampling
	During Cold Period	32	
Custódio et al. (2014)	No Occupant	35.7	Gravimetric Sampling
	Indoor smokers	116.4	
	Other houses	52.6, 58.6, 59.9	
This Study	Near a quiet road	15.3 (30-54), 7.2 (14-25), 10.1(20-35), 13(26-45), 15.1 (30-53)	Light Scattering
	Near a traffic light	20.4 (41-71), 15.9 (32-56), 19 (38-66), 28.4 (57-99)	
	Near a busy road	20 (40-70), 26.7 (53-93), 31.4 (63-110), 110.3 (221-386)	
	Near a major road	24.9 (50-87), 40.9 (82-143), 14.7 (29-51), 12.7 (25-44), 42.2 (84-148)	

8.2.3 Indoor Kitchen

Table 8-3 shows the descriptive statistics data for the kitchens studied. The road traffic near these properties varied from a state of quiet to congested, PM_{10} levels in the kitchen varied from one week to another for house H01, which is located near a signal controlled traffic junction. In general whilst the range of PM_{10} levels was higher in the kitchen than in the lounge the interquartile range was lower. PM_{10} minimum (maximum) levels were 0 (607) µg m^{-3} at the property in the vicinity of a quiet road which was lower than at property near a major road with PM_{10} levels 2 (2680) µg m^{-3}. On the other hand as expected PM_{10} interquartile levels were lower 2 (7) µg m^{-3} at the property near a quiet road compared to near a major road 5 (14) µg m^{-3} PM_{10} median at H05 near a major road (7 µg m^{-3}) was lower than other properties except H08 (5 µg m^{-3}).

Table 8-3 Descriptive statistics for static monitoring kitchen

ID	Location in the network	Time dd Hr:min	μg m-3							
			Mean	**Median**	**Mode**	**Q1**	**Q3**	**Min**	**Max**	**GM[a]**
H01W1**	Signalled junction	04 00:47	28.0	14	13	11	21	7	988	17.2
H01W2**	Signalled junction	07 00:00	15.1	10	11	8	15	2	749	11.1
H01W3**	Signalled junction	06 23:56	21.2	12	7	8	17	3	2150	12.9
H02W1*	A busy road	07 00:00	24.5	18	12	13	27	5	1010	19.7
H05**	A major road	07 00:00	32.6	7	5	5	14	2	2680	9.6
H08*	A quiet road	07 00:00	7.8	5	2	2	7	0	607	4.5

* The lounge is in a separate room without interconnecting door to the kitchen, ** the lounge is separated by a door only and *** open floor plan
[a] Geometric mean

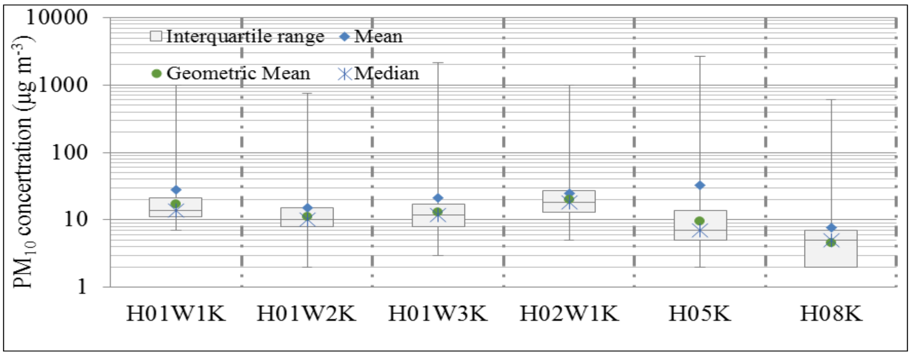


Figure 8-2 Box plot of PM_{10} levels for static monitoring kitchen

8.2.4 Outdoor

The descriptive statistics of PM_{10} concentrations of the four outdoor measurements are presented in Table 8-4. The statistics for PM_{10} levels varied greatly with minimum (maximum) values 3 (1830) μg m^{-3} and mean, median and mode are 20.3 (55.9) μg m^{-3}, 10 (31.5) μg m^{-3} and 6 (23) μg m^{-3} respectively. Figure 8-3 shows the interquartile of PM_{10} concentrations in each location for the outdoor measurements. The interquartile range of the second campaign varied between 7 and 50 μg m^{-3}. Given that for all microenvironments means are greater than the medians, their distributions are not Gaussian and systematically geometric means were always lower than and most frequently close to the mean values. Outdoor PM_{10} levels varied 3 (1830) μg m^{-3} at the H12 property near a major or busy road whilst property H10 near a quiet road was 3 (122) μg m^{-3} which were in fact similar to other properties located on busy roads, for example H01 4 (104) μg m^{-3} and H02 PM_{10} levels varied 9 (111) μg m^{-3} respectively. These statistics alone are indicating that there are a number of processes that come into play and influence pollutant levels outdoor. This examination of outdoor levels is showing clearly that outdoor levels are higher and more variable than those measured in the kitchen but maximum short duration peaks can reach higher levels during cooking than transient levels measured outdoors.

Table 8-4 Descriptive statistics for static monitoring outdoor

ID	Location in the network	Time dd Hr:min	$\mu g\ m^{-3}$							
			Mean	**Median**	**Mode**	**Q1**	**Q3**	**Min**	**Max**	**GM**[a]
H01W4	Signalled junction	07 00:00	25.5	23	21	15	30	4	104	22.1
H02W2	Busy road	05 23:30	34.1	31.5	23	23	43	9	111	30.9
H10W2	Quiet road	05 23:30	20.3	10	6	7	24	3	122	13.2
H12	Busy road	07 00:00	55.9	14	8	7	50	3	1830	27.4

[a] Geometric mean

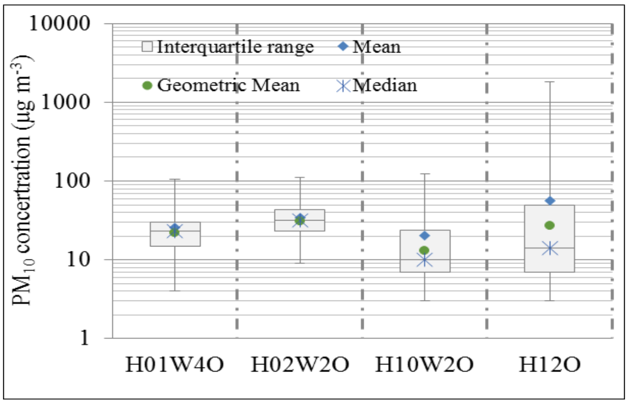


Figure 8-3 Box plot of PM_{10} levels static monitoring outdoor

8.2.5 *Indoor/Outdoor Ratio*

As with indoor, outdoor levels are governed substantially by often transient sources of emission. Table 8-5 shows the PM_{10} average indoor/outdoor ratio. The range of indoor/outdoor ratios were observed between 0.74 and 1.98 for this study. PM_{10} indoor/outdoor ratio was less than one for H02 and H10. Indoor/outdoor ratio of PM_{10} was 0.78 for H02 which can be explained by the fact that a reception area and hall separated the kitchen from the lounge and the doors were generally kept closed. In the case of property H10 the ratio of 0.74 averaged over the five days was due to the residents of H10 being away from home for three days during the monitoring period. PM_{10} indoor/outdoor ratios were 0.34 and 1.48 for H10 during the period when residents were absent from the property and when at home respectively. The lower ratio was due to the absence of indoor sources, reducing levels to below those measured out of doors, consistent with the research by Ch Monn *et al.* (1997) who noted low ratio in the absence of sources and (Custódio *et al.*, 2014) when premises are without occupants. The highest ratio was found in the takeaway restaurant of 1.98 which was due to cooking activities and continues movement of staff this ratio was of the similar magnitude of 1.84 found indoors by Ch Monn *et al.* (1997) due to smoking. The indoor/outdoor ratios of this study were found to be in the range of other studies as shown in Table 8-5.

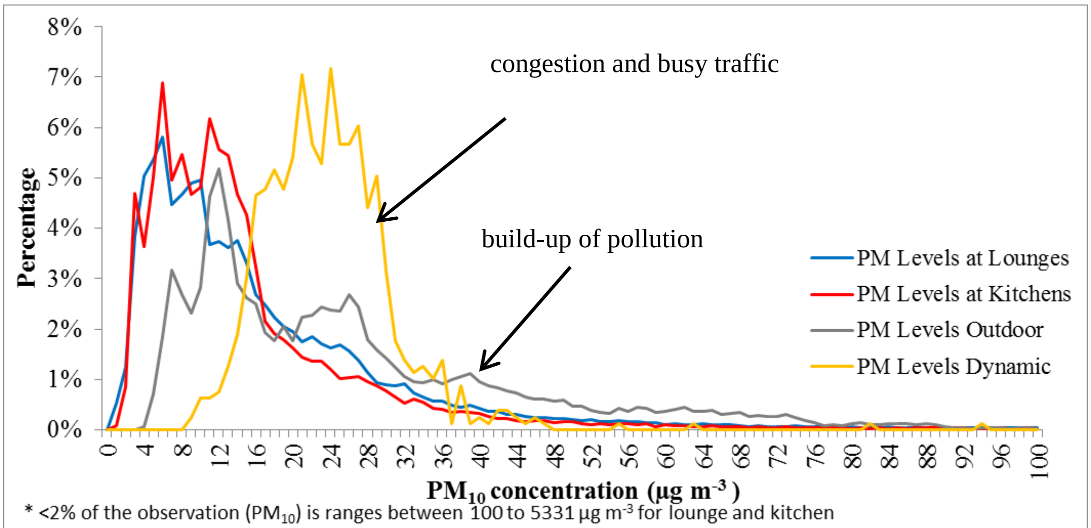
Table 8-5 Indoor/outdoor PM_{10} ratio

Study	**City, Country**	**PM_{10} (µg/m^3) I/O**	**Number of dwelling or dwelling ID**	**Location**	**Notation**
Jones et al. (2000)	Birmingham, United Kingdom	1.6	4	Urban	Flats near roadside
		2.1	2	Urban	Flats in multi-story building
		2.5	1	Rural	
Ch Monn *et al.* (1997)	Zürich, Switzerland	0.71	[a]	Urban	Low Indoor Activity
		1.4	[a]	Urban	Normal Indoor Activity
		1.84	[a]	Urban	Indoor smokers
Fischer et al. (2000)	Amsterdam, Netherlands	0.86	18	Urban	Along High Traffic Street
		0.61	18	Urban	Along Low Traffic Street
Stranger et al. (2007)	Antwerp, Belgium	0.95	15	Urban and Suburban	
Diapouli et al. (2011)	Athens, Greece	0.7	3	Urban	During Warm Period
		0.6			During Cold Period
Custódio et al. (2014)	Aveiro and São João da Madeira, Portugal	0.8	1	Urban	No Occupant
		1.4	4		
This Study	Newcastle upon Tyne, United Kingdom	1.11	H01	Urban	House
		0.78	H02	Urban	House
		0.74	H010	Urban	House
		1.98	H12	Urban	Restaurant

[a] Not specified by authors

8.2.6 *Distributions of PM_{10} Levels all Similar Microenvironments*

Distributions of PM_{10} levels were plotted for all data sets separately for the lounge, kitchen and outdoor using 1 µg m^{-3} bin at 1 minute sample averaging interval. Given the extremely long tail the distribution is cut at 100 µg m^{-3} in plotting the distributions otherwise the detail in the structure of the distribution will be lost. However, please note that all analysis have been conducted on the entire data set. Figure 8-4 serves as an overview of all the data gathered across all campaigns disaggregated into the four main MEs studied namely kitchens and lounges indoors and property facades and roadside dynamic outdoors. The distributions show very clearly that the data is not normally distributed. A great deal of structure was evident with all distributions exhibiting a "long tail" and the four datasets were quite different. One noticeable fact was that not only was the distribution in the kitchen quiet different in shape to that of the lounge the number of peaks observed is up to an additional three in the individual campaigns. Indeed, the first mode around 12 µg m^{-3} of the kitchen is similar to that of outdoor peaks suggesting similar exposures but with essentially different sources. In addition, it can be seen that overall the kitchen activity (mainly cooking) in the majority of properties influenced the PM_{10} levels monitored in the lounge. Also, the role of dispersion is evident because the overall pdf shifts to the lower levels of concentrations and are more spread out in the lounges compared to the kitchens The effect of traffic outdoors on levels indoors was less pronounced but suggested by the coincidence of a slight bulge in the range of about 22 to 28µg m^{-3} in the kitchen and lounge where the outdoor measurements are dominated by traffic sources. This was evidenced from the analyses presented in section 5.6 and 5.7 where at H1 traffic congestion at the nearby signal controlled junction and at H2 located on a busy road close to a traffic calming hump outdoor pollution was likely to be influencing the indoor levels. The peak at about 26 µg m^{-3} monitored at the façade of properties is coincident with the bulk of the dynamic pdf which is dominated by congestion and heavy traffic along the Gosforth High Street. Finally the higher proportion of PM_{10} levels (≈36 µg m^{-3}) in the ambient outdoor façade levels are likely be due to the build-up of pollution due to canyon and meteorological influences. Given that the decomposition analysis has explained over 83% of the pdf in all cases the approach seems to show some promise. In the next section the residuals are considered across all properties disaggregating data into three microenvironments namely kitchen, lounge/business and outdoor.



* <2% of the observation (PM_{10}) is ranges between 100 to 5331 µg m^{-3} for lounge and kitchen

Figure 8-4 PM_{10} Distributions measured at four microenvironments, the lounge, the kitchen and outdoor across all properties monitored and dynamic monitoring

8.3 Model Residuals

The residuals are the differences between the measured data and the predicted value based on the decomposition technique. These constitute the unexplained variation and if normally distributed are synonymous with “error”. However, if the median is a statistically significantly different from zero then one can argue that there is an ambient background level associated with the build-up of pollution. This may or not be sourced within the building but instead from outdoors. Table 8-6 shows the descriptive statistics of the residuals. The residuals of PM_{10} minimum (maximum) levels were -275.4 (725) µg m^{-3}, for the lowest (and highest) values of means and medians were 0.1 (17) µg m^{-3} and -0.5 (0.6) µg m^{-3} respect. Figure 8-1 shows the interquartile of PM_{10} concentrations in each location for the first and second campaigns. The interquartile of the residuals ranged from -3.8 and 14 µg m^{-3}.

The residuals were not normally distributed. Therefore, a one sample Wilcoxon test was conducted to investigate whether the medians of the residuals were statistically significantly different from zero. The residual medians were not statistically significantly different from the zero for H01W2L, H02W1L, H03L, H07L, H09W1L, H10W1L, H01W4O, H02W2L, H02W2O, H10W2L, H11L and H12O as shown in Table 8-6 and Table 8-7.

Table 8-6 Descriptive Statistics of the residuals

ID	Total Count	Mean	Median	Q1	Q3	Min	Max
H01W1K	989	0.4	0.0	0.0	0.0	-40.1	69.1
H01W1L	943	0.4	0.0	0.0	0.0	-48.8	232.4
H01W2K	750	0.6	0.0	0.0	0.0	-132.3	321.9
H01W2L	943	0.3	0.0	0.0	0.0	-86.4	190.4
H01W3K	2151	0.2	0.0	0.0	0.0	-135.4	117.6
H01W3L	679	0.5	0.0	0.0	0.5	-96.5	111.7
H02W1K	1011	0.4	0.0	0.0	0.0	-82.3	92.9
H02W1L	508	0.4	0.0	-0.1	0.0	-54.6	97.5
H03L	87	0.8	-0.5	-1.4	2.6	-275.4	327.1
H04L	542	0.6	0.0	0.0	0.7	-73.7	108.7
H05K	2681	0.2	0.0	0.0	0.0	-152.5	295.2
H05L	4271	0.1	0.0	0.0	0.0	-69.0	44.0
H06L	337	1.3	0.5	-0.1	1.3	-117.5	193.8
H07L	51	17.0	0.0	-1.0	6.9	-74.5	725.0
H08K	2681	0.2	0.0	0.0	0.0	-163.2	191.8
H08L	496	0.7	0.0	0.0	0.7	-112.0	143.1
H09W1L	361	1.3	0.0	0.0	0.0	-108.6	249.2
H10W1L	82	2.7	0.6	-1.3	3.0	-139.1	293.2
H01W4O	105	4.4	-0.5	-3.0	10.5	-84.8	112.9
H01W4L	810	1.0	0.0	0.0	1.0	-68.4	291.8
H02W2O	112	0.7	0.0	-3.8	8.5	-63.3	54.2
H02W2L	583	1.2	0.0	0.0	0.0	-130.9	175.2
H09W2L	3551	0.4	0.0	-0.1	0.0	-103.3	355.9
H10W2O	123	6.2	0.0	-2.3	14.0	-131.6	261.3
H10LW2	265	2.6	-0.1	-0.3	0.9	-139.5	648.1
H11	199	2.8	-0.1	-0.8	2.5	-68.4	137.0
H12O	1831	0.6	0.0	0.0	0.0	-103.9	492.6
H12L	5331	0.2	0.0	0.0	0.0	-118.1	239.7

Table 8-7 One sample Wilcoxon test result for the residuals

ID	Total Count	Number for Test	Wilcoxon Statistic	Estimated P value	Estimated Median	Statistically Significantly Different from 0
H01W1K	989	290	36397.5	0	0.0000	Yes
H01W1L	943	309	35973	0	0.0000	Yes
H01W2K	750	242	20726	0	0.0000	Yes
H01W2L	943	383	35922	0.697	0.0000	No
H01W3K	2151	307	38086.5	0	0.0000	Yes
H01W3L	679	284	30268.5	0	0.0000	Yes
H02W1K	1011	348	36891	0.001	0.0000	Yes
H02W1L	508	382	36038.5	0.803	-0.0050	No
H03L	87	84	1794.5	0.968	0.0000	No
H04L	542	393	44418	0.011	0.0000	Yes
H05K	2681	499	95496	0	0.0000	Yes
H05L	4271	528	111388	0	0.0000	Yes
H06L	337	334	39446	0	0.4850	Yes
H07L	51	49	687	0.462	0.4650	No
H08K	2681	316	44209.5	0	0.0000	Yes
H08L	496	280	26173.5	0	0.0000	Yes
H09W1L	361	200	9742	0.708	0.0000	No
H10W1L	82	79	1847.5	0.192	0.7450	No
H01W4O	105	101	2812	0.424	0.9700	No
H01W4L	810	383	60103.5	0	0.3300	Yes
H02W2O	112	102	2819	0.522	0.3700	No
H02W2L	583	274	17821	0.439	0.0000	No
H09W2L	3551	3324	1117920	0	-0.0300	Yes
H10W2O	123	120	4658.5	0.007	3.9900	Yes
H10LW2	265	264	18488.5	0.422	0.1250	No
H11	199	190	9541.5	0.537	0.1300	No
H12O	1831	1215	384811	0.207	-0.0050	No
H12L	5331	2453	1175452	0	-0.0050	Yes

On the other hand, those properties that were statistically significantly different from zero, namely H01W1K, H01WL, H01W2K, H01W3K, H01W3L, H01W4L, H02W1K, H04L, H05K, H05L, H06L, H09W2 and H12L were all on a busy roads. However, H08K, H08L, median 6 µg m^{-3} mode 3 µg m^{-3} respectively and H10W2L were on quiet roads and were statistically significantly different to others, whilst H05 with median 7 µg m^{-3} mode 5 µg m^{-3} were statistically significantly similar to H08 was on a main road whilst H03 with median 13 µg m^{-3}, mode 9 µg m^{-3}, exhibited high level of residual but located on a quiet road. Again whilst there is evidence emerging that higher ambient levels (residuals higher than zero) occurred in properties near busy roads and junctions the picture is by no means straight forward. Therefore, the next step was to apply further statistical tests to delve deeper into the interrelationships between the many variables being explored.

Table 8-8 illustrates that there was a statistically significantly difference between H02W1K residuals and other kitchen residuals which could be due to the kitchen in property H02 not being fitted with an extractor fan. Also, the residuals of H01W1K were statistically significantly different from other kitchens of other properties.

However, they were statistically significantly similar during the second and third week of monitoring. Residuals of the kitchen for the second and third week were statistically significantly similar given that these weeks coincided with Ramadan and school holiday and household activity was quite different from the first week which was during school term. When the residuals of the kitchen and lounge were compared there was no statistically significantly difference for the properties H01W3, H05 and H08 see Table 8-9. The Mann Whitney test was carried out to compare the residuals across all lounges as shown in Table 8-10. Interestingly, the residuals of low frequency of use of lounges in H03 and H07 were not statistically significantly different from the other lounges except for property H03 where residuals were statistically significantly different from H01W1 and H01W4. H02 and H10, the residuals of the first period were not statistically significantly different from the second period residuals but it was not the case for H09. This was likely to be due to an outdoor event, which took place on two days, at H09 during the second week that caused it to be statistically significantly different from the first week.

Table 8-8 Mann Whitney test results comparing kitchen residuals

	H01W1K	H01W2K	H01W3K	H02W1K	H05K	H08K
H01W1K	-	0.0001	0	0	0	0
H01W2K		-	0.4086	0.0118	0.955	0.2911
H01W3K			-	0	0.1765	0.7662
H02W1K				-	0.0004	0
H05K					-	0.0779
H08K						-

Table 8-9 Mann Whitney test results comparing kitchen and lounge residuals

	H01W1K	H01W2K	H01W3K	H02W1K	H05K	H08K
H01W1L	0.0011	-	-	-	-	-
H01W2L	-	0	-	-	-	-
H01W3L	-	-	0.0817	-	-	-
H02W1L	-	-	-	0	-	-
H05L	-	-	-	-	0.7838	-
H08L	-	-	-	-	-	0.1569

Table 8-10 Mann Whitney test results comparing lounge residuals

	H01W1L	H01W2L	H01W3L	H02W1L	H03L	H04L	H05L	H06L	H07L	H08L	H09W1L	H10W1L	H01W4L	H02W2L	H09W2L	H10LW2	H11L	H12L
H01W1L	-	0.00	0.30	0.00	0.06	0.00	0.06	0.24	0.72	0.17	0.00	0.03	0.00	0.00	0.00	0.00	0.00	0.00
H01W2L		-	0.00	0.00	0.14	0.38	0.00	0.00	0.94	0.00	0.21	0.01	0.00	0.63	0.00	0.00	0.00	0.00
H01W3L			-	0.00	0.05	0.00	0.00	0.67	0.59	0.05	0.00	0.07	0.01	0.00	0.00	0.00	0.00	0.00
H02W1L				-	0.16	0.07	0.00	0.00	0.99	0.00	0.08	0.04	0.00	0.01	0.00	0.00	0.01	0.03
H03L					-	0.11	0.09	0.03	0.42	0.08	0.20	0.30	0.01	0.26	0.29	0.25	0.38	0.16
H04L						-	0.00	0.02	0.84	0.00	0.81	0.07	0.00	0.84	0.00	0.00	0.00	0.27
H05L							-	0.01	0.99	0.65	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
H06L								-	0.30	0.24	0.00	0.52	0.20	0.00	0.00	0.00	0.00	0.00
H07L									-	0.69	0.93	0.91	0.37	0.79	0.70	0.97	0.79	0.84
H08L										-	0.00	0.07	0.00	0.00	0.00	0.00	0.00	0.00
H09W1L											-	0.03	0.00	0.47	0.00	0.00	0.01	0.47
H10W1L												-	0.23	0.01	0.00	0.20	0.35	0.00
H01W4L													-	0.00	0.00	0.00	0.00	0.00
H02W2L														-	0.00	0.00	0.01	0.02
H09W2L															-	0.04	0.01	0.00
H10LW2																-	0.27	0.00
H11L																	-	0.00
H12L																		-

A Mann Whitney test was carried out to compare the residuals across all microenvironments. Outdoor residuals were found not to be statistically significantly different from each other see Table 8-11. Also, there were no statistically significant differences between lounge/business indoor and outdoor residuals for each property as shown in Table 8-12. The box plots of the residuals for kitchen, lounge and outdoor are presented in Figure 8-5, Figure 8-6 and Figure 8-7 respectively.

Table 8-11 Mann Whitney test results comparing outdoor residuals

	H01W4O	H02W2O	H10W2O	H12O
H01W4O	-	0.6112	0.1977	0.1814
H02W2O		-	0.0816	0.4561
H10W2O			-	0.5931
H12O				-

Table 8-12 Mann Whitney test results comparing lounge and outdoor residuals

	H01W4L	H02W2L	H10W2L	H12L
H01W4O	0.0691	-	-	-
H02W2O	-	0.5553	-	-
H10W2O	-	-	0.4509	-
H12O	-	-	-	0.9038

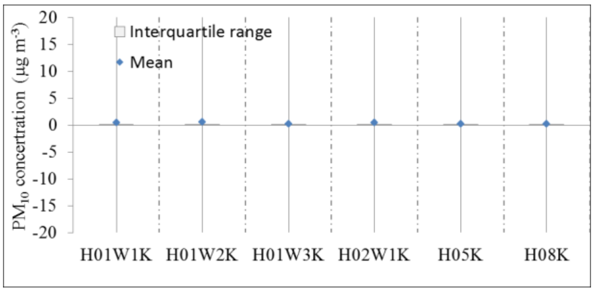


Figure 8-5 Box plot of the residuals static monitoring Kitchen

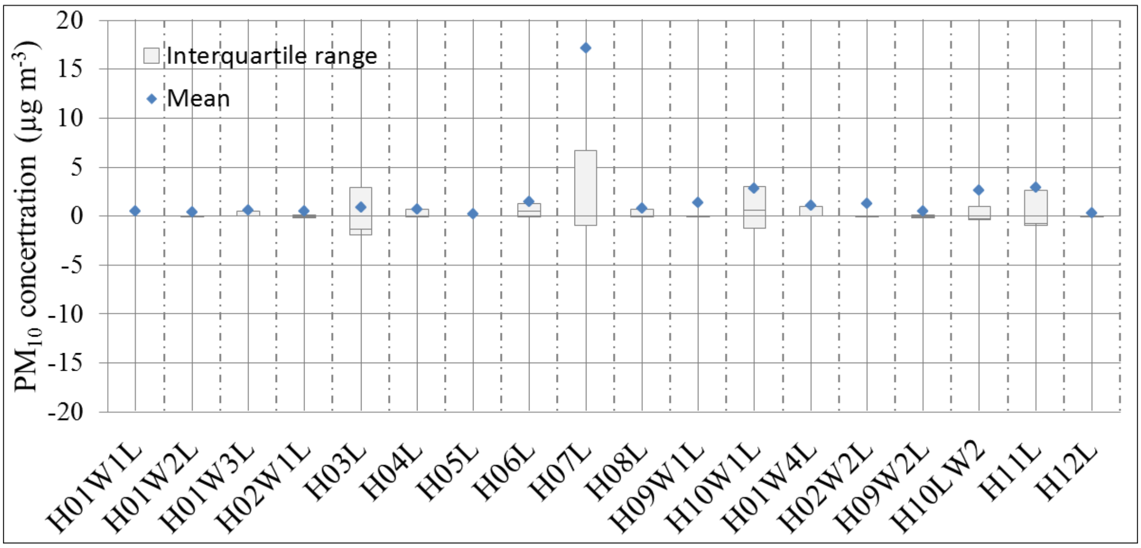


Figure 8-6 Box plot of the residuals static monitoring lounge

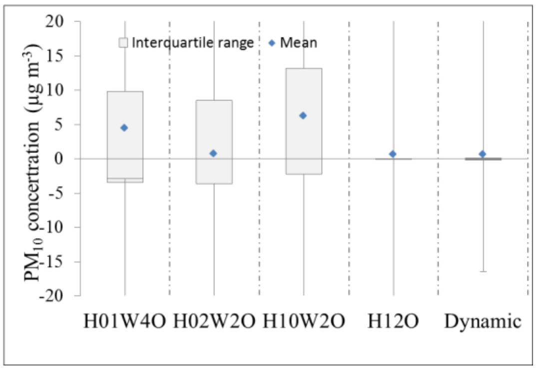


Figure 8-7 plot of the residuals static outdoor and dynamic monitoring

The outdoor residuals were not statistically significantly different across the four locations (H1, H2, H10 and H12) measured and levels of PM_{10} measured indoors simultaneously with out of doors were not statistically significantly different. Differences emerged only when comparing kitchens with other microenvironments. Residual concentrations in the kitchen were found to be the highest levels measured and were a function of the cooking duration and whether grilling or frying (which were most polluting) took place. This suggests that the decomposition method has either been unable to explain with statistical significance some of the source emissions in the kitchen due to their infrequency and /or an ambient background level prevails.

Given that outdoor measurements were made generally at the façade of the properties the final step in the research was to investigate the extent to which levels monitored in the lounges compared to those measured whilst walking along footpaths. Figure 8-7 compares the residuals with those resulting from the decomposition applied to the outdoor façade levels with that resulting from the dynamic data analysis and they are shown not to be statistically different. Therefore it follows that the residuals are not statistically different from those observed in the lounges.

8.4 Model Validation

This was achieved by superimposing components of the pdfs derived by the decomposition technique with period over which the emissions sources were prevalent in the time series. The Fityk software was then used to calculate the R^2 for the goodness of fit of the fitted distribution to the subset of the data. The goodness of fit of the model (component probability density function) to the sub-sample extracted manually by hand as being judged to be representative of the actual event distribution (cooking, night time, etc.). A number of dwellings were selected to present the performance of the decomposition as a technique appropriate for identifying particular sources of pollution within a ME separate from those being transported from outside.

Table 8-13 The R^2 value of goodness of fit of the model

Dwelling ID	Height	Centre	Width	Event	R^{2*}
H01W2 K	432.55	4.49	5.31	Night	0.64
	772.51	8.35	4.76	Activity	0.85
	32.83	25.29	10.47	Cooking	0.35
H01W2 L	250.87	2.25	1.34	Specific Nights	0.01
	715.11	6.24	7.46	Mix (Activities + Night)	0.75
	25.49	19.39	20.72	Cooking	0.58
H09 W1 L	724.42	3.28	5.83	Premises closed	0.09
	365.03	11.78	3.78	Tuesday, Wednesday and Thursday Nights	0.70
	108.54	20.64	6.68	Open Hour	0.46
H10 W2 O	899.7	5.7	4.6	Other days and times	0.93
	41.4	26	16.3	Outdoor events	0.48
	58.9	67	5.7	Outdoor events Tuesday	0.31
H10 W2 L	3356.6	1.4	1	Away from home + night	0.00
	155.6	10.9	3.5	Other night	0.79
	88.5	22	16.4	Cooking + activities	0.09
	11.9	92.2	5.6	Packing activities	0.08
H12 O	710.4	4.9	5.1	Night	0.76
	182.9	16.2	0.7	Wednesday night	0.00
	303.6	24.4	1.1	Tuesday night	0.09
	26.9	39.7	71.3	Opening hours	0.76
H12 I	1055.5	10.2	3.3	Night	0.95
	254	25.1	1	Tuesday night	0.11
	12.4	80.7	169.4	Opening hours	0.71
Dynamic Monitoring	7.6	11.8	7.1	Light free flow	0.31
	42.7	17	5.5	Steady free flow	0.20
	41.6	23.5	4.1	Heavy start/ stop	0.01

* (nonlinear curve) of goodness if fit of the model distribution of corresponded data

The results are presented in Table 8-13 which gives the statistics for the difference in the component distribution defined by the decomposition analysis and the selected sub-sample for the properties H01W2 K, H01W2 L, H09 W1 L, H10 W2 O, H10 W2 L, H12 O, H12 I and Dynamic Monitoring along with the R^2 value of the nonlinear curve fitted which shows the goodness of fit of the model to evaluated. The R^2 value varied from 0.01 to 0.95. The low R^2 value was due to several reasons. The distributions were fitted to the dataset without disaggregating data representative of source emissions caused by other events that may be occurring at the same time or have occurred prior to the current event but the dispersing effects have not yet completed. The performance of the fit of the subcomponent depends on the event recurring frequently with a sufficiently high intensity and conforming to a lognormal distribution during the monitoring period to allow good statistical significance to be achieved. Indeed the model showed good prediction for the events that have distinctive features, occur frequently and conformed well to a log normal distribution. This will be illustrated by using selected examples from the Table 8-13.

Figure 8-8 for property H10W2 the specific event of residents packing prior to going away for a few days holiday shows that by selecting the time series based on the diary it is clear that the record was not sufficiently representative as other activity such as preparing a light meal was taking place at the same time as well as there being general dispersal of pollution from emissions sources that had occurred earlier in the day. This means that when the fitted distribution from the Fityk software is overlaid the performance of the fit appears to be poor (0.08). This is because the decomposition technique has explained a substantial part of the time series sample selected as being relevant to the reported period as part of other sub-components which explained activity which was occurring at the same time. In other words, the packing component in reality is superimposed on another decomposed distribution(s) which explains other activity type(s). This can be seen as being coincident with the “bump” at about 90 $\mu g\ m^{-3}$ in Figure 8-8 (left). This illustrates the power of the decomposition technique.

Similarly the low-polluting environment explained by decomposition extends over a far longer period than was selected manually as being relevant from the time series. This is because the periods outside the night time and when the residents were away, there were periods when low levels of pollution prevailed. These would become part of this fitted component as illustrated in Figure 8-8 (right). Again illustrating the power of the decomposition technique.

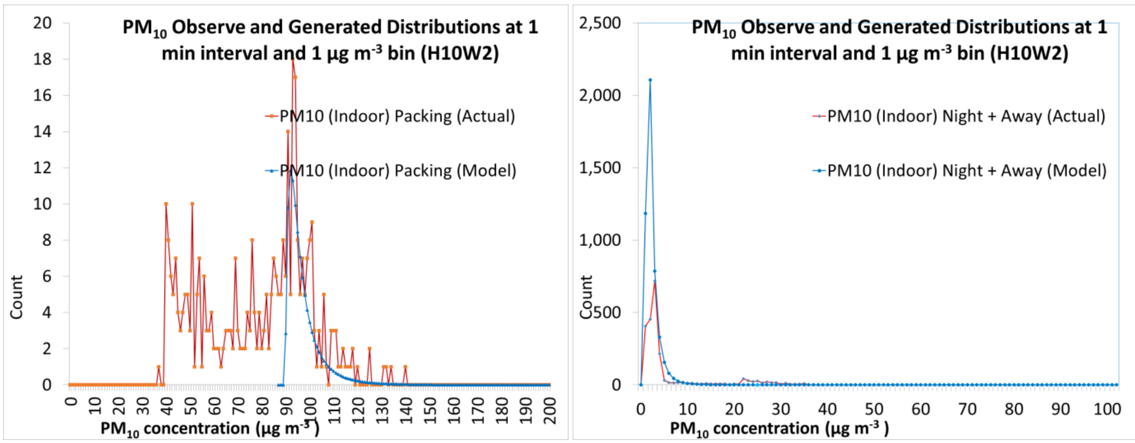


Figure 8-8 Sub components of the pdf for H10W2 fitted to by-hand selected time series data to illustrate the performance of the decomposition technique

Figure 8-9 illustrates how the decomposition in each case matches the mode that is coincident with the extracted event but the effects of other simultaneous activity or of source emissions occurring earlier are masking the event as is the case for the reception area during the day. For the period when the dental practice is closed good clear consistency is observed between the modelled peak and measured peak however the decomposition due to the basic assumption of source emissions being log normally distributed is statistically assigning some of the higher levels of pollution which could be considered to be due to dispersion taking place from the activity sources occurring earlier in the day.

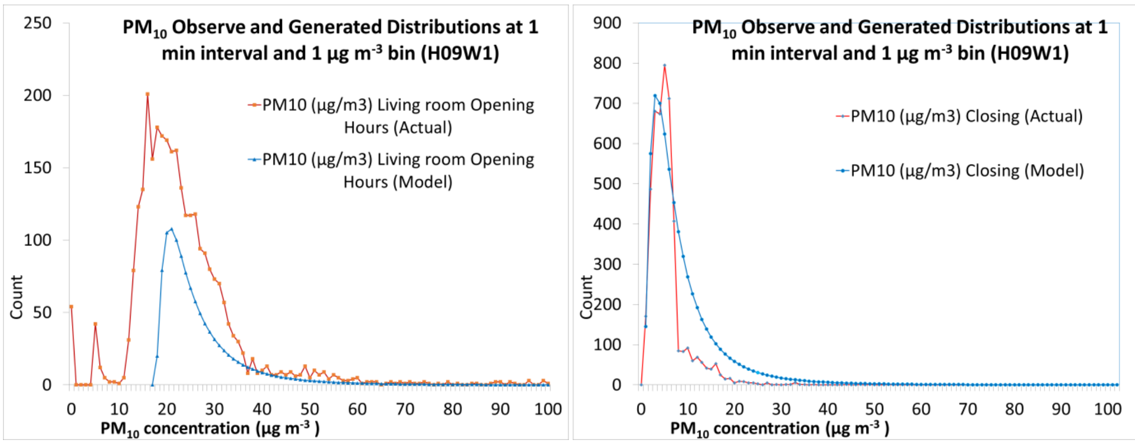


Figure 8-9 Sub components of the pdf for H09W1 fitted to the by-hand selected time series data to illustrate the performance of the decomposition technique

Alternatively, as this period corresponds to the majority of time for business premises is without occupation during closing times the lowest of pollution levels correspond mainly to the ambient background of the property which are less well predicted. In this context, it may be that the assumption of a lognormal distribution for these more ambient background environments was incorrect. Based on this analysis which has suggested that the decomposition technique has three main limitations in its application to time series pollution concentration data it is suggested that the technique performs well when pollution events:

a- have significant impact on the concentrations

b- occur frequently during the observation period to give statistical significance

c- result in concentrations that conform to the same distribution across all sources which in this research was chosen as lognormal

Certainly the analysis of individual days presented in section 6.3.8 of this thesis endorses the above and the poor prediction for dynamic monitoring is the need to consider a different distribution to the lognormal but more importantly to carry out many more survey campaigns. These shortcomings need to be examined further and form the basis of future work.

The usefulness of the decomposition technique relative to other analysis techniques such as simple inspection of time series carried out by a number of researchers that analysed concentration data along with detailed activity diaries completed either by the participants or the surveyors, now will be considered. (Jones et al., 2000; Lai et al., 2004; Saraga et al., 2011; Tan et al., 2012) showed that it was possible to associate a specific activity to a pollution event such as cooking (Tan et al., 2012) and smoking. However, as clearly demonstrated in the previous section, compared to the inspection of time series, the value of the decomposition technique is in its ability to separate an activity related event from within periods when other activity occurs. However, a limitation of the decomposition technique is in its fundamental assumption that source emissions are all governed by the same probability density function, which was shown to be log normal for the static measurements made in this study. However, evidence has emerged from this research which suggests that some source emissions (in the dynamic pdfs and the low level 'background' periods in the static measurement) may be better described by a normal distribution. Therefore, future work to allow different distributions to be fitted to the multimodal pdfs would be beneficial.

Particle composition by chemical analysis is another method of identifying the source of particulate matter. However this analysis mainly is useful for sources characterised by a unique element (such as silicon from the road/tyre interface, and platinum group elements associated with catalytic converters) or a chemical signature which reveal sources such as salt from road gritting or at the seaside outdoors, cooking including alkanes, dicarboxylic acids, lactones and polycyclic aromatic hydrocarbons and burned food etc. and from humans such as dead skin indoors. This method of speciation is quite specific to identifying the origin of a particular particle type which is not what the decomposition technique aims to achieve. Decomposition simply explains the total particle emissions associated with specific activity type. A method more similar to decomposition is using multiple regression which seeks to explain statistically the monitored levels in terms of the location, type of activity etc. Whilst regression models can be used as predictive tools, decomposition as developed in this thesis, is limited to explaining the component distributions of monitored pdfs of microenvironments. However, because the decomposition analysis separates the source emission it has the potential to develop generic distributions for types of activity such as cooking, cleaning, shredding etc. which are likely to have centre and half widths that are functions of the activity type and the duration over which that activity prevails. Therefore, there is potential to provide a method by which the total exposure can be estimated based on the known activity and their duration. This conclusion was made possible by proving that the characteristics of the recorded activity do have significant influence on the PM_{10} levels monitored and thus "families" or "clusters" responsible for multiple peaks in measured pdf were shown to exist in the overall data sets. Finally, consistent with decomposition and chemical analysis, the regression analysis research has revealed huge variations caused by the different types and prevalence of pollution source emission present in microenvironments which result in a wide range of R^2 value.

8.5 Summary

This chapter has attempted to bring together the results of the analysis of the data from the static campaigns whether collected indoor and outdoor with the dynamic. The time series plots of PM_{10} levels measured inside properties, whether on main, minor or residential roads, have revealed complexity. In addition, pollutant levels were dominated by the sources whether it is cooking in the kitchen; children playing in the lounge, shredding paper in the dentist or collection of refuse outdoors. The characteristics of the recorded activity, cooking, cleaning, shredding, window open etc. do have similar influences on the PM_{10} levels monitored in properties which means that "families" or "clusters" exist in the overall data sets and are responsible for multiple peaks in the pdf. In order to address the key research question as to whether there is a measureable change in ambient pollution inside a building due to traffic related pollution, it is necessary to separate the "families" of data which govern the features (peaks) dominant in the pdf. Therefore, further statistical analysis was carried out, using the technique of decomposition to establish a consistent platform to allow comparison between microenvironments whether static or dynamic.

Firstly, the technique of decomposition was used to explore the characteristics of the multimodal pdf which were found to typify the activity (cooking, cleaning, shredding, opening hours etc.) taking place in these twelve properties. The pdf of each microenvironment, namely kitchen, lounge and outdoor, was separately fitted with up to five component lognormal distributions by systematically applying the decomposition technique employing the Fityk software. All R^2 values of fitting to the weekly data with a curve which comprised of a set of component distributions were greater than 89%. The time series plot for each microenvironment was used to identify the component distribution of the total pdf. Indoor characteristics included cooking, night time and day time, opening and closing hours etc. This technique was useful in classifying the component distributions into night time, during the morning and cooking as well as in most cases other activities. However, on a number of occasions, it was not possible to identify precisely the distribution characteristic due to the limited data that was recorded by the householder or staff, however given the activity pattern over the remainder of the week inferences were possible. Decomposition was demonstrated to be promising to classify the distributions in a generic way. However, its performance in identifying particular features depended on the significance of their impact, their recurrence and whether they conformed to the same distribution namely lognormal.

For properties H01, H02 and H05, cooking activity was associated with high levels in the kitchen compared to the lounge where the kitchen was separated from the lounge by a door only. This suggested that pollution was being brought into the lounge from the kitchen. However, this was not the case for property H08 where cooking activity was not associated with higher levels in the lounge. The lounge in H08 is in a separate room without an interconnecting door and separated by a long (3m) hall and both lounge and kitchen doors remained closed most of the time so there was limited transport of pollution from the kitchen. In addition, it was more surprising that the levels were higher in the lounge. However, the lounge has a door into a conservatory with doors used for frequent to access the outdoors which offers a potential explanation. The reported differences in activity in H01 with more cooking in preparation for Ramadan resulted in elevated levels over longer periods. Cooking activity, as expected, was associated with the highest of levels in the lounge across properties with interconnecting doors into the kitchen with the exception of property H10W2 due to a specific event of packing to go away for a short break. Night time levels were consistently lower than day time activities in all properties except H11 which could not be investigated further due to the diary records were not completed. For property H10W2 given the majority of time was spent away from home measured the lowest of PM_{10} levels due to the absence of indoor sources. The most interesting result in H01W3 was when the door at the rear of the property and windows were left open, centre levels were high in the kitchen and lounge with narrow widths. This suggested that pollution was being brought into the property from outside (a busy signalised junction was close by) and rendered levels fairly evenly within both the kitchen and lounge. This was found to be due to meteorological conditions related to a pollution episode registered by AURN measurements.

For properties H09 and H10 in the first campaign, the pdf was derived for each day of the week before the decomposition analysis was carried out to identify the component distributions as before. It was clear that the decomposition technique and time series plots were able to characterise specific events occurring in the 24 hour periods and revealed further features such as in H09 the opening hours were disaggregated into morning and evening period although the morning of the Monday corresponded to a different day to the evening when monitoring started on the afternoon of the previous week. In addition, decomposition was able to detect an outdoor event in property H08.

Specific events also were associated with high PM_{10} levels outdoor of the properties H01, H02, H09 and H10 during the second campaign. The analysis suggested that pollution was caused by such events, as refuse collection and grass cutting, which contributed significantly to background levels. Specifically, PM_{10} levels outdoor varied from day to day often gradually increasing during the day and much lower overnight. But this was seen not to be the case on some days. Property H02 outdoor levels very closely tracked indoor levels and this pattern was consistent with features observed at H01 and can be explained in terms of the absence of indoor pollutant sources. This suggested that outdoor pollution was infiltrating indoor at property H02.

Given that the distribution of residuals were not normal non parametric tests were used to compare microenvironments to establish whether they were statistically significantly different from zero. The results showed that for the four properties measured, outdoor levels were statistically significantly similar across all outdoor locations which were spread over 6 km^2 and 193 days of monitoring and no statistical significant difference was found between indoor (lounge/business) compared to outdoor. Levels each week over three weeks in first campaign measured within property H01 statistically significant differences were evident and governed by the type and duration of activity. The highest of levels were observed at the façades of buildings due to dispersion effects governed by the orientation of the road with respect to the wind direction. However, the roadside exposure was greater than at facades because higher levels prevailed for a longer duration. Peak levels of pollution in the kitchen were the highest but the exposure to pollution levels was lower than at either the roadside or façade of buildings outdoors. The lounge/business microenvironments exhibited lowest of exposures.

A great deal of structure was evident with the “long tails” for the distribution of dynamic monitoring data. The peak at about 26 µg m^{-3} monitored during the dynamic campaign is coincident with congestion and heavy traffic along the Gosforth High Street. Also, the higher proportion of PM_{10} levels (≈40 µg m^{-3}) in the dynamic campaign are likely to be due to the build-up of pollution due to canyon and meteorological influences. Whilst the decomposition technique demonstrated the ability to identify the individual events causing the significant contribution to the total pollution over the period of a campaign, that fitted to the dynamic data performed less well compared to the static monitoring. This model has estimated the likely to improve by using a different distribution for fitting of subcomponents. In fact ideally the overall performance of the decomposition technique applied to the pdf may be improved if different distributions could be used to explain the source components rather than the same distribution having to be used. The software employed in this study cannot handle the fitting of different subcomponent distributions. When the transient events in the tails (more specifically for the dynamic measurements) occur less frequently then they are unexplained with statistical significance using the decomposition technique and therefore they have a bias on the residuals not allowing them to be normally distributed. This limitation means that it was not possible with statistical significance to prove that properties located on quiet rather than heavily traffic road have lower ambient indoor background levels. The next and final chapter will summarise finding, draw conclusions and outline future.

9 Summary, Conclusions and Future Work

This chapter provides a brief a summary of the research conducted and limitations are presented, a number of conclusions emerging from this study are highlighted and future research is presented.

9.1 Summary

There are many studies which have observed the link between indoor and outdoor pollution. The fabric of a building, such as doors, windows and ventilation, has an important factor on outdoor pollution infiltration to the building (Ní Riain *et al.*, 2003; He *et al.*, 2004; Chun Chen and Zhao, 2011; Saraga *et al.*, 2011). Building occupants are exposed to air pollution that is composed of indoor sources (eg. cooking and smoking) and infiltrated outdoor pollution. Typically, people spend more than 80% of their time indoors as a result, they are exposed to indoor and infiltrated outdoor air pollution.

Dynamic and static monitoring of traffic pollutants has been conducted in streets by a number of studies (Ní Riain *et al.*, 2003; Kaur *et al.*, 2005a; Murena and Favale, 2007; Briggs *et al.*, 2008; Heudorf *et al.*, 2009; Zhang and Batterman, 2009; McAdam *et al.*, 2011). In addition, personal exposure has been investigated in depth for vehicular modes of transport (De Bruin *et al.*, 2004; J. Gulliver and Briggs, 2004; John Gulliver and Briggs, 2007; Briggs *et al.*, 2008; Zhang and Batterman, 2009), but pedestrian personal exposure has not been examined to the same extent. A series of research projects confirm that indoor air pollution is influenced by indoor activities as well as outdoor air pollution levels (Heudorf *et al.*, 2009; Boogaard *et al.*, 2011; Lawson *et al.*, 2011; Saraga *et al.*, 2011; Tan *et al.*, 2012). Some of these activities are identified as smoking and cooking indoors and road traffic levels outdoor in the vicinity of the property. The pollutants have an effect on the human health. This effect depends on exposure duration and type of pollutant. There are two type of monitoring either personal monitoring or static monitoring (monitor station, outdoor/indoor monitor) (P. J. Lioy and Pellizzari, 2008).

The aim of this study was to investigate PM_{10} exposure to indoor and outdoor air pollution as a function of indoor activity patterns and traffic flow regimes in streets in urban areas to achieve this aim. A number of sites along quiet, busy and congested roads were selected. Two types of data were collected namely PM_{10} levels and personal activity diaries. In addition, dynamic exposure to air pollution whilst walking along a road in an urban area in the UK was investigated. The High Street in Gosforth was selected for this study and meta data collected to map air pollution levels onto traffic flow regime based on observation. Also, application of a novel approach analysis was adopted by using the decomposition technique which was applied to both static and dynamic measurements thus to create a consistent platform for comparing results.

This research was conducted to record static and dynamic measurements of PM_{10} inside and outside the air quality management area, in Gosforth, Newcastle upon Tyne. PM_{10} levels were measured at fixed locations at several houses and commercial premises, and each was monitored for a minimum period of five to seven days duration. PM_{10} measurements were taken in kitchens, lounges/indoors of business premises and outdoor at number of houses and commercial properties. The participants recorded their activities, such as cooking, vacuum cleaning and door opening, in a diary. An observer carried a portable particulate matter PM monitor (TSI DustTrak 8534) and a GPS monitor inside a back pack and walked on the pavement on a specific route along High Street Gosforth, for dynamic monitoring along a busy radial road. Also, the observer made notes of the traffic condition, passing of HGV and buses, crossing of junctions and other activities which was deemed to have an influence on PM levels such as construction work and persons smoking.

For all of the dynamic monitoring campaigns, Arc GIS software and statistical techniques were required to map spatial and temporal variations of PM_{10} measurements. Timestamps of traffic activities and events were aligned with the time series data for the dynamic monitoring to help identify their influence on PM_{10} levels. Similarly time series plots were produced of static PM_{10} measurements to gain a better understanding of temporal variations and activities such as cooking, cleaning were noted synchronised time. It was observed that cooking, doors and windows opening and vacuum cleaning have stronger bearing on indoor PM_{10} concentrations for static monitoring. However, outdoor PM_{10} levels were governed more by the stop-start and idling characteristics rather than level of flow and given the high variation in levels both indoor and outdoor, pollution originating outdoors had little influence on temporal variations in indoor PM_{10} over time in the day. This research has concluded that outdoor PM_{10} levels along a busy traffic route can be influenced by traffic particularly in the vicinity of junctions and pedestrian crossings, construction activities and passing of buses close to the observer. In addition, this research has shown that indoor levels can be quite different to outdoor and they are not always correlated with ambient level or traffic but depend also on indoor activities such as cooking and vacuum cleaning.

The application of the basic theory of the statistical technique known as 'decomposition' to reveal features in the probability density functions (pdfs) derived from static and dynamic measurements (indoor/outdoor) was presented. Decomposition is a statistical technique used to characterise the contribution of various sources and events component distributions to the total indoor and outdoor PM_{10} levels to provide a richer understanding of whether exposure is influenced by the traffic flow regimes in the vicinity of properties. The decomposition technique can be used to fit multi modal distributions to explain the sources of measured indoor PM_{10} levels in houses and commercial premises and in this research indoor and outdoor pdfs were mainly characterised by three or more log-normal distributions. The component distributions indoors included cleaning, cooking, sleeping and outdoors, traffic activity, street works. The Decomposition technique was found to be useful for application to both indoor and dynamic PM_{10} levels to help us explain the variations in PM_{10} levels. Typically, multi-lognormal distributions explained about 93% to 98% and 88% of the measured variance for indoor and outdoor respectively. The decomposition technique identified cooking, doors and windows opening and vacuum cleaning had the stronger influence on indoor PM_{10} concentrations. The author has not identified any other studies which have used the decomposition statistical technique to analyse dynamic and static indoor/outdoor monitoring in the same urban area to establish relative levels of exposure in the different microenvironments and determine the contribution of various activities and events to personal exposure levels.

9.2 Limitation

This research has strived to obtain a greater understanding of air pollution levels inside and outside properties near urban roads using the novel statistical approach known as convolution. In spite of its extensive analysis beyond what is currently available in the literature, this research has limitations. The first limitation was the lack of sufficient traffic data near to the properties study to classify the roads as congested, busy or quiet. Therefore, the survey sites were classified based on type of road near the property such as side road or main with traffic activity (refuse collection) or commercial activity such as loading/unloading or pedestrian conflict.

The study also relied on householders recording specific activity during the full week monitoring period. On a number of occasions, it was not possible to identify precisely the distribution characteristic due to the limited data that was recorded by the householder or staff. Given time pressures on family life and businesses residents/workers were not able to record all activities. However, across all the monitoring periods sufficient meta data concerning activities was collected to develop an improved understanding of the causes of the higher pollution emitting activity.

Another limitation was that the component distributions identified by the decomposition technique were matched with activity subjectively. This means that the characteristics, cooking, night time and day time were associated with a component distribution of the total pdf subjectively. The interquartile of each fitted distribution was identify on the time series figure then categorised or explained based on the logged events or time of day of occurrence.

The DustTrak 8534 is known to underestimate the actual PM_{10} levels according to the literature which was one of the limitations. The DustTrak 8534 measurement is based on photometric measurement which estimates PM_{10} mass based on the Arizona Test Dust calibration factor. Consequently, this does not give actual PM_{10} levels. Therefore, this limitation of the device has to be kept on mind throughout this thesis. The availability of only two monitors limited the monitoring to selected locations only. Ideally a larger number of monitors to measure pdfs at more locations simultaneously could have provided more comprehensive dataset.

9.3 Conclusions

The main conclusions that can be drawn from this research are as following:

1) Static pilot study:
    a. The proposed methodological approach was appropriate and should yield statistically significant results.
    b. Knowledge regarding the occurrence of polluting related events to be logged by participants was very important therefore given the pressures on individuals' time it was requested that the diaries be completed for at least one week day and one weekend day.
    c. The results showed that the sharp spikes of PM_{10} levels were associated mainly with using gas cooker events consistent with other studies (Jones *et al.*, 2000; Lai *et al.*, 2004; Tan *et al.*, 2012).

2) Static and dynamic monitoring campaigns

a. Generally kitchen levels were higher than those measured in lounges except for property H08. Homes with a hall separating the kitchen from the lounge experienced the lowest of levels. There was an indication that the use of an extractor fan and when the window was opened pollution levels indoors were reduced. These results were consistent with the findings of other studies (Aizlewood and Dimitroulopoulou, 2006; Chun Chen and Zhao, 2011; Dimitroulopoulou, 2012).

b. During one ventilation event (opened window during daytime H01W3) on a day when a pollution episode was registered as high by the AURN measurements, pollution was being brought into the property from outside and rendered levels fairly evenly within both the kitchen and lounge. This observation was consistent with Chun Chen and Zhao (2011) who concluded that indoor/outdoor ratio would be equal to one in case of opening the windows.

c. Specific outdoor events, such as refuse collecting and grass cutting, were associated with high levels outdoor across the properties and contributed statistically significantly to outdoors background levels.

d. For property H10W2, the majority of the time was spent away from home explains the lowest levels of indoor pollution due to the absence of indoor activities sources. Also, the indoor levels were lower than outdoor during the absence of indoor pollutant sources (Kingham *et al.*, 2000).

e. Due consideration of the prevailing wind direction in relation to each property within the decomposition analysis revealed that H01W4, H02W2 and H10W2 were most affected by outdoor traffic related pollution but non the less the extremely high levels of indoor pollution source as observed in H12 can dominate outdoor levels in close proximity to the window.

f. Peak levels of pollution were measured to be at their highest in the kitchens but the exposure to pollution levels was lower in the kitchen than at either the roadside or at the façade of buildings outdoors.

g. During the first dynamic monitoring campaign the wind had a significant effect on PM_{10} levels that was similar to the finding of Buonanno *et al.* (2011). The PM_{10} levels were highest for high wind speeds demonstrating the significance of the re-suspension of particles from ground/road surface.

h. For static monitoring decomposition is a promising technique to classify the component distributions generically into night time, during the morning and cooking as well as identifying in most cases other specific activities/events.
i. The decomposition technique was also shown to be applicable to dynamic measurements and disaggregated the pdf into component sources including traffic flow regimes.
j. The performance of the decomposition technique was less for dynamic compared to the static probably due to the fact the highest of transient pollutant events (pass by of heavy goods vehicles, buses or smokers) were not sufficient in number to give statistical significance. Longer duration surveys for dynamic measurements is advised.
k. The decomposition was demonstrated to be a potential technique that was able to disaggregate overall pdfs of concentrations of PM_{10} into their components in a statistical way and thus provide an indication of concentration sources.
l. When the model was compared with simple extraction of time series concentrations associated with specific activities/events, some limitations of the application of the technique were revealed namely (i) sources of pollutants need to be significant within the sample (ii) the sources need to be distributed with the same distribution and there was an indication that background levels are normally distributed whilst the sources were lognormal and finally (iii) the residuals are distorted in the presence of transient high pollution 'spikes' that have a low occurrence and therefore are not identified with statistical confidence by the decomposition technique as being significant events.

9.4 Future Research Suggestions

1) The decomposition technique has been applied and demonstrated to show promise in explaining the variations in PM_{10} levels in the distributions of both static and dynamic PM_{10} levels. It is suggested that this technique is applied to another set of static and dynamic air quality monitoring data in similar and

different situations to demonstrate the transferability of the decomposition technique.

2) Explore ways to use different distributions (normal, log normal, geometric etc) when applied to the same multi-modal distribution.
3) Apply the technique to data from pervasive sensor monitoring in a dense network and equivalence the multi modal distributions to different traffic flow regimes depending on the position of the monitor along a link and proximity to junctions, bus stops, pedestrian crossings and traffic calming humps to gain a better understanding of the microclimates within urban street networks.

9.5 Contribution to Academic Research and Practice

Characteristics of the recorded activity, cooking, cleaning, shredding, window open etc. do have significant influence on the PM_{10} levels monitored which means that "families" or "clusters" exist in the overall data sets and are responsible for multiple peaks in measured pdf. In order to address the key research question as to whether there is a measureable change in ambient pollution inside a building due to traffic related pollution it was necessary to separate the "families" of data which govern the features (peaks) evident in the pdf. This work demonstrated the potential for the statistical technique of decomposition to explain in excess of 92% of the variation in measured pdf irrespective of being gathered statistically or dynamically.

This novel approach has provided analysis consistent with previous research and provides evidence for policy recommendations as follows:

1) Doors separating kitchens from other rooms such as hall and lounges should be kept closed especially when cooking.
2) Install or use existing ventilation equipment provided in kitchens.
3) Keep external doors and windows closed during refuse collection when pollution levels are forecast to be high.
4) Maintain low levels of dust inside property through regular cleaning and ventilate homes overnight and during periods of good air quality.
5) Avoid walking along heavily trafficked and congested street and instead use parallel streets of paths through open space taking advantage of the natural ventilation of the built environment.
6) Take every effort to reduce waiting time when crossing busy streets and junctions.

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Appendices

Appendix A Information Sheet

Personal Exposure to Air Pollution
Newcastle University

What is Personal Exposure?

Personal exposure is defined as an incident that happens when a person comes in contact with a pollutant. It refers to any form of contact, which does not necessarily mean inhaling or ingesting the pollutant. Air pollution has diverse effects on human health. Air pollution levels are influenced by the level of car exhaust emissions which vary depending on fuel type, engine size, and vehicle age. Other factors, such as speed, traffic flow regime, whether congested, busy or quiet, also influence pollution levels.

What is the purpose of the study?

The personal exposure monitoring study aims to collect information about the amount of air pollution (nitrogen oxides, carbon monoxide and particulate matter) to which people are exposed when living along quiet, busy and congested roads. It will help to characterise personal exposure to air pollution as a function of road traffic flow regime.

Who is doing the study?

The study is being carried out by the Transport Operations Research Group (TORG) at Newcastle University

Who can participate in the study?

The study will involve a number of households located in the Gosforth area of Newcastle. A number of households will be selected of which two households each will be located along quiet, busy and congested roads.

What is involved?

The study consists of three main stages and participation in all three activities is essential to create useful data sets.

Personal/household questionnaires

Each participant will be asked to complete a personal and home characteristics questionnaire at the beginning of the study. The questionnaire will take approximately 15 minutes to complete.

Air monitoring/GPS Tracking

Each participant will be asked to carry a GPS tracker during the experiment which will be used to estimate exposure. Air pollution monitoring devices will be installed by a technician in the kitchen, living room, one of the bedrooms and at a building facade.

Time/activity diary

The participants will be asked to complete an activity diary during this study. The participant will record in a diary details of when and where each activity type takes place.

What sort of questions will be asked?

The personal questionnaire will ask about age, employment status, travel, etc. The home characteristics questionnaire is interested in knowing number of rooms, ventilation, heating, etc. All information provided, including GPS tracking data and the time/activity diary, will be treated in the strictest confidence. You will be assigned a code number. The code number will appear on the all forms, so your name and personal details will be anonymous and only used for communication. When the final results of the study are published, you will not be identifiable either directly or indirectly.

How much time is involved?

The study involves air monitoring and completing a time activity diary log. This will take place over four separate one week periods. More information about the schedule for the surveys will be provided later.

Are there any risks in taking part in the study?

All devices are electrically powered, some of them need power supply and others use batteries. All the devices produce low levels of noise and devices should be placed out of the reach of children and pets.

How will I find out the results of the study?

Individual feedback and a summary of observations will be provided to each participant. The final report of research findings will be available at the Newcastle University, towards the end of the project.

Is there any incentive for the volunteers in the study?

At the conclusion of the study a voucher, worth £50 will be given to each household for taking part in all four surveys.

What if I agree to participate and then change my mind?

Taking part in the study is voluntary. After you agree to participate in the study, you can withdraw at any time without giving a reason.

Complaints / Concerns?

The Newcastle University Ethics Committee has approved this study. In case of any complaints or concerns about the conduct of the study, please do not hesitate to contact: School of Civil Engineering and Geosciences on: (0191) 222 8486.

If interested?

Please contact me at the email below with your name and contact details if you are interested in participating in the study.

Contact details:
School of Civil Engineering and Geosciences
Newcastle University
NE1 7RU, UK
E- mail: h.b.matar@newcastle.ac.uk
Contact: Mr Hamad Matar

Appendix B Consent Form

ID:______________

Consent Form

(Researcher's Copy)

Personal Exposure to Air Pollution

Thank you for agreeing to participate in this research project — Please tick box

1. I am eighteen years of age or above. ☐
2. I agree to take part in the above study. ☐
3. I confirm that I have read and understood the Information Sheet for the above study and have had the opportunity to ask questions. ☐
4. I understand that my participation is voluntary and that I am free to withdraw at any time, without giving any reason, without legal rights being affected. ☐
5. I agree to the publishing of the results of this study provided no reference is made to my personal details. ☐

--------------------------------	--------------------------------	--------------------------------
Participant	Signature	Date

--------------------------------	--------------------------------	--------------------------------
Researcher	Signature	Date

Civil Engineering and Geosciences

ID:______________

Consent Form

(Participant's Copy)

Personal Exposure to Air Pollution

Thank you for agreeing to participate in this research project — Please tick box

1. I am eighteen years of age or above. ☐
2. I agree to take part in the above study. ☐
3. I confirm that I have read and understood the Information Sheet for the above study and have had the opportunity to ask questions. ☐
4. I understand that my participation is voluntary and that I am free to withdraw at any time, without giving any reason, without legal rights being affected. ☐
5. I agree to the publishing of the results of this study provided no reference is made to my personal details. ☐

--------------------------------	--------------------------------	--------------------------------
Participant	Signature	Date

--------------------------------	--------------------------------	--------------------------------
Researcher	Signature	Date

ID:______________

Personal Exposure to Air Pollution
Questionnaire Form

Thank you for agreeing to complete this questionnaire. Many studies have observed a link between indoor and outdoor pollution. The fabric of a building (doors, windows, ventilation etc.) influences the amount of outdoor pollution entering the building. Occupants of a building are exposed to total pollution, which is composed of both indoor sources (e.g. cooking, smoking) and outdoor pollution. A number of studies suggest that most people spend more than 80% of their time indoors. There is a lack of knowledge of how much of indoor pollution is due to traffic on roads within the vicinity of the building. The pollution levels along a road will vary continuously depending on traffic flow characteristics; namely smooth, interrupted or congested. The data you provided will allow us to begin to assess the importance of traffic related pollution.

The contents of this questionnaire will be confidential. Under no circumstances will the information provided by you be disclosed to a third party.

ID: ________
Address: ______________________ ______________________ ______________________

Post Code ____________

Personal Information

1. Details of the people who usually live in the household

Household member	Age group*	Gender	Employment
1		□ Male □ Female	□ Full time job □ Part time job □ Full time student □ Part time student □ Unemployed/seeking work □ Retired □ Never worked or long term unemployment □ N/A □ Other______
2		□ Male □ Female	□ Full time job □ Part time job □ Full time student □ Part time student □ Unemployed/seeking work □ Retired □ Never worked or long term unemployment □ N/A □ Other______
3		□ Male □ Female	□ Full time job □ Part time job □ Full time student □ Part time student □ Unemployed/seeking work □ Retired □ Never worked or long term unemployment □ N/A □ Other______
4		□ Male □ Female	□ Full time job □ Part time job □ Full time student □ Part time student □ Unemployed/seeking work □ Retired □ Never worked or long term unemployment □ N/A □ Other______
5		□ Male □ Female	□ Full time job □ Part time job □ Full time student □ Part time student □ Unemployed/seeking work □ Retired □ Never worked or long term unemployment □ N/A □ Other______
6		□ Male □ Female	□ Full time job □ Part time job □ Full time student □ Part time student □ Unemployed/seeking work □ Retired □ Never worked or long term unemployment □ N/A □ Other______

* Please enter age group 1 = under 16 years, 2 = 16-24 years, 3 = 25-44 years, 4 = 45-64 years, 5 = 65-74 years, 6 = over 75 years

2. Does anybody in the household suffer from respiratory illness? □ Yes □ No

   If yes, please stated the household member here ____ ____ ____ ____ ____

   If no, please go to the next question

Commuting

3. On average, how much time each day does each family member spend commuting on a typical weekday?

Household member	Duration (minutes per day)							
	Car	Bus	Metro	Train	Motorcycle	Cycling	Walking	Other ___________
1								
2								
3								
4								
5								
6								

4. On average, how much time each day does each family member spend commuting on a typical weekend?

Household member	Duration (minutes per day)							
	Car	Bus	Metro	Train	Motorcycle	Cycling	Walking	Other ___________
1								
2								
3								
4								
5								
6								

Home Characteristics

Exposure to pollution from traffic needs to be understood in relation to the infiltration of outdoor pollution into the building. The construction material and fabric of a building has an influence on the infiltration of outdoor pollution into the building.

5. Type of Dwelling

□ Detached □ Semi detached □ End terrace

□ Centre terrace □ Apartment □ Other (Pl. specify)_______

6. Approximately, when was the dwelling built?

□ Before 1919 □ 1919-1940 □ 1941-1960 □ 1961-1980

□ 1981-2000 □ After 2000 □ Do Not Know

7. Building Characteristics

Room Type[1]	Level[2]	Floor material[3]	Type of Windows[4]		No. of Opening[5]	Ext. Fan[6]	Heating system	Other[7]
			Single glazed	Double glazed				
							Gas central heating □ Electricity □ Gas fire □ Oil □ Open coal fire □	
							Gas central heating □ Electricity □ Gas fire □ Oil □ Open coal fire □	
							Gas central heating □ Electricity □ Gas fire □ Oil □ Open coal fire □	
							Gas central heating □ Electricity □ Gas fire □ Oil □ Open coal fire □	
							Gas central heating □ Electricity □ Gas fire □ Oil □ Open coal fire □	
							Gas central heating □ Electricity □ Gas fire □ Oil □ Open coal fire □	
							Gas central heating □ Electricity □ Gas fire □ Oil □ Open coal fire □	
							Gas central heating □ Electricity □ Gas fire □ Oil □ Open coal fire □	
							Gas central heating □ Electricity □ Gas fire □ Oil □ Open coal fire □	
							Gas central heating □ Electricity □ Gas fire □ Oil □ Open coal fire □	
Kitchen							Gas central heating □ Electricity □ Gas fire □ Oil □ Open coal fire □	□ Gas Hob □ Electric Hob □ Other _____ □ Gas Oven □ Electric Oven □ Other _____
Garage								Is the garage integrated in the house? □ Yes □ No If yes, is there a door from the house to the garage? □ Yes □ No Which room has a door to the garage?

(1) Living room= 1, Conservatory=2, Study=3, Bedroom= 4, Dining room= 5, Bathroom= 6, Toilet= 7, Ensuite shower room= 8, Utility room=9.
(2) Basement (B), Ground floor (G), First (1), Second (2), Third (3) Level etc.
(3) Floor material: concrete, wood, laminated wood , carpet tile or other (specify).
(4) Indicate how many windows are single and double glazed at each room.
(5) Number of window panes which could be opened at each room.
(6) Extractor Fan
(7) Indicate the location of the boiler (B) and how many coal fires.

Exposure

We need to understand the exposure to pollution from indoor sources such as heating, cooking, commuting, cleaning (vacuuming) and smoking sources.

Cooking

8. On average, how much time do you spend for cooking (minutes per day)

	Cooking (minutes per day)		
	Hob	Oven	Microwave
On a weekday			
On a weekend			

9. When cooking, please indicate the frequency of the following activities:

	Never	Rarely	Sometimes	Often
Opening the window in the kitchen	□	□	□	□
Using an extractor fan	□	□	□	□

Ventilation

10. In the warm weather do you use? □ Fan □ Air-conditioning □ Other________

11. During the warm weather please indicate the frequency of the following activities when any of your family members are at home:

	Never	Rarely	Sometimes	Often
Opening the windows during the day time	□	□	□	□
Opening the trickle vent during the day time	□	□	□	□
Opening the windows during the night time	□	□	□	□
Opening the trickle vent during the night time	□	□	□	□

12. During cold weather please indicate the frequency of the following activities when any of your family members are at home:

	Never	Rarely	Sometimes	Often
Opening the windows during the day time	□	□	□	□
Opening the trickle vent during the day time	□	□	□	□
Opening the windows during the night time	□	□	□	□
Opening the trickle vent during the night time	□	□	□	□

Cleaning

13. On average, please indicate the frequency of the cleaning each week:

	Never	1-2	3-4	More than 4
Using a vacuum cleaner	◻	◻	◻	◻
Using sweeping broom/brush	◻	◻	◻	◻
Clean surfaces by wet/dry cloth	◻	◻	◻	◻

Smoking

14. Exposure to pollution from traffic needs to be understood in relation to other sources such as smoking, cooking and heating. If a household member smokes, please enter the number of cigarettes /weight of tobacco that is consumed in the household per day.

Household member	Cigarettes (number)	Cigars (number)	Pipe tobacco (oz.)
1			
2			
3			
4			
5			
6			
Visitor			

15. Please indicate how often the following items are burned in the household.

	Number each week				
	Never	1-2	3-4	5-7	More than 7
Candles					
Essential oil					
Incense					
Other _______					

ID:______________

Personal Exposure to Air Pollution
Questionnaire Form

Thank you for agreeing to complete this questionnaire. Many studies have observed a link between indoor and outdoor pollution. The fabric of a building (doors, windows, ventilation etc.) influences the amount of outdoor pollution entering the building. Occupants of a building are exposed to total pollution, which is composed of both indoor sources (e.g. cooking, smoking) and outdoor pollution. A number of studies suggest that most people spend more than 80% of their time indoors. There is a lack of knowledge of how much of indoor pollution is due to traffic on roads within the vicinity of the building. The pollution levels along a road will vary continuously depending on traffic flow characteristics; namely smooth, interrupted or congested. The data you provided will allow us to begin to assess the importance of traffic related pollution.

The contents of this questionnaire will be confidential. Under no circumstances will the information provided by you be disclosed to a third party.

ID: ________
Address: ______________________ ______________________ ______________________

Post Code ____________

Personal Information

16. Details of the people who usually work in the building

Staff member	Age group*	Gender	
1		□ Male	□ Female
2		□ Male	□ Female
3		□ Male	□ Female
4		□ Male	□ Female
5		□ Male	□ Female
6		□ Male	□ Female

* Please enter age group 1 = under 16 years, 2 = 16-24 years, 3 = 25-44 years, 4 = 45-64 years, 5 = 65-74 years, 6 = over 75 years

17. Does anybody of staff member? suffer from respiratory illness? □ Yes □ No

If yes, please stated the staff member here ____ ____ ____ ____ ____

If no, please go to the next question

Commuting

18. On average, how much time each day does each staff member spend commuting on a typical weekday?

Staff member	Duration (minutes per day)							
	Car	Bus	Metro	Train	Motorcycle	Cycling	Walking	Other ___________
1								
2								
3								
4								
5								
6								

19. On average, how much time each day does each staff member spend commuting on a typical weekend?

Staff member	Duration (minutes per day)							
	Car	Bus	Metro	Train	Motorcycle	Cycling	Walking	Other ___________
1								
2								
3								
4								
5								
6								

Office Characteristics

Exposure to pollution from traffic needs to be understood in relation to the infiltration of outdoor pollution into the building. The construction material and fabric of a building has an influence on the infiltration of outdoor pollution into the building.

20. Type of business

□ Bank □ Pub □ Coffee house

□ Retail store □ Office building □ Restaurant

□ Warehouse □ Medical centre □ Shopping mall

□ Other (Pl. specify)________________________

21. Type of Dwelling

□ Detached □ Semi detached □ Terrace

□ End terrace □ Apartment □ Other (Pl. specify)_______

22. Approximately, when was the dwelling built?

□ Before 1919 □ 1919-1940 □ 1941-1960 □ 1961-1980

□ 1981-2000 □ After 2000 □ Do Not Know

23. Building Characteristics

Room Type[1]	Level[2]	Floor material[3]	Type of windows[4]		No. of Openings[5]	Ext. fan[6]	Heating system	Other[7]
			Single glazed	Double glazed				
							Gas central heating □ Electricity □ Gas fire □ Oil □ Open coal fire □	
							Gas central heating □ Electricity □ Gas fire □ Oil □ Open coal fire □	
							Gas central heating □ Electricity □ Gas fire □ Oil □ Open coal fire □	
							Gas central heating □ Electricity □ Gas fire □ Oil □ Open coal fire □	
							Gas central heating □ Electricity □ Gas fire □ Oil □ Open coal fire □	
							Gas central heating □ Electricity □ Gas fire □ Oil □ Open coal fire □	
							Gas central heating □ Electricity □ Gas fire □ Oil □ Open coal fire □	
							Gas central heating □ Electricity □ Gas fire □ Oil □ Open coal fire □	
							Gas central heating □ Electricity □ Gas fire □ Oil □ Open coal fire □	
							Gas central heating □ Electricity □ Gas fire □ Oil □ Open coal fire □	
							Gas central heating □ Electricity □ Gas fire □ Oil □ Open coal fire □	
Kitchen							Gas central heating □ Electricity □ Gas fire □ Oil □ Open coal fire □	□ Gas hob □ Electric hob □ Other _____ □ Gas oven □ Electric oven □ Other _____

(1) Lounge = 1, Office room=2, Meeting room= 3, Toilet= 4, Utility room=5.
(2) Basement (B), Ground floor (G), First (1), Second (2), Third (3) Level etc.
(3) Floor material: concrete, wood, laminated wood, carpet tile or other (specify).
(4) Indicate how many windows are single and double glazed at each room.
(5) Number of window panes which could be opened at each room.
(6) Extractor fan
(7) Indicate the location of the boiler (B) and how many coal fires.

Ventilation

24. In the warm weather do you use? □ Fan □ Air-conditioning □ Other________

25. During the warm weather please indicate the frequency of the following activities when any of your staff members are at the building:

	Never	Rarely	Sometimes	Often
Opening the windows during the day time	□	□	□	□
Opening the trickle vent during the day time	□	□	□	□
Opening the windows during the night time	□	□	□	□
Opening the trickle vent during the night time	□	□	□	□

26. During cold weather please indicate the frequency of the following activities when any of your staff members are at the building:

	Never	Rarely	Sometimes	Often
Opening the windows during the day time	□	□	□	□
Opening the trickle vent during the day time	□	□	□	□
Opening the windows during the night time	□	□	□	□
Opening the trickle vent during the night time	□	□	□	□

Cleaning

27. On average, please indicate the frequency of the cleaning each week:

	Never	1-2	3-4	More than 4
Using a vacuum cleaner	□	□	□	□
Using brooms/brushes	□	□	□	□
Cleaning surfaces by wet/dry cloth	□	□	□	□

Appendix E Activity Diary

Newcastle University

Activity Diary

Study ID:____________ Day of week: ____________ Date: ____/____/______

Time Activity Diary Instructions

- Please complete the diary for each 30 minutes of activity.
- Example: During 30 min that started at 08:30 hrs you prepare your breakfast and then walk to the metro station. Record details the Activity Description box identifying the location using Location Category Code (see below).
- Provide details as appropriate regarding cooking, smoking and ventilation as shown below.

Day	Time	Activity Description	Location	Near Smoker (mins)	Cooking (mins)	Window (open/closed)	Extractor Fan (on/off)
1	08:30	Making a breakfast Walking to metro station	IHK OF	-- --	5 min --	Open --	On --

Thank You

Activities Example List

Sleeping	Computer Work	Laundry
Shower/bath	Reading	Cleaning
Cooking	Watching TV	Washing
Eating		Ironing
Walking	Social Interaction	
	Leisure	Office
Commuting (driver)	Dancing	Shopping
Commuting (passenger)	Exercising	Other (please specify)

Location Category

Indoor At Home		Indoor Away From Home		Travelling	
Lounge	IHL	Work	IAW	Car	TC
Bedroom	IHB	Restaurant/bar	IAR	Bus	TB
Kitchen	IHK	Shopping	IAS	Metro	TM
				Rail Train	TR
				Other	TO
Outdoor At Home		**Outdoor**			
Yard	OHY	Park	OP		
Facade (at door)	OHF	Footpath	OF		
Driveway	OHD	Playground	OPG		
Garden	OHG				

Day	Time	Activity Description	Location	Near Smoker (mins)	Cooking (mins)	Window (open/closed)	Extractor Fan (on/off)
1	07:00						
1	07:30						
1	08:00						
1	08:30						
1	09:00						
1	09:30						
1	10:00						
1	10:30						

Day	Time	Activity Description	Location	Near Smoker (mins)	Cooking (mins)	Window (open/closed)	Extractor Fan (on/off)
1	11:00						
1	11:30						
1	12:00						
1	12:30						
1	13:00						
1	13:30						
1	14:00						
1	14:30						

Day	Time	Activity Description	Location	Near Smoker (mins)	Cooking (mins)	Window (open/closed)	Extractor Fan (on/off)
1	15:00						
1	15:30						
1	16:00						
1	16:30						
1	17:00						
1	17:30						
1	18:00						
1	18:30						

Day	Time	Activity Description	Location	Near Smoker (mins)	Cooking (mins)	Window (open/closed)	Extractor Fan (on/off)
1	19:00						
1	19:30						
1	20:00						
1	20:30						
1	21:00						
1	21:30						
1	22:00						
1	22:30						

Day	Time	Activity Description	Location	Near Smoker (mins)	Cooking (mins)	Window (open/closed)	Extractor Fan (on/off)
1	23:00						
1	23:30						
2	00:00						
2	00:30						
2	01:00						
2	01:30						
2	02:00						
2	02:30						

Day	Time	Activity Description	Location	Near Smoker (mins)	Cooking (mins)	Window (open/closed)	Extractor Fan (on/off)
2	03:00						
2	03:30						
2	04:00						
2	04:30						
2	05:00						
2	05:30						
2	06:00						
2	06:30						

Cooking Diary

Study ID:______________ Day of week: ____________ Date: __/__/____Time

Activity Diary (version 1.1) July 2011

Time Cooking Activity Instructions

- Please complete the diary for each time you have done cooking activity.
- Example: During 20 min that started at 19:00 hrs you prepare your diner. Record details the Cooking Activity box identifying the type cooking.
- Provide details as appropriate regarding cooking, ventilation, etc. as shown below.

Day	Time	Cooking Activity	Kitchen Door (open/Close)	Cooker Type	Cooker (mins)	Window (open/Trickle/ Close)	Extractor Fan (On/Off)
01/06/2012	19:00	White Rice	Open	Gas cooker	20 min	Open	On
01/06/2012	19:05	Meat	Open	Electric Grill	15 min	Open	On

Cooking Activity such as:
Cooking pizza, Frying, Grilling, Boil water, etc.

Cooker Type such as:
Microwave, Oven, Stove, Toaster, etc.

Day	Time	Cooking Activity	Kitchen Door (open/Close)	Cooker Type	Cooker (mins)	Window (open/Trickle/ Close)	Extractor Fan (On/Off)

Cleaning Diary

Study ID:______________ Day of week: ____________ Date: __/__/____Time

Time Cleaning Activity Instructions

- Please complete the diary for each time you have done cleaning activity.
- Example: During 20 min that started at 19:00 hrs you clean the house. Record details the Cleaning Activity box identifying the type cleaning .
- Provide details as appropriate regarding cleaning, location, etc. as shown below.

Day	Time	Cleaning Activity	Location	Window (open/Trickle/ Close)	Door	Other
01/06/2012	19:00	Hovering	Living room	Open	Open	

Day	Time	Cleaning Activity	Location	Window (open/Trickle/ Close)	Door	Other

Newcastle University

Civil Engineering and Geosciences

Occupancy Diary

Study ID:______________ Day of week: ____________ Date: __/__/____

Time Occupancy Diary Instructions

- Please complete the diary at 30 minutes interval for a typical day.
- Example: During 30 min that started at 09:00 am two occupants are in the reception/office. Record the number of occupants in the box.
- Provide details as appropriate regarding ventilation, etc. as shown below.

* Smoking: please record if someone smoked near façade of the building.
** Please record other activities or evens such as cleaning/hovering

Time	Number of Occupants	Main Door (Open/Close)	Window (Open/Trickle/Close)	Smoking *	Fan (On/Off)	Others **
09:00	2	Open (3)	Open	2 min	On	
09:30	5	Close	Trickle	-	On	

Time	Number of Occupants	Main Door (Open/Close)	Window (Open/Trickle/Close)	Smoking *	Fan (On/Off)	Others **
8:00						
8:30						
09:00						
09:30						

Appendix H Field Work Procedure

Power Supply and Software

All equipment must be recharge before each trial, and DusTrak must be turned on in order to be recharge.

Install Qstarz and HOBOware software's for GPS tracker and Langan

Equipment Setup Procedure

GPS – Qstarz

1. Setup the computer clock to GPS time (GMT time) with consideration of time daylight savings, see the link to edit the time : http://wwp.greenwichmeantime.com/
2. Plug in via USB to the computer and the device should be in log mode.
    a. Open the Q Travel programme
    b. File > Configure GPS > Log Criteria > Log Criteria (choose time, setup for one second)
    c. File > Configure GPS > Log Criteria > Log Memory (up to a maximum of 4days)
    d. Set schedule: Date and time
    e. Time on bottom right of screen ensure it is set to London GMT and daylight savings is unselected

Langan n15 Carbon Monoxide Monitor

1. Attach via USB to the computer
2. Open HOBOware software
3. To configure
    a. Device > Launch > HOBO > Log Interval (choose)
    b. Device > Launch > HOBO > Date + Time (should sync with computer and therefore GPS)
    c. Device > Launch > HOBO > Delayed start (Note: this clears the memory of the unit.)

Particulate Monitor – dustrak drx8534

1. This does not require installation of any software.
2. Time
    a. Sync time with compute

b. Settings > Time + Date

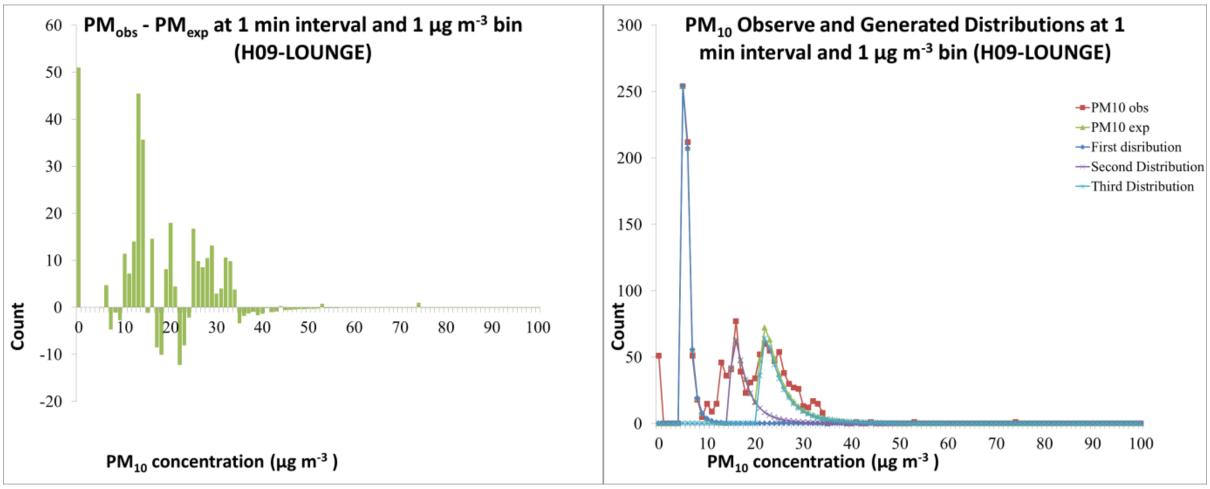
3. Calibration
    a. Setup> record calibration + filter info
    b. Zero calibration > attach calibration pipe > start (this takes 1 minute)
4. To collect data
    a. Main > start

Backpack

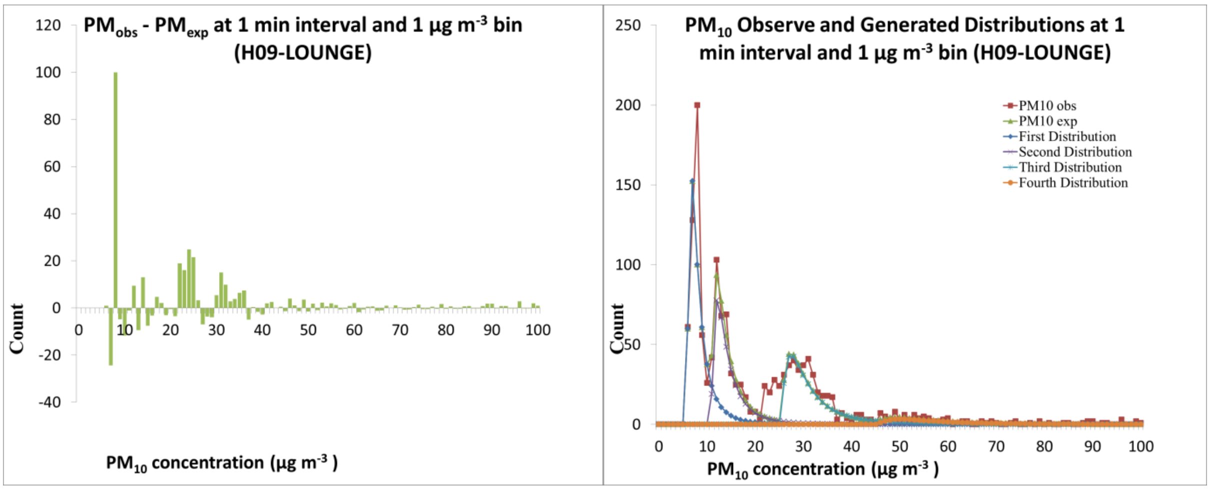
1. Must wear yellow jacket
2. Assemble 2 part pipe to PM monitor and insert rubber tube, which attaches to unit and sticks above the end of the tube.
3. Position the DustTrak vertically in the main compartment.
4. Conduct zero calibration for the DustTrak and then start data collection.
5. Langan's are attached to each shoulder strap – ensure these are the same way up and correctly labelled (S- Right, L – Left). Note: this equipment is not waterproof.
6. Logbook – log weather and busyness of bus/metro/road.

Import files

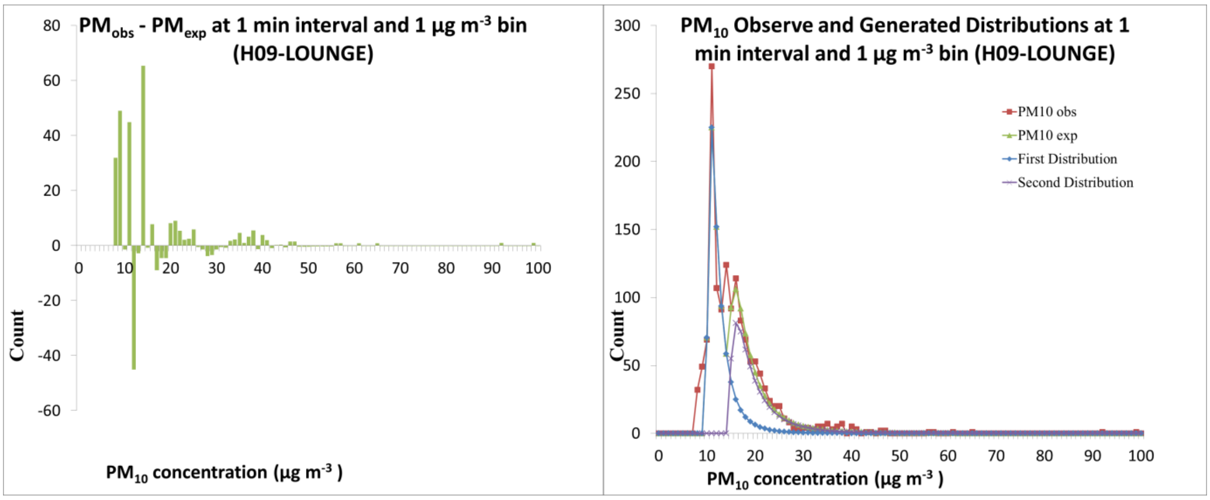
1. From Qstarz
    b. File> Read device Log > select trial
    c. File > Export wizard > MS Excel file (this save this in csv. Format)
    d. N.B. To transfer to GIS longitudes must be adjusted to negative
2. From Langan
    a. Device > Readout > Ok > Save > Plot
    b. File > Export table data > Export single file (csv.)
    c. This data can be correlated with GPS using time
3. From Dusttrak
    a. USB – save all (csv) *Note: Files are easily overwritten so change the names when transferred
    b. Files automatically save into a folder starting 8534…..
    c. This records PM2.5-5-10. Must decide which to measure and be consistent
    d. Put start time adjacent to first reading and add a second to sync
4. Use time as comment variable to establish master dataset.



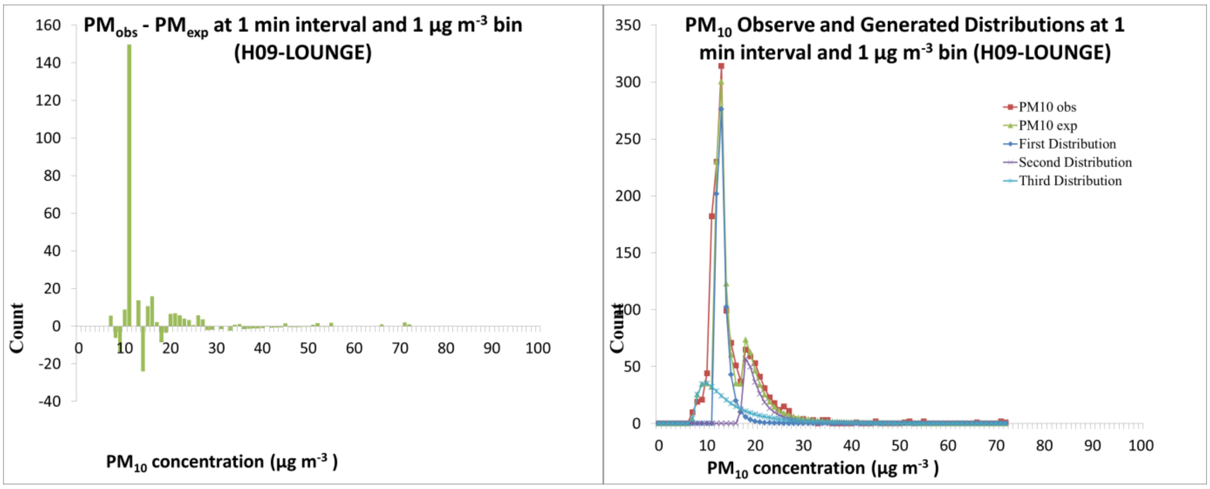
Appendix I PM$_{10}$ Distributions at H09 on Monday (Monitored, Modelled and Residuals)



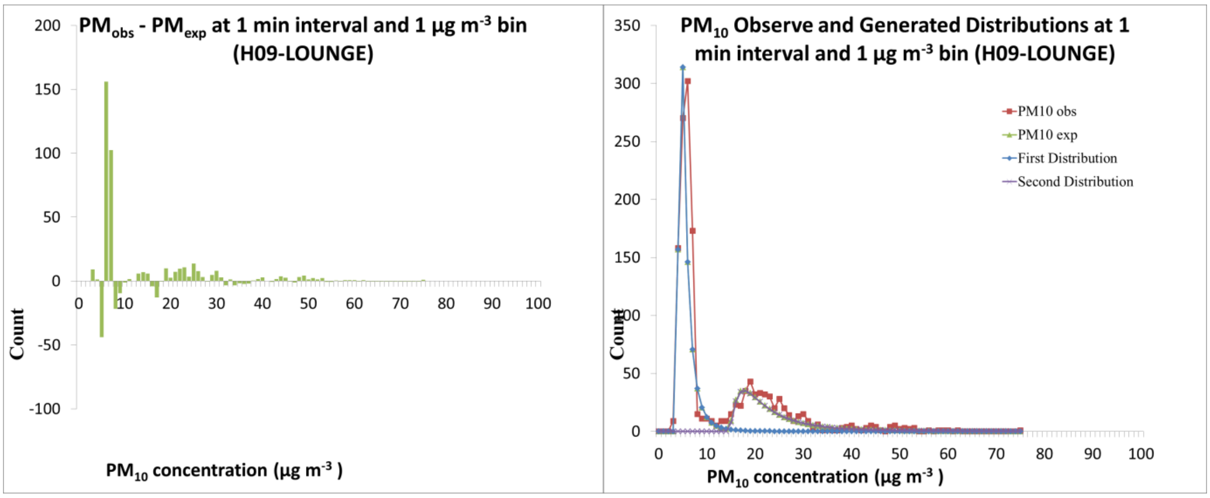
Appendix J PM$_{10}$ Distributions at H09 on Tuesday (Monitored, Modelled and Residuals)



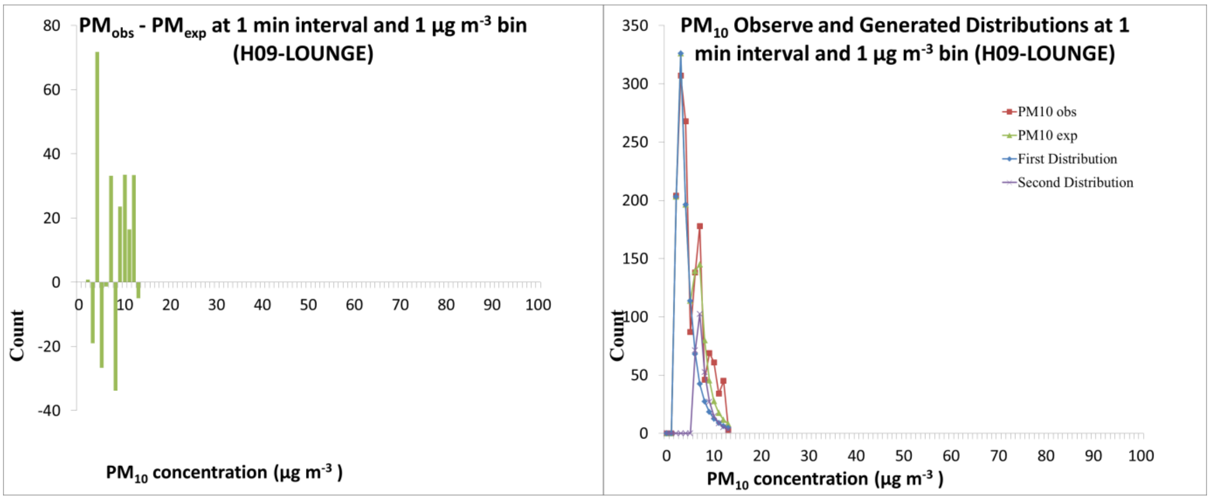
Appendix K PM$_{10}$ Distributions at H09 on Wednesday (Monitored, Modelled and Residuals)



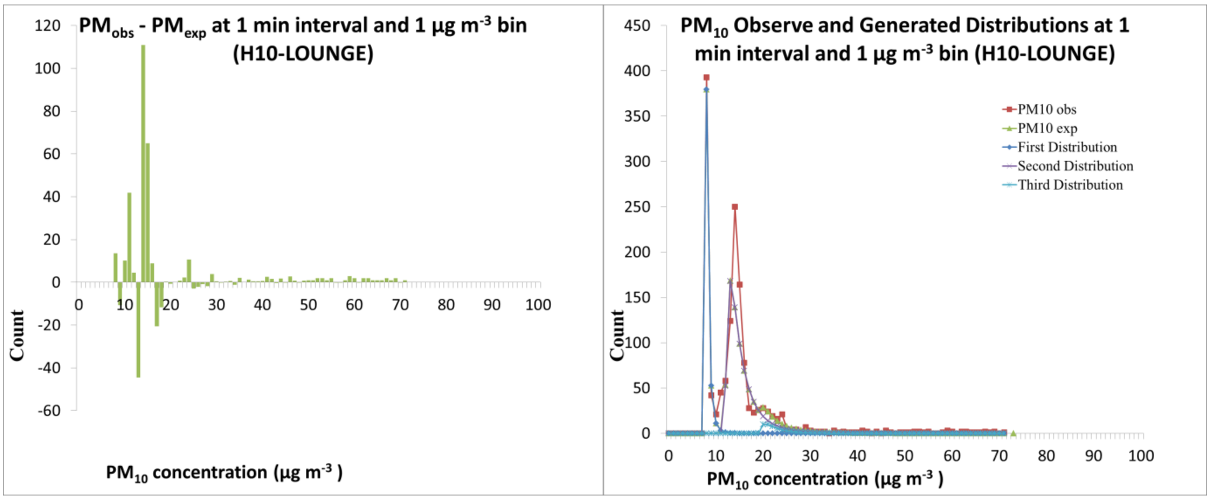
Appendix L PM_{10} Distributions at H09 on Thursday (Monitored, Modelled and Residuals)



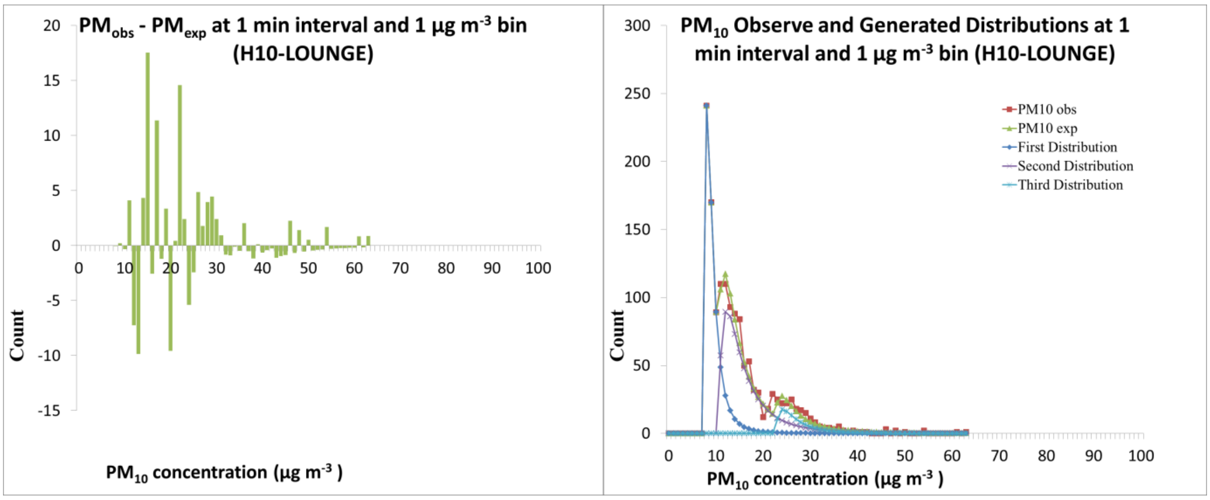
Appendix M PM_{10} Distributions at H09 on Friday (Monitored, Modelled and Residuals)



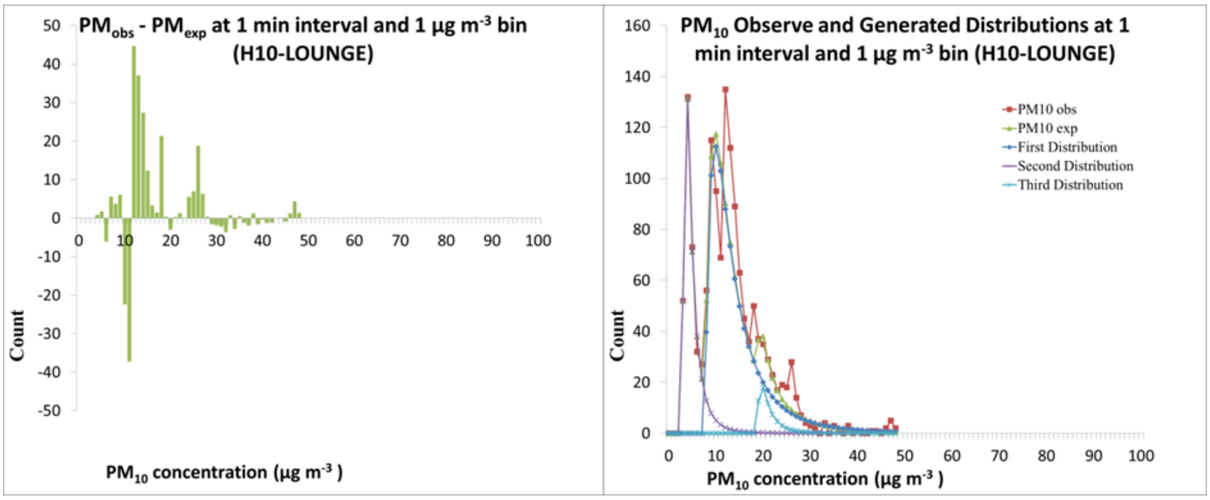
Appendix N PM_{10} Distributions at H09 on Saturday (Monitored, Modelled and Residuals)



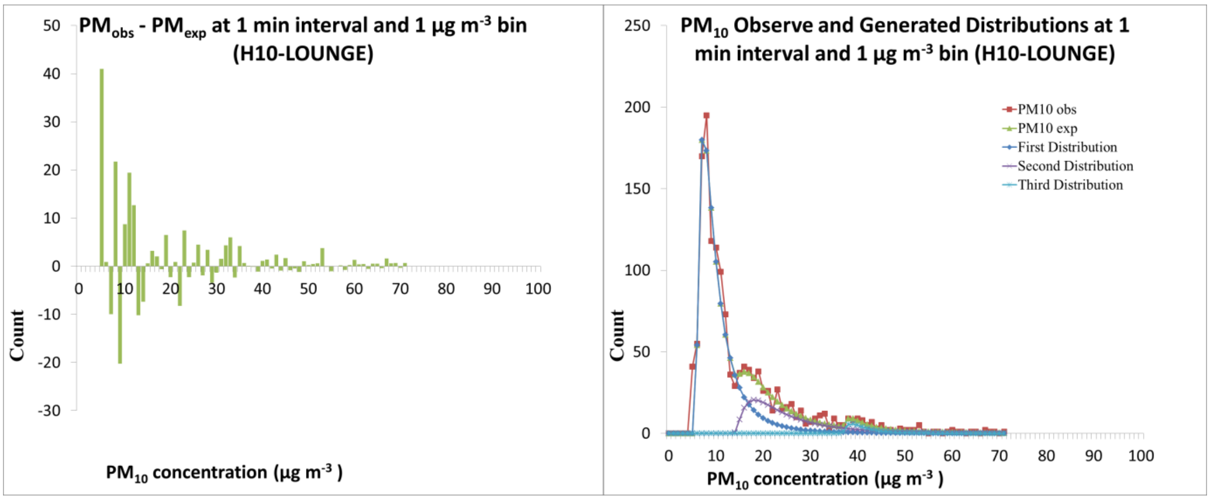
Appendix O PM_{10} Distributions at H10 on Sunday (Monitored, Modelled and Residuals)



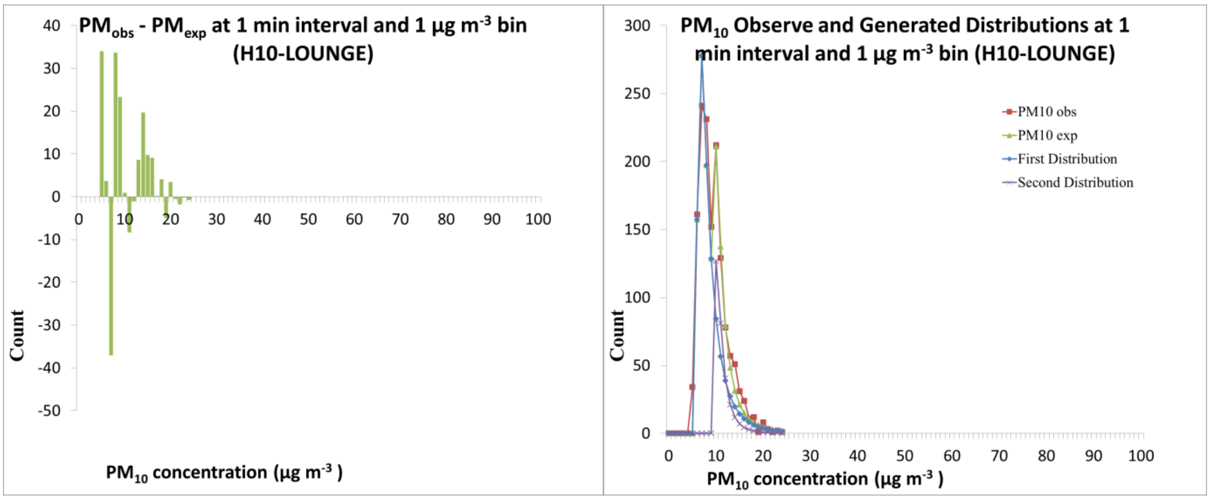
Appendix P PM_{10} Distributions at H10 on Monday (Monitored, Modelled and Residuals)



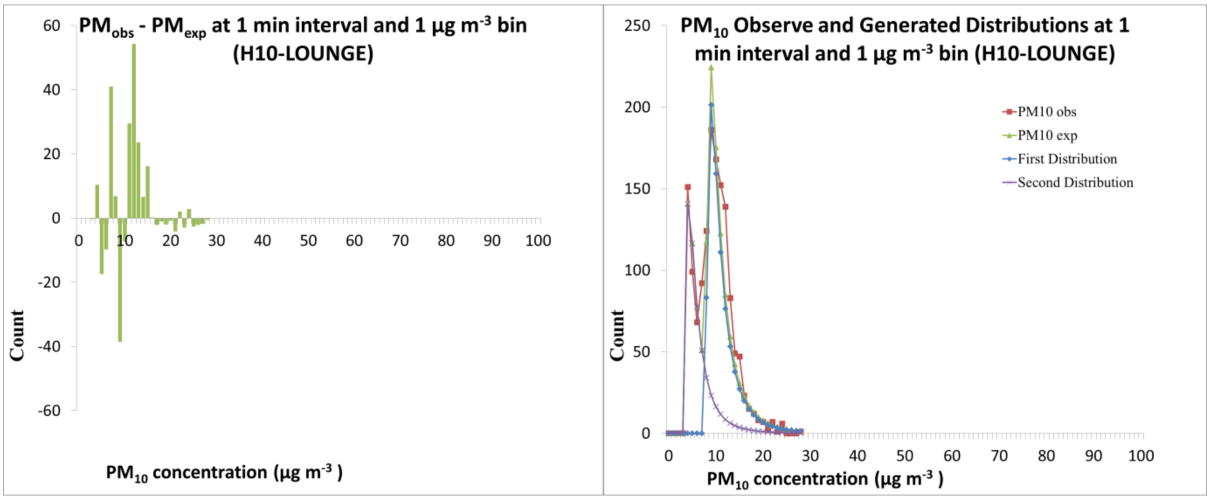
Appendix Q PM_{10} Distributions at H10 on Tuesday (Monitored, Modelled and Residuals)



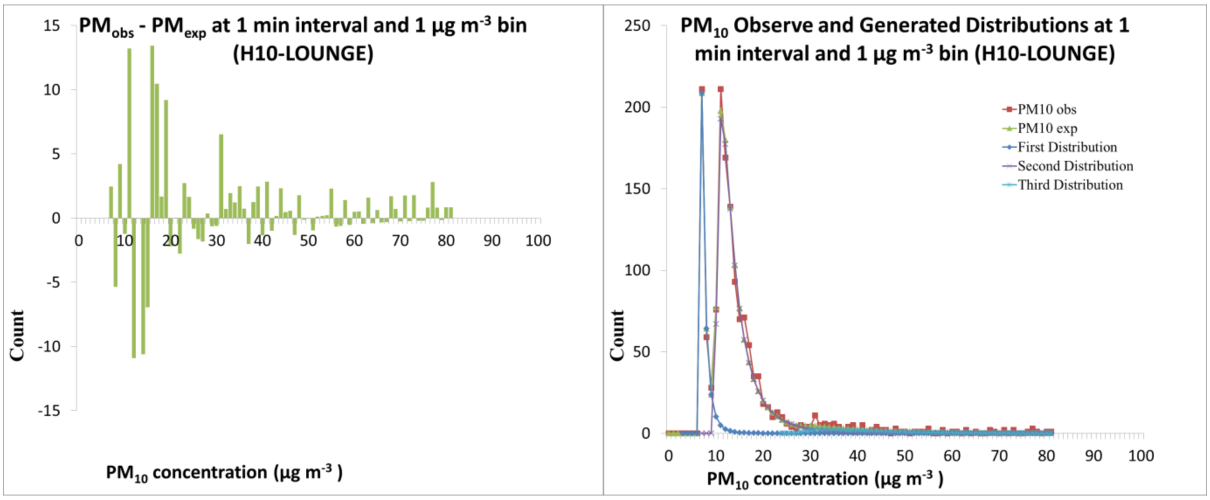
Appendix R PM_{10} Distributions at H10 on Wednesday (Monitored, Modelled and Residuals)



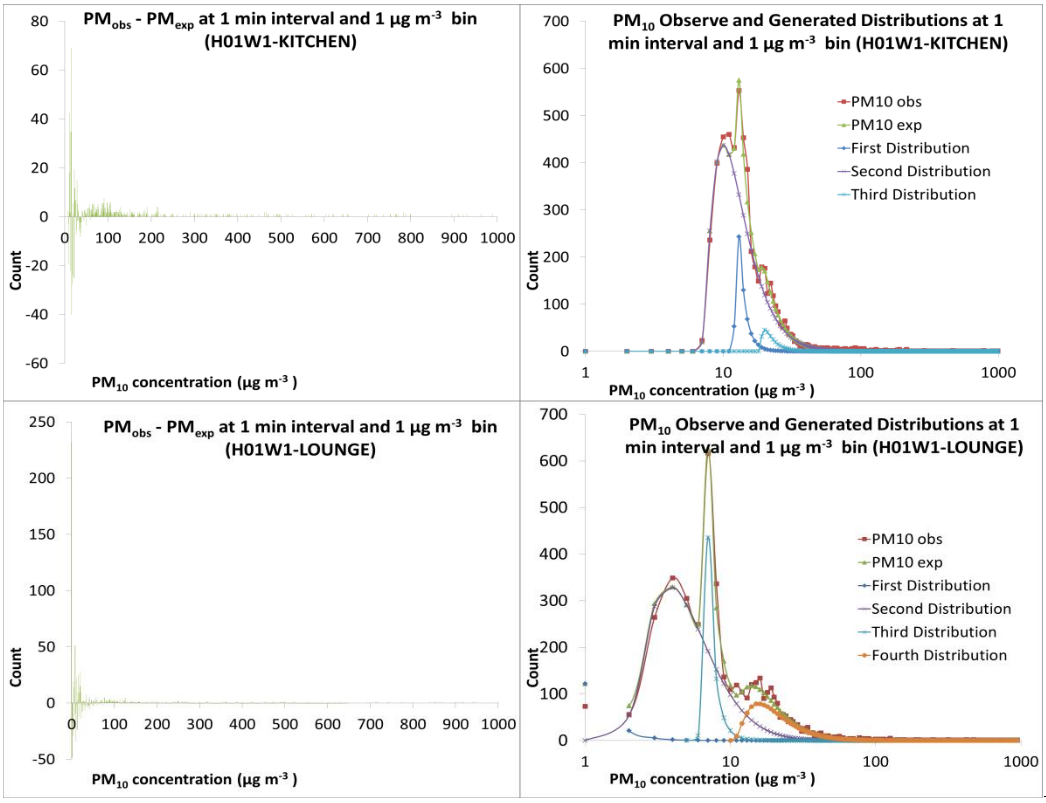
Appendix S PM_{10} Distributions at H10 on Thursday (Monitored, Modelled and Residuals)



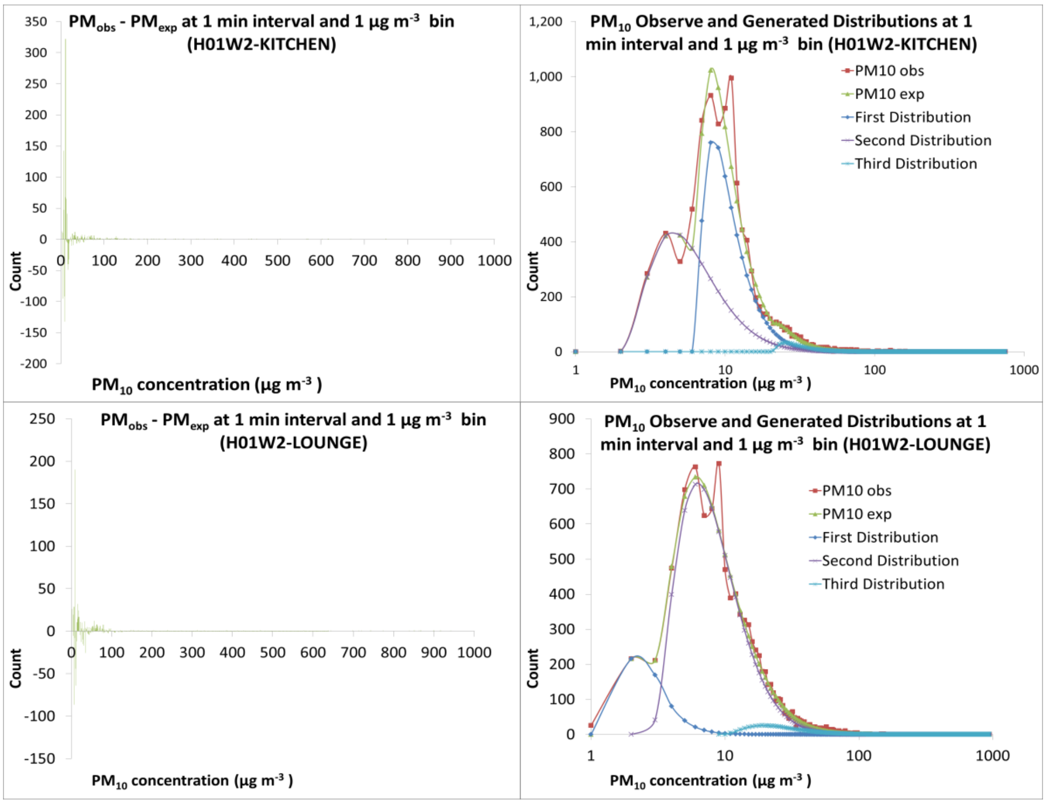
Appendix T PM_{10} Distributions at H10 on Friday (Monitored, Modelled and Residuals)



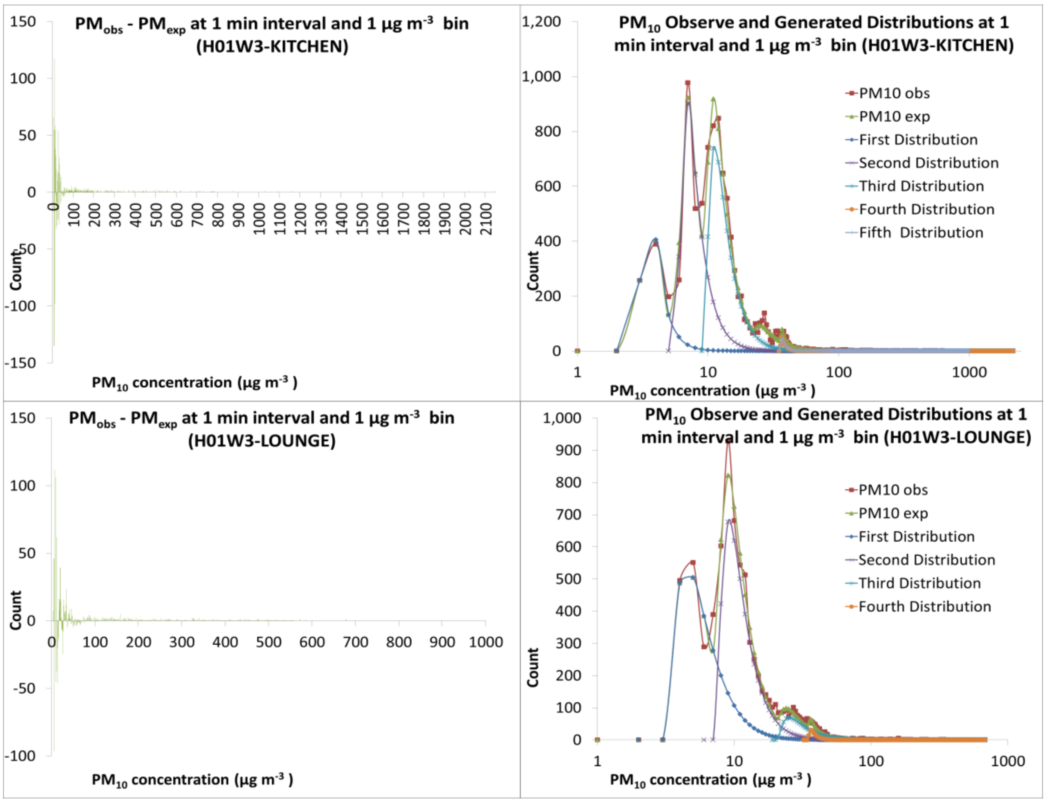
Appendix U PM_{10} Distributions at H10 on Saturday (Monitored, Modelled and Residuals)



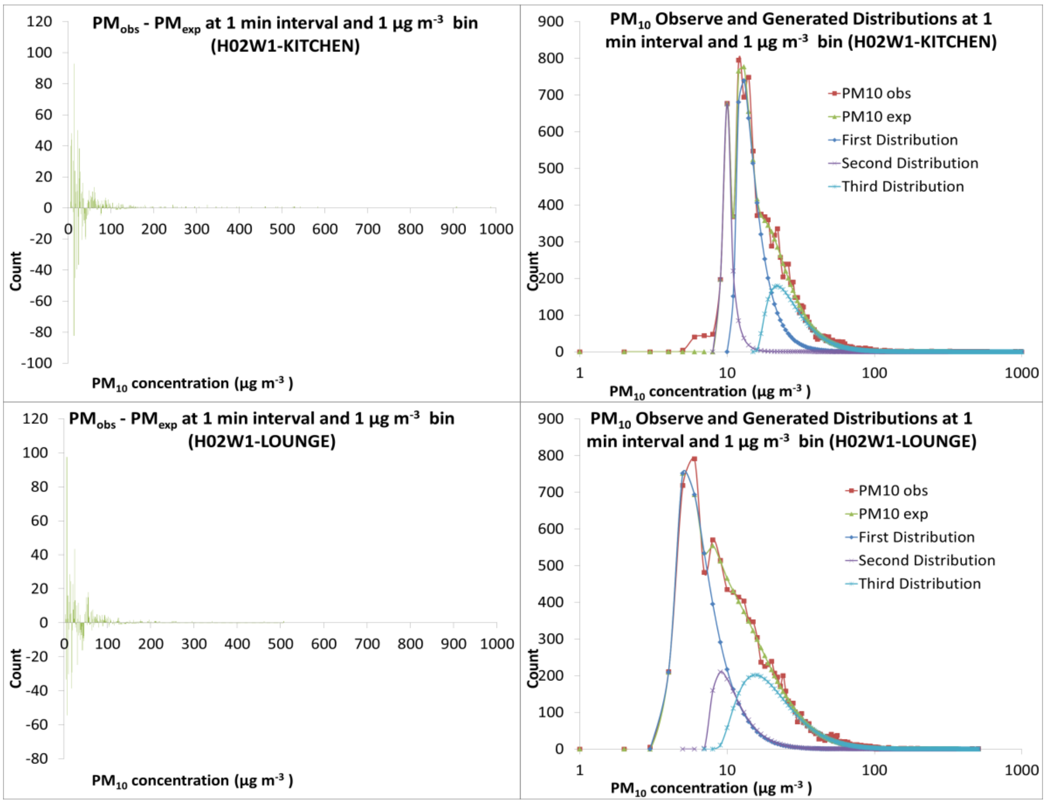
Appendix V PM_{10} Distributions at H01W1 (Monitored, Modelled and Residuals)



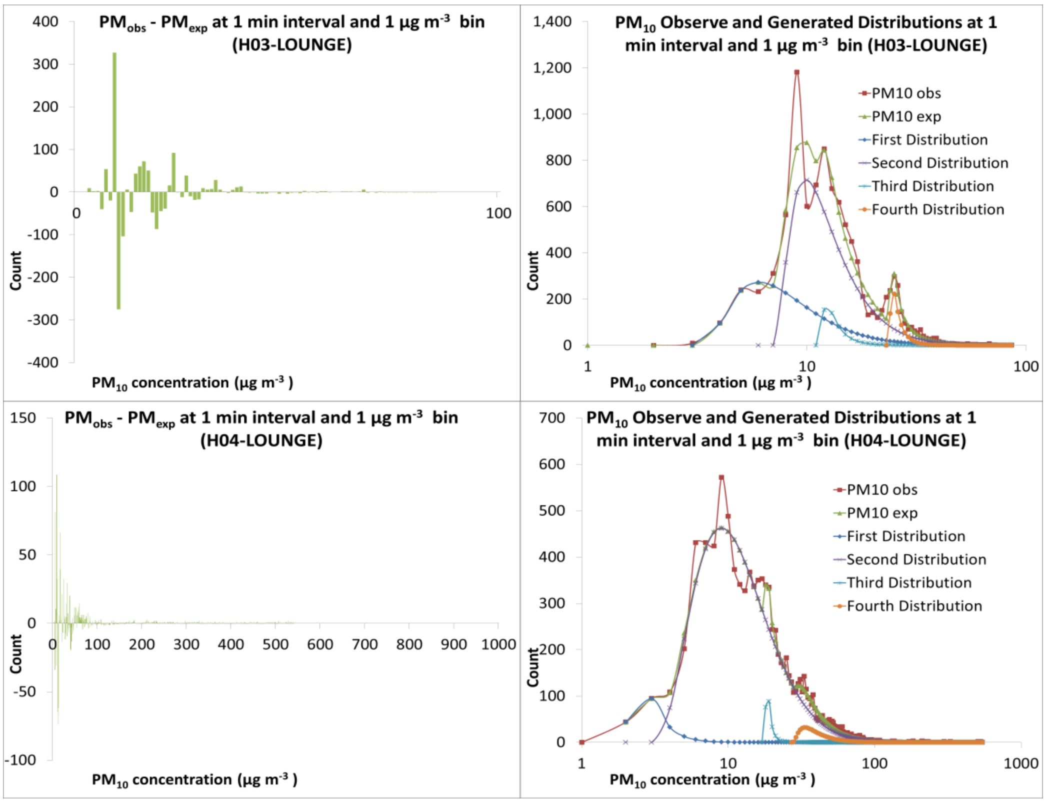
Appendix W PM_{10} Distributions at H01W2 (Monitored, Modelled and Residuals)



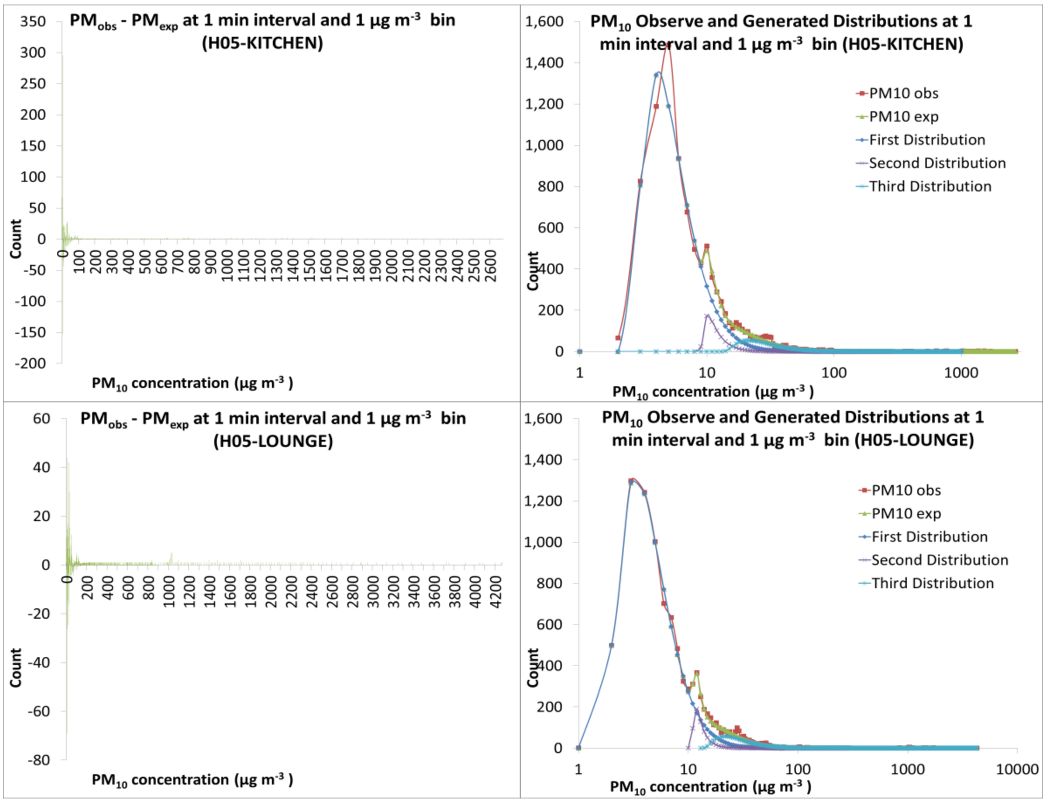
Appendix X PM_{10} Distributions at H01W3 (Monitored, Modelled and Residuals)



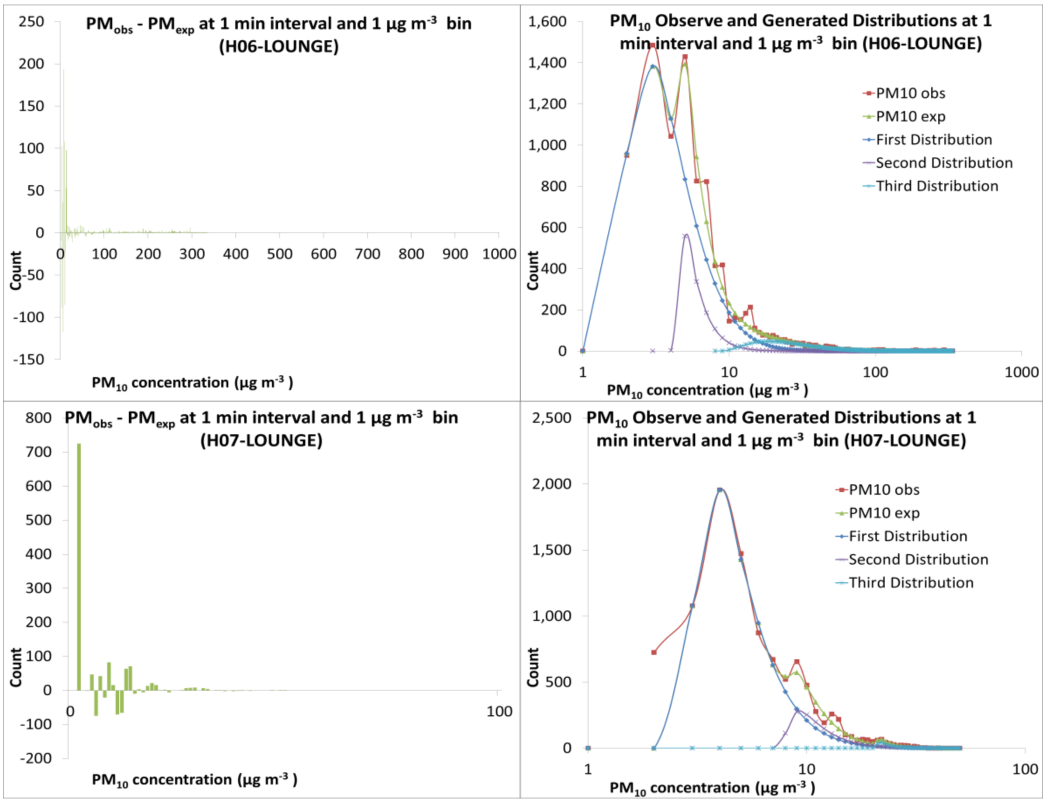
Appendix Y PM_{10} Distributions at H02W1 (Monitored, Modelled and Residuals)



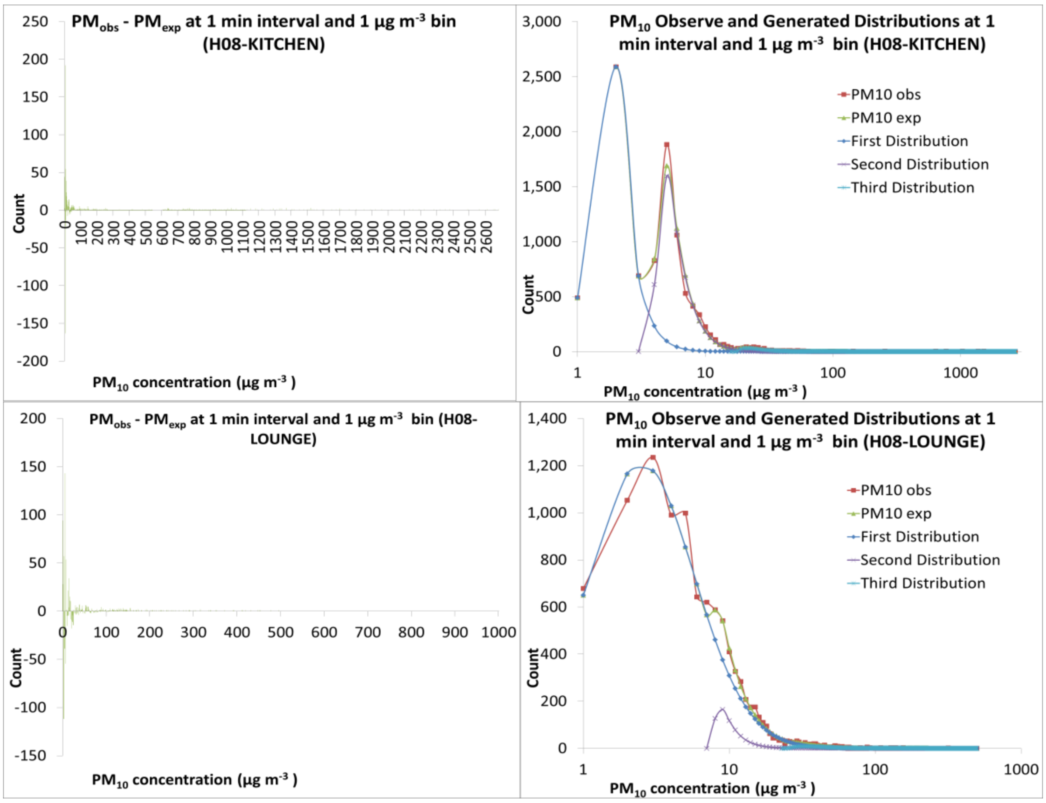
Appendix Z PM$_{10}$ Distributions at H03 andH04 (Monitored, Modelled and Residuals)



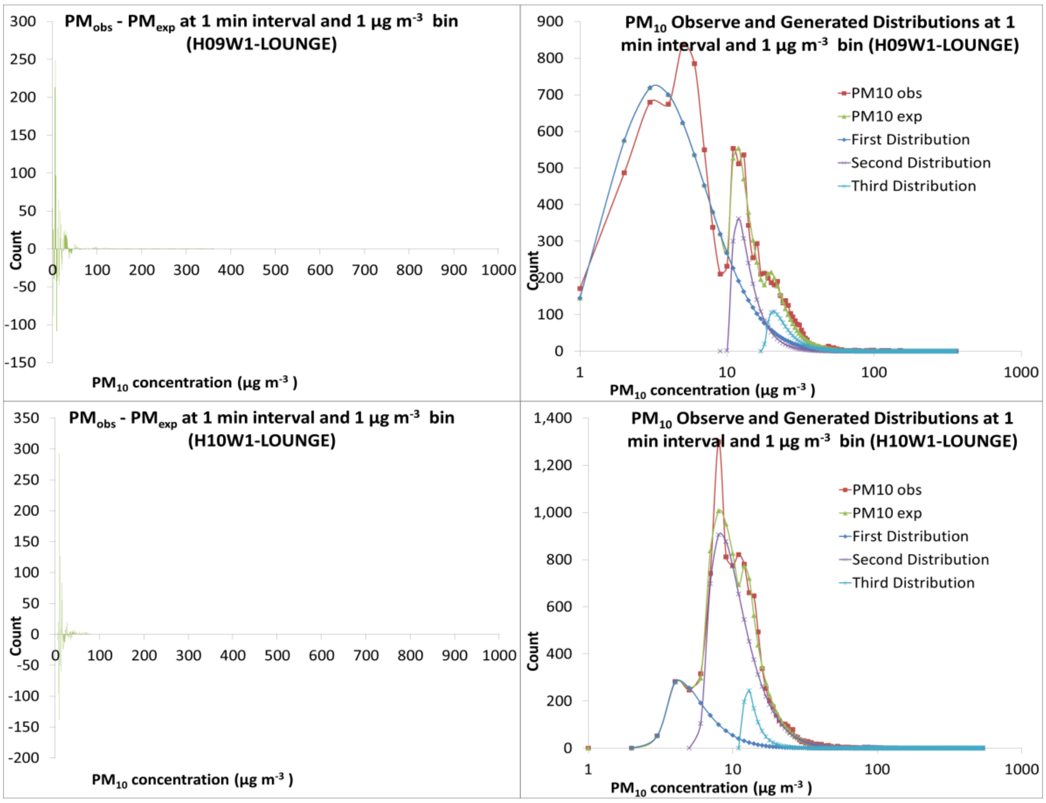
Appendix AA PM$_{10}$ Distributions at H05 (Monitored, Modelled and Residuals)



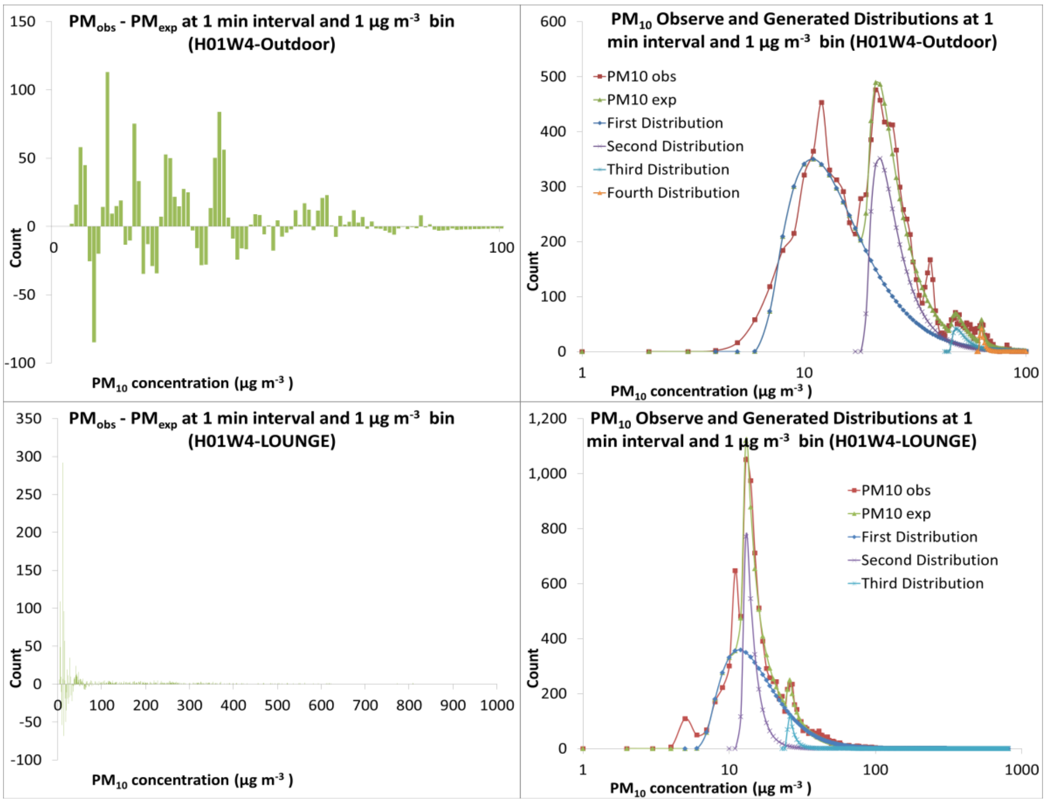
Appendix BB PM$_{10}$ Distributions at H06 and H7 (Monitored, Modelled and Residuals)



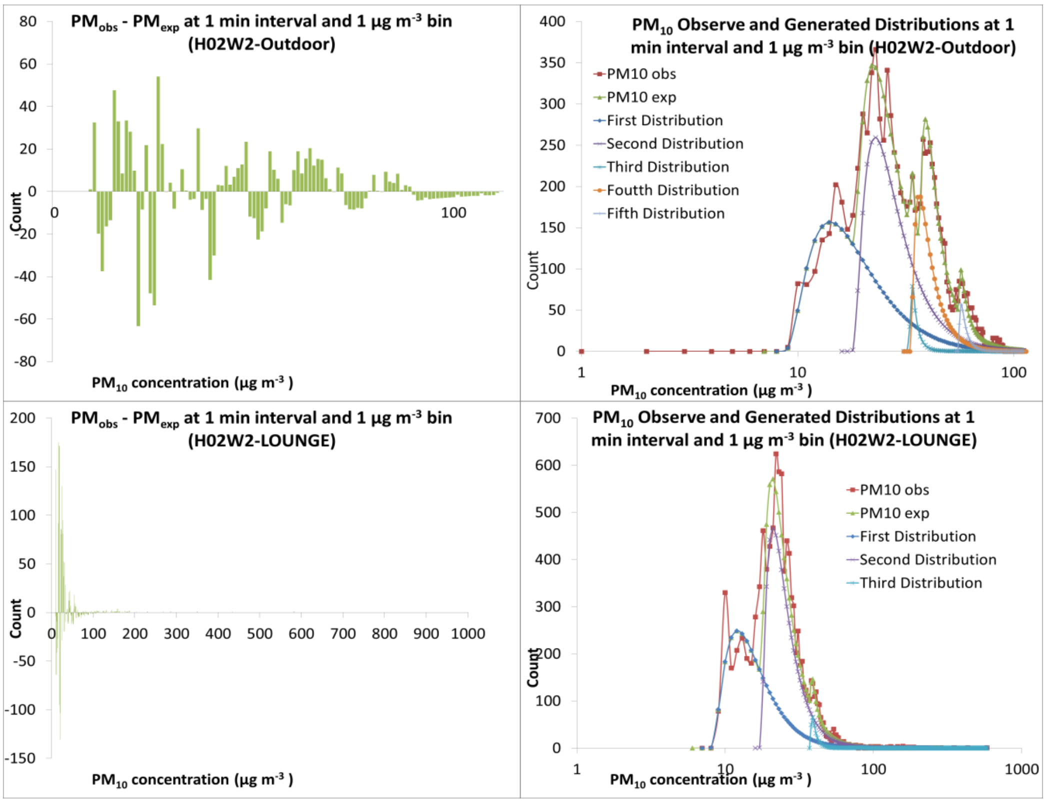
Appendix CC PM$_{10}$ Distributions at H08 (Monitored, Modelled and Residuals)



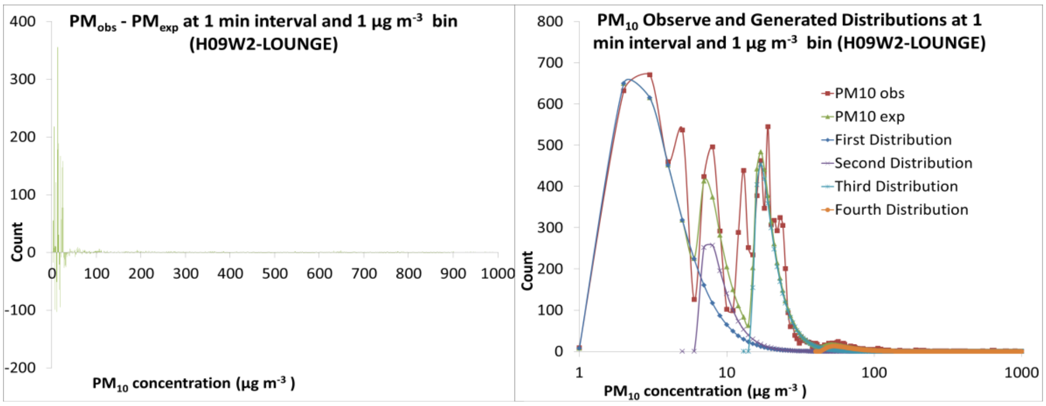
Appendix DD PM$_{10}$ Distributions at H09W1 and H10W1 (Monitored, Modelled and Residuals)



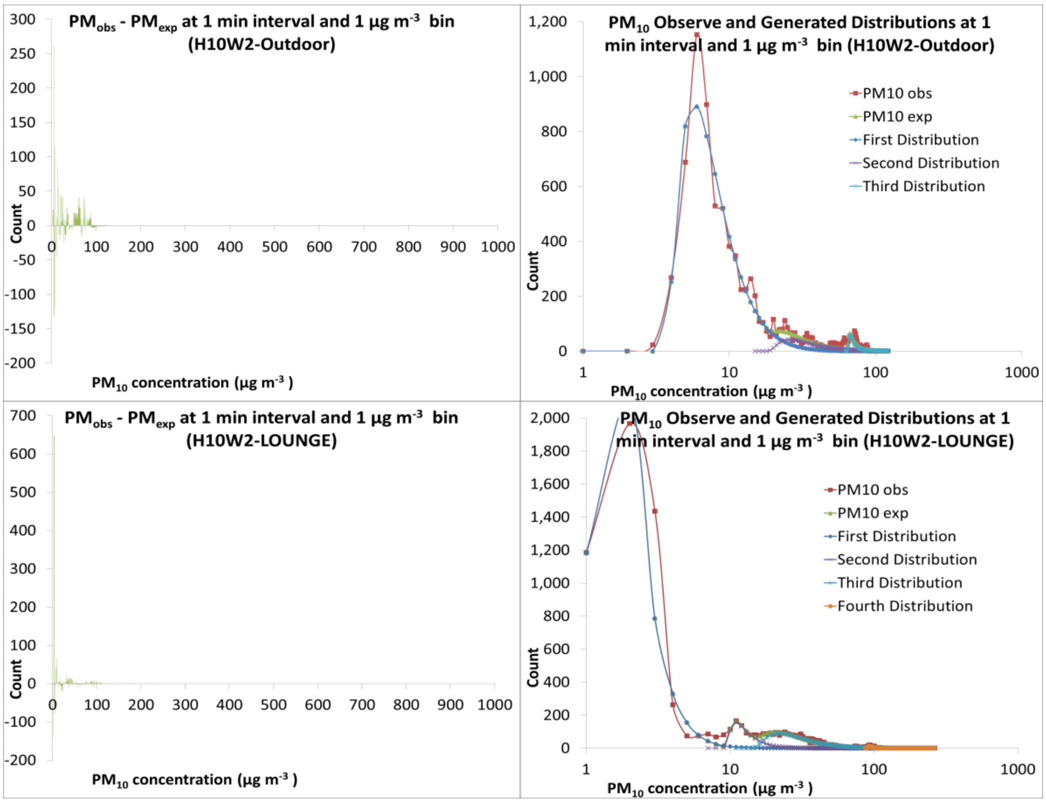
Appendix EE PM$_{10}$ Distributions at H01W4 (Monitored, Modelled and Residuals)



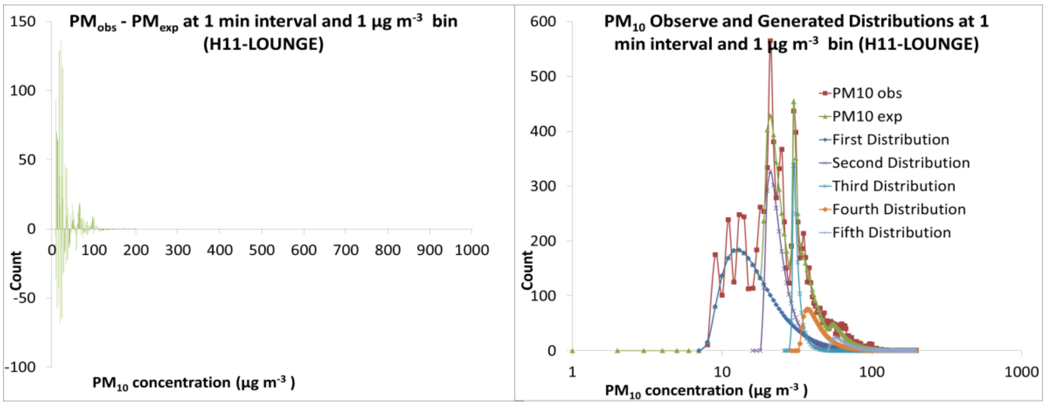
Appendix FF PM_{10} Distributions at H02W2 (Monitored, Modelled and Residuals)



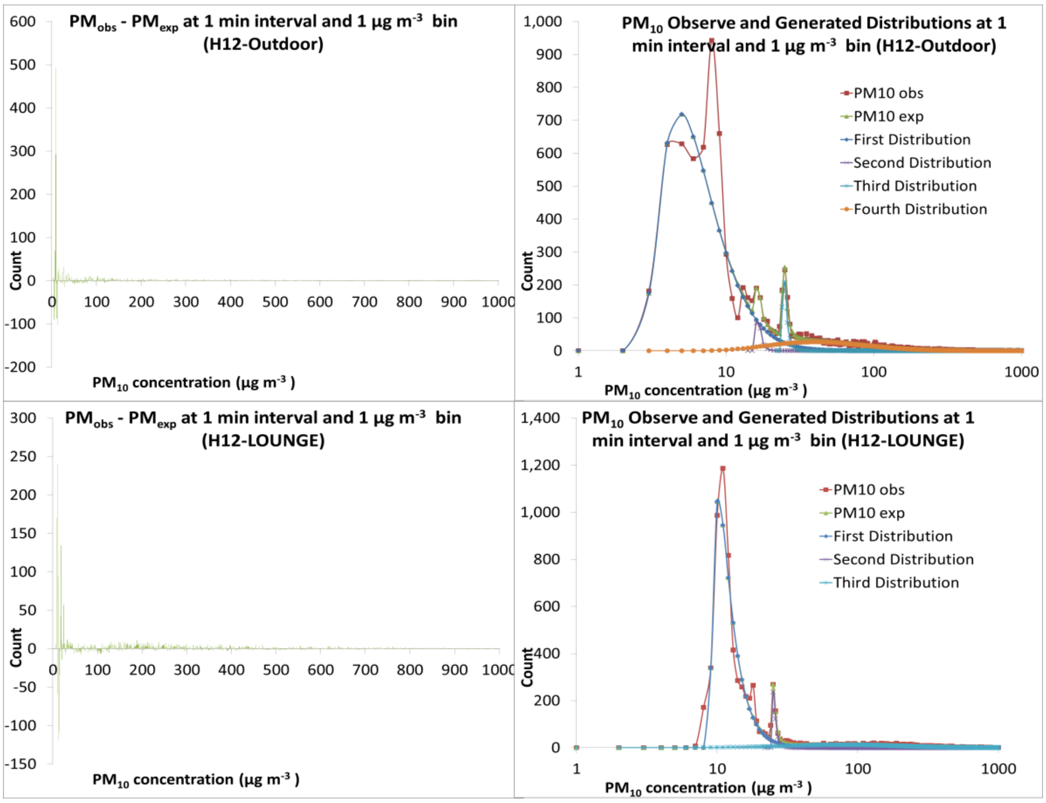
Appendix GG PM_{10} Distributions at H09W2 (Monitored, Modelled and Residuals)



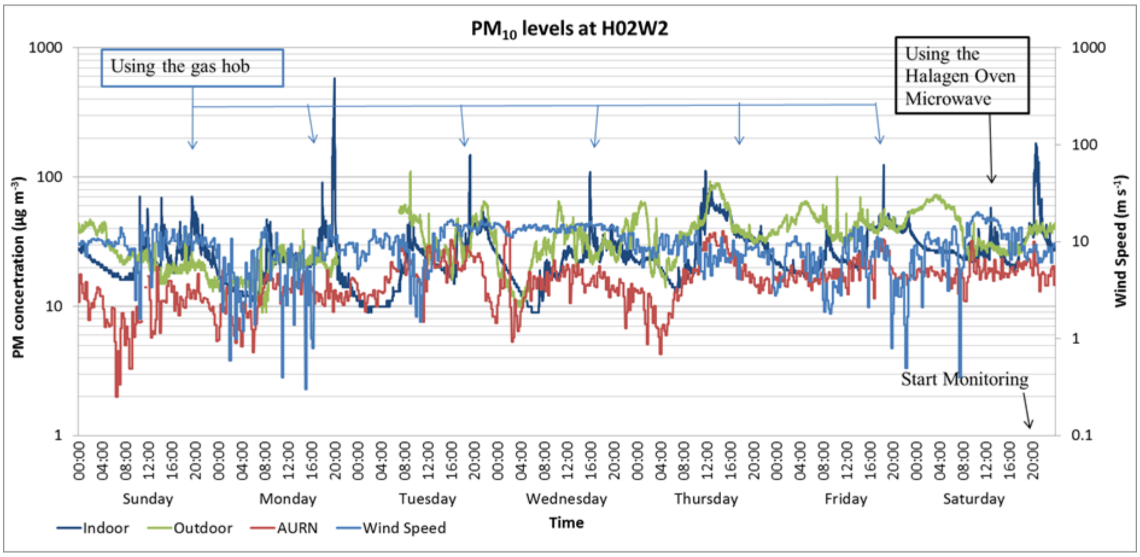
Appendix HH PM_{10} Distributions at H00W2 (Monitored, Modelled and Residuals)



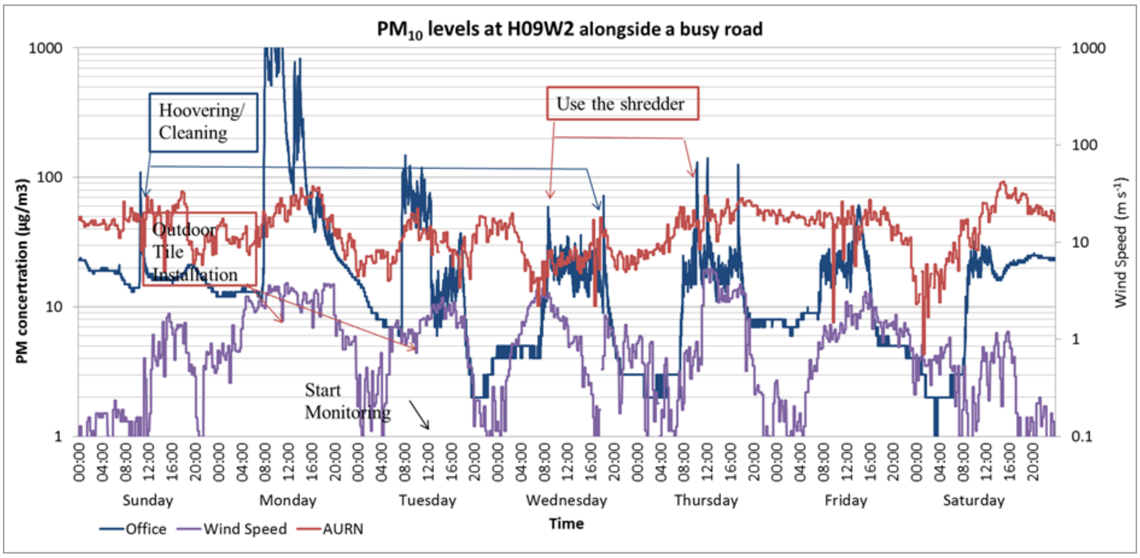
Appendix II PM_{10} Distributions at H11 (Monitored, Modelled and Residuals)



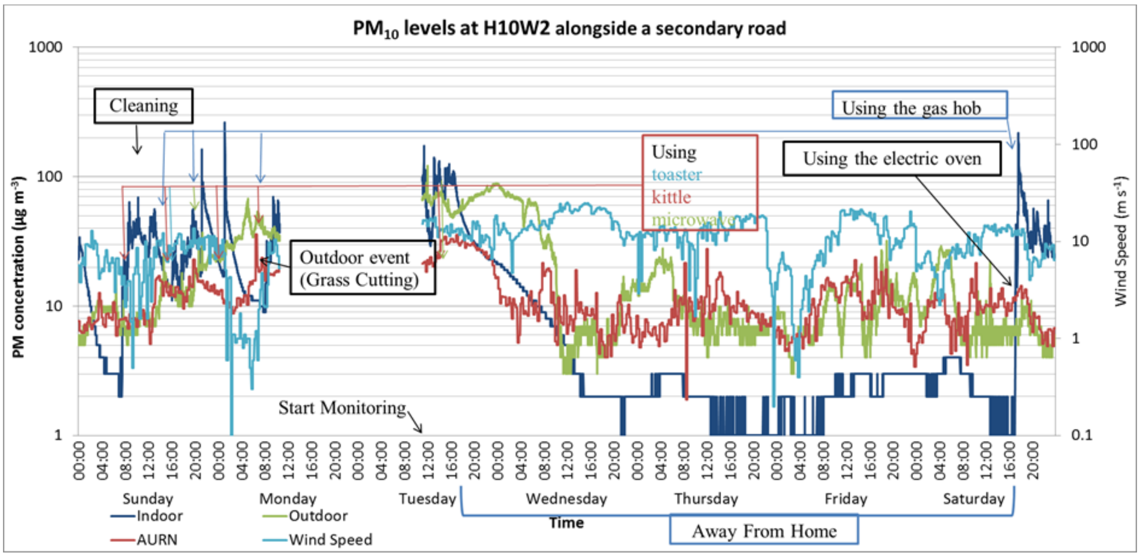
Appendix JJ PM_{10} Distributions at H12 (Monitored, Modelled and Residuals)



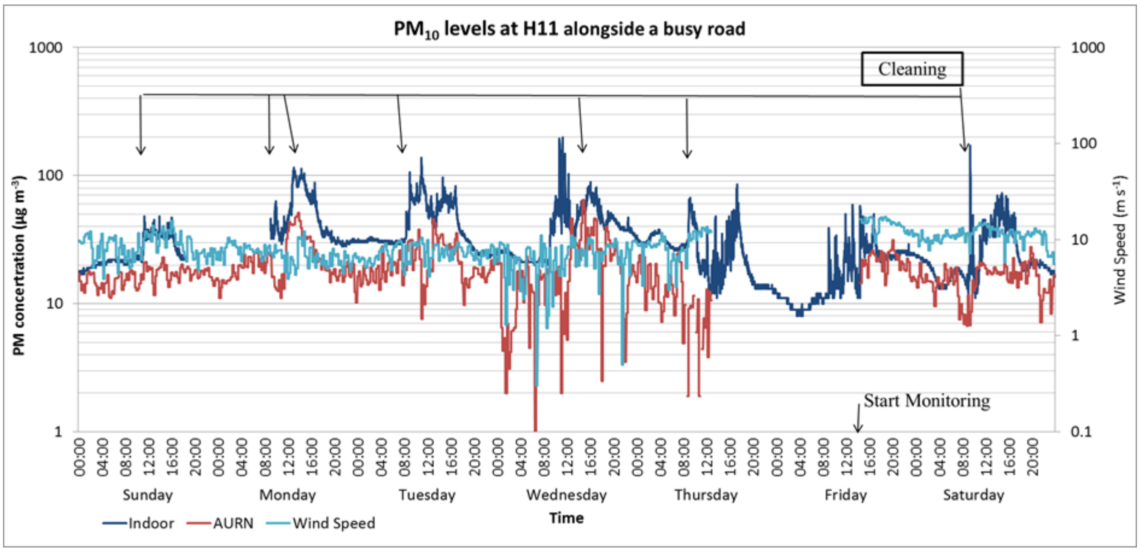
Appendix KK PM_{10} time series of H02W2 and AURN and wind speed



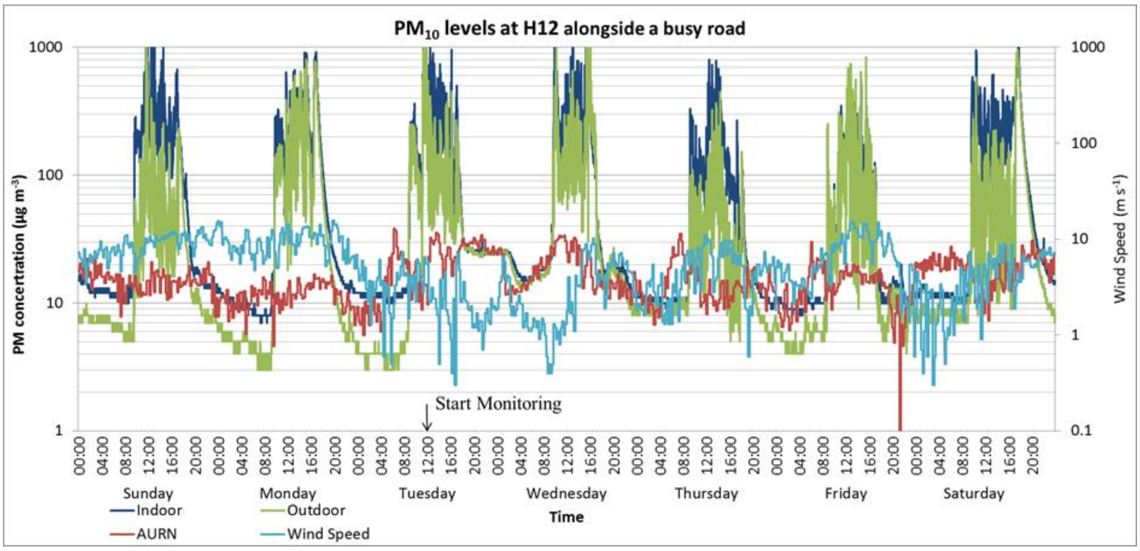
Appendix LL PM_{10} time series of H10W2 and AURN and wind speed



Appendix MM PM_{10} time series of H10W2 and AURN and wind speed



Appendix NN PM_{10} time series of H11 and AURN and wind speed



Appendix OO PM_{10} time series of H12 and AURN and wind speed