RICARDO-AEA

Air Quality Study - Scotland

Assessing variations in roadside air quality with sampling height (CR/2013/10)

Customer:

Scottish Government

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Executive summary

The Scottish Government commissioned a study to undertake a mobile air quality monitoring study. The two key aims of the study were:

- Determine the relationship between height from pavement and air quality under a range of conditions; and

- Investigate the relationship between concurrent air quality sampling obtained from mobile and fixed sampling stations.

The study primarily focussed on particulate matter with mean aerodynamic diameters of 2.5 μm ($PM_{2.5}$) and 10 μm (PM_{10}), ultrafine particles (UFP) between the sizes of 10 nm and 300 nm and black carbon (BC). In addition, the following pollutants were monitored:

- Nitrogen dioxide (NO_2);
- Sulphur dioxide (SO_2);
- Carbon monoxide (CO);
- Benzene (C_6H_6);
- Particulate matter with a mean aerodynamic diameter of 0.5 μm ($PM_{0.5}$);
- Particulate matter with a mean aerodynamic diameter of 1.0 μm ($PM_{1.0}$);
- Particulate matter with a mean aerodynamic diameter of 5.0 μm ($PM_{5.0}$);
- Total particulate matter (TPM).

The study was carried out in Glasgow City Centre with a total of 11 colocation exercises to evaluate agreement between samplers; and 8 mobile monitoring exercises to evaluate potential concentration gradients between 0.80 m and 1.68 m. All monitoring exercises were carried out between February 2014 and September 2014. In order to maximise the range of conditions captured (e.g. traffic and weather conditions), the monitoring exercises were carried out over 6 weekdays (2 x Fridays) and 2 weekend days.

Contour plots of pollutant concentrations throughout the mobile monitoring route were produced in order to help analyse the spatial distribution of pollutants and assess the influences of local factors, such as traffic density.

The findings of the Glasgow study demonstrated the complexity of ambient air quality within the urban environment and the challenges of monitoring a range of important pollutants within such an environment. Within a limited duration exercise, the study provided valuable insights into not only spatial variations of key air pollutants in Glasgow City centre but also the influence of exposure height on the concentrations observed. In addition, the study also helped to elucidate correlations between observed concentrations of different pollutants at different exposure heights and also provide useful information regarding the application of mobile monitoring and the application of personal sampler/ sensor technology for assessing human exposure to air pollutants in an urban environment.

In brief summary, the study identified that spatial and temporal variations in pollutant concentrations in Glasgow City centre are generally species specific and can also be influenced by a wide range of other environmental parameters, such as the proximity to pollution sources. Whilst a large number of initial conclusions have been drawn, several of the findings are considered to merit further attention. These were:

- It was identified that consistently higher average concentrations of $PM_{2.5}$ (42% higher) and PM_{10} (47-63% higher) were recorded by the mobile monitoring trolley when monitoring along the study route than those reported at the fixed Glasgow Kerbside AURN monitoring site.
- Average concentrations of PM_{10} were shown to be consistently higher (up to 12.6% higher) at 0.80 m than at 1.68 m throughout the mobile monitoring trolley study route. This finding is significant, as it appears to indicate that in the urban environment

children may be exposed to higher concentrations of PM_{10} on average than adults. However, this relationship was not observed for concentrations of $PM_{2.5}$.

- For NO_2, at lower ambient concentrations, no consistent influence of exposure height was identified on observed concentrations. However, at higher ambient concentrations, such as that may be observed in close proximity to busy road junctions, significantly higher concentrations were observed at adult breathing height (1.68 m) than at child breathing height (0.80 m).
- Visualisation of pollutant concentrations monitored through the application of the mobile monitoring trolley demonstrated potential for the identification or confirmation of pollutant hotspots within urban environments. Through the application of such a mobile monitoring 'screening' approach, authorities may be able to confirm the presence and extent of pollution hotspots, and thus investigate, design and implement appropriate mitigation measures.

Overall, the study provided valuable insights into spatial (vertical and horizontal) variations of concentrations of key air pollutants in Glasgow City centre. The study has generated numerous interesting findings which with further research could help to inform and guide future air quality research and policy in Scotland.

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1 Introduction

1.1 Purpose of the Study

A wide range of air quality monitoring is undertaken in Scotland, primarily by the Scottish Government to fulfil the requirements of EU Directive 2008/50/EC on ambient air quality and by local authorities under the Local Air Quality Management regime (LAQM) as set out in the Environment Act 1995 and associated regulations. Other monitoring is undertaken by SEPA, Transport Scotland and various academic, research and commercial organisations.

Although both the Directive and LAQM are focused towards protecting human health, current monitoring strategies fail to consider variations in air quality with height above the ground. Heights of monitoring station sampling points vary depending on local conditions and with the type of equipment installed.

One of the main sources of air pollution in Scotland is road traffic, and most vehicle emissions tend to originate at heights of less than 1 m above the ground. Consequently, in urban environments close to roads, human exposure to air pollution may be influenced by the age and height of the exposed population, with children and pushchairs located closer to vehicle emissions. Current fixed-site monitoring approaches may not adequately reflect any vertical variations in air quality. The application of a mobile monitoring platform simultaneously measuring a number of air pollutants at adult breathing height (1.68 m) and child/pushchair breathing height (0.80m) within an urban environment thus provides the opportunity to guide and inform any future detailed work on the potential impact of air quality on children's health.

The study has two key aims:

- Determine the relationship between height from pavement and air quality under a range of conditions; and

- Investigate the relationship between concurrent air quality sampling obtained from mobile and fixed sampling stations.

The focus of the study is on the following pollutants:

- Particulate matter with a mean aerodynamic diameter of 2.5 μm ($PM_{2.5}$).
- Particulate matter with a mean aerodynamic diameter of 10 μm (PM_{10});
- Ultrafine particles (UFP) between the sizes of 10 nm and 300 nm.
- Black carbon (BC).

With the following additional pollutants also measured:

- Nitrogen dioxide (NO_2).
- Sulphur dioxide (SO_2).
- Carbon Monoxide (CO).
- Ozone (O_2).
- Carbon Dioxide (CO_2).
- Benzene (C_6H_6).
- Particulate matter with a mean aerodynamic diameter of 0.5 μm ($PM_{0.5}$);
- Particulate matter with a mean aerodynamic diameter of 1.0 μm ($PM_{1.0}$);
- Particulate matter with a mean aerodynamic diameter of 5.0 μm ($PM_{5.0}$);
- Total particulate matter (TPM).

1.2 Policy Background

The air quality objectives applicable to Local Air Quality Management (LAQM) in Scotland are set out in the Air Quality (Scotland) Regulations 2000 (Scottish SI 2000 No 97), the Air Quality (Scotland) (Amendment) Regulations 2002 (Scottish SI 2002 No 297), and are shown in
Table 1.1. This table shows the objectives in units of micrograms per cubic metre µg m^{-3} (milligrams per cubic metre, mg m^{-3} for carbon monoxide) with the number of exceedances in each year that are permitted (where applicable). For these pollutants, Local Authorities have an obligation to work towards achieving these objectives.

Table 1.1 Air Quality Objectives included in Regulations for the purpose of LAQM in Scotland

Pollutant	Air Quality Objective	
	Concentration	Measured as
Benzene	16.25 µg m^{-3}	Running annual mean
	3.25 µg m^{-3}	Running annual mean
1,3-Butadiene	2.25 µg m^{-3}	Running annual mean
Carbon Monoxide	10 mg m^{-3}	Running 8-hour mean
Lead	0.50 µg m^{-3}	Annual mean
	0.25 µg m^{-3}	Annual mean
Nitrogen Dioxide	200 µg m^{-3}, not to be exceeded more than 18 times a year	1-hour mean
	40 µg m^{-3}	Annual mean
Particulate Matter (PM$_{10}$) (Gravimetric)	50 µg m^{-3}, not to be exceeded more than 7 times a year	24-hour mean
	18 µg m^{-3}	Annual mean
Sulphur dioxide	350 µg m^{-3}, not to be exceeded more than 24 times a year	1-hour mean
	125 µg m^{-3}, not to be exceeded more than 3 times a year	24-hour mean
	266 µg m^{-3}, not to be exceeded more than 35 times a year	15-minute mean

New air quality objectives for PM$_{2.5}$ were adopted in May 2008 under European Directive 2008/50/EC. The Directive introduced additional PM$_{2.5}$ objectives targeting the exposure of the population to fine particles. These objectives are set at the national level and are based on the average exposure indicator (AEI). The AEI is determined as a 3-year running annual mean PM$_{2.5}$ concentration averaged over the selected monitoring stations in agglomerations and larger urban areas, set in urban background locations to best assess the PM$_{2.5}$ exposure to the general population.

In line with the stricter PM$_{10}$ objectives, the Scottish Government has adopted a draft national air quality objective of 12 µg m^{-3} as an annual mean and is currently considering adopting the more stringent WHO's Guideline Value of 10 µg m^{-3} as an annual mean. The PM$_{2.5}$ objective has not yet been incorporated into LAQM Regulations and therefore Local Authorities are not currently required to monitor concentrations of PM$_{2.5}$. PM$_{2.5}$ is currently monitored at 6 Automatic Urban and Rural Network monitoring sites throughout Scotland located at:

- Aberdeen
- Auchencorth Moss
- Edinburgh St Leonards
- Glasgow Kerbside
- Grangemouth
- Inverness

A Consultation[1] on the existing LAQM regime within Scotland was carried out by the Scottish Government during 2014. The role of Local Authorities in monitoring $PM_{2.5}$ and the current monitoring programme for $PM_{2.5}$ may therefore change following the publication of the conclusions of the review. Black carbon and ultra-fine particles (UFP) are not covered under the current EU or UK air quality legislation but are currently the focus of significant international research regarding their potential impacts on health and the environment.

Scottish, UK and European policy on assessing exposure to air pollution is currently geared towards fixed location monitoring "in the breathing zone", typically accepted to be up to about 4 m above the ground. In practical terms, it is usually extremely challenging to measure at heights much below 1.5 m, because of analyser infrastructure requirements and the risk of vandalism. For multi-pollutant sites, the analysers are generally housed in walk-in enclosures, which further hampers the ability to measure air quality at reduced heights.

A key policy driver for LAQM and EC Directive compliance is to ensure that measurements are made using methods that fulfil specified Data Quality Objectives (DQO). This ensures that measurements across regions and member states are comparable and of sufficient quality to enable robust assessment of compliance with standards and objectives. Portable analysers have not yet demonstrated compliance or equivalence to these requirements, so are not currently used to determine or inform policy in this way. The weakness in the current approach to fulfilling statutory obligations for air quality monitoring and assessment is that it may not provide a representative measure of personal exposure and therefore enable accurate assessment of the likely health impact.

This study provides a cutting edge assessment of a situation that falls outside of current statutory monitoring policy; measurement of vertical concentration gradients in a moving and variable environment is not currently mandated in EC Air Quality Directives or LAQM. However, the European AQ monitoring community is currently extremely interested in micro-scale monitoring through initiatives like AirMonTech (http://www.airmontech.eu/) which are part of the ongoing EC Directive Review. This study contributes valuable insight into personal exposure and health impact through the use of portable sampling devices and profiling spatial AQ concentrations both horizontally and vertically.

1.3 Conclusions Drawn from Literature Review

As part of this project a literature review was undertaken. For the review, the online scientific database ScienceDirect was utilised together with wider internet and literature searches. Three main search criteria were used, which provided a targeted examination in the first instance. Further refinement of the search criteria was made by specifying other sub-criteria. For example, it was found while searching for air quality versus height studies that street canyon studies were also informative to the study. As a result, a map of relevant search criteria was developed and this is summarised briefly below:

- ➢ Air quality versus height.
    - + Urban air quality.
    - + Street canyons.
    - + Pollutants measured.
    - + Samplers used.
        - + Data processing/visualisation.

- ➢ Mobile monitoring studies.
    - + Urban air quality.
    - + Street canyons.

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[1] Consultation on review of Local Air Quality Management in Scotland, The Scottish Government, June 2013 [Online] Available at http://www.scotland.gov.uk/Resource/0042/00425194.pdf [Accessed on 10/07/2013]

- + Pollutants measured.
- + Samplers used.
  - + Data processing/visualisation.

- ➢ Personal exposure studies.
  - + Pollutants measured.
  - + Samplers used.
    - + Data processing/visualisation

1.3.1 Air Quality versus Height Studies

One of the principal objectives of the study was to determine the nature of the relationship between pollutant concentrations and height; in this case, 2 exposure heights, average child and adult breathing heights. Of the published studies that have investigated vertical profiles of pollutants, the majority of these have focussed on heights of greater than 2 m and have reported a range of conclusions. Trompetter et al (2013) and Ferrero et al (2011) explored the variation in concentrations of BC at heights of up to 100 m and 500 m, respectively. By measuring the vertical profile of BC the studies found that concentrations decreased with height and were mostly confined to heights of less than 50 m.

Imhof et al (2005) measured aerosol particle number, surface area (particles with a diameter of between 30 nm to 10 μm) and NOx upwind and downwind of a motorway at heights of 5 m to 50 m, together with wind speed and direction. In this case it was found that particle numbers, surface area and NOx concentrations decreased with height at downwind locations at times before noon, thus supporting the general findings of Trompetter et al, 2013. However after noon, it was found that the maximum concentration of particles was measured at 10 m, indicating an increase in particle concentrations between 5 m and 10 m.   Vertical profiles of the pollutants at upwind locations showed concentrations were constant throughout the sampling height range.   This research suggests that meteorology and sampling location relative to emission sources will have a direct influence on the vertical profile of pollutants. The study undertaken by Imhof et al (2005) was carried out using fixed monitoring points and therefore the pollutant concentrations measured do not necessarily reflect personal exposure.

Further studies looking at particle concentrations at heights closer to ground level indicate that pollutant concentrations increase with height for the first few meters from ground level. Meilu et al (2011) investigated horizontal and vertical dispersion of particles emitted from freeway vehicles. Three monitoring sites located on flat terrain 15, 50 and 100 m from the road measured particle numbers at 9 sampling heights between 0 – 10 m. It was found that at low wind speeds <1 m s^{-1}, the particle number concentrations were unchanged up to approximately 7.7 m above ground level. For wind speeds of >1 m s^{-1}, particle number concentrations increased to a maximum at approximately 3.4 m above ground level. Again it was found that wind speed and direction relative to the emission source had a direct influence on the vertical profile of pollutant concentrations. However, this monitoring study was also carried out using fixed monitoring points and therefore the pollutant concentrations measured may not necessarily reflect personal exposure.

Local topography can also play an important role in pollutant dispersion and in street canyons are a common feature in many urban environments. Micallef and Colls (1998) investigated vertical profiles of suspended particulate matter (PM) within a street canyon at six heights between 0.35 and 2.88 m ground level. It was found that daily average concentrations of PM_{10} and $PM_{2.5}$ were 35% and 12% greater at 0.81 m than at 2.88 m, respectively. This monitoring study was carried out at a fixed monitoring location and therefore does not necessarily reflect personal exposure. However, the study again indicates that a concentration gradient does exist within the first 3 m from ground level.

In summary, it has been shown that research has been carried out investigating pollutant concentrations at a variety of heights. However, this review has identified no research that has been undertaken to investigate both pollutant concentrations at heights of less than 2 m utilising a mobile monitoring platform. From the findings of the literature review, it was concluded that Glasgow mobile monitoring study provided the opportunity to help inform future air quality monitoring techniques and also assess the potential differential impact of urban air pollution on children and adults respectively.

1.3.2 Mobile Monitoring Studies

Mobile air quality monitoring provides data on the spatial and temporal variability of air pollutants. The Glasgow study investigated mobile air quality monitoring versus the current system which uses fixed monitoring sites to assess population exposure.   In this section we look at the general approach employed for mobile monitoring studies carried out to date.

Through the review it was found that mobile monitoring campaigns take the form of monitoring whilst on the move around a predetermined route(s). Of the mobile monitoring studies reviewed for this report, it was noted that the authors used either portable monitoring equipment carried by a person (Poppel et al, 2013; Leonard et al, 2012; Pirjola et al, 2012; Cambridge Urban Mobile Sensing (CambMobSens), 2010) or a mobile laboratory to carry out the measurements with monitoring equipment installed within a vehicle (Martinez et al, 2012; Hu et al, 2012; Westerdhal et al, 2005). The obvious necessity for all studies was that GPS was used in combination with the mobile monitoring.

Poppel et al (2013) proposed a methodology for the setup and data processing for a mobile monitoring campaign within an urban environment. The study focussed on UFP, BC and $PM_{2.5}$ measurements using a TSI P-Trak at 1 s resolution, Magee Scientific AE51 Micro-Aethelometer at 1 s resolution, and a GRIMM dust monitor at 6 s resolution, respectively. The sampling equipment together with GPS was installed on a modified bicycle, The Aeroflex (Berghmans et al, 2009), and a fixed sampling route was repeated 20 times in 10 days (all weekdays). For analysis, the route was split into six zones based on traffic characteristics e.g. major road, green space, city centre road. This reinforces the approach that was developed for the Glasgow study; using a predetermined route, carrying out repeat runs over a number of separate days and categorise areas/roads within the sample route.

When data processing was considered, it was identified in the Poppel et al (2013) study that the BC data collected using AE51 micro-aethelometer suffered from 'data noise' especially at low concentrations. In the study, an optimized noise-reduction averaging (ONA) algorithm was used (Hagler et al, 2011) in post-processing. The algorithm reduces noise by increasing the time-averaging window at low measured BC concentrations and decreasing the time-averaging window at high measured BC concentrations. The data resolution used for the AE51 BC monitor in the Glasgow study was 1 minute and consequently 'data noise' did not pose the same problems.

In terms of mobile laboratory-based monitoring, a wider range of pollutants can be measured. For example, Hu et al (2012) investigated the spatial distribution of UFP, $PM_{2.5}$, BC, particle-bound polycyclic aromatic hydrocarbons (PAH), carbon monoxide (CO), CO_2, NOx combined with fixed meteorological measurements and traffic conditions. All pollutants were sampled at a single height. Again, a predetermined route was sampled twice daily during 11 weekdays further validating the approach used for the Glasgow study.

Pirjola et al (2012) utilised a mobile laboratory to investigate UFP, BC, $PM_{2.5}$ and NOx in combination with rooftop meteorological measurements. In the study, three street canyons of differing widths, lengths and orientations were selected to carry out the mobile sampling. Both mobile sampling and fixed sampling were carried out to investigate pollutant concentrations at a number of distances from the road and on upwind and downwind sides of the street canyons. The monitoring data from the mobile laboratory were also compared to that from a fixed roadside air quality monitoring site located on the same road as the three canyons. Again, the sampling runs were carried out two to three times daily during a two

week period. It was found that pollutant concentrations were greater on the upwind sides of the canyons than the downwind side. In addition, higher concentrations of UFP were measured during the mobile monitoring runs than at the fixed monitoring site.

In summary, the general methodology for carrying out mobile monitoring is consistent, whether using portable equipment or mobile laboratories. All studies that have been reviewed used at least two sample runs daily around a predetermined route. It has also been shown that fixed meteorological measurements are generally recorded. It was therefore deemed appropriate to collect similar fixed meteorological data as part of the Glasgow Study, in addition to the mobile measurements that were taken.

This review indicated that all of the reviewed mobile monitoring studies undertaken to date have only sampled at one height and there are no studies that have combined mobile monitoring with sampling at two or more heights.

1.3.3 Personal Exposure Studies

Personal exposure can be defined as exposure of individuals as experienced during their real-life, day-to-day activities and as such take into account indoor and outdoor air quality. Where personal exposure studies and the Glasgow study converge is with the monitoring equipment used, the mobile monitoring aspect and the pollutants measured. The Glasgow study provides data mirroring the personal exposure of individuals (children and adults) to UFP, BC and $PM_{2.5}$ in Glasgow City Centre. Measurements of these pollutants were carried out using the portable Philips NanoTracer (UFP), Magee Scientific AE51 micro-aethelometer (BC), the Harvard-PEMs (gravimetric $PM_{2.5}$) and the Lighthouse IAQ 3016 (PM).

A number of recent personal exposure studies have been carried out using the AE51 microaethelometer and the Philips NanoTracer (Buonanno et al, 2013 and 2012; Dons et al, 2012 and 2011) combined with GPS.   In these studies, individuals carried the samplers throughout a typical day of activity. Buonanno et al (2013 and 2012) investigated personal exposure of adults and children to UFP and BC. The studies classified a number of microenvironments as school, indoor, outdoor and transport. It was found that UFP and BC exposure varied depending on the activity and microenvironment the individual was in with the highest exposure measured indoors.

A studies by Dons et al (2012 and 2011) these findings were confirmed, however, a further emphasis was carried out in the Dons et al (2012) study where the focus was on personal exposure to BC in transport microenvironments e.g. car passenger, car driver, on foot, bus and train. Again, it was found that the BC concentrations individuals were exposed to were dependent on the transport microenvironment; with the highest concentrations measured for the car driver.

Although these studies are not directly comparable to the Glasgow study, they demonstrate that the Philips NanoTracer and AE51 Micro-aethelometer have been successfully deployed in a mobile monitoring regime. It is also reasonable to hypothesise, using these studies and the research discussed in Sections 1.3.2 and 1.3.1 that the pollutant concentrations measured during the Glasgow study may be dependent on the microenvironments that exist within Glasgow City Centre e.g. street canyons of varying orientations, pedestrian areas and open street environments. Again, the review of personal exposure of air quality research indicates that no studies have been carried out that combine both personal exposure and sampling at multiple heights.

1.3.4 'Other' Relevant Findings

A further useful criteria investigated during the literature review was the processing and visualisation of mobile air quality data. It was found that data processing is dependent upon the type of sampler used, for example the AE51 micro-aethelometer may suffer from 'data noise', as discussed in Section 1.3.2 (Poppel et al, 2013). Hudda et al (2013) also mentions the AE51 sampler, suggesting the micro-aethelometer also suffers from interference from

vibrations and mechanical shocks in the form of data spikes. However, it was concluded that these spurious data are easily distinguishable from 'normal' data and can be removed from the dataset during processing; in the case of the Hudda et al (2013) study, < 3% of data were rejected. Such studies provided useful information and tools for the processing AE51 micro-aethelometer data.

The Glasgow study used time-stamped video recording alongside pollutant measurements. This provided information on the possible causes of episodes of high pollutant concentrations that are likely to be encountered during each sample run. Kaur et al, 2006 used video recording in conjunction with measured UFP mobile monitoring time-series data to investigate personal exposure in a variety of microenvironments.

In terms of data analyses, there are a number of approaches that have been identified. Box plots have been used in a number of studies (e.g. Buonanno et al, 2013 and 2012; Dons et al, 2012 and 2011; Hu et al, 2012). These plots provide information of the spread of pollutant concentrations measured during a specified time period. Due to the large amount of data collected during the Glasgow study, box plots are used to compare mobile and fixed monitoring results.

For direct comparison of different pollutants e.g. UFP and BC, regression analysis will be a useful. Westerdhal et al (2005) used a scatter plot matrix to visualise the correlation between 7 pollutants. Similar analysis has been carried out in this study with orthogonal regression analysis being used to investigate the relationship between pollutant concentrations measured at child and adult height.

GPS combined with pollutant measurements have provided the opportunity to carry out GIS-based analyses of data.   Martinez et al (2012) and Pirjola et al (2012) used a GIS based visualisation to show UFP number concentrations change throughout a mobile sampling route.   In terms of this study, this helped with the identification/classification of different microenvironments. As discussed in Section 3.2.1, vertical profiles of pollutants are influenced by a number of factors, including topography.

2 Pollutants Investigated

There are many different air pollutants within a city with numerous sources. For 2012 the Scotland Air Quality Pollutant Inventory for emission of air quality pollutants (Defra et al., 2014) noted the sources and contribution of many of the major air pollutants within Scotland. It can be clearly seen in Table 2.1 that transport is responsible for a major proportion of the pollutants of interest, with industrial & residential combustion and energy production also contributing significantly. As the Glasgow study has taken place within an urban environment in close proximity to roads and focuses on the measurement of particulate matter, black carbon and oxides of nitrogen, it is likely that the majority of pollutant concentrations observed originate from road traffic sources, with the other sources being of less significance.

Table 2.1 Scotland Air Quality Pollutant Inventories 2012: Source Emission Contributions (Defra et al. 2014)

Sector	NH_3	CO	NOx	NMVOC	PM_{10}	SO_2	Pb	NH_3
Commercial, domestic and agricultural combustion	1.05%	38.98%	11.78%	3.81%	36.94%	13.63%	24.63%	1.05%
Transport Sources	2.09%	30.11%	37.79%	2.53%	19.59%	2.18%	5.42%	2.09%
Energy Industries	0.00%	5.72%	33.25%	0.00%	9.16%	74.74%	33.35%	0.00%
Industrial Processes	0.22%	2.81%	0.02%	44.42%	9.74%	1.16%	9.34%	0.22%
Industrial Combustion	0.00%	20.23%	14.51%	1.14%	6.90%	7.35%	24.14%	0.00%
Agriculture	86.51%	0.00%	0.00%	7.11%	10.77%	0.00%	0.00%	86.51%
Other	5.51%	1.75%	2.65%	0.49%	3.96%	0.74%	3.12%	5.51%
Fugitive	0.00%	0.42%	0.00%	16.73%	0.97%	0.20%	0.00%	0.00%
Solvent Processes	0.00%	0.00%	0.00%	19.82%	1.96%	0.00%	0.00%	0.00%
Waste	4.62%	0.00%	0.00%	3.96%	0.00%	0.00%	0.00%	4.62%

Emission of many of the pollutants listed in Table 2.1 have been substantially reduced (by more than 50%) in recent years when compared with figures from 1990 (Table 2.2). Many of these reported reductions can be accounted for by improved technologies, for example improved vehicle engine efficiency and changes in exhaust processing, or due to a change in combustion sources, for example the use of renewable for energy production.

Table 2.2 Pollutant emissions and reduction in Scotland (adapted from Defra et al., 2014)

Pollutant	Emissions in 2012 (kt)	Reduction since 1990 (%)
Carbon Monoxide (CO)	169.0	79
Nitrogen Oxides (NO$_x$)	98.1	65

PM_{10}	11.8	59
Sulphur Dioxide (SO_2)	64.9	78

A more detailed description of the pollutants investigated in this study together with their reported effects on human health and the environment is provided below.

2.1 Particulate Matter

Particulate matter (PM) or particulates are microscopic solid or liquid matter suspended in the air we breathe. It is well established that increased PM concentrations in ambient air have a direct impact on the general public's health, with worldwide epidemiological studies establishing a connection between PM exposure and adverse health effects (Pope III and Dockery, 2006, Nawrot et al., 2007). More recently the World Health Organisation published a survey linking poor air quality to stroke and heart disease, as well as respiratory diseases, with 7 million estimated deaths worldwide attributed to air pollution in 2012, with particulates being the chief cause (WHO, 2014). The European Environment Agency recently stated that "of all air pollutants, PM is the most harmful to health in Europe" (EEA, 2014). As such, PM is regarded as a non-threshold pollutant and so any reduction in PM concentrations in ambient air is likely to have a beneficial effect on health.

Particulate matter encompasses a wide range of particle sizes and can be principally split into two categories; ultrafine particles with a diameter of less than 0.1 μm (or 100 nm); and fine particles with a diameter of greater than 100 nm. Figure 2.1 illustrates the size difference between particles of 4 diameters; 10 μm, 1 μm, 0.1 μm and 0.01 μm. To provide additional context, Figure 2.2 shows examples of particulate matter sources in relation to particle diameter.

Figure 2.1 Pollutant emissions and reduction in Scotland (adapted from (MacCarthy et al., 2012)

Ultrafine Particles	Fine Particles		
0.01 μm 10 nm	0.1 μm 100 nm	1 μm 1.000 nm	10 μm 10.000 nm

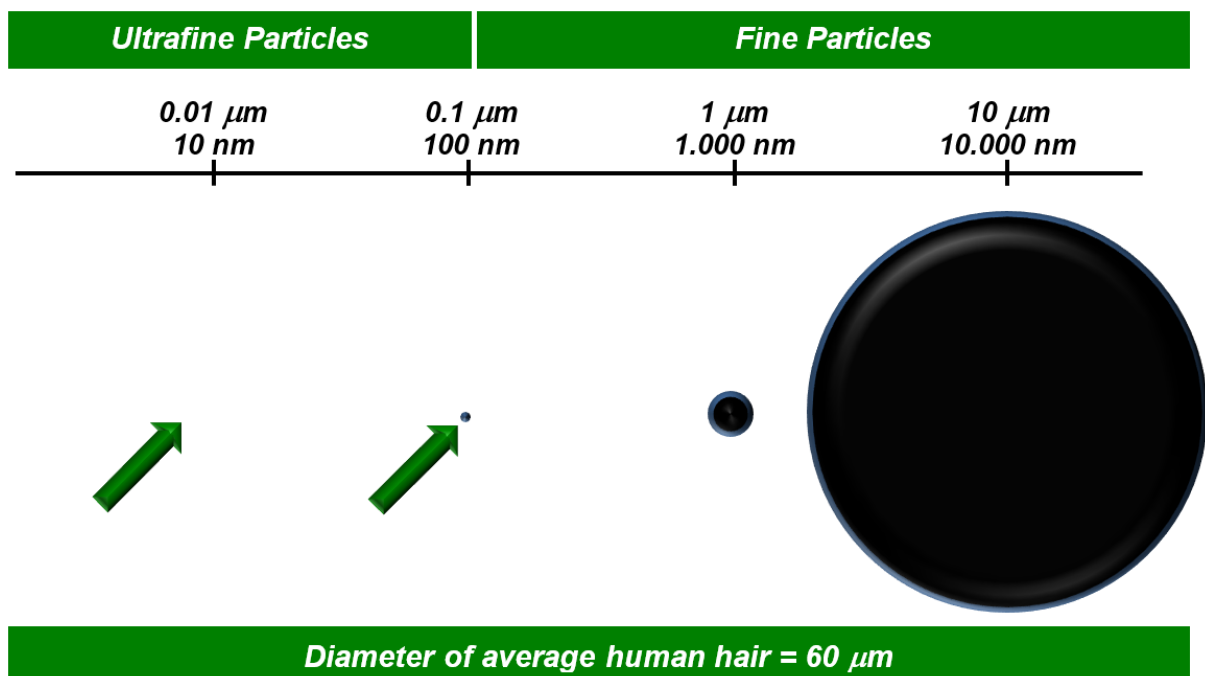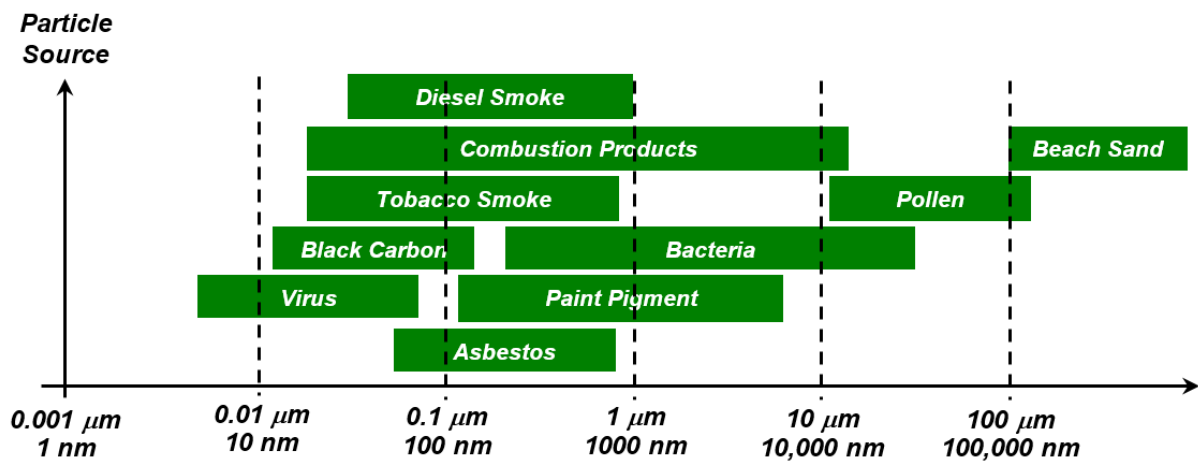**Diameter of average human hair = 60 μm**

Figure 2.2 Particulate Matter (adapted from (Hinds, 1999)

For the purposed of Local Air Quality Management, local authorities in Scotland are currently only required to measure the mass of particulate matter with an aerodynamic mean diameter of 10 μm (PM_{10}). However, national measurements of $PM_{2.5}$ concentrations are made with monitoring sites within the national Automatic Urban and Rural Network (AURN). Fine Particles are composed of a wide range of materials arising from a variety of sources including:

- Combustion sources: The sources within developed countries are primarily from transport, mainly diesel vehicles, whereas biomass within developing countries is probably more important (Dons et al., 2012).
- Secondary particles, comprising of mainly sulphates and nitrates formed by chemical reactions in the atmosphere, and often transported from far across Europe.
- Coarse particles, suspended soils and dusts (e.g. from the Sahara), sea salt, biological particles and particles from construction work.

Particles are measured in a number of different size fractions according to their mean aerodynamic diameter. Most monitoring is currently focussed on PM_{10}, which has a mean aerodynamic diameter of 10 μm. However, the finer fractions such as $PM_{2.5}$ and PM_1 are becoming of increasing interest in terms of health effects. These fine particles can be carried deeper into the lungs where they can cause inflammation and a worsening of the condition of people with heart and lung diseases. In addition, they may carry surface-absorbed carcinogenic compounds into the lungs. Dons et al. (2012) noted that the health effects of $PM_{2.5}$ were well documented, and that black carbon was one of the most harmful constituents; with cardiovascular, respiratory disease and even mortality being the effects of exposure.

Most commonly, Particulate Matter is measured using mass-based techniques, but as a particle gets smaller they tend to be more numerous, hence measurement of ultrafine particles is carried out using a particle counting technique involving light scattering or absorption.

2.2 Other Pollutants Investigated in the Study

In addition to particulate matter, which was the focus pollutant of the study, the study took the opportunity to monitor and compare concentrations of other key pollutants that are of interest in terms of their potential impact on human health and the wider environment. A brief summary of these pollutants is provided in Table 2.3.

Table 2.3 Other Pollutants Monitored

Pollutant	Summary
Black Carbon (BC)	Black carbon (BC) is a measure of airborne 'soot-like' carbon. It is typically formed through the incomplete combustion of fossil fuels, biofuel, and biomass, and is emitted in both man-made and naturally occurring soot. BC is a useful indicator of traffic pollution and is relatively simple and inexpensive to measure. It is linked to adverse health effects but also affects the planet by absorbing heat in the atmosphere and by reducing the earth's ability to reflect sunlight when deposited on snow and ice.
Ultrafine Particles (UFPs)	Ultrafine particles (UFPs) make up approximately 80% of the total particle numbers in air, even though the majority of the particulate mass is due to larger fine particles. Thus, this means although by mass (concentration) there are less finer or ultrafine particulates, these particles are normally significantly more numerous (Hinds, 1999); and as even small numbers of particles may be detrimental to health. Thus, the role and measurement of number concentration could be equally important to PM mass in the local air quality management context.
Nitrogen dioxide (NO$_2$)	Nitrogen dioxide is a key air pollutant of concern within the UK Local Air Quality Management regime. It can irritate the lungs and lower resistance to respiratory infections such as influenza (Barnett et al., 2005, Bernstein et al., 2004), with increased asthma and respiratory admissions typical with higher NO$_2$ concentrations.
Carbon monoxide (CO)	Carbon Monoxide (CO) is a colourless, odourless poisonous gas produced by incomplete, or inefficient, combustion of fuel. It is predominantly produced by road transport, in particular petrol-engine vehicles. The gas prevents the normal transport of oxygen by the blood and can lead to acute health effects, such as a significant reduction in the supply of oxygen to the heart.
Carbon dioxide (CO$_2$)	Carbon dioxide is produced when a material, or fuel, containing carbon is burned. Globally, much of the carbon dioxide in the atmosphere comes from natural sources, but increasingly humans are adding carbon dioxide to the atmosphere through the combustion of fossil fuels for energy. CO$_2$ displaces oxygen in the air and in confined spaces can lead to shortness of breath and headaches. CO$_2$ as an important greenhouse gas contributes to climate change.
Sulphur dioxide (SO$_2$)	Anthropogenic sulphur dioxide (SO$_2$) is produced when a material, or fuel, containing sulphur is burned. Concentrations of SO$_2$ measured in Scotland's air are primarily associated with emissions from power stations burning fossil fuels, such as heavy oils or coal. Sulphur dioxide is both damaging to health, the environment and to where we live, as it forms a corrosive acid when combined with water. Acid rain from the formation of sulphuric acid has been implicated in the damage and destruction of vegetation and in the degradation of soils, building materials and watercourses (US EPA, 2006).
Benzene (C$_6$H$_6$)	Benzene (C$_6$H$_6$) is an aromatic organic compound which is a minor constituent of petrol (about 2% by volume). The main sources of benzene in the atmosphere are normally from the distribution and combustion of petrol, and to a limited extent industrial usage and processes. Benzene is a known human carcinogen and is associated with a large number of health effects include cancer, damage to the central nervous system, liver, kidneys, reproductive disorders and birth defects birth defects (US EPA, 2003).

3 Methodology

3.1 Monitoring Equipment

3.1.1 Mobile

Table 3.1 below details the monitoring equipment used for the Glasgow study. For $PM_{2.5}$, both automatic and gravimetric sampling was carried out using the Lighthouse IAQ 3016 and Harvard-PEMs sampler, respectively. Measurement of BC was carried using the Magee MicroAeth AE51 and UFP using the Philips NanoTracer. All four particulate samplers are handheld and are principally designed for personal exposure measurements.

In addition to the particulate analysers, measurements of NO_2, CO_2 and benzene were made using AQMesh, COZIR optical sensor and pumped tube sampling, respectively. Meteorology measurements of wind speed/direction, temperature, humidity, pressure and rainfall were made using the Lufft WS600. GPS measurements were recorded using the Garmin 110 GPS watch, which provided location and speed data every 20 s. Lastly, the sampling route was filmed allowing pollution events to be further investigated in addition to enhancing data visualisation.

All data were logged on a web-based logging system (web logger) or on the sampler's internal memory with integrated GPS and 3G telemetry.

Table 3.1 Mobile Monitoring Equipment

Parameter	Instrument type	Description
Particulate matter (PM)	Lighthouse IAQ 3016 PM analyser	This analyser provides fast response particle counts of 6 size bins from 10 microns down to 500 nm. It uses proprietary algorithms to estimate PM_{10}, $PM_{2.5}$ and PM_1 concentrations.
$PM_{2.5}$	Harvard-PEMS + BGI pump (Personal Exposure Monitor)	Ambient air is drawn through a filter at a constant flow rate of 4 l min^{-1}. The filter is weighed pre and post-sampling and a mass concentration derived from the weight of material collected and the volume of air sampled.
Black Carbon	Magee AE51 MicroAeth	The spectrometer used in this analyser is identical to the spectrometer used in the Aethalometer used in the UK national research network. The MicroAeth is used as a transfer calibration standard for the research network analysers
Ultrafine Particles	Philips NanoTracer	This analyser detects and counts particles between 10 nm and 300 nm in size.
Meteorology	Lufft WS600	This portable met sensor makes high resolution measurements of wind speed, wind direction, temperature, pressure, relative humidity and rainfall.
GPS	Garmin 110	This watch accurately records position and time.
NO_2, SO_2 and CO	AQMesh	The sampler measured gaseous pollutant concentrations at 1-minute resolution.

| Video | Roadhawk Recorder | This camera records standard definition video at 15 frames per second. |

The monitoring equipment was mounted on a purpose-modified industrial trolley, which was pushed around the chosen routes. The equipment was mounted at two fixed heights: 1.68 m, to reflect the typical breathing height of a Scottish adult (The Scottish Health Survey, 2009); and 0.80 m to reflect the breathing height of a child in a buggy. All data were recorded using high resolution 1-minute averaging. Figure 3.1 shows a schematic of the mobile monitoring trolley and equipment.

Figure 3.1 Mobile Monitoring Trolley Schematic
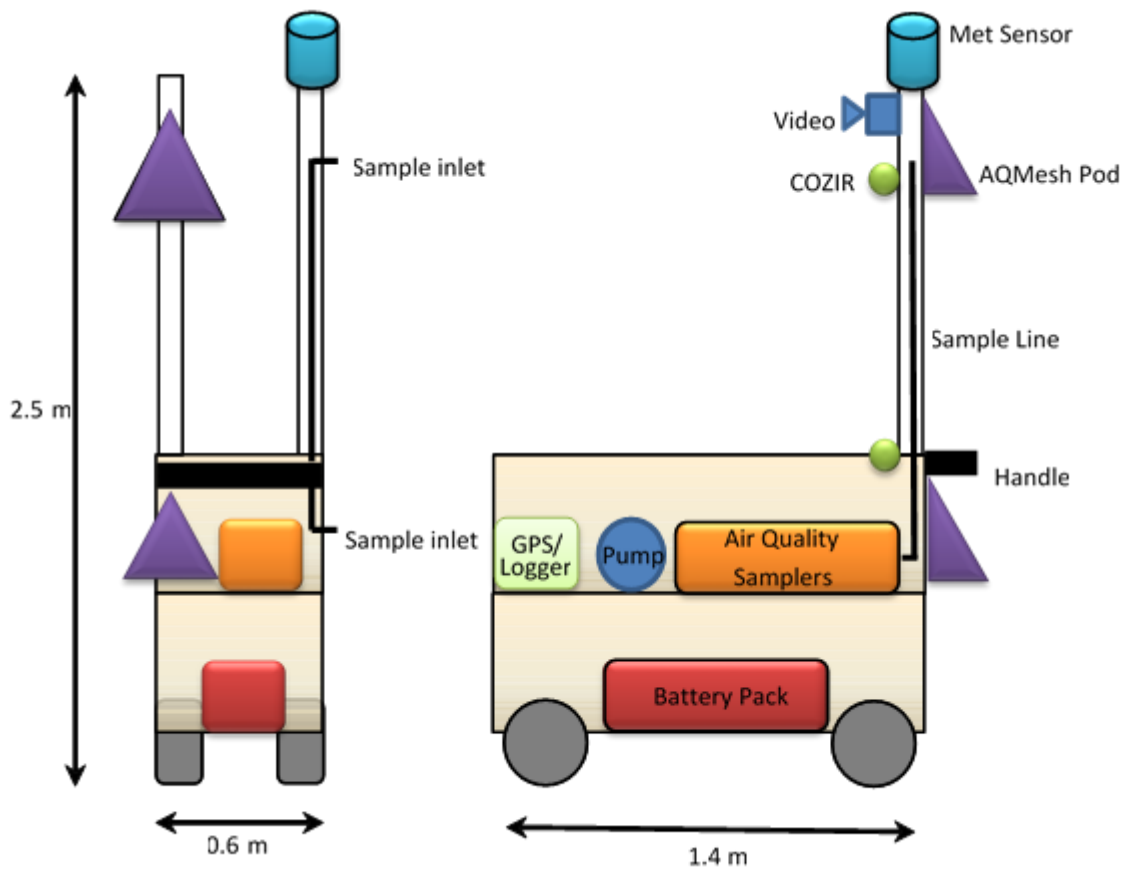
3.1.2 Fixed

Table 3.2 lists the measurement techniques utilised at 5 fixed monitoring sites that were used for co-location exercises (details provided in Section 3.2). Measurements of NO_2 are carried out using the EU reference method using chemiluminescence[2]. Measurements of PM_{10} and $PM_{2.5}$ are carried out using a Filter Dynamics Measurement System[3] (FDMS) at Glasgow Townhead, Glasgow Kerbside and Fife Dunfermline. This measurement technique has been assessed as equivalent to the EU reference method. Measurements of PM_{10} concentrations were carried out using a Tapered Element Oscillating Microbalance[4] (TEOM) at Perth Atholl Street and Waltham Crooked Billet. The TEOM has been assessed as not equivalent to the

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[2] http://uk-air.defra.gov.uk/assets/documents/reports/ageg/chapter4.pdf

[3] http://www.scottishairquality.co.uk/laqm/lso-manual
[4]
http://www.thermoscientific.com/content/dam/tfs/ATG/EPD/EPD%20Documents/Product%20Manuals%20&%20Specifications/Air%20Quality%20Instruments%20and%20Systems/Particulate/EPM-manual-TEOM1400ab.pdf

EU reference method however, these data can be corrected using the Volatile Correction Model (Green et al, 2008). This correction has been assessed as providing reference equivalent PM_{10} data from TEOMs.

Table 3.2 Measurement Techniques – Fixed Sites

Colocation Site	NO_2 Measurement Technique	PM_{10} Measurement Technique	$PM_{2.5}$ Measurement Technique
Glasgow Townhead	Chemiluminescence	FDMS	FDMS
Glasgow Kerbside	Chemiluminescence	FDMS	FDMS
Fife Dunfermline	Chemiluminescence	FDMS	n/a
Perth Atholl Street	Chemiluminescence	TEOM	n/a
Perth Atholl Street	n/a	TEOM	n/a

3.2 Co-location Exercises

A number of colocation exercises were carried out to characterise both the intra-sampler responses (e.g. between Low and High samplers of the same type) and to assess the samplers against fixed point measurement methods for PM_{10}, $PM_{2.5}$ and NO_2.

Table 3.3 details the colocation exercises carried out as part of this study. A total of 8 exercises were carried out between February and September 2014. Glasgow Townhead, Glasgow Kerbside and London Marylebone Road monitoring sites are part of the UK Automatic Urban and Rural Network (AURN - http://uk-air.defra.gov.uk/interactive-map). Note that a co-location of UFP only was carried out at the London Marylebone Road monitoring site. However, no comparison could be made to the on-site Scanning Mobility Particle Sizer Spectrometer (SMPS) due to a fault with this analyser. In addition to the on-site colocations carried out at fixed monitoring sites, a mobile colocation exercise was carried out along Hope St, Glasgow on 13/08/2014.

A range of urban environments were used (urban background, roadside and kerbside) to try and maximise the range of pollutant concentrations measured by each sampler. In the case of the Hope Street mobile co-location exercise, all samplers were set up to sample ambient air at 0.8 m. A further 4 co-location exercises were carried out as part of parallel studies and are detailed in Table 3.4. Fife Dunfermline and Perth Atholl Street both form part of the Scottish Air Quality Database (SAQD) network (www.scottishairquality.com) and Waltham Crooked Billet forms part a local authority monitoring site in London (http://www.airqualityengland.co.uk/site/graphing?site_id=WL4).

Table 3.3 Colocation Exercises as Part of this Study

Colocation Site	Site Type	Coordinates (Lat/Long)	Date
Glasgow Townhead	Urban Background	55.865782, -4.243631	14/02/2014
Glasgow Kerbside	Kerbside	55.859170, -4.258889	25/04/2014
Glasgow Kerbside	Kerbside	55.859170, -4.258889	17/07/2014
Hope Street, Glasgow	n/a	n/a	13/08/2014
Glasgow Kerbside	Kerbside	55.859170, -4.258889	19/08/2014
London Marylebone Road (UFP)	Kerbside	51.522530, -0.154611	21/08/2014
Glasgow Townhead	Urban Background	55.865782, -4.243631	27/08/2014
Glasgow Kerbside	Kerbside	55.859170, -4.258889	03/09/2014

Table 3.4 Colocation exercises as Part of Other Studies

Colocation Site	Site Type	Coordinates (Lat/Long)	Date
Fife Dunfermline	Roadside	56.073830, -3.448620	15/04/2014
Perth Atholl Street	Roadside	56.399327, -3.434182	26/06/2014
Waltham Crooked Billet	Kerbside	51.601728, -0.016442	16/09/2014

3.3 Mobile Monitoring Exercises

A total of 8 mobile monitoring exercises were carried out between March and August 2014, with Table 3.5 listing the day and dates of the exercises. All exercises were carried out using the same predetermine route, shown in Figure 3.2. The route was designed to incorporate as many urban microenvironments as possible (Table 3.6), such as street canyons, pedestrianised zones and busy streets. The route was approximately 2.6 miles in distance with one lap of the route taking approximately 1 hr 15 min to travel around. All exercises were carried out, where possible, on days with no rain and low wind speeds.

The mobile exercises were carried out between 0700 and 1900 during six weekdays (2 x Fridays) and 0900 to 1600 during two weekend days to ensure that pollutant concentrations during rush hour periods were recorded. This resulted in between five and ten loops of the route being completed during each exercise with a total 185 miles over 82 hours being covered as part of the study.

Table 3.5 Mobile Monitoring Exercises - 2014

Location	Day	Date
Glasgow City Centre	Friday	14/03/2014
	Thursday	10/04/2014
	Wednesday	21/05/2014
	Monday	23/06/2014
	Tuesday	08/07/2014
	Sunday	13/07/2014
	Saturday	09/08/2014
	Friday	15/08/2014

Figure 3.2 Mobile Monitoring Route – Glasgow City Centre

Map data ©2014 Google, © 1996-2015 Garmin Ltd.

Table 3.6 Mobile Monitoring Route Details – Glasgow City Centre

Street name	Description of street on route	Approximate Length of street within study route (miles)
Hope Street	Busy urban canyon orientation south to north (partially restricted to buses and taxes)	0.42
Sauchiehall Street	Urban pedestrian precinct orientation west to east	0.16
Buchanan Street	Urban pedestrian precinct orientation north to south	0.22
St Vincent Street	Busy urban canyon orientation west to east	0.10
George Square	Busy urban street orientation west to east	0.14
George Street	Busy urban canyon orientation west to east	0.14
Montrose street	Busy urban canyon orientation north to south	0.11
Ingram Street	Busy urban street orientation west to east	0.18
High street	Busy urban street orientation north to south	0.21
Saltmarket	Busy urban street orientation north to south	0.34
Clyde	Busy Urban street orientation east to west	0.44
Oswald Street	Busy urban street orientation north to south	0.16

3.4 Quality Assurance/ Quality Control (QA/QC)

3.4.1 Fixed Monitoring Sites

Data from monitoring sites included within both the Automatic Urban and Rural Network and the Scottish Air Quality Database are underpinned by a comprehensive Quality Assurance/Quality Control regime. These QA/QC procedures include:

Intercalibration and Audit procedures

The audit and intercalibration procedures adopted by Ricardo-AEA rely upon the principle that a set of recently certified gas cylinders (called "audit gas") is taken to all the stations in a monitoring network. This gas is certified at the Ricardo-AEA Gas Calibration Laboratory. At each station, analyser response to audit gas is recorded to check if the expected concentration (i.e. the certified value for the cylinder) is obtained. The analyser response to audit gas is obtained using calibration factors obtained from the site operator. The audit procedure checks the validity of the provisional data, the correct overall operation of the analyser and the reliability of calibrations undertaken routinely at that station. These site audit procedures are compliant with the requirements of the CEN standard methods of measurement and are used throughout the UK AURN network.

The results of the audit exercises form an integral part of the data management system and are fed directly into the data ratification process. After the audit exercise, data from all the stations visited are traceable to recently calibrated UKAS accredited gas calibration standards (the audit gas).

UKAS Accreditation

Ricardo-AEA holds UKAS accreditation to ISO 17025 for the on-site calibration of the gas analysers (NO_X, CO, SO_2, O_3), for flow rate checks on particulate (PM_{10}) analysers and for the determination of the spring constant, k_0, for the TEOM analyser. ISO17025 accreditation provides complete confidence that the analyser calibration factors are traceable to national metrology standards, that the calibration methods are sufficient and fit for purpose, and that the uncertainties are appropriate for data reporting purposes.

Ricardo-AEA also holds ISO17025 accreditation for laboratory certification of NO, NO_2, CO and SO_2 gas cylinders.

Ratification tasks and output

When ratifying data the following are closely examined:

- Issues that have been flagged up automatically by the software
- Zero and sensitivity factors used on each day
- General review of the result to make sure that there are no other anomalies.

Ratified Data Checking

Once the data have been initially ratified proforma reports are produced and passed to the data checker. The role of the data checker is to:

- Assess if there are any station problems if not the data can be marked as ratified
- Return the station to the data ratifier if there are any issues requiring further action by the data ratifier
- Forward the report to the project Quality Circle if there are data quality issues which require a group discussion to resolve.

Following the Quality Circle meeting the data are then corrected if required and uploaded as ratified to the database and web site.

3.4.2 Mobile Monitoring Equipment

A similar QA/QC approach to that that is described above was used for the mobile monitoring data with the following differences:

AQMesh

Data from AQMesh were uploaded real-time to a web-based server via 3G telemetry. Data acquisition was checked before, during and after each mobile exercise. No calibrations could be carried out in the traditional sense as this is not possible due to interferences and the algorithms used in data processing. Therefore, the performance of the AQMesh pods needed to be "characterised" at fixed sites by carrying out co-location exercises. The co-location exercises were used to correct NO and NO_2 data (Appendix D). Once corrected, the mobile data were compared to the fixed site data and spurious data (e.g. negative data spikes) were removed.

For CO and SO_2 data no co-locations comparing mobile to fixed monitoring data were carried out. Data were adjusted for offset using the minimum measured CO and SO_2 concentrations as a reference.

AE51 Micro-Aethelometer

BC data were recorded on the sampler's internal memory and downloaded and validated at the end of each monitoring exercise. The flow rate of the samplers were set to 100 ml min^{-1}, which was checked using a calibrated BIOS Defender flowmeter[5] at the beginning of each exercise. In addition, a new filter was used for each monitoring exercise. Negative data points were removed during final data ratification.

A potential further adjustment of AE51 data may have been required had the relationship between the attenuation of light, filter loading and the calculated mass concentration not being linear. As a result, there is potential for the AE51 to underestimate black carbon concentrations as the filter loading increases (Virrkula et al, 2007). However, it was found that no such correction was necessary. Appendix C details the algorithm and the analysis used to determine whether the BC data required this correction.

Lighthouse

Patriculate Matter data were recorded on the sampler's internal memory and downloaded and checked at the end of each monitoring exercise. The flow rate of the samplers were set to 4 l min^{-1}, which was checked using a calibrated BIOS Defender flowmeter at the beginning of each exercise. A further zero check was carried out using a disposable filter unit attached to the sample inlet to check that PM concentrations dropped to zero.

No calibrations could be carried out, however, the colocation exercises were used to correct $PM_{2.5}$ and PM_{10} data (Appendix E).

NanoTracer

UFP data were recorded on the sampler internal memory and downloaded and checked at the end of each monitoring exercise. The flow rate of the samplers were set to 300 ml min^{-1}, which was checked using a calibrated BIOS Defender flowmeter at the beginning of each exercise. Negative data were removed during final data ratification.

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[5] http://drycal.mesalabs.com/

H-PEMs

Ambient air was drawn through a filter at a constant flow rate of 4 l min^{-1}, which was checked every 30 - 60 mins during the monitoring exercises. The flowrate, start time and finish time were recorded. Pall Corporation Teflo™ PTFE Membrane filters with plastic ring (Pore = 2 µm, Dia. = 37 mm) were used. All filters were weighed in line with BS EN 12341:2014[6]. The filters were uniquely identified and conditioned in the weighing room at 19 °C to 21 °C and 45 % RH to 50 % RH for ≥ 48 hr pre and post-sampling.

Benzene Pumped Sampling

Ambient air was sampled through analytical desorption tubes (ATD) at a constant flow rate of 250 ml min^{-1}, which was checked every 30 - 60 mins during the monitoring exercises. The flowrate, start time and finish time were recorded. Environmental Scientifics Group (ESG) were used to supply and analyse the samples. Standard preparation and sample measurement was carried out according to UKAS accredited method ASC/SOP/236 Issue 2 (http://www.ukas.org/testing/schedules/Actual/1015Testing%20Multiple.pdf).

3.5 Data Analyses

A number of analysis software packages have been utilised for this study:

- Openair (Carslaw, Ropkins, 2012)
- Microsoft Excel 2013
- ArcGIS

The following analyses have been carried out:

- Regression analyses.
- Outlier Testing.
- Uncertainty calculation.
- Summary statistics.
- Time-series plots.
- Wind rose/polar plots.
- Contour plots summarising the spatial distribution of 1-minute average pollutant concentrations.

3.5.1 Regression Analyses

Regression analysis was used to investigate the relationships between monitors sampling at 0.80 m (LOW) and 1.68 m (HIGH), the relationships between mobile and fixed monitoring, and cross-pollutant relationships. In order to take account of the uncertainty associated with each component (x and y) of the analysis, orthogonal regression was used as opposed to linear regression, which only takes into account of the variation in the y-axis.

Three key statistics are provided in the regression model: the slope (b) and intercept (a) of the regression line and the coefficient of determination (r^2). Both the slope and intercept provide a relationship of the form $y = a + bx$ where x and y are the data pairs, where x is always the recorded measurements from the LOW samplers and y from the HIGH samplers. The value of r^2 is given between 0 – 1 with a value closer to 1 indicating a stronger correlation and more accurate model between the two datasets under investigation. For this study, the following strength of correlation are defined:

- 0 - 0.2 = weak, slight
- 0.2 - 0.4 = mild/modest

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[6] BS EN 12341 - Ambient air. Standard gravimetric measurement method for the determination of the PM$_{10}$ or PM$_{2.5}$ mass concentration of suspended particulate matter, June 2014

- 0.4 - 0.6 = moderate
- 0.6 - 0.8 = moderately strong
- 0.8 - 1.0 = strong

Appendix A details the calculations used to carry out orthogonal regression.

3.5.2 Grubbs' Outlier Test

The resultant regression model from the comparison of two datasets may consist of outliers and although these outliers are valid data they may unduly influence the regression model. As a result, Grubbs' outlier test was used to identify and remove potential outliers.

For the purposes of this study and due to the large numbers of data points collected, Grubb's' outlier test was used iteratively until no more outliers were identified. This resulted in data rejection of between 0% and 7.6% - Appendix B details Grubbs' Outlier Test

3.5.3 Uncertainty Analyses

A number of uncertainty calculations were used within this study:

- The between-sampler uncertainty (u_{bs}).
- The Mean Absolute Error (MAE).
- The expanded relative uncertainty (W).
- Uncertainty in slope (u_b) and intercept (u_a).

The between-sampler uncertainty provides an indication of the error between two measurements taken by two samplers during the colocations. The MAE is the error in the measured values as compared to the regression model and has been reported for the pollutant vs height results. The relative expanded uncertainty has been calculated using the fixed monitoring versus mobile monitoring samplers colocations. In this case charts plotting the calculated W versus the measured concentration have been provided for NO_2, NO, PM_{10} and $PM_{2.5}$. The standard CEN/TS 16450:2013[7] was used as a guide.

The calculated uncertainty in slope and intercept are provided in all regression analyses and Appendix A details the uncertainty calculations used.

3.5.4 Statistics

Openair uses R (http://www.r-project.org/), a computing language and environment for statistical computing and graphics. The Openair project (http://www.openair-project.org/) provides analytical tools for use with air quality data and can be used to quickly analyse large amounts of data.

Summary statistics are provided in tabular and chart form and consist of the minimum, quartiles, mean and maximum.

3.5.5 Geographical Information System

ArcGIS 10 was used to create the contour plots measured of 1-minute average pollutant concentrations at each of the four study areas using inverse distance weighted (IDW) interpolation. This provides a visualisation of the spatial variation of pollutant concentrations throughout study route.

Please note that the concentrations shown in the contour plots are indicative as they are the result of a geo-processing routine in ArcGIS. Also, the pollution gradients can be seen to be wider than the roads, which are an artefact of the GPS accuracy and the GIS processing.

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[7] Ambient air. Automated measuring systems for the measurement of the concentration of particulate matter (PM10; PM2,5)

When interpreting the plots all concentrations shown are from roadside measurements and indicate potential exposure a pedestrian might experience when walking along the road.

Figure 3.3 shows the GPS points recorded during all mobile sampling exercises. On average, three GPS measurements were recorded every minute. Each point was then assigned a pollutant concentration e.g. three GPS points within the same minute would be assigned the same associated 1-minute average pollutant concentration. A total of 33,753 points were recorded during the 8 mobile monitoring exercises.

All map data within this report Contains Ordnance Survey data © Crown copyright and database right 2015

Figure 3.3 Mobile Monitoring Sampling Points
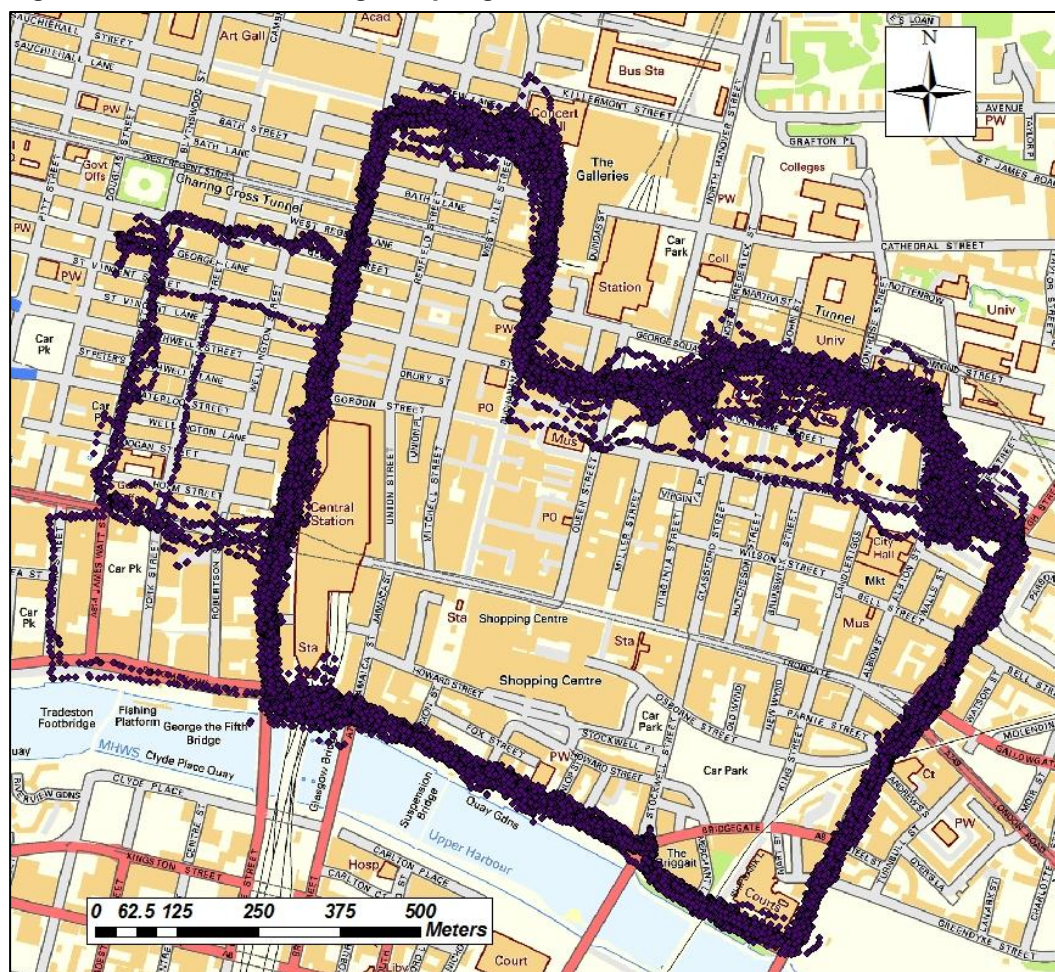
Contains Ordnance Survey data © Crown copyright and database right 2015

3.6 Equipment Issues

A number of issues with equipment were encountered during the monitoring programme. This section details these problems with associated impacts regarding data quality and analyses.

3.6.1 AQ Mesh

Overall, during the study, the AQMesh samplers performed well. However, it was not possible to use the samplers for one mobile monitoring exercise on 23/06/2014 due to an aerial fault. Although this reduced the number of 1-minute average data available for

analyses by approximately 600, over 3700 data points were recorded. It is therefore thought that this loss of data has had minimal effect on the final results.

In addition, the NO_2 sensor used within the AQMesh is known to suffer from cross sensitivity with ozone (O_3), resulting in an overestimation of NO_2 concentrations at higher O_3 concentrations. Accurate measurements of O_3 are required to correct for this and are available at the Glasgow Townhead monitoring site. However, the Townhead site is located in an urban background location and therefore O_3 concentrations measured there will at times differ considerably from concentrations measured at a roadside location. This has added uncertainty to the regression analysis between AQMesh and fixed site (chemiluminescence) data (Appendix D) due to a lack of accurate O_3 measurements within the Glasgow town centre.

3.6.2 Meteorological Measurements

A temporary fault with the meteorological mast bracket resulted in an inability to measure microsite weather conditions during one mobile monitoring exercise on 10/04/2014. This resulted in the loss of approximately 600 1-minute average measurements. However, a total of 3193 measurements were taken and therefore it is considered that this loss has had a minimal effect on the final results.

3.6.3 COZIR

The COZIR CO_2 sensor response was reset at the beginning of each monitoring exercise. This was done by assuming that CO_2 concentrations were close to 500 ppb prior to commencement of each exercise. Unfortunately, it was found that the sensor reset was not consistent between the two sensors (0.80 m and 1.68 m) and therefore no consistent relationship can be inferred between the two sensors from the intra-sampler regression results (shown in Table 3.7 and Figure 3.4). As a result, no further analyses were carried out using the CO_2 data.

Table 3.7 Intra-Sampler Orthogonal Regression Results – CO₂

COZIR CO₂	Dataset	Date	1 minute		Orthogonal Regression		
			n_{bs}	u_{bs}	r^2	Slope (b) ± u_b	Intercept (a) ± u_a
Colocations Exercises	1	25/04/2014	467	2191.86	0.964	1.065 ± 0.009	7.727 ± 8.211
	2	17/07/2014	508	7657.61	0.015	0.342 ± 0.038	446.619 ± 31.072
	3	13/08/2014	458	954.11	0.839	1.054 ± 0.02	-24.294 ± 14.662
	4	27/08/2014	439	4133.93	0.438	-1.042 ± 0.037	1421.669 ± 26.658
All Exercises	All Data		1872	3788.70	0.517	1.455 ± 0.021	-378.439 ± 16.832

Figure 3.4 Intra-Sampler Orthogonal Regression Lines – CO$_2$ (μg m^{-3})
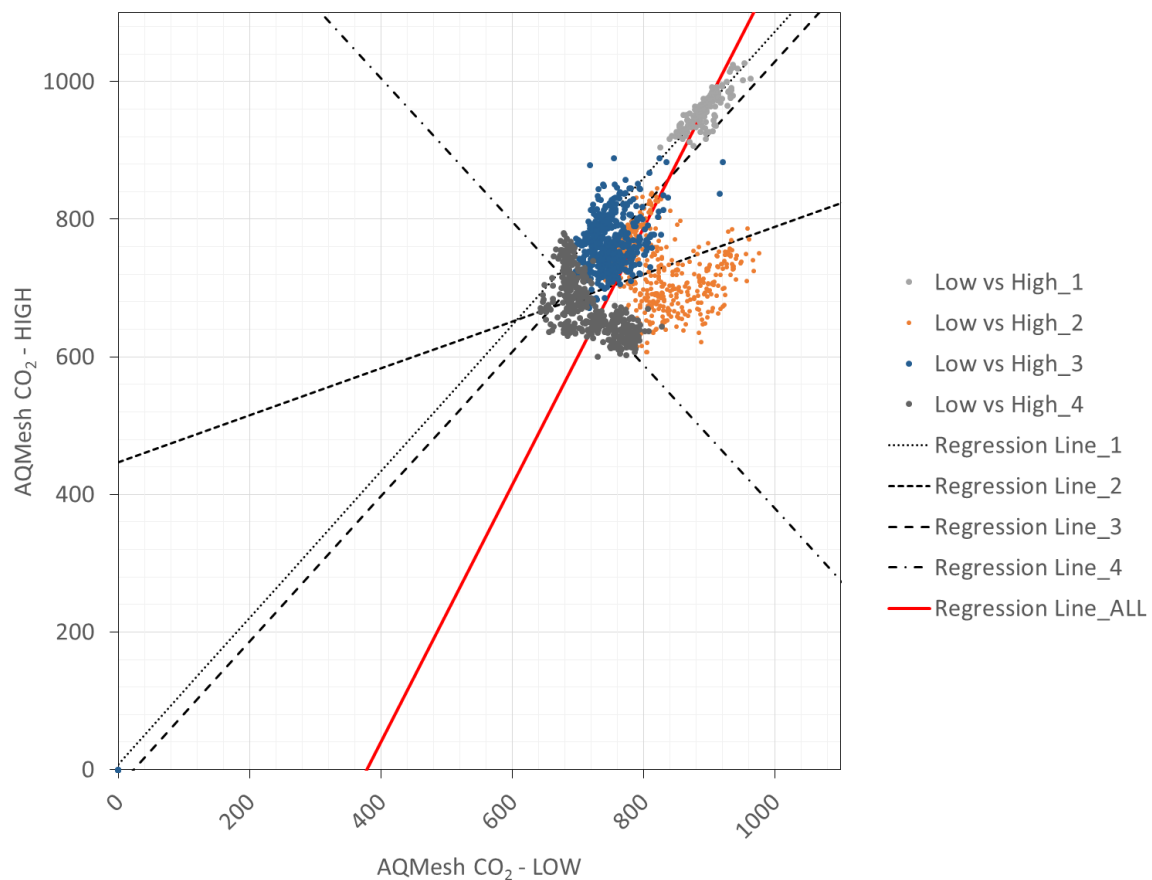
3.6.4 PM$_{2.5}$ Gravimetric

The results from gravimetric sampling of PM$_{2.5}$ using the Harvard-PEMS samplers are detailed in Table 4.3.3. Inconsistencies were found in the results from mobile monitoring exercises. In order to attempt to identify and rectify the problem, flow measurements were taken at ½ hourly intervals during the monitoring exercises and was adjusted back to 4 l min^{-1} where necessary. No significant fluctuations in flow rate were recorded however, and a possible cause was attributed to the use of a power supply without a voltage regulator causing fluctuations in the flowrate. Although analyses have been carried out using these data, the fault has increased the uncertainty of the results.

4 Results

The following Sections detail the results from the study.

4.1 Mobile vs Fixed Monitoring

This section compares hourly mean concentrations of $PM_{2.5}$, PM_{10}, NO_2 and NO measured during the mobile monitoring exercises and compared to concentrations measured at two fixed monitoring sites located at Glasgow Kerbside and Glasgow Townhead. Orthogonal regression results between hourly mean pollutant concentrations measured at 0.80 m (LOW) and 1.68 m (HIGH) are summarised in Appendix G. Summary statistics of measured hourly average pollutant concentrations are provided in Appendix L.

4.1.1 PM$_{2.5}$

Hourly mean $PM_{2.5}$ concentrations as measured at the fixed monitoring sites, Kerbside and Townhead, and by the mobile monitoring samplers during each mobile monitoring exercise are graphed in Figure 4.1.

The minimum hourly mean $PM_{2.5}$ concentrations measured at Glasgow Townhead and Glasgow Kerbside were 0 $\mu g\ m^{-3}$ and 5 $\mu g\ m^{-3}$, respectively; during the 13th July (Sunday) and the 9th August (Saturday). In comparison, minimum hourly mean concentrations of $PM_{2.5}$ were measured by the mobile monitoring trolley on the 13th July (Sunday), with a mean measured concentration of 11 $\mu g\ m^{-3}$, being recorded at both 0.80 m and 1.68 m respectively.
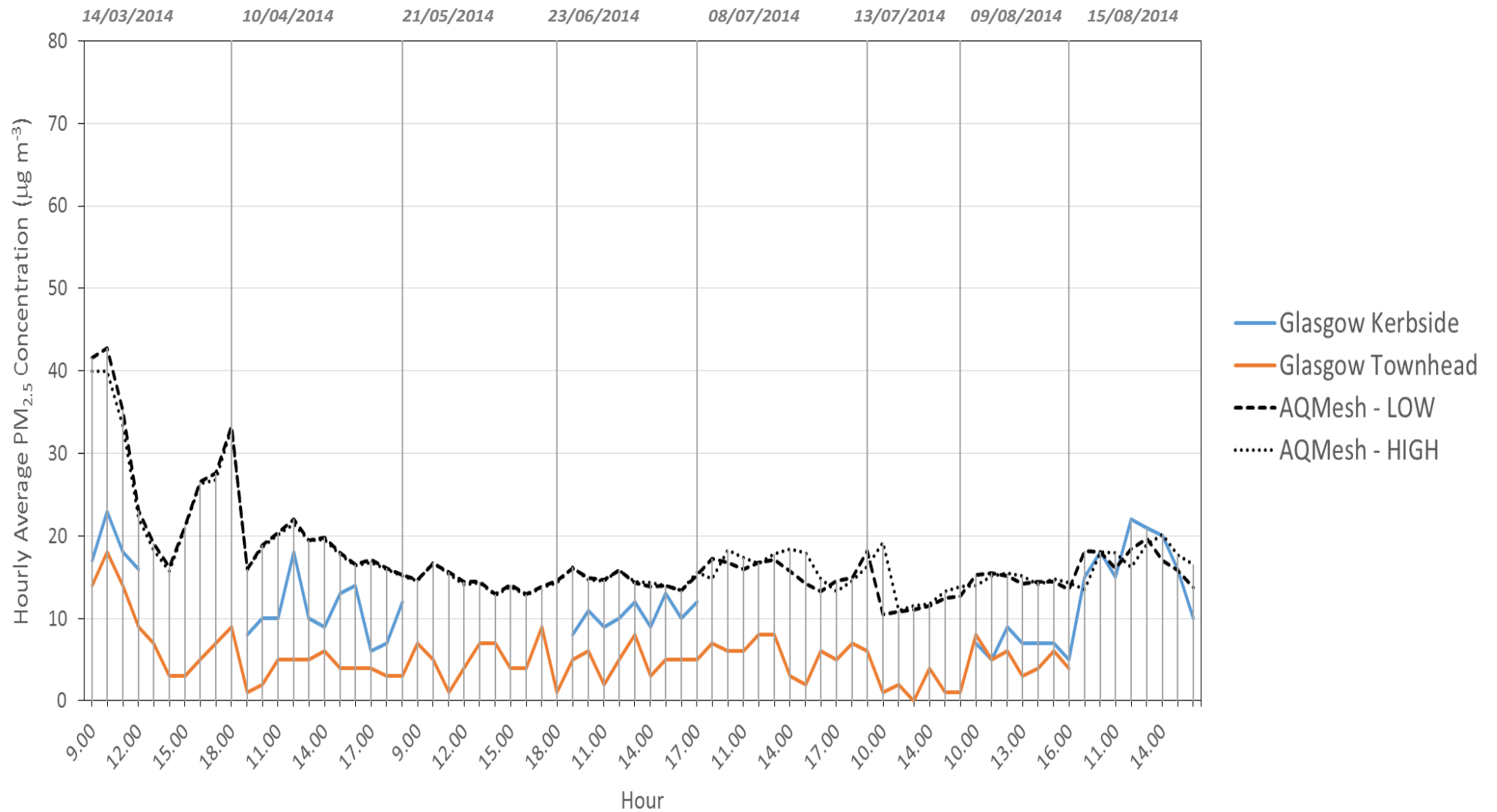
The maximum hourly mean $PM_{2.5}$ concentrations measured at Kerbside and Townhead were 23 $\mu g\ m^{-3}$ and 18 $\mu g\ m^{-3}$, respectively; during the 14th March (Friday). The maximum hourly mean $PM_{2.5}$ concentrations measured by the mobile monitoring unit were 43 $\mu g\ m^{-3}$ and 40 $\mu g\ m^{-3}$ at 0.80 m and 1.68 m, respectively, also during 14th March (Friday).

Over all mobile monitoring exercises, an average $PM_{2.5}$ concentration of 17 $\mu g\ m^{-3}$ was measured by the mobile monitoring unit at both 0.80 m and 1.68 m. A mean $PM_{2.5}$ concentration of 5 $\mu g\ m^{-3}$ and 12 $\mu g\ m^{-3}$ was measured at Townhead and Kerbside, respectively. These results show that on average, $PM_{2.5}$ concentrations were 12 $\mu g\ m^{-3}$ and 5 $\mu g\ m^{-3}$ higher travelling along the mobile monitoring route than at the Kerbside or Townhead fixed monitoring sites, respectively. The differences in concentrations of $PM_{2.5}$ reported at both fixed sites used in the study reflect the kerbside and urban background locations of these analysers, with the kerbside site located to higher emissions from road traffic.

Analysis of hourly $PM_{2.5}$ concentrations measured at 0.80 m and 1.68 m used a total of 72 hourly average data pairs with a mean absolute error (MAE) of 0.86 $\mu g\ m^{-3}$ and were found to have be strongly correlated (r^2) of 0.928. No data points were rejected by the Grubbs' outlier test. Using the calculated slope of 0.920 and intercept of 1.477, at the $PM_{2.5}$ annual mean objective level of 12 $\mu g\ m^{-3}$ as measured as an hourly mean, comparison of concentrations at 0.80 m and 1.68 m indicate that the hourly mean $PM_{2.5}$ concentration at 1.68 m is likely to be 4% greater than that measured at 0.80 m (e.g. 12.5 $\mu g\ m^{-3}$). In comparison, when the maximum measured hourly mean $PM_{2.5}$ concentration of 43 $\mu g\ m^{-3}$ is used as the basis for comparison between the two exposure heights, the findings indicate that hourly mean concentration reported at 1.68 m is 4.7 % lower than that recorded at 0.80 m (e.g. 41 $\mu g\ m^{-3}$). So in general, higher hourly mean $PM_{2.5}$ concentrations were likely to be measured at adult

breathing height when PM$_{2.5}$ concentrations are low. Whilst when concentrations are high, higher concentrations were likely to be measured at child breathing height.

Figure 4.1 Hourly Average PM$_{2.5}$ Concentrations Time-series - Mobile vs Fixed
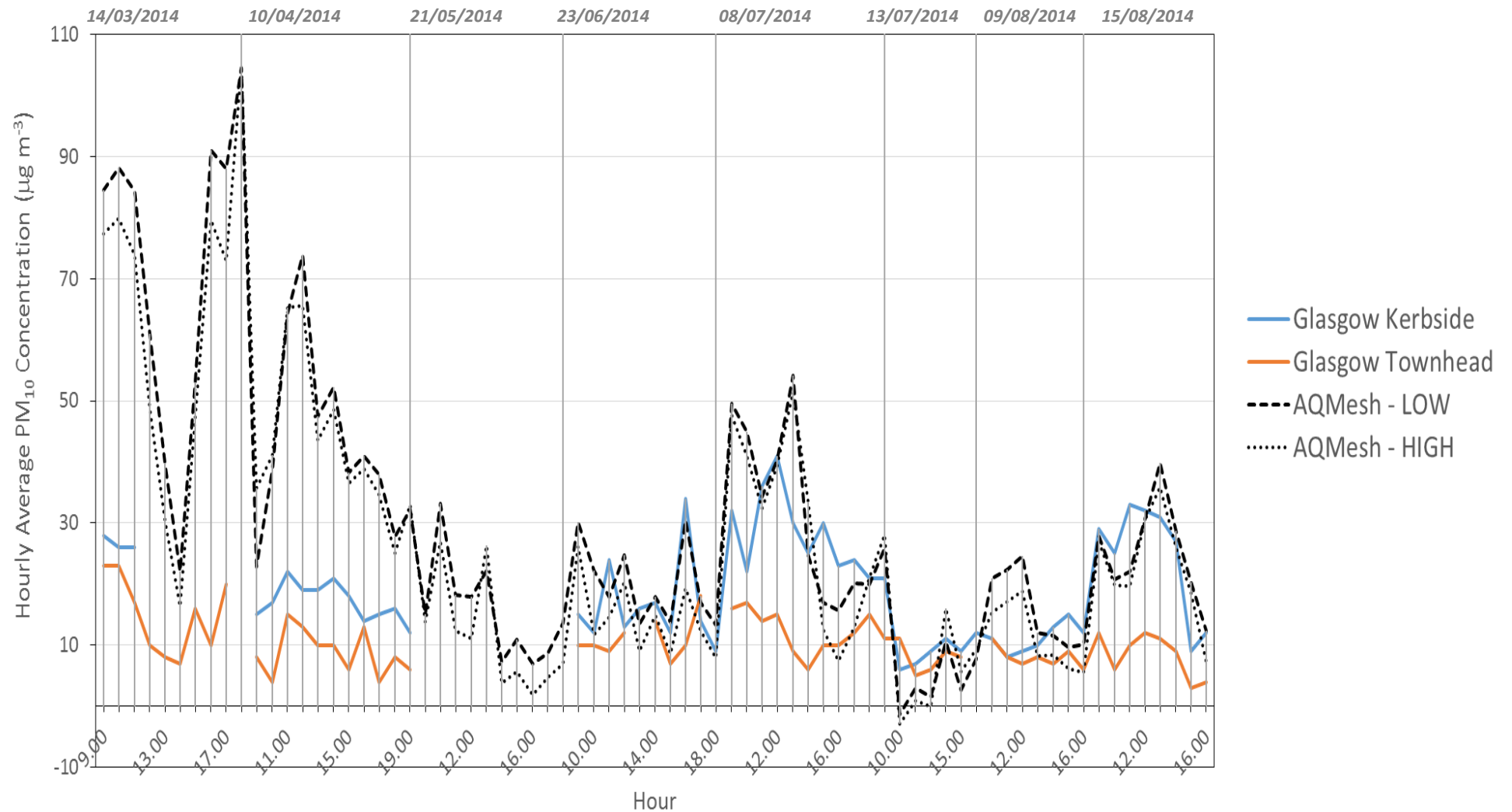
4.1.2 PM$_{10}$

Hourly mean PM$_{10}$ concentrations measured at the fixed monitoring sites, Kerbside and Townhead, and by the mobile monitoring samplers during each mobile monitoring exercise are graphed in Figure 4.2.

The minimum hourly mean PM$_{10}$ concentration measured at Kerbside and Townhead was 6 μg m^{-3} and 3 μg m^{-3} during the 13th July (Sunday) and 15th July (Saturday), respectively. The minimum hourly mean PM$_{10}$ concentration measured by the mobile monitoring unit was 2 μg m^{-3} and 0 μg m^{-3} at 0.80 m and 1.68 m, respectively, during the 13th July (Sunday).   The maximum hourly mean PM$_{10}$ concentration measured at Kerbside and Townhead was 41 μg m^{-3} and 23 μg m^{-3} measured on the 23rd June (Monday) and 14th March (Friday), respectively. The maximum hourly mean PM$_{2.5}$ concentration measured by the mobile monitoring unit was 105 μg m^{-3} being reported at 0.80 m and 1.68 m during the 14th March (Friday).

Over the eight mobile monitoring exercise, mean PM$_{10}$ concentrations of 31 μg m^{-3} and 28 μg m^{-3} were recorded by the mobile monitoring unit at a height of 0.80 m and 1.68 m, respectively.   A mean PM$_{10}$ concentration of 10 μg m^{-3} was measured at the Townhead fixed monitoring site and 19 μg m^{-3} at Kerbside. These results show that on average, PM$_{10}$ concentrations were 21 μg m^{-3} and 18 μg m^{-3} higher at 0.80 m and 1.68 m travelling along the mobile monitoring route than at the Townhead fixed monitoring site, respectively; and 12 μg m^{-3} and 9 μg m^{-3} higher at 0.80 m and 1.68 m travelling along the mobile monitoring route than at the Kerbside fixed monitoring site.

Comparison of concentrations of PM$_{10}$ recorded by the monitoring trolley at both exposure heights over the entire study period was undertaken using orthogonal regression.   The analyses used a total of 73 hourly average data points and were recorded with a mean absolute error (MAE) of 3.13 μg m^{-3} and a strong correlation (r^2) of 0.964. No data points were rejected by the Grubbs' outlier test. By application of the calculated slope of 0.955 and intercept of -2.115, and using the PM$_{10}$ annual mean objective level of 18 μg m^{-3}, the analysis indicated that concentrations of PM$_{10}$ at 1.68 m are likely to be 17% lower (15 μg m^{-3}) than the concentration observed at 0.80 m (18 μg m^{-3}). Similarly, application of the same calculated slope and intercept but using the higher daily mean objective concentration of 50 μg m^{-3} indicated that the hourly mean PM$_{10}$ concentration at 1.68 m was shown to be approximately 8% lower (46 μg m^{-3}) at 1.68 m than concentrations observed at child breathing height (0.80 m). At the maximum measured hourly mean PM$_{10}$ concentration of 105 μg m^{-3} at 0.80 m, the calculated hourly mean concentration at 1.68 m would be 98 μg m^{-3}; 7% lower than at the lower exposure height. Therefore in general, higher hourly mean PM$_{10}$ concentrations were observed at child breathing height.

Figure 4.2 Hourly Average PM$_{10}$ Concentrations Time-series - Mobile vs Fixed
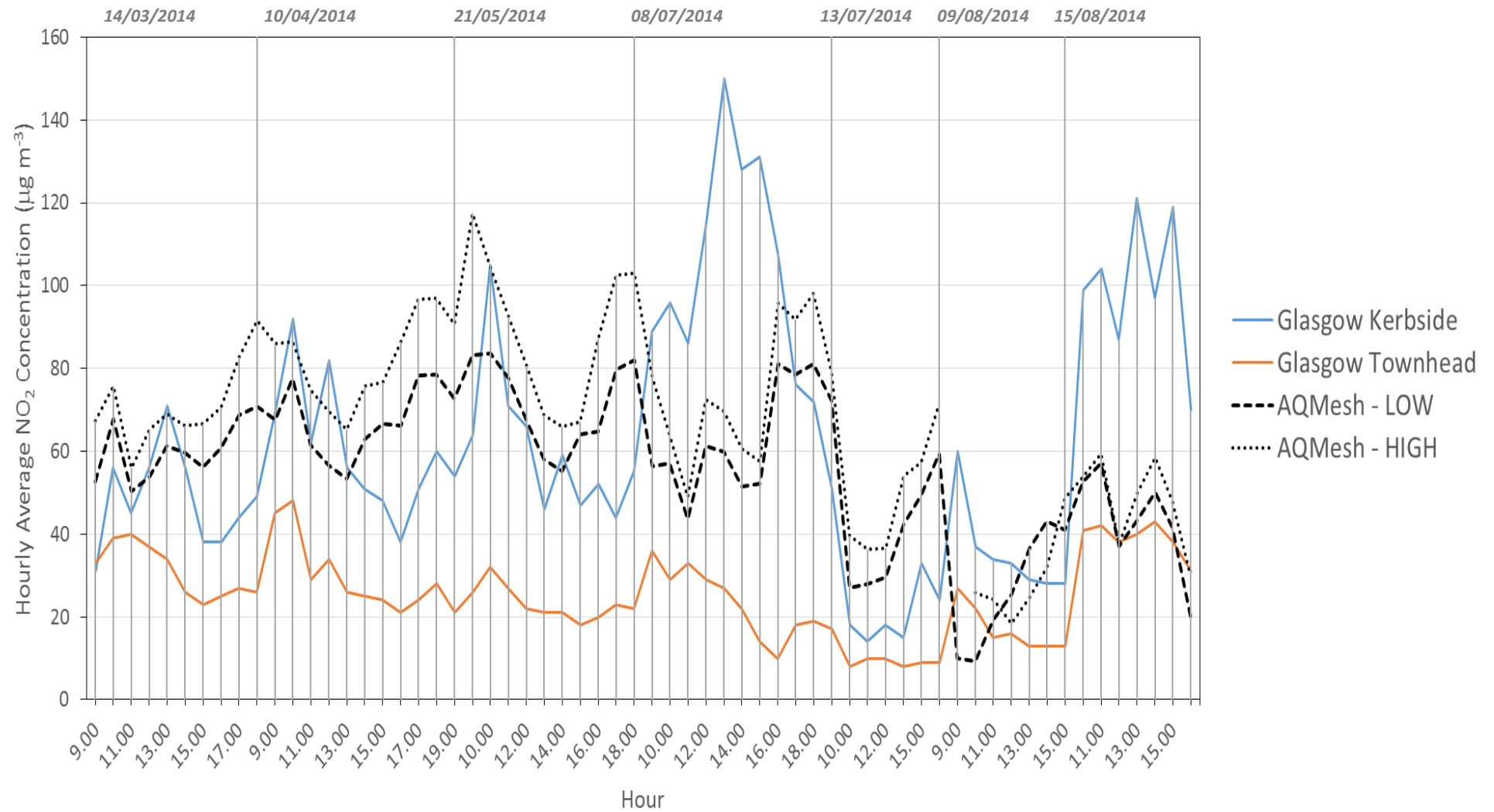
4.1.3 NO$_2$

Hourly mean NO$_2$ concentrations as measured at the fixed monitoring sites, Kerbside and Townhead, and by the mobile monitoring samplers during each mobile monitoring exercise are graphed in Figure 4.3. Minimum hourly mean NO$_2$ concentrations at Townhead and Kerbside were observed on the 13th July (Sunday) with measured mean concentrations of 20 μg m^{-3} and 9 μg m^{-3} being reported at the sites respectively. In contrast, minimum hourly mean NO$_2$ concentrations were measured by the mobile monitoring trolley on the 9th August (Saturday) with measured mean concentrations of 26 μg m^{-3} and 29 μg m^{-3} being reported at 0.80 m and 1.68 m, respectively.

Maximum hourly mean NO$_2$ concentrations at Townhead and Kerbside were measured on the 8th July (Tuesday) and 15th August (Friday) with measured mean NO$_2$ concentrations of 100 μg m^{-3} and 39 μg m^{-3}, respectively. In comparison, maximum hourly mean NO$_2$ concentrations of 72 μg m^{-3} and 89 μg m^{-3} were measured by the mobile monitoring trolley at 0.80 m and 1.68 m on the 21st May (Wednesday), respectively.

Over the entire duration of the monitoring study, a mean NO$_2$ concentrations of 56 μg m^{-3} and 68 μg m^{-3} was measured by the mobile monitoring trolley at a height of 0.80 m and 1.68 m, respectively. A mean NO$_2$ concentration of 25 μg m^{-3} was recorded at the Glasgow Townhead fixed monitoring site and 63 μg m^{-3} at Glasgow Kerbside. These data therefore suggest that average NO$_2$ concentrations measured at 1.68 m during the entire study duration were 5 μg m^{-3} higher than the concentrations recorded at the Glasgow Kerbside. However, this relationship was not mirrored when the data from the mobile trolley at a height of 0.80 m was considered. At this lower height, the mean NO$_2$ concentrations recorded over the study duration were 7 μg m^{-3} lower than those reported at Glasgow Kerbside.

Comparison of concentrations of NO$_2$ recorded by the monitoring trolley at both exposure heights over the entire study period was undertaken using orthogonal regression. The analyses utilised a total of 61 hourly average data pairs and recorded a mean absolute error (MAE) of 4.72 μg m^{-3} and a strong correlation (r^2) of 0.918. No data points were rejected in the Grubbs' outlier test. By application of the calculated slope of 1.314 and intercept of -6.798, and using the NO$_2$ annual mean objective level of 40 μg m^{-3} as the basis for initial comparison, the analyses indicated that the hourly mean NO$_2$ concentration at 1.68 m is likely to be 46 μg m^{-3}, approximately 15% greater than that observed at 0.80 m.   When the NO$_2$ hourly mean objective level of 200 μg m^{-3} is used as the basis for comparison, the analyses indicates that the hourly mean NO$_2$ concentration at 1.68 m is likely to be 256 μg m^{-3}, 28% higher than the concentration observed at 0.80 m. Therefore in general, higher hourly mean NO$_2$ concentrations are likely to be measured at adult breathing height.

Figure 4.3 Hourly Average NO$_2$ Concentrations Time-series - Mobile vs Fixed

4.1.4 NO

Hourly mean NO concentrations as measured at the fixed monitoring sites, Kerbside and Townhead, and by the mobile monitoring samplers during each mobile monitoring exercise are graphed in Figure 4.4.

Minimum hourly mean NO concentrations at Kerbside and Townhead were observed on the 8th July (Tuesday) and 13th July (Sunday) with mean concentrations of 18 μg m^{-3} and 1 μg m^{-3} being reported on these days and at these sites, respectively. In contrast, minimum hourly mean NO concentrations were observed by the mobile monitoring trolley on the 21st May (Wednesday) and 14th March (Friday), with a measured mean concentration of 4 μg m^{-3} being observed at both 0.80 m and 1.68 m. Maximum hourly mean NO concentrations of 321 μg m^{-3} and 18 μg m^{-3} were recorded at Kerbside and Townhead on the 8th July (Tuesday), respectively. Maximum hourly mean NO concentrations were also observed by the mobile monitoring trolley on the 8th July (Tuesday), with measured mean NO concentrations of 129 μg m^{-3} and 154 μg m^{-3} being reported at heights of 0.80 m and 1.68 m, respectively.

Over the entire study period, mean NO concentrations of 102 μg m^{-3} and 7 μg m^{-3} were recorded at Glasgow Kerbside and Glasgow Townhead, respectively. Mean NO concentrations of 54 μg m^{-3} were measured by the mobile monitoring unit at both 0.80 m and 1.68 m. These data therefore suggest that NO concentrations were approximately 89% higher at the Glasgow Kerbside monitoring site higher than mean NO concentrations measured by the mobile monitoring site over the prescribed study period.

Comparison of concentrations of NO recorded by the monitoring trolley at both exposure heights over the entire study period was undertaken using orthogonal regression. The analyses utilised a total of 53 hourly average data pairs and recorded a mean absolute error (MAE) of 11.47 μg m^{-3} and a strong correlation (r^2) of 0.900. No data points were rejected in the Grubbs' outlier test. Both the slope of 1.036 and intercept of 2.490 are deemed insignificant using the criteria detailed in Section A1.3, Appendix A. Therefore, the data indicate that there is no significant difference in hourly mean NO concentrations measured at 0.80 m and 1.68 m.

Figure 4.4 Hourly Average NO Concentrations Time-series - Mobile vs Fixed
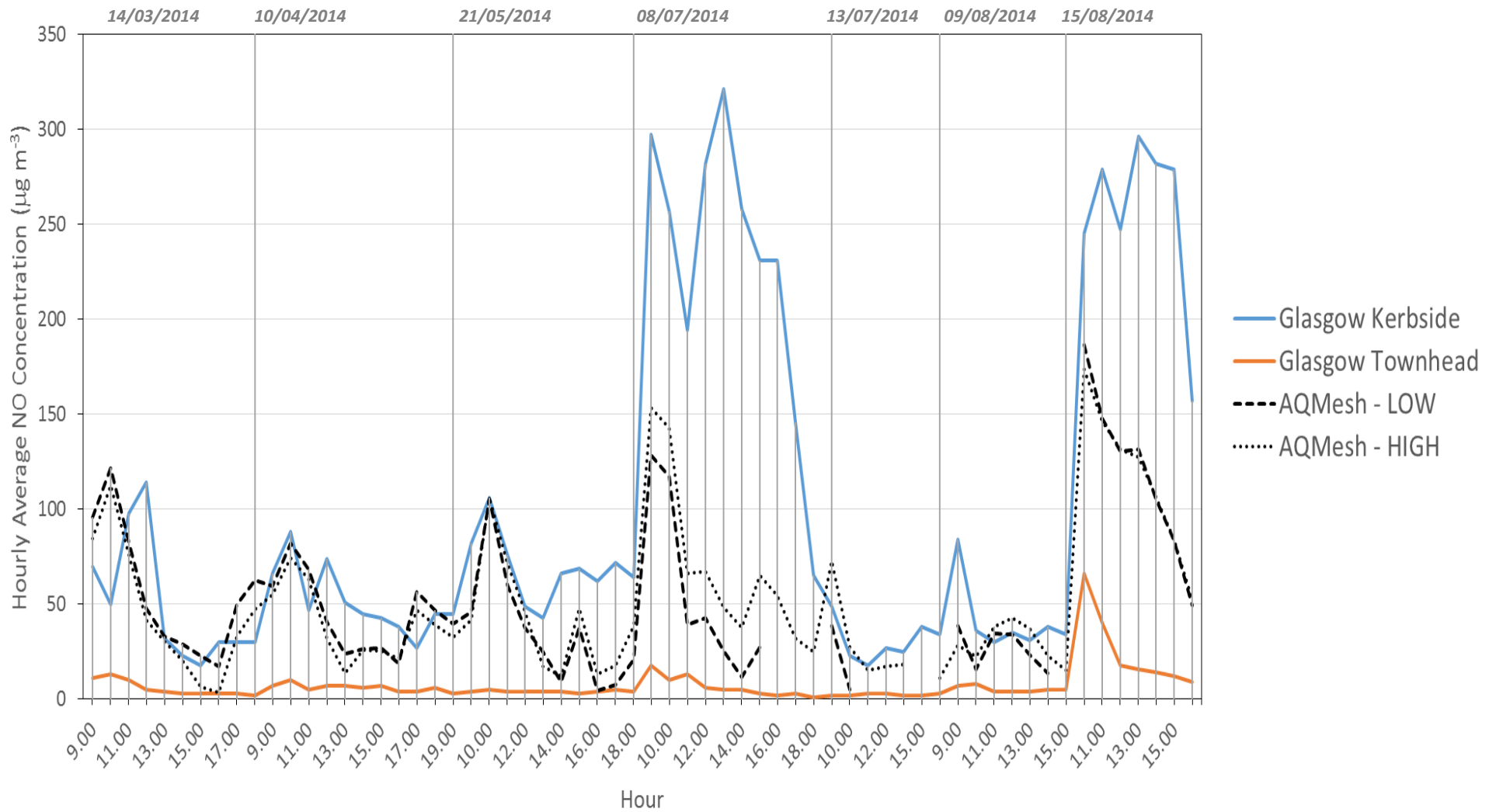
## 4.2 Pollutant Concentrations vs Height

In order to investigate the relationship between pollutant concentrations and height within different urban environments, points from 4 areas of the mobile monitoring route were selected for detailed analyses. The 4 areas selected for detailed analyses are summarised in Table 4.1. In addition to the entire route, these sections of the route were selected for separate analysis due to the environment types they are known to represent and also because it was anticipated that these sections would have some of the highest and lowest concentrations of pollutants due to the proximity of relevant sources and the opportunity for dispersion.

Table 4.1 Sections of Study Route selected for detailed analysis of the influence of exposure height on observed pollutant concentration

Section of Route	Description of street on route
Entire Study Route	Representative of Glasgow City Centre
Hope Street	Busy street canyon orientation south to north (partially restricted to buses & taxis)
Sauchiehall/ Buchanan Street	Pedestrianised section of route – predominantly urban background in nature
High Street	Busy urban street orientation north to south

Figure 4.5 shows the sampling points by street used for the analyses, with all points for Glasgow City Centre shown previously in Figure 3.3; together with photographs of each street in Figure 4.6.

Figure 4.5 Sampling Points – Hope Street, High Street and Sauchiehall St/Buchanan St
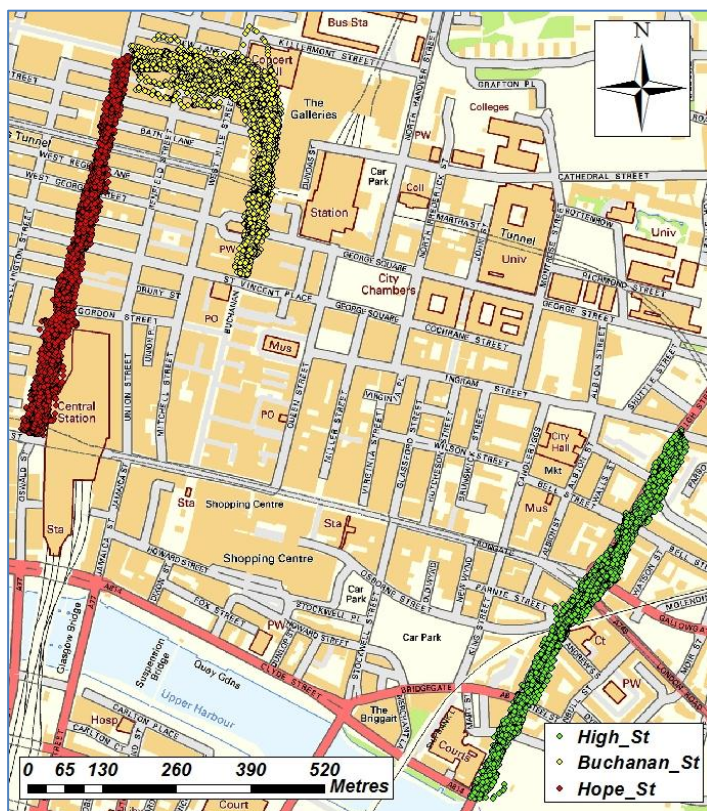
Contains Ordnance Survey data © Crown copyright and database right 2015

The Hope Street section was selected as it is a busy narrow street surrounded by high buildings and therefore fits the classic description of a street canyon where dispersion of pollutants is likely to be restricted (aspect ratio canyon width/building height) of between 1.5 and 2.5. Sections of Hope Street are also restricted to buses and taxis, and large volumes of these vehicles (approximately 120 buses per hour during the day) operate in this street on a daily basis[8]. The Sauchiehall and Buchanan Street sections of the route were selected as these are largely pedestrianised in nature and thus more representative of the urban background situation. The High Street section was selected as it is characterised by high traffic volumes in close proximity to the pavements. High Street is an A-Road (A8) and in 2013 Transport Scotland's automatic traffic counters reported an annual average daily traffic flow for this street of 14,520 vehicles[9]. Figure 4.7 provides details of the 2013 traffic composition from these counts which was largely dominated by cars.

*Figure 4.6 Photographs - Hope Street, High Street (A8) and Buchanan Street*

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[8] Go Bike – Strathclyde Cycle Campaign [Online]
Available at http://www.gobike.org/pdfs/city-centre-cllrs-note-feb09.pdf [Accessed on 23/02/2015]
[9] Department for Transport figures [Online]
Available at http://www.dft.gov.uk/traffic-counts/download.php [Accessed on 19/01/2015]

Figure 4.7 Traffic Composition – High Street, Glasgow 2013
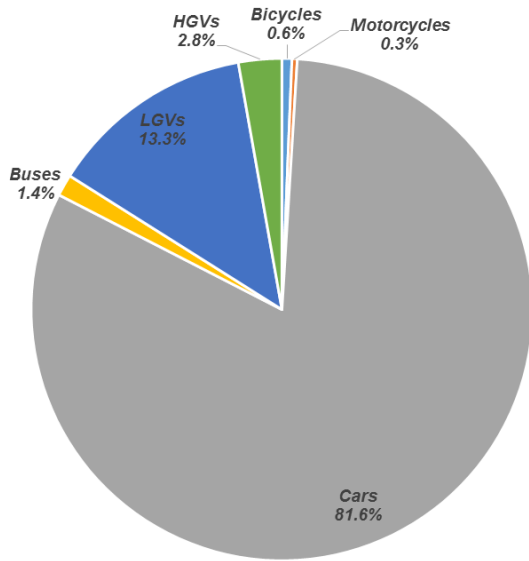
4.2.1 Glasgow City Centre

Full details of the orthogonal regression undertaken for each pollutant versus height over all sampling points are presented in detail in Appendix G. The resultant relationships identified between pollutant concentrations measured at 1.68 m ($C_{1.68}$) and at 0.80 m ($C_{0.80}$) are of the form:

$$C_{1.68} = c + d \times C_{0.80}$$

Where c is the intercept of the regression line and d is the slope of the regression line. Again, if the slope and intercept are deemed significant then they are highlighted in ***red italic***. Therefore, the following relationships between pollutant concentrations at 1.68 m and 0.80 m have been derived:

Nitrogen Dioxide:	$NO_{2\,(1.68\,m)} = 1.224 \times NO_{2\,(0.80\,m)} - 9.155$
Nitric Oxide:	$NO_{(1.68\,m)} = 0.959 \times NO_{(0.80\,m)} + 7.534$
Sulphur Dioxide:	$SO_{2\,(1.68\,m)} = 0.866 \times SO_{2\,(0.80\,m)} + 31.274$
Carbon Monoxide:	$CO_{(1.68\,m)} = CO_{(0.80\,m)} + 6.971$
Particulate Matter (diameter = 0.5 μm):	$PM_{0.5\,(1.68\,m)} = 0.995 \times PM_{0.5\,(0.80\,m)}$
Particulate Matter (diameter = 1.0 μm):	$PM_{1.0\,(1.68\,m)} = 0.941 \times PM_{1.0\,(0.80\,m)} + 0.291$
Particulate Matter (diameter = 2.5 μm):	$PM_{2.5\,(1.68\,m)} = 0.937 \times PM_{2.5\,(0.80\,m)} + 0.703$
Particulate Matter (diameter = 5.0 μm):	$PM_{5.0\,(1.68\,m)} = 0.876 \times PM_{5.0\,(0.80\,m)} + 2.452$
Particulate Matter (diameter = 10 μm):	$PM_{10\,(1.68\,m)} = 0.876 \times PM_{10\,(0.80\,m)} + 0.583$
Total Particulate Matter:	$TPM_{(1.68\,m)} = 0.824 \times TPM_{(0.80\,m)}$
Black Carbon:	$BC_{(1.68\,m)} = BC_{(0.80\,m)} - 0.101$
Ultrafine Particles:	$UFP_{(1.68\,m)} = 0.973 \times UFP_{(0.80\,m)} + 1923$
Benzene:	$C_6H_{6\,(1.68\,m)} = C_6H_{6\,(0.80\,m)}$

Table 4.2 Pollutant vs Height Regression Results – Glasgow Centre

Pollutant	1 minute		Orthogonal Regression			No of Data Pairs Rejected
	n_{bs}	MAE	r^2	Slope (d) ± u_d	Intercept (c) ± u_c	
NO$_2$	3705	19.01	0.764	*1.224 ± 0.010*	*-9.155 ± 0.873*	22 (0.1%)
NO	3629	27.15	0.781	*0.959 ± 0.007*	*7.534 ± 0.619*	98 (2.6%)
SO$_2$	3713	31.08	0.734	*0.866 ± 0.007*	*31.274 ± 0.735*	14 (0.4%)
CO	3611	15.01	0.976	0.997 ± 0.003	*6.971 ± 0.613*	116 (3.1%)
PM$_{0.5}$	4101	0.14	0.991	*0.995 ± 0.002*	-0.005 ± 0.006	199 (4.6%)
PM$_{1.0}$	4162	0.34	0.987	*0.941 ± 0.002*	*0.291 ± 0.012*	138 (3.2%)
PM$_{2.5}$	4174	0.80	0.978	*0.937 ± 0.002*	*0.703 ± 0.029*	126 (2.9%)
PM$_{5.0}$	4244	2.89	0.942	*0.876 ± 0.003*	*2.452 ± 0.110*	56 (1.3%)
PM$_{10}$	4218	5.36	0.897	*0.876 ± 0.004*	*0.583 ± 0.221*	81 (1.9%)
TPM	4195	7.31	0.843	*0.824 ± 0.005*	-0.292 ± 0.308	105 (2.4%)
BC	4121	0.87	0.868	1.007 ± 0.006	*-0.101 ± 0.026*	209 (4.8%)
UFP	4137	4129	0.877	*0.973 ± 0.005*	*1923 ± 153*	176 (4.1%)

With the exception of NO$_2$, NO and SO$_2$, the majority of samplers showed strong correlations ($r^2 > 0.80$). NO$_2$, NO and SO$_2$ demonstrated moderately strong correlations (r^2) of 0.764, 0.781 and 0.734, respectively. The application of Grubbs' outlier test to the datasets resulted in rejection of between 0.1% (NO$_2$) and 4.8% (BC) of data. The number of data-pairs included in the analyses ranged from 3611 for CO to 4244 for PM$_{5.0}$, and the calculated mean absolute error ranged from 0.14 μg m^{-3} for PM$_{0.5}$ to 31.04 μg m^{-3} for SO$_2$ and 4129 Particles cm^{-3} for UFP.

These data suggested that the difference in measured 1-minute average concentrations at 0.80 m and 1.68 m were pollutant specific. Most notably, for particulate pollutants, excluding UFP, the data indicated that higher concentrations were measured at 0.80 m and that the extent of the difference is dependent upon the size of the particulate particles measured. In general the results indicated that the larger the particle the greater the difference between concentrations measured at 0.80 m and 1.68 m. For gaseous pollutants and UFP, the data indicated that the opposite relationship is true with higher concentrations being measured at 1.68 m.

In terms of the concentrations defined by the air quality strategy (AQS) objectives, Table 4.33 summarises the percentage difference in pollutant concentrations measured at 1.68 m relative to concentrations measured at 0.80 m. For example, if the percentage difference (P) is 15%, then the pollutant concentrations measured at 1.68 m ($C_{1.68}$) were 15% higher than that measured at 0.80 m. The following equation was used for this calculation:

$$P = \frac{C_{1.68} - C_{0.80}}{C_{0.80}}$$

As can be seen in Table 4.3, the data indicate that there is only a small difference between $C_{0.80}$ and $C_{1.68}$ at the CO running 8-hour mean objective concentration (10 mg m^{-3}), the NO$_2$ annual mean objective concentration (40 μg m^{-3}), the PM$_{2.5}$ annual mean objective concentration (12 μg m^{-3}) and the SO$_2$ 15-minute mean objective concentration (266 μg m^{-3}), with calculate percentage differences of 0.1%, -0.5%, -0.4% and -1.7%, respectively.

Measured concentrations of NO$_2$ and SO$_2$ were 17.8% and 11.6% higher at 1.68 m than 0.80 m at the NO$_2$ 1-hour mean concentration of 200 μg m^{-3} and the SO$_2$ 24-hour mean concentration of 125 μg m^{-3}, respectively. In contrast, concentrations of PM$_{10}$ and SO$_2$ were 11.2%, 9.1% and 4.5% lower at 1.68 m than at 0.80 m when the PM$_{10}$ annual mean objective

concentration of 18 µg m^{-3}, the PM$_{10}$ daily mean objective concentration of 50 µg m^{-3} and the SO$_2$ 1-hour mean objective of 350 µg m^{-3} were used as the basis for analyses.

Table 4.3 Percentage Difference between Pollutant Concentrations at 0.80 m and 1.68 m in the Context of the Concentration Levels of the AQS Objectives – Glasgow City Centre

Pollutant	Air Quality Objective		Percentage Difference Between 0.80 m and 1.68 m (P) High:Low
	Concentration	Measured as	
Carbon Monoxide	10 mg m^{-3}	Running 8-hour mean	0.1%
Nitrogen Dioxide	200 µg m^{-3}, not to be exceeded more than 18 times a year	1-hour mean	17.8%
	40 µg m^{-3}	Annual mean	-0.5%
Particulate Matter (PM$_{10}$) (Gravimetric)	50 µg m^{-3}, not to be exceeded more than 7 times a year	24-hour mean	-11.2%
	18 µg m^{-3}	Annual mean	-9.1%
Particulate Matter (PM$_{2.5}$) (Gravimetric)	12 µg m^{-3}	Annual mean	-0.4%
Sulphur Dioxide	350 µg m^{-3}, not to be exceeded more than 24 times a year	1-hour mean	-4.5%
	125 µg m^{-3}, not to be exceeded more than 3 times a year	24-hour mean	11.6%
	266 µg m^{-3}, not to be exceeded more than 35 times a year	15-minute mean	-1.7%

Summary statistics – minimum (Min), 2nd quartile (2nd Q), median (med), mean, 3rd quartile (3rd Q) and maximum (max) of 1-minute average concentrations over all mobile monitoring exercises, together with the percentage difference in measured concentrations at 1.68 m and 0.80 m (P) are detailed in Appendix L. Figure 4.1 summarises the percentage differences in measured pollutant concentrations at 0.80 m and 1.68 m as a function of the calculated summary statistics.

The data indicated that the difference in measured 1-minute average concentrations at 0.80 m and 1.68 m are pollutant or species specific. Most notably, for particulate pollutants, excluding UFP, the data indicated that higher concentrations are measured at 0.80 m and that the extent of the difference is dependent upon particle size, with the larger the particle the greater the difference between concentrations measured at 0.80 m and 1.68 m. For gaseous pollutants and UFP, the data indicate that the opposite is true with higher concentrations being measured at 1.68 m. No appreciable difference in PM$_{0.5}$ concentrations at 0.80 m and 1.68 m was identified.

Over the course of the study, the largest differences in concentrations measured at 0.80 m and 1.68 m were observed for TPM and SO$_2$, with TPM concentrations measured at 1.68 m observed to be 21.4% lower than that measured at 0.80 m. Conversely, average SO$_2$ concentrations measured at 1.68 m were 40.1% greater than that measured at 0.80 m. Little or no difference in the mean of 1-minute average pollutant concentrations at 0.80 m and 1.68 m was seen for BC, PM$_{0.5}$, PM$_{1.0}$, PM$_{2.5}$ and NO with calculated percentage differences of 0.7%, -0.2%, -1.2%, -2.3%, and 2.9%, respectively. The percentage difference between 0.80 m and 1.68 m at the mean of all measured 1-minute average concentrations was calculated to be -4.1%, -12.0%, 3.9%, 4.7% and 7.6% for PM$_{5.0}$, PM$_{10}$, CO, UFP and NO$_2$, respectively.

At the measured minimum, the greatest difference between concentrations measured at 0.80 m and 1.68 m was seen for PM$_{5.0}$ with a calculated percentage difference of 79.1%. Little or no difference between concentrations at 0.80 m and 1.68 m was seen for BC and PM$_{2.5}$ with calculated percentage differences of 1.6% and 0.7%, respectively. The percentage difference between 0.80 m and 1.68 m was -21.4% for TPM.

At the maximum concentrations observed by the mobile monitoring trolley, the most significant difference between concentrations measured at 0.80 m and 1.68 m was seen for TPM and NO$_2$ with calculated percentage differences of -19.4% and 15.9%, respectively. Little or no difference in the mean of 1-minute average pollutant concentrations at 0.80 m

and 1.68 m was seen for UFP, BC, $PM_{0.5}$, and CO with calculated percentage differences of -2.4%, 0.7%, 0% and 0.2%, respectively. The percentage differences observed between 0.80 and 1.68 m were -5.9%, -6.1%, -13.5%, -14.0%, -3.9% and -10.2% for $PM_{1.0}$, $PM_{2.5}$, $PM_{5.0}$, PM_{10}, NO and SO_2. These findings therefore indicated that at the measured maximum concentrations of UFP, NO and SO_2 concentrations, higher concentrations were observed at 0.80 m than at 1.68 m, in contrast to what was observed at lower concentrations. This may be due to the maximum concentrations being measured when close by direct sources of these pollutants, in this case likely to be road traffic, are experienced. As the emission point of traffic sources is below 0.80 m in many cases and due to the mobile nature of the monitoring, pollutant may be measured at 0.80 m before they have dispersed fully to 1.68 m.

Figure 4.1 Summary Statistics vs Percentage Difference in Measured 1-minute Average Concentrations at 0.80 m and 1.68 m
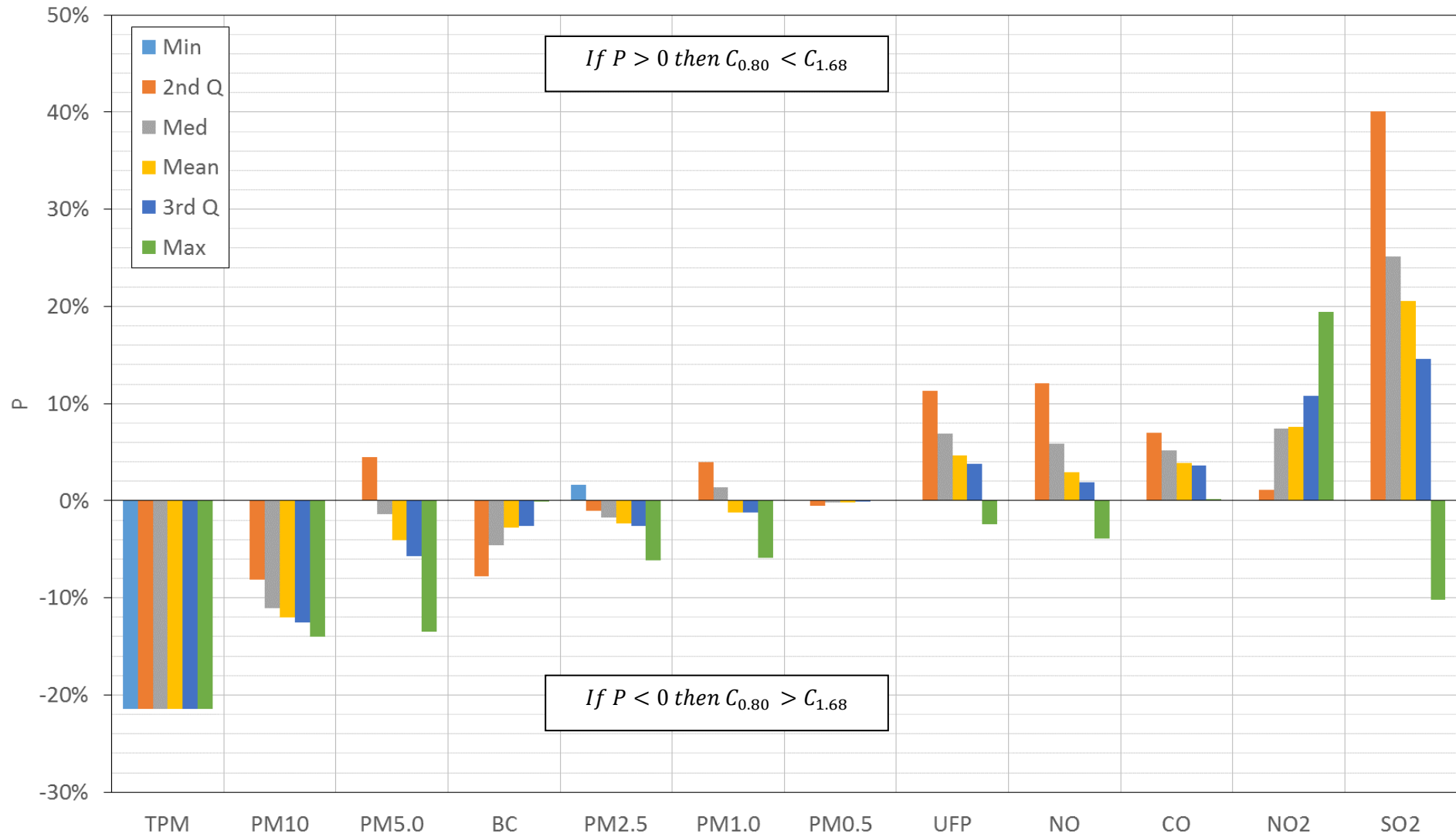
4.2.2 Glasgow City Centre - Benzene

Average benzene concentrations ranged from 0.22 μg m^{-3} on 09/08/2014 at 0.80 m to 1.80 μg m^{-3} on 23/06/2014 at 0.80 m. The average benzene concentrations measured over all exercises was 0.68 μg m^{-3} and 0.71 μg m^{-3} at 0.80 m and 1.68 m, respectively.

Orthogonal regression analysis of average benzene concentrations measured at 0.80 m versus 1.68 m was undertaken on a total of 6 data-pairs, giving a calculated mean absolute error of 0.10 μg m^{-3} and strong r^2 value of 0.954. Two data pairs were identified as outliers and rejected. The slope of the regression line was calculated at 1.144 with an intercept of 0.006 μg m^{-3}, both of which have been determined as insignificant when compared to the associated uncertainties of 0.241 μg m^{-3}, and 0.147 μg m^{-3}, respectively. As a result, these results suggested that there was no significant difference between average benzene concentrations measured at 0.80 m and 1.68 m. However, it is appropriate to note that this monitoring study of benzene is limited and that additional monitoring would be required to confirm these results. Full details of the regression and data are provided in Appendix G.

4.2.3 *Hope Street*

Full details of the orthogonal regression results for each pollutant versus height along Hope Street, Sauchiehall St/Buchanan St and High St are detailed in Appendix I. In the context of the concentration levels defined by the AQS objectives, Table 4.4 summarises the percentage difference in pollutant concentrations measured at 1.68 m relative to concentrations measured at 0.80 m using the relationships derived from the regression analyses.

With the exception of NO$_2$ and SO$_2$, on the Hope Street route data for all other samplers showed strong correlations (r^2 > 0.80). NO$_2$ and SO$_2$ both exhibited moderately strong correlations (r^2) of 0.793, and 0.736, respectively. Application of Grubbs' outlier test to the datasets resulted in rejection of between 1.0% (PM$_{5.0}$) and 6.2% (BC) of data. The number of data-pairs included in the analyses ranged from 740 for NO to 865 for PM$_{5.0}$. The calculated MAE ranged from 0.18 μg m^{-3} for PM$_{0.5}$ to 29.90 μg m^{-3} for SO$_2$ and 4413 Particles cm^{-3} for UFP.

As presented in Table 4.4 the data indicated that a small difference existed between $C_{0.80}$ and $C_{1.68}$ at the CO running 8-hour mean concentration (10 mg m^{-3}), the NO$_2$ annual mean concentration (40 μg m^{-3}), the PM$_{2.5}$ annual mean concentration (12 μg m^{-3}) and the SO$_2$ 15-minute mean concentration (266 μg m^{-3}); with calculate percentage differences of -1.4%, 2.5%, -0.5% and -2.8%, respectively. Concentrations of NO$_2$ and SO$_2$ were found to be 12.7% and 9.8% higher at 1.68 m than at 0.80 m when the NO$_2$ 1-hour mean concentration of 200 μg m^{-3} and the SO$_2$ 24-hour mean concentration of 125 μg m^{-3} were used for comparison. Concentrations of PM$_{10}$ and SO$_2$ were found to be 8.4%, 12.6% and 5.5% lower at 1.68 m than those reported at 0.80 m when the annual mean PM$_{10}$ Standard (18 μg m^{-3}), the daily mean PM$_{10}$ standard (50 μg m^{-3}) and the 1 hour mean SO$_2$ standard (350 μg m^{-3}) were used as the basis for comparison.

4.2.4 Sauchiehall Street/Buchanan Street

On the Sauchiehall Street/Buchanan Street section, with the exception of NO$_2$, SO$_2$ and BC, all other samplers showed strong correlations (r^2 > 0.80). NO$_2$, SO$_2$ and BC were found to exhibit moderately strong correlations, with r^2 vales of 0.786, 0.762 and 0.759, respectively. Applying Grubbs' outlier test to the datasets resulted in rejection of between 0.2% (PM$_{5.0}$) and 4.9% (BC) of data. The number of data-pairs included in the analyses ranged from 364 for NO to 417 for UFP. The calculated MAE ranged from 0.12 μg m^{-3} for PM$_{0.5}$ to 29.90 μg m^{-3} for SO$_2$ and 4413 Particles cm^{-3} for UFP.

As can be seen in Table 4.4, the data for the Sauchiehall Street/ Buchanan Street section indicated negligible differences between $C_{0.80}$ and $C_{1.68}$ at the CO running 8-hour mean

concentration (10 mg m^{-3}) and the PM$_{2.5}$ annual mean concentration (12 μg m^{-3}) with calculate percentage differences of 0% and -2.0%, respectively. Concentrations of NO$_2$ and SO$_2$ were found to be 20.4% and 3.3% higher at 1.68 m than 0.80 m at the NO$_2$ 1-hour mean concentration of 200 μg m^{-3} and the SO$_2$ 24-hour mean concentration of 125 μg m^{-3}, respectively. At the NO$_2$ annual mean standard (40 μg m^{-3}), annual mean PM$_{10}$ standard (18 μg m^{-3}), the PM$_{10}$ daily mean standard (50 μg m^{-3}), the 1 hour mean SO$_2$ standard (350 μg m^{-3}) and the SO$_2$ 15-minute mean concentration (266 μg m^{-3}), concentrations of NO$_2$, PM$_{10}$ and SO$_2$ concentrations were found to be 4.8%, 6.2%, 11.3%, 8.3% and 6.3% lower at 1.68 m than at 0.80 m.

4.2.5 High Street

On the High Street section, with the exception of NO$_2$, NO, SO$_2$ and BC, all other samplers showed strong correlations (r^2 > 0.80). The NO$_2$, NO, SO$_2$ and BC samplers exhibited moderately strong correlations (r^2) of 0.770, 0.705, 0.744 and 0.7879, respectively. Applying Grubbs' outlier test to the datasets resulted in rejection of between 0% (SO$_2$) and 6.1% (PM$_{0.5}$) of data. The number of data-pairs included in the analyses ranged from 457 for CO to 534 for PM$_{10}$. The calculated MAE ranged from 0.10 μg m^{-3} for PM$_{0.5}$ to 33.62 μg m^{-3} for SO$_2$ and 3598 Particles cm^{-3} for UFP.

As can be seen in Table 4.4, the data indicated that a small difference was observed between $C_{0.80}$ and $C_{1.68}$ at the CO running 8-hour mean concentration (10 mg m^{-3}), NO$_2$ annual mean concentration (40 μg m^{-3}), the PM$_{2.5}$ annual mean concentration (12 μg m^{-3}) and the SO$_2$ 1-hour mean of 350 μg m^{-3} with calculate percentage differences of 0.1%, 2.5%, 0.6% and 2.3%, respectively. Concentrations of NO$_2$ and SO$_2$ were found to be 20.4%, 20.6% and 5.5% higher at 1.68 m than reported at 0.80 m when the 1 hour mean NO$_2$ standard (200 μg m^{-3}), the 24 h mean SO$_2$ standard (125 μg m^{-3}) and the 15 min mean SO$_2$ standard (266 μg m^{-3}) were used for analyses. Concentrations of PM$_{10}$ were found to be 11.6% lower at 1.68 m than those reported at 0.80 m at both the annual mean PM$_{10}$ standard (18 μg m^{-3}) and the daily mean PM$_{10}$ standard (50 μg m^{-3}).

Table 4.4 Percentage Difference between Pollutant Concentrations at 0.80 m and 1.68 m in the Context of the Concentration Levels of the AQS Objectives – Hope St, Sauchiehall St/Buchanan St and High St

Pollutant	Air Quality Objective		Percentage Difference Between 0.80 m and 1.68 m (P) High:Low		
	Concentration	Measured as	Hope St	Sauchiehall St/ Buchanan St	High St
Carbon Monoxide	10 mg m^{-3}	Running 8-hour mean	-1.4%	0%	0.1%
Nitrogen Dioxide	200 μg m^{-3}, not to be exceeded more than 18 times a year	1-hour mean	12.7%	20.4%	20.4%
	40 μg m^{-3}	Annual mean	2.5%	-4.8%	2.5%
Particulate Matter (PM$_{10}$) (Gravimetric)	50 μg m^{-3}, not to be exceeded more than 7 times a year	24-hour mean	-12.6%	-11.3%	-11.6%
	18 μg m^{-3}	Annual mean	-8.4%	-6.2%	-11.6%
Particulate Matter (PM$_{2.5}$) (Gravimetric)	12 μg m^{-3}	Annual mean	-0.5%	-2.0%	0.6%
Sulphur dioxide	350 μg m^{-3}, not to be exceeded more than 24 times a year	1-hour mean	-5.5%	-8.3%	2.3%
	125 μg m^{-3}, not to be exceeded more than 3 times a year	24-hour mean	9.8%	3.3%	20.6%

| Pollutant | Air Quality Objective | | Percentage Difference Between 0.80 m and 1.68 m (P) High:Low | | |
	Concentration	Measured as	Hope St	Sauchiehall St/ Buchanan St	High St
	266 µg m^{-3}, not to be exceeded more than 35 times a year	15-minute mean	-2.8%	-6.3%	5.5%

4.2.6 Filtered Concentrations

Further analysis of the relationship between pollutant concentrations at 0.80 m and 1.68 m was also carried out using 6 concentration ranges: data less than the measured 25th percentile (<25th%'ile); data less than the measured 50th percentile (<50th%'ile), data less than the measured 75th percentile (<75th%'ile), data greater than the measured 25th percentile (>25th%'ile)¸ data less than the measured 50th percentile (>50th%'ile) and data greater than the measured 75th percentile (>75th%'ile).

Figure 4.2 summarises the calculated percentage differences in pollutant concentrations at 0.80 m and 1.68 m using the filtered datasets. The vertical axis scaling has been adjusted for clarity and therefore differences of greater than +100% are not shown for NO and SO$_2$. A pattern can be seen with lower concentrations, from the minimum measured concentrations up to the 75th%'ile concentration for each pollutant, showing a bias towards higher concentrations being experienced at 1.68 m than at 0.80 m. As the pollutant concentrations under investigation are increased to include data from the 25th%'ile to the maximum, the bias switches to increased concentrations being measured at 0.80 m compared to 1.68 m. There are exceptions to this; SO$_2$ and CO were found not follow this pattern, with a bias for higher concentrations at 1.68 m throughout the concentration range. Also, both PM$_{10}$ and TPM indicated a bias for higher concentrations at 0.80 m throughout the concentration range.

Full details of the orthogonal regression results using these filtered concentration ranges are provided in Appendix H. It is important to note that where the r^2 is below 0.40, the relationships are mild. For example, this is the case for NO$_2$, SO$_2$, PM$_5$, BC and UFP data <25th%'ile, which showed mild r^2 of 0.262, 0.273, 0.237, 0.311 and 0.394, respectively. Weak correlations were also seen comparing NO, PM$_{10}$ and TPM data, with r^2 of 0.087, 0.191 and 0.156, respectively. In general, lower r^2 were seen for the lower concentration ranges.

Figure 4.2 Percentage Difference in Filtered Concentrations (<25th%'ile, <50th%'ile, <75th%'ile, >25th%'ile¸>50th%'ile¸>75th%'ile) at 0.80 m and 1.68 m

$$If\ P > 0\ then\ C_{0.80} < C_{1.68}$$

$$If\ P < 0\ then\ C_{0.80} > C_{1.68}$$
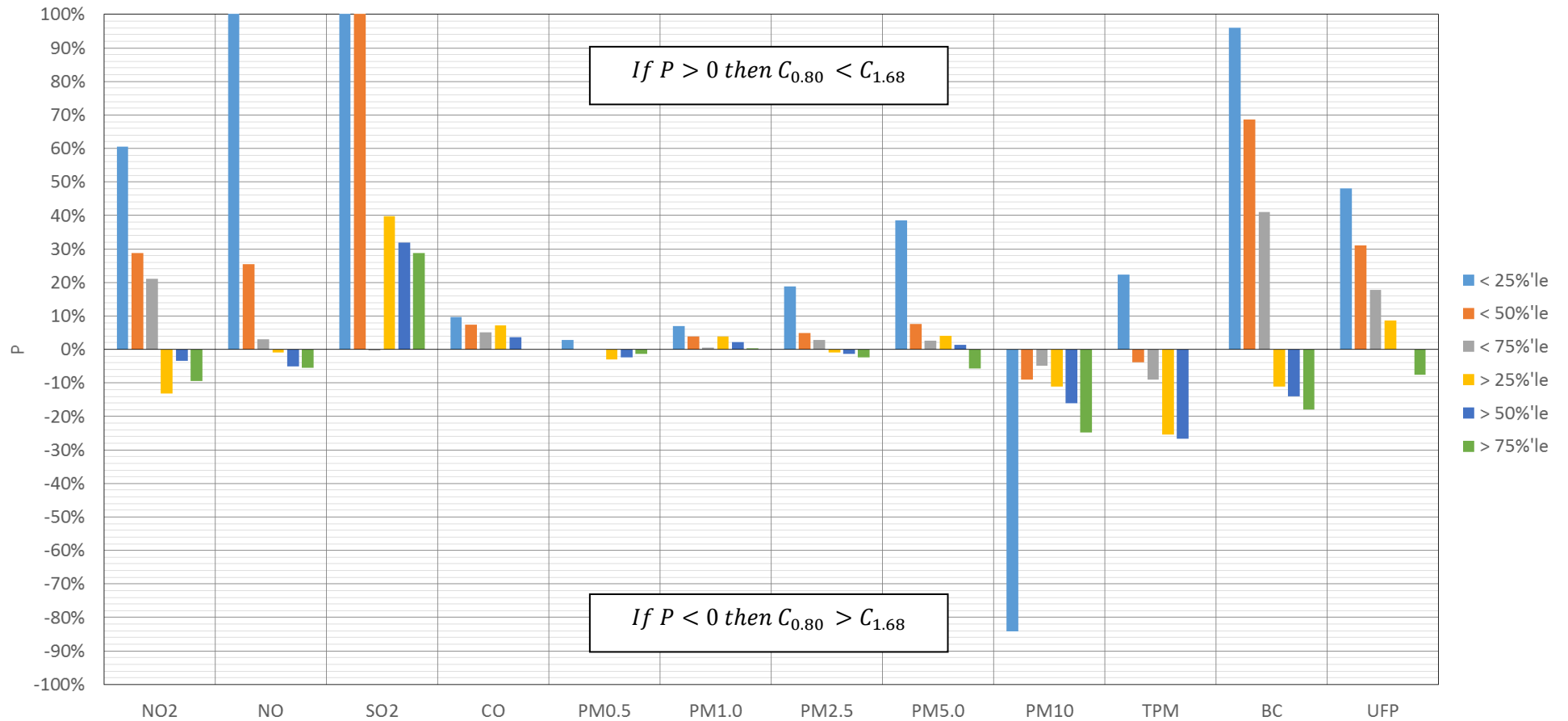
4.3 Meteorology

4.3.1 Wind Direction and Speed

During the study, data from a Met mast attached to the mobile monitoring trolley was used to monitor local variations in meteorology. However, following detailed analysis no clear conclusions could be drawn from the data and consequently the data is not discussed in detail within this report, but further information is presented in Appendix K. Data from Glasgow Airport was also observed during the monitoring study and is summarised below. During the eight days of sampling the 30 minute average wind speeds were between 2 and 11.7 m s $^{-1}$, with the direction of the stronger winds primarily from a westerly direction, and the lighter winds all around the compass. This is illustrated in the wind rose in Figure 4.10 below.

Figure 4.10 Wind rose for 30 minute average wind speed and directions during the eight sampling days of the experiments (as recorded at Glasgow Airport)

Frequency of counts by wind direction (%)
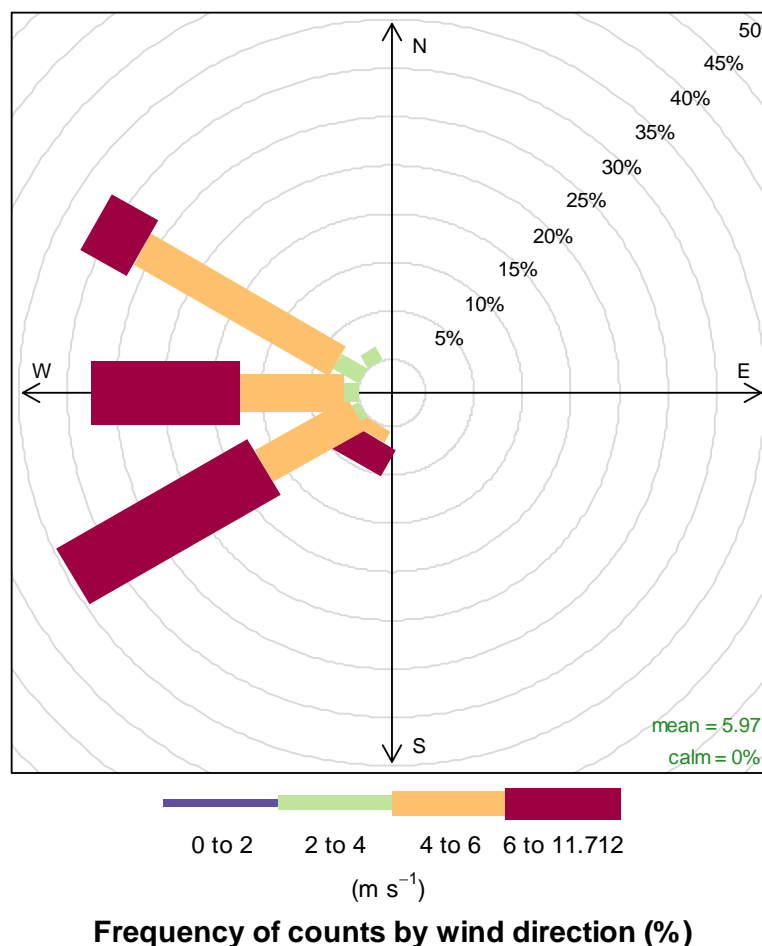
4.4 Cross-Pollutant Correlations

The following section reviews the correlations between pollutants using the 'corPlot' (Carslaw, 2014) function from the openair package. Matrices of the linear correlation coefficients between 1-minute average pollutant concentrations measured at 0.80 m and 1.68 m for each mobile monitoring exercise are shown in Appendix M.

Whilst differences were observed between individual mobile monitoring exercises, the following correlations can be identified:

- $PM_{0.5}$, $PM_{1.0}$, $PM_{2.5}$ show moderately strong to strong positive correlations.

- $PM_{2.5}$, $PM_{5.0}$ and PM_{10} show moderately strong to strong positive correlations.

- The relationships between TPM with $PM_{2.5}$, $PM_{5.0}$ and PM_{10} are inconsistent with moderate to strong positive correlations on 14/03/2014 (Fri), compared to weak to mild correlations on 13/07/2014 (Sun). This may be due to factors such as meteorological conditions combined with reduced traffic flows and therefore resulting in background particulate concentrations being the dominant source.

- Moderate to strong positive correlations can be seen between BC with NO, NO_2, SO_2, $PM_{0.5}$, $PM_{1.0}$, $PM_{2.5}$ and UFP, but again these relationships are inconsistent between monitoring exercises.

- Moderate to moderately strong negative correlations between NO_2 and SO_2 are apparent on 10/04/2014 (Thu), 21/05/2014 (Wed), 08/07/2014 (Tue) and 13/07/2014 (Sun).

- Moderate positive correlations between CO and SO_2 are apparent on 14/03/2014 (Fri), 21/05/2014 (Wed) and 13/07/2014 (Sun).

In addition to the correlations mentioned above, the data exhibited added complexity in that the observed relationships were shown to be inconsistent at 0.80 m and 1.68 m. For example on 23/06/2014 a moderately strong correlation was seen between UFP concentrations at 0.80 m and BC concentrations at 1.68 m with an r of 63%. However, this relationship was not seen between UFP at 0.80 m and BC at 0.80 m,   UFP at 0.80 m and BC at 1.68 m, and UFP at 1.68 m and BC at 1.68 m with r of 31%, 25% and 40%, respectively. These findings indicated the extreme complexity of the intra-pollutant relationships.

4.5 Spatial Distributions of Pollutants

Contour plots of 1-minute average $PM_{2.5}$, BC and UFP concentrations throughout the mobile monitoring route at 0.80 m on 10/04/2014 are shown in Figure 4.11, Figure 4.42 and Figure 4.513, respectively. Contour plots of all measured pollutants are provided in Appendix N.

In general, increased pollutant concentrations were seen in areas were road traffic flow and congestion were elevated. In this case, this was observed along Hope Street, High Street and around George Square. Elevated concentrations of BC and UFP were more pronounced and visualised more clearly than other pollutants, perhaps indicating that road traffic may me the main local source for these pollutants. Concentrations of BC and UFP were found to decrease along Sauchiehall Street and Buchanan Street, however, this finding was not mirrored in $PM_{2.5}$ concentrations where increased concentrations were observed. These findings indicated a difference in sources for each pollutant or more likely in the way the pollutants disperse. Fugitive sources such as re-suspension of particulates may have a greater influence on the spatial variability of $PM_{2.5}$ concentrations.

Construction of the Strathclyde University Technology Innovation Centre at Albion Road was ongoing during the mobile monitoring exercises and higher concentrations of $PM_{2.5}$ and BC were clearly visible in this location. However, higher concentrations of UFP were not observed in the same area. It is considered that possible reasons for this could be that emissions from construction machinery may not be significant emitters of UFP with older diesel and petrol generators, for example, emitting coarser particles. There may also be significant fugitive emissions of particulate from mechanical processes, which again may consist primarily of coarser particles.

Figure 4.31 1-minute Average PM₂.₅ Concentrations at 0.80 m – 10/04/2014 (μg m⁻³)
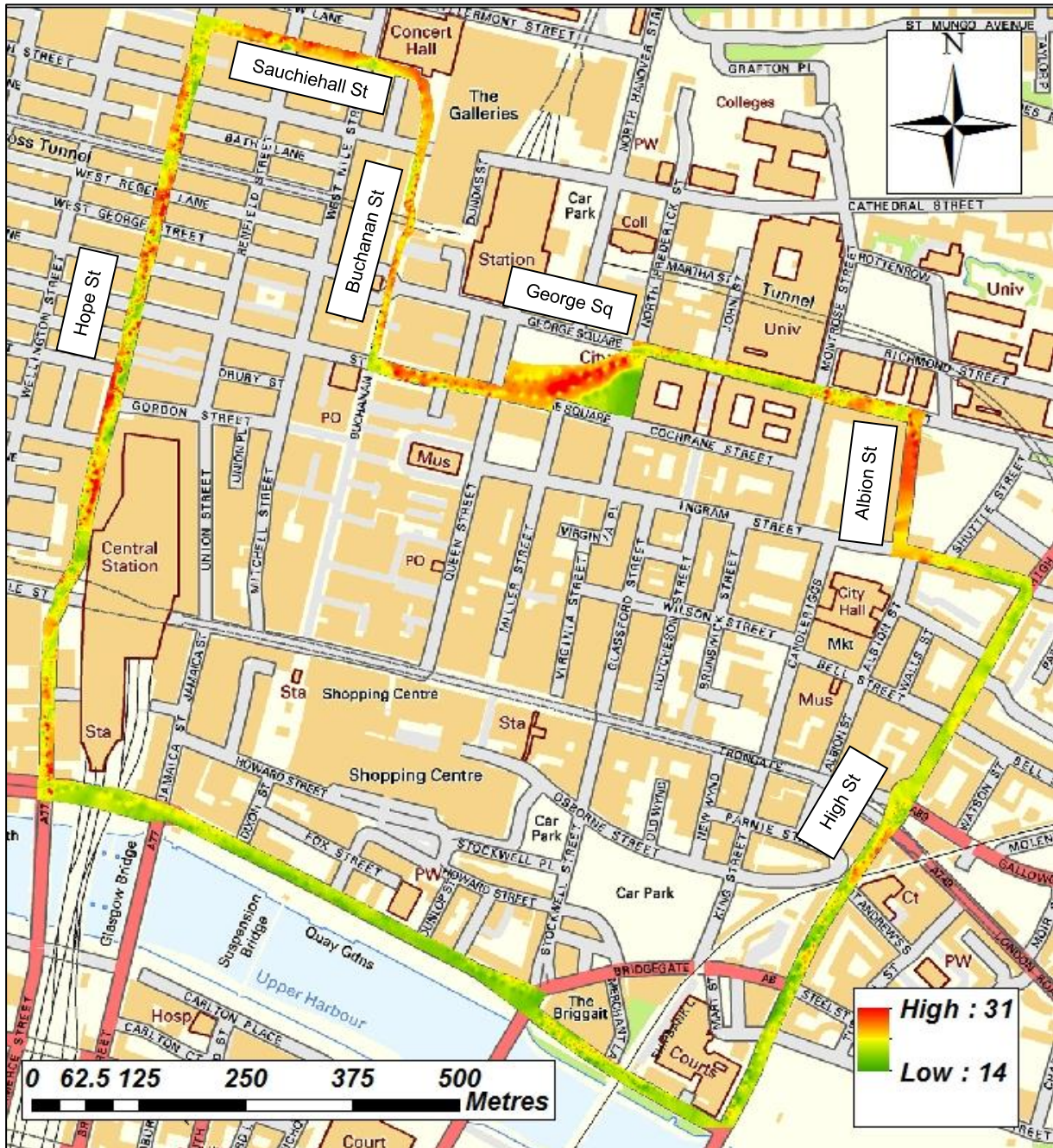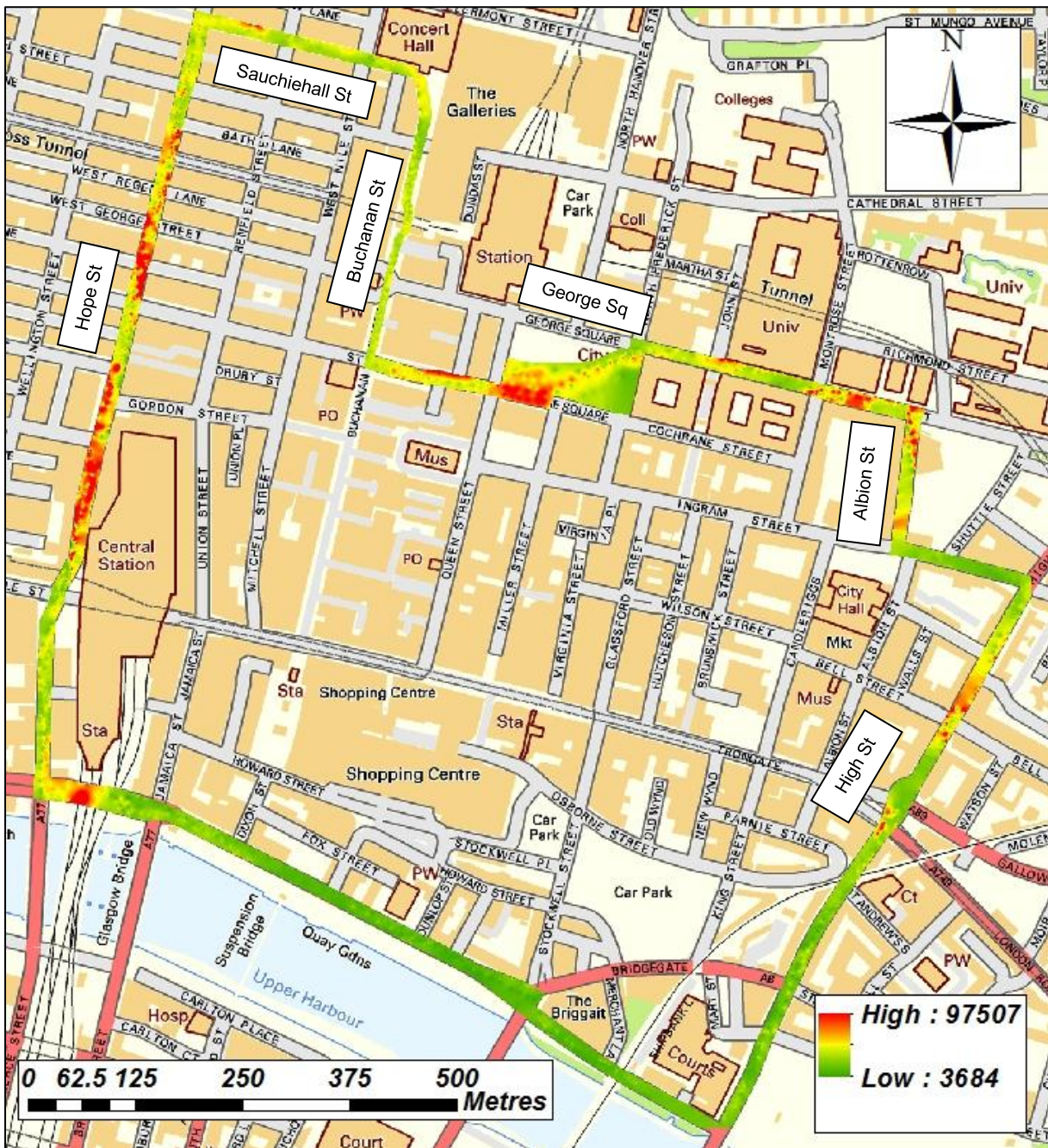

Contains Ordnance Survey data © Crown copyright and database right 2015

Figure 4.42 1-minute Average BC Concentrations at 0.80 m – 10/04/2014 (μg m^{-3})
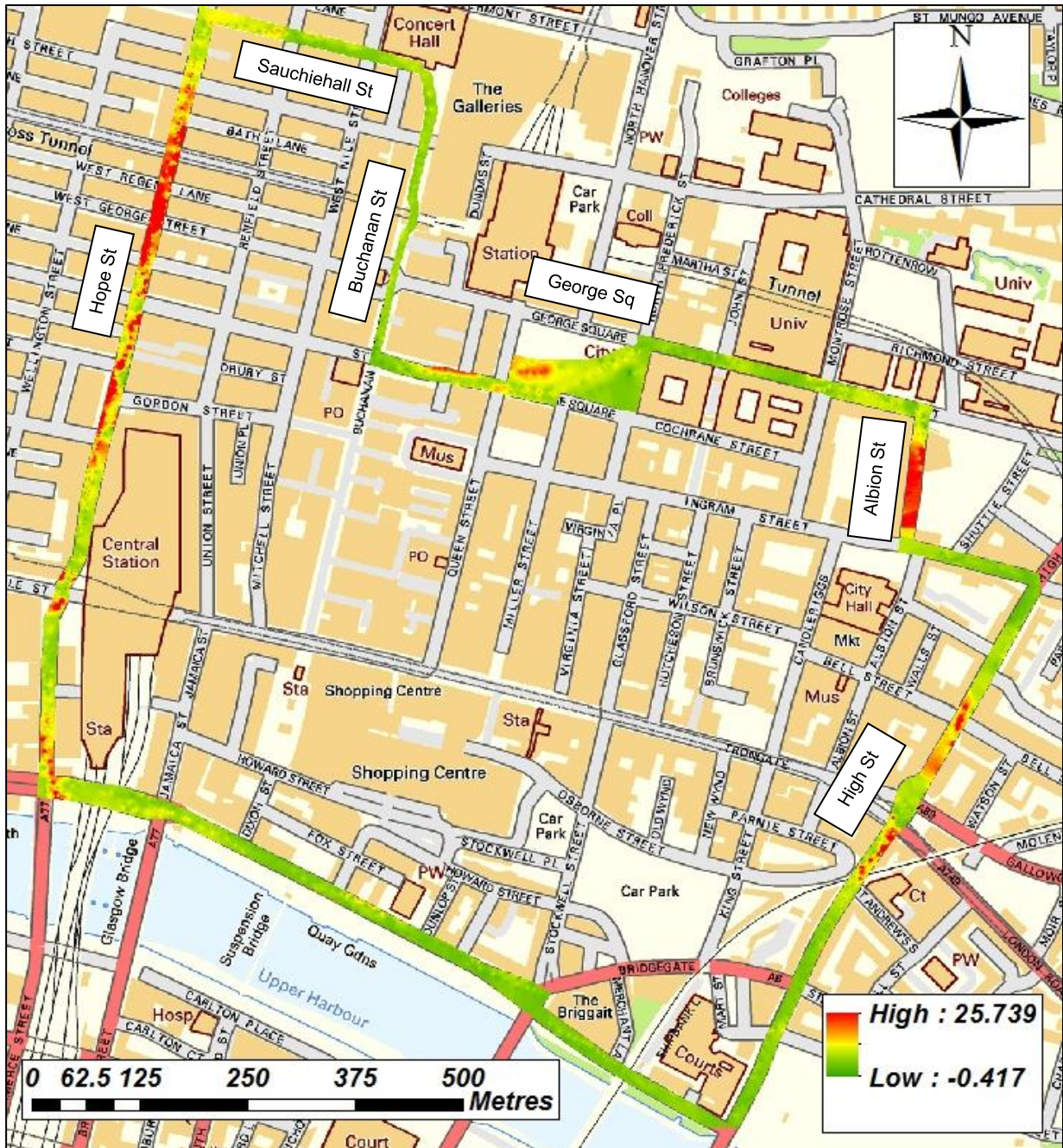
Contains Ordnance Survey data © Crown copyright and database right 2015

Figure 4.53 1-minute Average UFP Concentrations at 0.80 m – 10/04/2014 (N Particles m⁻³)

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5 Discussion and Conclusions

The findings of the Glasgow study provided numerous insights into not only spatial variations of key air pollutants in Glasgow City centre and the influence of exposure height on concentrations observed. In addition, the study also helped to elucidate correlations between observed concentrations of different pollutants at different exposure heights and also provide useful information regarding the application of mobile monitoring and the application of personal sampler/ sensor technology for assessing human exposure to air pollutants in an urban environment. From the literature review it was evident that the study was rather unique in nature, with no other directly comparable published study identified.

A primary driver of the study was to assess the concentrations of pollutants, primarily particulate matter at child (0.80 m) and adult breathing heights (1.68 m) at a number of locations within an urban environment. However, due to its nature it was identified at the outset that it would be possible to also include other important pollutants in the study, notably NO_2, black carbon and ultrafine particulates and enhance research into the variation of these pollutants within Glasgow City Centre. The mobile and multiple parameter nature of the study resulted in the generation of large volumes of data which were used to investigate 4 principal areas of research, these being:

- Mobile vs Fixed Monitoring
- Pollutant Concentrations vs Height
- Cross-Pollutant Correlations
- Spatial Distribution of Pollutants

5.1 Mobile vs Fixed Monitoring

Scottish, UK and European policy on assessing exposure to air pollution is currently reliant upon fixed location monitoring "in the breathing zone", which is typically accepted to be up to about 4 m above the ground. In practical terms, it is difficult to routinely measure at heights much below 1.5 m, due partly to analyser infrastructure requirements and also the potential risk of vandalism or interference with the equipment. Furthermore, the scale and technical requirements of air quality monitors that are used for LAQM and EC Directive compliance means that in general this equipment must typically operate in a fixed location, or on a large motor vehicle. Whilst this requirement provides continuity in terms of data reporting and the data quality it is recognised that such fixed monitoring may not be provide a representative measure of personal exposure to air pollution. Consequently, numerous Governments and international expert groups are currently exploring the future opportunity to utilise innovative technologies for ambient air quality monitoring purposes (Defra, 2015).

In the current study, the need to undertake mobile monitoring at multiple heights and for multiple pollutants necessitated the use of a selection of portable analysers and pervasive samplers. Whilst these samplers are not accredited for compliance monitoring purposes, the study provided the opportunity to test the technology available against data from fixed AURN monitoring sites following co-location.

From the study it was identified that concentrations of pollutants recorded by the mobile trolley along the prescribed route reported different concentrations than those reported at Glasgow Kerbside over the comparable period. In addition, the findings indicated that the observed differences were pollutant specific and in some cases influenced by the monitoring height. Notably it was identified that consistently higher concentrations of $PM_{2.5}$ (42% higher) and PM_{10} (47-63% higher) were recorded by the mobile monitoring trolley than at Glasgow Kerbside AURN.

In contrast, comparison of average concentrations of NO also identified that lower concentrations were observed by the mobile trolley (89%) over the prescribed study than by those recorded by the Glasgow Kerbside monitoring station.   When NO_2 was considered, the findings of the study were shown to be influenced by the inlet height on the monitoring trolley, with slightly higher concentrations (8%) being recorded at 1.68 m, and slightly lower concentrations (11%) recorded at 0.80 m when compared to concentrations recorded at Glasgow Kerbside over the same study period.

Overall, the findings appear to indicate that in certain circumstances, fixed monitoring may either under- or over-estimate the concentrations of pollutants to which members of the public are routinely exposed to in urban environments. However, this is perhaps not overly surprising, given that by being mobile, the trolley experiences greater variation in its proximity to pollutant sources (e.g. road traffic, commercial sources and fugitive emissions), but also exposure to localised meteorology. This finding may also be influenced by the height of the inlet at the fixed monitoring site which is significantly higher than either of the inlet heights on the mobile monitoring trolley. There may thus be some benefit in evaluating the influence of inlet height on concentrations measured at a fixed monitoring site to ascertain the influence on concentrations reported.

The finding that average concentrations of $PM_{2.5}$ and PM_{10} were significantly higher along the mobile monitoring route is particularly interesting. In many circumstances, due to their proximity to road traffic emissions, kerbside and roadside monitoring stations are often considered to represent 'worst case' urban pollution. However, this finding questions the validity of this general belief and merits further study to help confirm these findings.

5.2 Pollutant Concentrations vs Height

One of the principal objectives of the study was to determine the nature of the relationship between pollutant concentrations and height; in this case, 2 exposure heights, average child and adult breathing height.

The study investigated the relationship between exposure height and pollutant concentration across the entire mobile study route, but also sought to undertake a basic evaluation of the potential influence of different environment types along the route on any relationships identified. These environment types were:

- A busy street canyon where traffic is dominated by high numbers of buses and taxis (Hope Street)
- A busy A-road with high volumes of traffic (High Street)
- A predominantly pedestrianised section of the route (Sauchiehall Street/ Buchanan Street)

The data from the study demonstrated the complexity of pollutant concentrations in the ambient environment, but several findings were consistently observed. Data obtained for the entire study route and each of the individual sections outlined above indicated that concentrations of CO and $PM_{2.5}$ observed were not significantly influenced by the inlet height (height of exposure), and the observed influence of inlet height on concentrations was too variable to draw a clear conclusion. In contrast, average concentrations of PM_{10} were shown to be consistently higher (up to 12.6% higher) at 0.80 m than at 1.68 m throughout the study route. This finding is significant, as it appears to indicate that in the urban environment children may be exposed to higher concentrations of PM_{10} on average than adults. This may reflect the view that the coarse PM fraction is deposited faster and thus may exert a more significant local impact than the finer fraction which may be transported over longer distances.

However, as no significant influence of height was observed for concentrations of $PM_{2.5}$, the respirable fraction of PM, it is recommended that further research is undertaken to confirm

the findings and ascertain if this observed effect is restricted to PM with an aerodynamic diameter of more than 2.5 μm, or whether the low concentrations of $PM_{2.5}$ simply make identifying the effect more challenging.

For NO_2, at lower ambient concentrations, no consistent influence of exposure height was identified on observed concentrations. However, at higher ambient concentrations, such as that may be observed in close proximity to busy road junctions, significantly higher concentrations were observed at adult breathing height (1.68 m) than at child breathing height (0.80 m). This finding is significant, as it appears to indicate that in the urban environment adults may be exposed to higher concentrations of NO_2 on average than children. Given that this influence was only noted at relatively high ambient concentrations, it is possible that the finding is influenced by proximity to local sources, notably elevated road traffic, as emissions of NO_2 will be associated with exhaust gas emissions, which being hot may rise upwards immediately following release from the exhaust before dispersing more widely in the environment. However, given that this finding was also observed on Sauchiehall Street and Buchanan Street sections of the study route which are largely pedestrianised this possibility must be questioned. Before any definitive conclusions are drawn from these results, it is recommended that further research is undertaken to confirm and help elucidate the conclusions.

5.3 Cross-Pollutant Correlations

The ambient urban environment commonly includes a complex mixture of pollutants from a range of sources. As such, humans are commonly exposed to a cocktail of pollutants, and in some situations, the presence of certain pollutants is often used as a marker to indicate the presence of other 'associated' pollutants. For example, whilst NO_2 has been associated with adverse effects on hospital admissions, detrimental effects on lung function and prevalence of asthma, in the past it has often been questioned whether these associations are caused by NO_2 itself, or due to some other pollutant with which it is correlated with in ambient air (COMEAP, 2015)

Data from the study demonstrated the extreme complexity of intra-pollutant relationships. Inconsistent or weaker correlations were observed between most of the pollutants studied, whilst consistently moderately-strong to strong correlations were identified with the PM fractions $PM_{0.5}$ with $PM_{1.0}$ and $PM_{2.5}$, and separately $PM_{2.5}$ with $PM_{5.0}$ and PM_{10}. These findings are perhaps not surprising but suggest that PM behaviour is related particle size, with the course fraction being deposited faster than the fraction $<PM_{2.5}$.

5.4 Spatial Distribution of Pollutants

Perhaps the most interesting findings from the study were generated by the spatial visualisation of the concentrations of pollutants measured by the mobile monitoring trolley along the prescribed monitoring route. In general, higher concentrations of pollutants were readily observed in areas where high road traffic volumes and traffic congestion were observed. Some of the most notably areas where elevated concentrations of pollutants were observed included Hope Street, High Street and around George Square, all 3 of which are areas of the study route where high traffic volumes and congestion are commonly observed.

Elevated concentrations of BC and UFP were more pronounced and visualised more clearly than other pollutants. This may be related to the way that these pollutants are reported or alternatively may indicate that road traffic is the main local source for these pollutants. Concentrations of BC and UFP were found to decrease along Sauchiehall Street and Buchanan Street which are largely pedestrianised, however, this finding was not mirrored in $PM_{2.5}$ concentrations, where increased concentrations were observed. These findings perhaps indicated different sources for each pollutant, or more likely reflect the different ways that the pollutants disperse. Fugitive sources such as re-suspension of particulates also may have a greater influence on the spatial variability of $PM_{2.5}$ concentrations.

The spatial visualisation of pollutants through the use of the mobile monitoring trolley shows significant potential for the identification or confirmation of pollutant hotspots within urban environments which are most commonly predicted through the use of dispersion modelling. Through the application of such a mobile monitoring 'screening' approach, authorities may be able to confirm the presence and extent of pollution hotspots, and thus investigate, design and implement appropriate mitigation measures. Furthermore, the capacity of the mobile monitoring approach to identify not only increased concentrations of pollutants associated with road traffic, but also elevated concentrations of $PM_{2.5}$ and BC in close proximity to the construction site at Strathclyde University indicates the potential application of the technology for assessing the potential air quality impact of proposed developments. This could relate not only to the construction and demolition processes, but also pre- and post-construction impacts which are currently challenging to monitor particularly when PM is a key consideration.

5.5 Possible Implications for Policy

A wide range of air quality monitoring is undertaken by the Scottish Government to fulfil the requirements of EU Directive 2008/50/EC on ambient air quality, and by local authorities under the Local Air Quality Management regime (LAQM) as set out in the Environment Act 1995 and associated regulations.

Although both the Directives and the LAQM regime are primarily focused on protecting human health, current monitoring approaches do not consider potential variations in air quality with height above the ground. The heights of monitoring station sampling points vary depending on local conditions and with type of equipment in use. The findings of the study indicate that in Glasgow City Centre, concentrations of key AQS pollutants, notably PM_{10} and NO_2 reported by fixed monitoring sites may not provide a good estimate of an individual person's exposure to these pollutants in such an urban environment. However, in reality, compliance monitoring sites are not designed or expected to represent individual personal exposure, but provide reliable and consistent data of concentrations of air quality pollutants representative of different environment types (e.g. kerbside and urban background) to inform compliance reporting and support the Scottish Government, UK Government and European Commission in targeting overall improvements in ambient air quality. The results from the Glasgow study are very informative and provide valuable insight into the potential variations of air pollutants in the urban environment. However, the study itself does not aim to, and does not provide a true reflection of personal exposure, as individuals don't tend to walk around urban environments constantly, but tend to spend time travelling and indoors at home or at work where they will be exposed to other sources of pollution.

A potentially important finding of the study was the suggestion that concentrations of some pollutants are influenced by the height of exposure/ monitoring inlet height. As the Air Quality Directives and the UK Air Quality Strategy are primarily concerned with protecting human health, the finding that in some urban environments that children may be exposed to higher concentrations of PM_{10} than adults is something that merits further investigation. In terms of monitoring policy, sample inlets used at fixed site are in many cases are set at a height much greater than 1.68 m; typically between 2.5 m and 3.5 m. The results from this study indicate that pollutant gradients exist for some pollutants between 0.80 m and 1.68 m and as a result, this may need to be taken into account in the future policy. For example, it is not known if a concentration gradient exists between 0.8 and 3.5 m: could a relationship be derived between pollutant concentrations and the height at fixed monitoring sites up to 3.5 m, and would this be representative of specific site types (e.g. Kerbside or Urban Background)? This could potentially provide a method to improve estimates of pollutant concentrations below the sample inlet height of a particular station.

Another important finding of the Glasgow study was that higher concentrations of $PM_{2.5}$ were observed in pedestrian sections of the monitoring route than in close proximity to many of the roads. As the Scottish Government is currently considering the addition of $PM_{2.5}$ to the

LAQM regime in Scotland, and the associated design of a $PM_{2.5}$ monitoring network, the findings from this and related studies may help inform this process, particularly the geographical spread of monitoring sites. However, it is recommended that this finding is evaluated in other pedestrianised/ urban background locations including in other towns and cities to determine whether this finding is more widely observed.

In passing, the study has also undertaken an evaluation of some personal air quality samplers and pervasive sensors which don't currently meet the requirements for air quality compliance monitoring. This applicability of such analysers for ambient air quality monitoring is currently the focus of considerable research across the UK and Europe and consequently not definitive conclusions should be drawn from this study. However, whilst the sensors are not currently suitable for compliance monitoring purposes, or for the declaration of an Air Quality Management Area, for example, in certain circumstances such technology could provide valuable insight into the spatial variation of pollutant concentrations, which with careful processing could potentially become valuable screening techniques (similar to NO_2 diffusion tubes). With appropriate research and the development of guidance, some of these technologies have the future potential to support the refinement of local dispersion models and the national compliance model and thus enhance the assessment of population exposure.

5.6 Recommendations for Further Research

The findings of this study are limited by the number of monitoring exercises carried out, with a total 8 mobile monitoring exercises and 11 co-location exercises during a six month period. As a result, it was not possible to capture all conditions (e.g. traffic, weather and pollution episodes), although the potential for doing so was maximised through monitoring on different days of the week; in different months and seasons of the year; and in a variety of urban microenvironments. Therefore, the results can only be considered to represent a snapshot of conditions within Glasgow City Centre.

There is obviously opportunity to enhance and refined the findings of the study by repeating the study and undertaking a more extensive mobile monitoring exercise using a number of towns and cities around Scotland throughout a calendar year. There are also a large number of potential studies that could be undertaken and bring value to air quality research in Scotland. However, for the purposes of this report there is potentially more benefit from focussing on confirming some of the key findings of the Glasgow study and where these may support the current and future air quality policy of the Scottish Government. Therefore, it is recommended that further research could focus on:

- Investigating the variation in concentrations of pollutants (most notably NO_2, PM_{10} and $PM_{2.5}$) with height at a number of fixed monitoring sites with different site classifications (e.g. kerbside, roadside and urban background) to determine whether the variations in pollutant concentrations observed by the mobile monitoring trolley are also observed at compliance monitoring sites.
- Investigating the spatial differences in ambient concentrations of $PM_{2.5}$ and PM_{10} observed in the current study. Such a study could help to inform Scottish Government policy with respect to PM, notably the potential inclusion of $PM_{2.5}$ within the LAQM regime and the associated development of a $PM_{2.5}$ monitoring network.

6 Conclusions

In conclusion, the Glasgow study has demonstrated the complexity of ambient air quality within the urban environment and the challenges of monitoring a range of important pollutants within such an environment. Within a limited duration exercise, the study has provided valuable insights into not only spatial variations of key air pollutants in Glasgow City centre but also the influence of exposure height on the concentrations observed. In addition, the study also helped to elucidate correlations between observed concentrations of different pollutants at different exposure heights and also provide useful information regarding the application of mobile monitoring and the application of personal sampler/ sensor technology for assessing human exposure to air pollutants in an urban environment.

In brief summary, the study identified that spatial and temporal variations in pollutant concentrations in Glasgow City centre are generally species specific and can also be influenced by a wide range of other environmental parameters, such as the proximity to pollution sources. Whilst a large number of initial conclusions have been drawn, several of the findings are considered to merit further attention. These were:

- It was identified that consistently higher average concentrations of $PM_{2.5}$ (42% higher) and PM_{10} (47-63% higher) were recorded by the mobile monitoring trolley when monitoring along the study route than those reported at the fixed Glasgow Kerbside AURN monitoring site.

- Average concentrations of PM_{10} were shown to be consistently higher (up to 12.6% higher) at 0.80 m than at 1.68 m throughout the mobile monitoring trolley study route. This finding is significant, as it appears to indicate that in the urban environment children may be exposed to higher concentrations of PM_{10} on average than adults. However, this relationship was not observed for concentrations of $PM_{2.5}$.

- For NO_2, at lower ambient concentrations, no consistent influence of exposure height was identified on observed concentrations. However, at higher ambient concentrations, such as that may be observed in close proximity to busy road junctions, significantly higher concentrations were observed at adult breathing height (1.68 m) than at child breathing height (0.80 m).

- Visualisation of pollutant concentrations monitored through the application of the mobile monitoring trolley demonstrated potential for the identification or confirmation of pollutant hotspots within urban environments. Through the application of such a mobile monitoring 'screening' approach, authorities may be able to confirm the presence and extent of pollution hotspots, and thus investigate, design and implement appropriate mitigation measures.

Overall, the study has provided valuable insights spatial (vertical and horizontal) variations of concentrations of key air pollutants in Glasgow City centre. The study has generated numerous interesting findings which with further research could help to inform and guide future air quality research and policy in Scotland.

7 References

Alfred Micallef, Jeremy J. Colls, Variation in airborne particulate matter concentration over the first three metres from ground in a street canyon: implications for human exposure, Atmospheric Environment, Volume 32, Issue 21, 1 November 1998, Pages 3795-3799

Barnett, A. G., Williams, G. M., Schwartz, J., Neller, A. H., Best, T. L., Petroeschevsky, A. L. & Simpson, R. W. 2005. Air pollution and child respiratory health: a case-crossover study in Australia and New Zealand. *American Journal of Respiratory and Critical Care Medicine,* 171**,** 1272-1278.

Berghmans, P., Bleux, N., Panis, L. I., Mishra, V. K., Torfs, R. & Van Poppel, M. 2009. Exposure assessment of a cyclist to PM10 and ultrafine particles. *Science of The Total Environment,* 407**,** 1286-1298.

Bernstein, J. A., Alexis, N., Barnes, C., Bernstein, I. L., Nel, A., Peden, D., Diaz-Sanchez, D., Tarlo, S. M. & Williams, P. B. 2004. Health effects of air pollution. *Journal of Allergy and Clinical Immunology,* 114**,** 1116-1123.

Bond, T. C. 2007. Can warming particles enter global climate discussions? *Environmental Research Letters,* 2**,** 045030.

Bond, T. C., Doherty, S. J., Fahey, D. W., Forster, P. M., Berntsen, T., Deangelo, B. J., Flanner, M. G., Ghan, S., Kärcher, B., Koch, D., Kinne, S., Kondo, Y., Quinn, P. K., Sarofim, M. C., Schultz, M. G., Schulz, M., Venkataraman, C., Zhang, H., Zhang, S., Bellouin, N., Guttikunda, S. K., Hopke, P. K., Jacobson, M. Z., Kaiser, J. W., Klimont, Z., Lohmann, U., Schwarz, J. P., Shindell, D., Storelvmo, T., Warren, S. G. & Zender, C. S. 2013. Bounding the role of black carbon in the climate system: A scientific assessment. *Journal of Geophysical Research: Atmospheres,* 118**,** 5380-5552.
Cambridge University, Cambridge Mobile Urban Sensing (CamMobSens), part of the Mobile Environmental Sensing System Across Grid Environments (MESSAGE) project, 2008, http://www.escience.cam.ac.uk/mobiledata/

Carslaw, D.C. (2014). The openair manual — open-source tools for analysing air pollution data. Manual for version 1.0, King's College London.

Carslaw, D.C. and K. Ropkins, (2012). Openair — an R package for air quality data analysis. Environmental Modelling & Software. Volume 27-28, 52-61.

Ciais, P., Sabine, C., Bala, G., Bopp, L., Brovkin, V., Canadell, J., Chhabra, A., Defries, R., Galloway, J. & Heimann, M. (2014). Carbon and other biogeochemical cycles. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge University Press.

COMEAP (2015). Statement on the evidence for the effects of nitrogen dioxide on health.

Joan Corbett, Lisa Given, Linsay Gray, Alastair Leyland, Andy MacGregor, Louise Marryat, Martine Miller, Susan Reid, The Scottish Health Survey 2008, The Scottish Government, September 2009, http://www.scotland.gov.uk/Publications/2009/09/28102003/0

Dane Westerdahl, Scott Fruin, Todd Sax, Philip M. Fine, Constantinos Sioutas, Mobile platform measurements of ultrafine particles and associated pollutant concentrations on freeways and residential streets in Los Angeles, Atmospheric Environment, Volume 39, Issue 20, June 2005, Pages 3597-3610

Daniel MacDougall , Warren B. Crummett, 1980. Guidelines for data acquisition and data quality evaluation in environmental chemistry, Anal. Chem., 1980, 52 (14), pp 2242–2249

David Green, Timothy Baker and Gary Fuller (2008). Volatile Correction Model (VCM) for PM10 Application to hourly time resolution and AURN FDMS purge measurements, Kings College London, http://uk-air.defra.gov.uk/assets/documents/reports/cat13/0902231025_VCM_Application_to_Hourly_and_AURN_FDMS_Purge_Measurements.pdf

Department for Environment, Food and Rural Affairs (Defra), The Scottish Government, The Welsh Government, The Northern Ireland Department of the Environment (2014). Air Quality Pollutant Inventories for England, Scotland, Wales and Northern Ireland: 1990 – 2012. http://uk-air.defra.gov.uk/reports/cat07/1410200846_DA_AQPI_1990-2012_Report_Issue2.pdf

Department for Environment, Food and Rural Affairs (Defra), The Scottish Government, The Welsh Government, The Northern Ireland Department of the Environment (2015). Investigating the feasibility of innovative technologies to improve air quality monitoring over the medium to long term - AQ0964. http://randd.defra.gov.uk/Default.aspx?Menu=Menu&Module=More&Location=None&Completed=0&ProjectID=19538

Dons, E., Int Panis, L., Van Poppel, M., Theunis, J. & Wets, G. 2012. Personal exposure to Black Carbon in transport microenvironments. *Atmospheric Environment,* 55**,** 392-398.

EEA. 2014. Black carbon: Better monitoring needed to assess health and climate change impacts â” European Environment Agency (EEA) [Online]. Available: http://www.eea.europa.eu/highlights/black-carbon-better-monitoring-needed [Accessed 17/12/2014.

EEA. 2015. Benzene (C6H6): annual mean concentrations in Europe. Available: http://www.eea.europa.eu/themes/air/interactive/c6h6

Eliasson, B. Offerle, C.S.B. Grimmond, S. Lindqvist, Wind fields and turbulence statistics in an urban street canyon, Atmospheric Environment, Volume 40, Issue 1, January 2006, Pages 1-16, ISSN 1352-2310, http://dx.doi.org/10.1016/j.atmosenv.2005.03.031.

Evi Dons, Luc Int Panis, Martine Van Poppel, Jan Theunis, Geert Wets, Personal exposure to Black Carbon in transport microenvironments, Atmospheric Environment, Volume 55, August 2012, Pages 392-398

Evi Dons, Luc Int Panis, Martine Van Poppel, Jan Theunis, Hanny Willems, Rudi Torfs, Geert Wets, Impact of time–activity patterns on personal exposure to black carbon, Atmospheric Environment, Volume 45, Issue 21, July 2011, Pages 3594-3602

G. Buonanno, L. Stabile, L. Morawska, A. Russi, Children exposure assessment to ultrafine particles and black carbon: The role of transport and cooking activities, Atmospheric Environment, Volume 79, November 2013, Pages 53-58

G. Buonanno, L. Stabile, L. Morawska, Personal exposure to ultrafine particles: The influence of time-activity patterns, Science of The Total Environment, Volumes 468–469, 15

January 2013, Pages 903-907

G. Buonanno, S. Marini, L. Morawska, F.C. Fuoco, Individual dose and exposure of Italian children to ultrafine particles, Science of The Total Environment, Volume 438, 1 November 2012, Pages 271-277

Hagler, G.S.W., Yelverton, T.L.B., Vedantham, R., Hansen, A.D.A., Turner, J.R., 2011. Post-processing method to reduce noise while preserving high time resolution in Aethalometer Real-time black carbon data. Aerosol and Air Quality Research, 11, 539-546

Hagler, G.S.W., Yelverton, T.L.B., Vedantham, R., Hansen, A.D.A., Turner, J.R., 2011. Post-processing method to reduce noise while preserving high time resolution in Aethalometer Real-time black carbon data. Aerosol and Air Quality Research, 11, 539-546

HINDS, W. C. 1999. *Aerosol Technology: Properties, Behaviour, and Measurement of Airborne Particles,* New York, John Wiley & Sons.

Hudda N., Fruin S., Delfino R. J.,Sioutas C. 2012. Efficient determination of vehicle emission factors by fuel use category using on-road measurements: downward trends on Los Angeles freight corridor I-710. Atmos. Chem. Phys., 13, 347–357, 2013.

I.D. Longley, M.W. Gallagher, J.R. Dorsey, M. Flynn, J.D. Allan, M.R. Alfarra, D. Inglis, A case study of aerosol (4.6 nm < Dp < 10 µm) number and mass size distribution measurements in a busy street canyon in Manchester, UK, Atmospheric Environment, Volume 37, Issue 12, April 2003

Imhof, D, et al, 2005, Vertical Distribution of aerosol particles and NOx close to a motorway, Atmospheric Environment, 5710–5721

Jae-Jin Kim, Jong-Jin Baik, A numerical study of the effects of ambient wind direction on flow and dispersion in urban street canyons using the RNG k–ε turbulence model, Atmospheric Environment, Volume 38, Issue 19, June 2004, Pages 3039-3048, ISSN 1352-2310, http://dx.doi.org/10.1016/j.atmosenv.2004.02.047.

Kaur, S., Nieuwenhuijsen, M. & Colvile, R. 2005. Pedestrian exposure to air pollution along a major road in Central London, UK. *Atmospheric Environment,* 39**,** 7307-7320.

L. Ferrero, G. Mocnik, B.S. Ferrini, M.G. Perrone, G. Sangiorgi, E. Bolzacchini, Vertical profiles of aerosol absorption coefficient from micro-Aethalometer data and Mie calculation over Milan, Science of The Total Environment, Volume 409, Issue 14, 15 June 2011, Pages 2824-2837

L. Pirjola, T. Lähde, J.V. Niemi, A. Kousa, T. Rönkkö, P. Karjalainen, J. Keskinen, A. Frey, R. Hillamo, Spatial and temporal characterization of traffic emissions in urban microenvironments with a mobile laboratory, Atmospheric Environment, Volume 63, December 2012, Pages 156-167

Leonard M. Zwack, Steven R. Hanna, John D. Spengler, Jonathan I. Levy, Using advanced dispersion models and mobile monitoring to characterize spatial patterns of ultrafine particles in an urban area, Atmospheric Environment, Volume 45, Issue 28, September 2011, Pages 4822-4829

Luz T. Padró-Martínez, Allison P. Patton, Jeffrey B. Trull, Wig Zamore, Doug Brugge, John L. Durant, Mobile monitoring of particle number concentration and other traffic-related air pollutants in a near-highway neighborhood over the course of a year, Atmospheric Environment, Volume 61, December 2012, Pages 253-264

Maccarthy, J., Thistlethwaite, G., Salisbury, E., Pang, Y. & Misselbrook, T. 2012. Air Quality Pollutant Inventories for England, Scotland, Wales and Northern Ireland: 1990–2010. AEA Technology, National Environmental Technology Centre, Culham, UK.

Martine Van Poppel, Jan Peters, Nico Bleux, Methodology for setup and data processing of mobile air quality measurements to assess the spatial variability of concentrations in urban environments, Environmental Pollution, Volume 183, December 2012, Pages 224-233

Martine Van Poppel, Jan Peters, Nico Bleux, Methodology for setup and data processing of mobile air quality measurements to assess the spatial variability of concentrations in urban environments, Environmental Pollution, Volume 183, December 2012, Pages 224-233 Meilu He, Suresh Dhaniyala, Vertical and horizontal concentration distributions of ultrafine particles near a highway, Atmospheric Environment, Volume 46, January 2012, Pages 225-236

N. Hudda, S. Fruin, R. J. Delfino and C. Sioutas. Efficient determination of vehicle emission factors by fuel use category using on-road measurements: downward trends on Los Angeles freight corridor I-710, Atmospheric Chemistry and Physics, 13, January 2013, 347

NIST/SEMATECH e-Handbook of Statistical Methods, http://www.itl.nist.gov/div898/handbook/, March 2015

Nawrot, T., Torfs, R., Fierens, F., De Henauw, S., Hoet, P., Van Kersschaever, G., De Backer, G. & Nemery, B. 2007. Stronger associations between daily mortality and fine particulate air pollution in summer than in winter: evidence from a heavily polluted region in western Europe. *Journal of epidemiology and community health,* 61**,** 146-149.

P. Berghmans, N. Bleux, L. Int Panis, V.K. Mishra, R. Torfs, M. Van Poppel, Exposure assessment of a cyclist to PM10 and ultrafine particles, Science of The Total Environment, Volume 407, Issue 4, 1 February 2009, Pages 1286-1298

Pope Iii, C. A. & Dockery, D. W. 2006. Health effects of fine particulate air pollution: lines that connect. *Journal of the Air & Waste Management Association,* 56**,** 709-742.

Ramanathan, V. & Carmichael, G. 2008. Global and regional climate changes due to black carbon. *Nature Geosci,* 1**,** 221-227.

Royal College of Paediatrics and Child Health, World Health Organisation, Department of Health, UK-WHO Growth Charts, January 2013, http://www.rcpch.ac.uk/child-health/research-projects/uk-who-growth-charts/uk-who-growth-charts

S. Kaur, R.D.R. Clark, P.T. Walsh, S.J. Arnold, R.N. Colvile, M.J. Nieuwenhuijsen, Exposure visualisation of ultrafine particle counts in a transport microenvironment, Atmospheric Environment, Volume 40, Issue 2, January 2006, Pages 386-398

SEPA 2014. Emissions of sulphur dioxide, nitrogen oxides and dust from Large Combustion Plants in Scotland. Available: http://www.scotland.gov.uk/SESO/Resources/StatFiles/AQlargecombustionplants.xls

Shishan Hu, Suzanne E. Paulson, Scott Fruin, Kathleen Kozawa, Steve Mara, Arthur M. Winer, Observation of elevated air pollutant concentrations in a residential neighbourhood of Los Angeles California using a mobile platform, Atmospheric Environment, Volume 51, May

2012, Pages 311-319

Tiwary, A. & Colls, J. 2009. Air pollution: measurement, modelling & mitigation, 2 Park Sq, Milton Park, Abingdon, Oxfordshire, OX14 4RN, UK, Routledge.

Trompetter, W, et al, 2013, Vertical and temporal variations of black carbon in New Zealand urban areas during winter months, Atmospheric Environment, 179-187

US EPA. 2006. Effects of Acid Rain [Online]. Available:
http://www.epa.gov/acidrain/effects/index.html

US EPA. 2014. Sulfur Dioxide: Health. Available:
http://www.epa.gov/airquality/sulfurdioxide/health.html

Vincent James Cogliano, Robert Baan, Kurt Straif, Yann Grosse, Béatrice Lauby-Secretan, Fatiha El Ghissassi, Véronique Bouvard, Lamia Benbrahim-Tallaa, Neela Guha, Crystal Freeman, Laurent Galichet Christopher P. WildPreventable, October 2011. Exposures Associated With Human Cancers, J Natl Cancer Inst 2011;103: 1827 – 1839 Available at: http://monographs.iarc.fr/ENG/Classification/Cogliano_2011_JNCI_Preventable_Exposures. pdf

WHO. 2014. 7 million premature deaths annually linked to air pollution. World Health Organization. Available: http://www.who.int/mediacentre/news/releases/2014/air-pollution/en/

Wikipedia. 2015. Pearson product-moment correlation coefficient - Wikipedia, the free encyclopedia. Available: http://en.wikipedia.org/wiki/Pearson_product-moment_correlation_coefficient

Virkkula A., Mäkelä, T. , Hillamo, R., Yli-Tuomi T., Hirsikko A., Hämeri K, Koponen, I., K. 2007. *A Simple Procedure for Correcting Loading Effects of Aethalometer Data, Journal of the Air & Waste Management Association, 57:10, 1214-1222, DOI:* 10.3155/1047-3289.57.10.1214

W.W. Song, K.B. He, Y. Lei, Black carbon emissions from on-road vehicles in China, 1990–2030, Atmospheric Environment, Volume 51, May 2012, Pages 320-328
WHO. 2014. 7 million premature deaths annually linked to air pollution [Online]. World Health Organization. Available: http://www.who.int/mediacentre/news/releases/2014/air-pollution/en/.

X.L. Li, J.S. Wang, X.D. Tu, W. Liu, Z. Huang, Vertical variations of particle number concentration and size distribution in a street canyon in Shanghai, China, Science of The Total Environment, Volume 378, Issue 3, 1 June 2007, Pages 306-316

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