Developing a methodology for monitoring personal exposure to particulate matter in a variety of microenvironments

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I certify that all material in this thesis which is not my own work has been identified and that no material has previously been submitted and approved for the award of a degree by this or any other University.

Signature: ……………………………………………………………..

Abstract

Adverse health effects from exposure to air pollution, although at present only partly understood, are a global challenge and of widespread concern. Quantifying human exposure to air pollutants is challenging, as ambient concentrations of air pollutants at potentially harmful levels are ubiquitous and subject to high spatial and temporal variability. At the same time, individuals have their very own unique activity-patterns. Hence exposure results from intertwined relationships between environmental and human systems add complexity to the assessment process.

It is essential to develop a deeper understanding of individual exposure pathways and situations occurring in people’s everyday lives. This is important especially with regard to exposure and health impact assessment which provide the basis for public health advice and policy development.

This thesis describes the development and application of a personal monitoring method to assess exposure to fine particulate matter in a variety of microenvironments. Tools and methods applied are tested with respect to feasibility, intrusiveness, performance and potential for future applications.

The development of the method focuses on the application in everyday environments and situations in an attempt to capture as much of the total exposure as possible, across a complete set of microenvironments. Seventeen volunteers took part in the pilot study, collected data and provided feedback on methodology and tools applied.

The low-cost particle counter applied showed good agreement with reference instruments when studied in two different environments. Based on the assessment of the two instruments functions to derive particle mass concentration from the original particle number counts have been defined.

The application of the devices and tools received positive feedback from the volunteers. Limitations are mainly related to the non-weatherproof design of the particle counter. The collection of time-activity patterns with GPS and time-activity diaries is challenging and requires careful processing.

Resulting personal exposure profiles highlight the influence of individual activities and contextual factors. Highest concentrations were measured in indoor environments where people also spent the majority of time. Differences between transport modes as well as between urban and rural areas were identified.

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Abbreviations & Acronyms

$\mu g/m^3$	Microgram per cubic meter
AURN	Automatic urban and rural network
BC	Black carbon
CA	Council Area
CCTV	Closed circuit television
CEH	Centre for Ecology & Hydrology
CHD	Coronary heart disease
CO	Carbon monoxide
DPSEEA	Drivers, Pressures, State, Exposure, Effects, Actions model
Dylos	Dylos DC 1700
DZ	Data Zone
eDPSEEA	Ecosystem-enriched Drivers, Pressures, State, Exposure, Effects, Actions model
EMEP	European Monitoring and Evaluation Programme
ETS	Environmental tobacco smoke
FDMS	Filter Dynamics Measurements System
FME	Feature Manipulation Engine
GIS	Geographic Information Systems
GPS	Global Positioning System
HIA	Health Impact Assessment
IARC	International Agency for Research on Cancer
IQR	Inter quartile range
LAQM	Local Air Quality Management
MARGA	Monitor for Aerosols & Gasses in Ambient Air
MAUP	Modifiable Area Unit Problem
mDPSEEA	Modified Drivers, Pressures, State, Exposure, Effects, Actions model
ME	Microenvironment
Na^+	Sodium
NH^{4+}	Ammonium
NO_2	Nitrogen dioxide
NO_3^-	Nitrate
NO_x	Oxides of nitrogen
O_3	Ozone
OS	Ordnance Survey
P1	Phase 1 (of fieldwork)
P2	Phase 2 (of fieldwork)
PC	Postcode
PDA	Personal digital assistant
PM	Particulate matter
PM_{10}	Coarse particulate matter
$PM_{2.5}$	Fine particulate matter
PNC	Particle number count
ppb	Parts per billion
RFID	Radio frequency identification
SHS	Second-hand smoke
SO_4^{2-}	Sulphate
TAD	Time Activity Diary
TEAM	Total exposure assessment methodology
TEOM	Tapered Element Oscillation Microbalance
TPM	Transport mode
UFP	Ultrafine particles
UNECE	United Nations Economic Commission for Europe
UPC	Ultrafine particle counts
URC	Urban Rural Classification
WHO	World Health Organisation

Author's declaration

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1 Introduction

1.1 Rationale

Despite continuous improvements in air quality in large parts of the world over the past decades, poor air quality remains a challenge in many urban areas, particularly in emerging and developing countries. The WHO's International Agency for Research on Cancer (IARC) has recently published a press release stating that outdoor air pollution is a major cause for cancer on a global scale (WHO, 2013a), indicating that health impacts due to exposure to air pollution are of widespread concern and by no means an issue of the past. Having clean air to breathe is a basic requirement of life and everyone is entitled to it (Brunekreef et al., 2012, WHO, 2010).

Air pollution can affect the respiratory, cardiovascular, cardio-pulmonary and reproductive system and lead to cancer. The evidence for these health effects is robust, even though there are still knowledge gaps regarding the exact mechanisms by which air pollutants affect human health (including the effects of pollutant mixtures), and which pollutants should be tackled with priority (EPA, 2012, EEA, 2013, WHO, 2013b, WHO, 2013a, Maudgalya et al., 2008, WHO, 2012). Reducing air pollution does not only directly reduce adverse health effects, but increases general well-being, quality of life and improves public health and can have positive impacts on ecosystem services. Reducing emissions can also have positive influence on regional agricultural crops, and the cultural landscape, reduce disruptions to the hydrological and biochemical cycles and adverse effects on the cryosphere (Harmens et al., 2011, Shindell et al., 2012). The monetary benefits due to avoided individual risk (e.g. quantified by assessing the willingness to pay for reduced risk of air pollution exposure), avoided primary and secondary health care expenditures and reduced absenteeism from work can be substantial and by far outweigh emission control costs (Watkiss et al., 2005, Pascal et al., 2013).

Because of the complex, intertwined relationships between the human and the environmental system it is necessary to integrate contextual factors such as environmental, socioeconomic and behavioural, into exposure assessment, which covers all aspects of estimating or measuring exposure to an agent. Investigating variations of individual exposure to pollutants of concern by age, gender, socioeconomic status, neighbourhood characteristics, activity level or ethnicity for instance requires new methods and tools.

Our modern society is moving away from a traditionally low mobility society living in an area with stable living conditions for large parts of an individual's life to a much more mobile lifestyle (Rainham et al., 2010). In fact mobility plays a role in daily life, with travelling for leisure and commuting for work being part of many people's life. People are constantly moving in time and space, while the (air) pollution landscape is spatially and temporally highly variable at the same time. This determines to a large part individual exposure to air pollution and monitoring needs to take account of this.

At the same time though, the amount of physical activity and manual labour as compared to being sedentary in a car or an office have decreased, resulting in people spending a lot of time in indoor and transport environments which makes these environments important for the total exposure assessment process.

The level of detailed information gained from personal monitoring is substantially different from what traditional methods to generate population level exposure estimates (based on fixed-site monitoring networks and location of residence) are able to provide (Steinle et al., 2013). Personal monitoring provides a much more detailed picture of indoor air quality, which is important since people spend a large part of their time in indoor environments, and this compares to the exposure outdoors, which has been the primary focus of air pollution exposure research to date.

Personal monitoring offers the opportunity to collect datasets of specific air pollutants at a much higher spatiotemporal resolution within a certain area than traditional fixed-site monitoring approaches which usually provide more pollutants but only for one point. Personal exposure monitoring methods are also well suited to be integrated into a citizen science approach where individuals are not only observers but at the same time the study subjects.

Working with personal data on an individual level and containing detailed information on individual habits and whereabouts raises confidentiality issues which need to be considered. The individual's privacy must be respected first and foremost and data protection requirements need to be considered (Tweddle et al., 2012)). This means that data cannot be released without measures being taken to anonymise data where required if intended for publication. This is inherent to the personal exposure assessment.

A variety of methodologies and study designs has been applied by the research community in recent years and the feasibility of personal exposure assessment methods has been widely demonstrated (e.g. Cole-Hunter et al., 2012, Delgado-Saborit, 2012, Dons et al., 2011). The research focus has been on certain exposure situations in specific environments. Such approaches however, leave the assessment of exposure incomplete as not all exposure situations that a person experiences in their daily life are included in the assessment. Conclusions about the total exposure, as a component of and a step towards a quantification of the exposome (a measure of effects of exposure over the full lifetime on human health) on an individual level are therefore not possible. It is important to consider not only the heterogeneity of individual exposure in a certain environment but also the diversity of environments in a person’s life as the variety of the environments visited leads to a heterogeneity of exposure components.

In line with this rationale a pilot study to assess personal exposure to particulate matter including the full heterogeneity of environments a person typically visits throughout a day has been designed, including the development of a portable monitoring solution for particulate matter.

1.2 Aims and hypotheses

The main objective of this thesis is to improve the knowledge about sources of particulate matter and exposure pathways in people’s everyday lives. Knowing when a person has been exposed to which concentration is vital information required for exposure assessment on individual and population scale, and ultimately to develop robust evidence for policy advice. This thesis describes the development, application and assessment of a methodology for monitoring personal exposure to particulate matter in a variety of microenvironments. The methodology has been tested and validated in a small scale pilot study in Scotland according to the following aims:

a) Evaluation of the performance of a portable particle monitor for personal air quality monitoring indoors and outdoors.
b) Assessment of a methodology for personal monitoring in everyday microenvironments.

c) Assessment of the implications of individuals moving through the changing air pollutant concentration field on the applicability of air quality monitoring solutions.

The thesis is divided into three key areas with the respective hypotheses relating to individual chapters:

a) The portable particle counter Dylos DC 1700 is a viable instrument for personal air quality monitoring, providing robust, reliable results when compared to reference instruments in outdoor settings (chapter 4).
b) Method and study design applied are feasible for monitoring personal exposure to particulate matter in everyday microenvironments (chapter 5).
c) Depending on environment, personal time-activity patterns and other contextual factors, exposure to air pollution is notably different between individuals, which can be revealed by personal monitoring (chapter 6).

1.3 Thesis Overview

Chapter 2 introduces the concept of exposure and exposure assessment and briefly discusses air pollution and its effects on human health. The literature on different methods of exposure research and air pollution monitoring is summarised and discussed. The need for an integrated exposure assessment approach taking account of the environment in its broadest sense is highlighted. This provides a detailed underpinning of the research methodology applied in the following chapters.

Chapter 3 provides an overview of the study design, briefly characterises the study area and introduces the study population. Tools and methods applied are explained and the data collection process is summarised.

Chapter 4 describes the approach taken to evaluate the performance of the particle monitor used against reference instruments. The development of functions derived based on this evaluation for converting particle number counts into $PM_{2.5}$ mass concentrations is outlined.

Chapter 5 explores the feasibility of the approach taken and monitoring system applied in the pilot study. Individual tools are evaluated and the development of data processing methods is described. The applicability of the method for future studies with a special emphasis on citizen science projects is assessed.

Chapter 6 presents results of the pilot study, showing time-activity patterns and neighbourhood characteristics of the study population. $PM_{2.5}$ concentrations are discussed and put into context. A number of individual exposure profiles are discussed in detail emphasising the variety of contextual influences affecting the ambient concentrations measured.

Chapter 7 reflects on the findings of the research, considers its implications for exposure research, public health and policy advice, and makes recommendations for further studies in this research area.

2 Quantifying human exposure to air pollution

In this chapter concepts of exposure, exposure assessment, air pollution and air pollution related health effects are introduced and discussed based on the latest research findings. A literature review on recent personal monitoring studies is included which leads the discussion to the need for an integrated exposure assessment approach taking account of the environment as a whole.

2.1 Introduction

Air pollution presents a challenge on global, regional/national and local levels. It affects not only human health, but also causes damage to ecosystems and agricultural crops, reducing the value of ecosystem services and impacting on the production of food and energy crops (Harmens et al., 2011). Having clean air to breathe is a basic requirement of life and everyone is entitled to it (Brunekreef et al., 2012). Substantial growth in individual transport activities and energy consumption reflect increasing affluence and contribute considerably to high ambient air pollutant concentrations especially in urban areas. These characteristically have high population densities and consequently high traffic flows and other pollution sources. Poor air quality remains a challenge in urban areas worldwide and the health impacts due to exposure to air pollution are of widespread concern (EEA, 2013).

Air pollution in Europe has significantly decreased over the last decade as a consequence of the successful implementations of air quality legislation. There is however still a lot to do regarding ambient and indoor air quality for which there is currently no dedicated European legislation in place (EEA, 2013, EEA, 2012). Air pollutants can affect human health in many ways, however there are still knowledge gaps regarding which pollutants need to be treated with priority as well as about the mechanisms by which air pollutants affect human health (EEA, 2013, EPA, 2012, WHO, 2012, WHO, 2013b). Good air quality also promotes a green and clean environment as well as public health and wellbeing and contributes to a sustainable society.

Air pollutants are ubiquitous and a certain level of exposure is inevitable, whether a person is indoors or outdoors. For risk and impact assessments of air pollution effects and the design of control policies, such as the EU Air Quality Framework Directive (Directive 2008/50/EC) and Local Air Quality Management (LAQM) (DEFRA, 2013) it is necessary to quantify human exposure to air pollution as accurately as possible. Traditionally, personal, environmental exposure has not been directly assessed for individuals, but rather by estimating population-wide exposure via networks of fixed monitoring sites deriving annual ambient average concentrations and spatial interpolation of the results. It is the quantification of exposure to air pollution in an assessment process however, which is particularly challenging because human exposure is a function of concentration and time (Nuckols et al., 2004). Exposure is thus not straightforward to calculate and based on complex relationships and interactions between environmental and human systems.

Technological advances now allow scientist to explicitly monitor personal exposure with portable or wearable devices. Time-geography is a crucial determinant of personal exposure in this context as it accounts for the movement of a person in space and time, acknowledging the fact that every human activity has a spatial and a temporal dimension (Rainham et al., 2008). The following quote from the founding father of time-geography, Torsten Hägerstrand, reflects this well:

“Existence in society implies people are constantly in motion. Virtually every individual possesses his own unique field of movement, with his residence in the centre and with places of work, shops, places of recreation, residences of intimate friends, and other similar locales serving as nodal points.”

(Hägerstrand, 1967p. 8).

In this chapter air pollution and its impacts on human health are discussed. Following this, concepts of exposure and the exposome as well as conceptual models to work with the complex interactions between human and environmental systems are introduced. Characteristics of air pollution and methods to monitor pollutants are discussed. The focus of the chapter is on personal exposure assessment methods and tools which are discussed along with example studies.

It is beyond the scope of this chapter to give a complete account of exposure science and human exposure research. The reader is hence referred to recent books and reports (Lazaridis and Colbeck, 2010, Ott et al., 2007, Committee on Human and Environmental Exposure Science in the 21st Century et al., 2012) and several articles (Lioy, 2010, Ashmore and Dimitroulopoulou, 2009, Hertel et al., 2001a, Monn, 2001, Morawska et al., 2013) covering the emergence, state and methods of this research area and its subtopics more comprehensively. Moreover this thesis concentrates on research in industrialised countries where time-activity patterns, emission sources and lifestyle, and hence the methods applicable, are different to the ones in developing countries.

2.2 The concepts of exposure and exposome

Exposure science addresses the intensity and duration of the contact between humans (or other organisms) and the respective agents, in this case air pollutants, as well as the fate of the agents in the human system (Committee on Human and Environmental Exposure Science in the 21st Century et al., 2012). The focus of this project is on personal exposure which can be defined as the event during which a person comes into contact with a pollutant of concern (Ott, 1982).

To assess human exposure to air pollution a pollutant concentration is required, which is simply the numerical amount of the respective pollutant per unit volume of air at a particular time (or averaged over a period of time) (Morawska et al., 2013). The spatial concentration field will change as a person moves through space; therefore exposure is a function of time (Ott, 1982). More specifically, Branis (2010) defines personal exposure as the measurement of a pollutant of concern performed by a monitor or sampler which is worn by a person at a point near the breathing zone of the person while sampling. According to Nieuwenhuijsen (2000) the breathing zone from where air is inhaled is within around 30 cm of nose and mouth. Personal exposure takes place when the pollution concentration at a particular place and time is above zero, and the person is present in that same place and at that time. However, this does not necessarily mean that the person receives a dose (i.e. the amount of a pollutant that actually enters the human body). Thus, exposure can be without a dose, but there can never be a dose without exposure (Ott, 1985).

Personal exposure to air pollution includes pollutants such as oxides of nitrogen (NO_x), particulate matter (PM), carbon monoxide (CO) or ozone (O_3) from outdoor and indoor air as well as pollutants generated by the person's activities itself. The latter is subject to the so called personal cloud effect (Rodes et al., 1991, Wallace, 1996). The personal cloud was one of the findings of the Total Exposure Assessment Methodology (TEAM) studies carried out by U. S. EPA and is discussed in more detail in other publications (Ozkaynak et al., 1996, Wallace, 1993, Wallace, 1987, Wallace et al., 1986)

Exposure assessment is defined as a process of measuring or estimating the frequency, magnitude and duration of exposure to the agent of interest together with the characteristics of the exposed population (Zartarian et al., 2007). Ideally, it is a complementary concept describing sources, pathways, routes as well as the uncertainties in the assessment. Personal exposure assessment is evolving quickly and the latest advances in technology enable the tracking of individuals while simultaneously measuring pollutant concentrations.

For this study the focus is on developing a method to measure short term exposure to elevated $PM_{2.5}$ concentrations in contrast to long-term or even lifelong exposure.

A relatively new concept is the exposome which was introduced by Wild (2005):

> *"At its most complete, the exposome encompasses life-course environmental exposures (including lifestyle factors), from the prenatal period onwards...the exposome is a highly variable entity that evolves throughout the lifetime of the individual."(Wild, 2005, p. 1848).*

The exposome has three broad categories on non-genetic exposures: internal (e.g. metabolism), specific external (e.g. air pollution) and general external (e.g. socioeconomic factors) (Wild, 2012). While a person's genome is fixed at conception, internal and external sources of exposure cause the human’s internal chemical environment to vary throughout life (Rappaport, 2011). Essentially, an individual will have a particular profile of exposure at any given point in time which makes the characterisation of the exposome so challenging (Wild, 2012). It is a concept to measure effects of a lifelong exposure to environmental influences on human health and therefore requires longitudinal sampling especially during foetal development, early childhood, puberty and the reproductive years (Rappaport, 2011). These measures include external monitoring and modelling of media such as air and water but also biomonitoring (i.e. measurements) of biological markers of exposure through methods such as blood or urine sampling (Lioy and Rappaport, 2011). Rappaport (2011) prioritises a top down approach applying biomonitoring to identify all important exposures, over a bottom up approach which is based on air, water or soils samples to identify all exogenous exposures. Van Tongeren and Cherrie (2012), on the other hand, support the aim of developing an integrated concept of exposomics taking all sources of available exposure information into account. Internal and external exposure data, personal behaviour and environmental measurements could thus be used to determine the exposome. This requires the collaboration of researchers from a variety of disciplines to promote the concept and unravel complex relationships between social interactions, biological effects and the risk of diseases (Wild, 2012).

The exposome has a public health orientated objective and the aim of its application is to upgrade from a group of individuals to a population, providing the basis for public health decisions (Wild, 2012). According to Wild (2012) even a partial description of the exposome can lead to major public health benefits. Nevertheless, Peters et al. (2012) caution against replacing environmental exposure assessment with exposome measurements as direct links to environmental exposure measures and their sources are likely to be excluded from analysis. Indicators and sources of environmental exposures are necessary to implement mitigation strategies on time. The authors (Peters et al., 2012) recommend that a strong link with the external environment needs to be maintained when applying the concept of exposome to environmental health problems.

The assessment of personal exposure has the advantage that not only ambient air quality is taken into account but also the person's actual and individual movements, activities and lifestyle in space and time. This way exposure assessment becomes a comprehensive snapshot of a person's exposome for a specific period of time.

2.2.1 Air pollutants

Air pollutants are ubiquitous and comprise a range of substances interacting, reacting in the atmosphere creating many heterogeneous pollutant mixes. It is impossible to attribute any individual air pollutant as a sole causal agent to an adverse health effect (Branis, 2010, Goldberg, 2007). Moreover, environmental, meteorological and microclimatic influences, which are changing dynamically, add to the complexity as well as people moving in space and time, showing individual behavioural patterns (McKone et al., 2008). As a consequence, individuals can be exposed in any environment to a large variety of individual pollutants as well as pollutant mixtures (Branis, 2010, Goldberg, 2007).

The pollutant of interest in this thesis is particulate matter (PM), as its adverse health effects (section 2.4) are currently the most prominent driver of policy development regarding air quality improvement (Monks et al., 2009). Commonly PM is split into different size fractions such as PM_{10} which refers to particles with an aerodynamic diameter smaller than 10 µm for analysis. This study specifically focuses on fine particulate matter which refers to particles with an aerodynamic diameter smaller than 2.5 µm ($PM_{2.5}$). Particulate matter is a complex atmospheric constituent. The term refers to any substance, except pure water, that exists under normal conditions in the atmosphere in the liquid or solid phase. Its size range reaches from a few nanometers to tens of micrometers. Primary PM is emitted directly from a source, secondary PM is formed from gases that react and interact in the atmosphere. Residence time in the atmosphere varies from a few days to a few weeks and particles are removed by settling, dry and wet deposition (Seinfeld and Pandis, 2006).

2.2.2 Outdoor and indoor air pollution

Air pollution has often been associated with outdoor air only, since sources such as power plant stacks or road traffic emit key pollutants such as NO_x, CO and PM which are visible and considered to be harmful to human and environmental health. Even though indoor air quality is not a new phenomenon (Colbeck and Nasir, 2010) it has been neglected in exposure research for a long time (Jantunen and Jaakkola, 1997, Lippmann and Lioy, 1985). It has, in recent years, however become an inherent part of exposure research, gaining particular attention in policy making (Colbeck and Nasir, 2010) and for the development of guidelines for certain pollutants (WHO, 2010). Indoor air quality is of special interest since according to the WHO (2005b) two thirds of an average person's time-activity is spent at home, and one fifth at the workplace. Notably, people in industrialised countries - depending on the climate zone -

spend most of their time in indoor environments, especially children and the elderly (Franklin, 2007, Harrison et al., 2002). Using only the outdoor component of exposure is not sufficient as several potentially confounding variables are omitted from the exposure assessment process (Quackenboss et al., 1986). Indoor air quality, exposure and health are discussed by several authors (Colbeck and Nasir, 2010, Mitchell et al., 2007, Wallace, 1996, Morawska et al., 2013, Fernandes et al., 2009) providing a good overview of research focusing on indoor air quality and indoor environments since the 1980s.

There are a variety of primary sources of potentially harmful substances in indoor environments such as environmental tobacco smoke (ETS) cooking and heating with natural gas or solid fuels which are independent of the outdoor environment, but can modify a resident's exposure substantially since they are often within their immediate personal space are sources too (Ferro et al., 2004, Franklin, 2007, Freeman and Saenz de Tejada, 2002, Lai et al., 2006, Rodes et al., 1991). Diffusion of outdoor air into buildings contributes to a mixture of indoor and outdoor pollutants. Resulting indoor exposure levels depend on ventilation, air conditioning and on the indoor-outdoor temperature gradient (Branis, 2010, Lai et al., 2004).

2.2.3 Legislative framework for air quality

Adverse effects of PM on human health have been known for many decades, especially in relation to coal combustion and associated smog events, such as the "London Smog" in 1952 (Met Office UK, 2014). However with the decline of emissions from this source the problem was perceived to be solved (Williams, 2007). Since it has emerged though that adverse effects can occur at much lower levels than previously thought and thus the development of stringent legislation for the protection of human and environmental health is vital.

The legislative framework for ambient air quality in Scotland is governed by European law, in particular the EU Air Quality Framework Directive (Directive 2008/50/EC) (European Commission, 2012) which is currently under review to provide robust guidance based on the latest scientific findings (Fowler et al., 2013). With regard to human health effects at present the most problematic pollutants are PM. The group $PM_{2.5}$ or fine particles are of particular concern as they can be small enough to penetrate from the lung into the bloodstream (EEA, 2012).

The annual mean limit value set by the European Union for PM_{10} is 40 $\mu g/m^3$. The Scottish Government set a more stringent annual mean objective of 18 $\mu g/m^3$ to be achieved by 2010, however this was not met at eight monitoring sites in Scotland in 2012 (The Scottish Government, 2013a).

For $PM_{2.5}$ the EU limit value is 25 $\mu g/m^3$ (annual mean) which in 2012, has been met at all sites in Scotland. The EU has also set a target to reduce $PM_{2.5}$ in urban areas as a three-year average of concentrations, which for the UK will be either a 10% or 15% reduction, depending on the 2010 baseline, over the period 2010-2020 in relation to a 13 $\mu g/m^3$ threshold. The Scottish Government has also set a lower annual mean objective for $PM_{2.5}$ of 12 $\mu g/m^3$ which is to be met by 2020 and does apply for all measurement locations apart from kerbsides (Air Quality Expert Group, 2012). The Scottish objectives are based on the Air Quality Standards (Scotland) Regulations 2007 (SSI, 2007) (meanwhile replaced by (Scottish Statutory Instrument, 2010)) for the purpose of Local Air

Quality Management (currently under review (The Scottish Government, 2013b)) but are not in Regulations (Air Quality Expert Group, 2012).

There is no overall legislation regulating indoor air quality other than for specific locations or environments, for instance the smoking ban in public buildings. The WHO provides guidelines for a number of selected pollutants, however, these do not cover PM (WHO, 2010). In private spaces (e.g. residential homes or, as currently discussed in Scotland, in private cars to protect children from second hand smoke inhalation) a legislative approach would be difficult to implement and monitor. Here educational work aiming to instigate behavioural change applying citizen science approaches, such as that conducted by Semple et al. (2013) on SHS exposure in homes to support smoking cessation can raise people’s awareness of air quality in their private space and their own contribution, respectively actions to reduce this.

2.3 Cause-effect models

The assessment of exposure to air pollutant concentrations in space and time is not trivial as it is affected by many determinants and governed by complex relationships and interactions between environmental and human systems. For risk and health impact assessment (HIA), different conceptual models and frameworks have been developed reflecting these relationships. The idea behind such cause-effect relationship models is to execute impact pathway analyses which means structuring and simplifying working with the complex interactions between environmental and socio-economic factors (EEA, 2007).

2.3.1 The basic risk model

In the 1980s Ott (1985) describes human exposure as an emerging scientific concept with a focus on human beings as receptors of environmental pollution. Compared to earlier studies the research is not primarily concerned with sources or transport, but with exposure levels of the population. Exposure research is based on aggregated populations as well as on individual daily activity patterns. The distance between source and receptor also influences the level of exposure to a certain degree, hence the geographic location of sources is an important determinant of exposure (Elliott et al., 2000). Based on this new approach Ott (1985) presents a risk model with the following five key components to describe correlations and impacts:

1. **Emission** – the source and specification of the pollutant
2. **Transport and transformation** – transport of pollutants from source to humans as well as physical and chemical processes in the atmosphere between source and exposed person
3. **Exposure** – the actual exposure of humans to the pollutant
4. **Dose** – amount of pollutants received by those who are exposed
5. **Effect** – adverse health effect/health outcome resulting from the dose

Note that the model does not take account of the different susceptibility of individuals to the environmental stressor as discussed in section 2.4.3 as the pilot study was focusing on the concept of monitoring exposure across a variety of microenvironments, not intake or difference in dose-effects. This environmental risk model describes a chain of events, where each component constitutes the input of the following one. Hence, the lack of valid information on any component seriously impairs the ability to make an accurate assessment of public health risks. Additionally, the absence of data on human exposure has serious adverse implications for policies designed to protect human health (Ott, 1985, Branis, 2010). None of the model components exists independently of the others, although each can be studied independently. The focus of the research presented in this thesis is on the “exposure” component.

In his article *“Personal exposure measurements”* Branis (2010) extends the basic risk model that had been described 25 years earlier by a sixth component, namely:

> *“6. Policies – regulations designed and measures taken to minimize emissions, prevent exposure, or mitigate/treat health impacts on human health…”*
>
> *(Branis, 2010, p. 99).*

The integration of policy as a component transforms Ott’s basic risk model into a cycle because policies can quantitatively or qualitatively change

- the behaviour of sources (by means of financial or legal constraints),
- the characteristics of exposure (e.g. by means of prescribed use of protective equipment) and
- the dose level or the severity of the effect (by application of medical treatment)

Nonetheless, neither the transport and transformation processes nor the ambient concentration of pollutants can be reliably influenced as long as the source of pollution is not regulated.

2.3.2 The mDPSEEA model

“Policies” in Branis’ approach also correspond to “actions” in the modified Driving forces–Pressures–State–Exposure–Effect-Action (mDPSEEA) model

(Figure 2-1) which is described as a conceptual model for a strategic approach to the environment and health (Morris et al., 2006). It represents an impact pathway analysis, structuring and mapping the complex interactions between environmental and socio-economic factors. The “modified” in mDPSEEA addresses the explicit recognition of context, i.e. socio-economic, demographic and environmental factors, as modifiers for potential exposure and effect. Context can thus account for aspects affecting the susceptibility to and severity of an effect due to the same or similar exposure in different receptors.

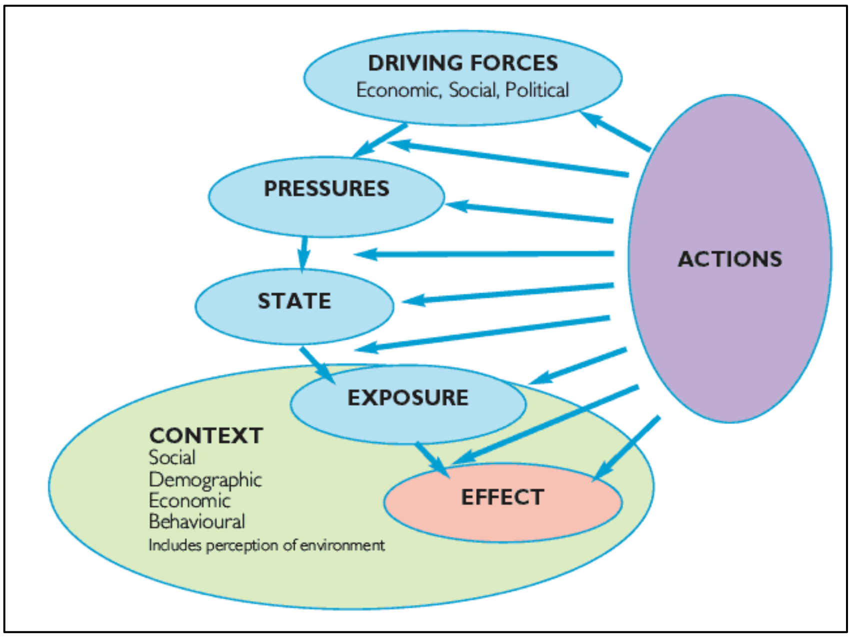


Figure 2-1 The modified DPSEEA (mDPSEEA) model (The Scottish Government, 2008)

Its linearity is similar to the basic risk model and represents a hierarchical chain of causation which allows mapping actions or interventions directly on to the chain. “Actions” can influence all other parts of the model in the same way as Branis’ “Policies” does.

2.3.3 The eDPSEEA model

Human health and wellbeing are intricately linked and dependent on the quality of the environment. In fact, human health depends on the functionality of ecosystems (Rayner and Lang, 2012) yet, interdisciplinary thinking and research have proven to be challenging (Phoenix et al., 2013). Based on the cause-effect models discussed above, a new conceptual model has been proposed, the ecosystems-enriched, in short “eDPSEEA” model which integrates the concept of ecosystem services (Lawton, 1998) and ecological public health to improve the assessment of environment and health (Reis et al., 2013). The model extends “State” of the mDPSEEA model (Figure 2-1) and allows reflecting upon different pathways from “Pressure” via ecosystem services to “Exposure”. “Actions” in eDPSEEA goes beyond just policies and also includes individual behaviour change and empowerment. Human health is not only affected by the actual pathogen but moreover by the whole environment the person is spending time in. This includes other humans and their activities, the state of the natural environment but also socio-economic factors. Two microenvironments might have the same concentration of a certain pollutant however other characteristics such as noise, the amount of green space and built-up area or access to services will also have both, positive and negative effects on human health and contribute to the whole exposure an individual will experience during their lifetime. This new model addresses the need to integrate human health, environment and societal factors to assess feedbacks and relations between these humans and their environment.

2.4 Human health effects from air pollution

Health is regarded as a fundamental human right by the World Health Organisation, WHO, which defines health as:

> *"A state of complete physical, mental and social well-being and not merely the absence of disease or infirmity."(WHO, 1946, p. 1)*.

Moreover it is a resource of everyday life and a positive concept which emphasises social and personal resources and physical capabilities (WHO, 1998).

2.4.1 Determinants of health

Health is strongly influenced by the social, cultural and physical environment in which we live as well as individual lifestyle. In other words, health has the environment of the respective person or population as its geographical context (Cromley and McLafferty, 2002). It is influenced by the so-called determinants of health - personal, social and environmental factors such as lifestyle, social status, education, access to health services and resources, state of the physical environment which contribute to and influence (i.e. determine) the status of health (WHO, 1998). Considerable impacts on health and well-being thus result e.g. from the state of the environment, access to any kind of resources, exposure to risks and the capacity to cope with these (Quigley et al., 2006).

Ecological public health is a concept dealing with emerging global environmental problems that have a substantial impact on human health. It highlights the fact that achieving health goes hand in hand with sustainable development and focuses on economic and environmental determinants of health (WHO, 1998). Human health and wellbeing, environment, societal and economic factors are interrelated in manifold and elaborate ways. A conceptual model like eDPSEEA (section 2.4.3) is designed to address these complex relations and ease the understanding and assessment process (Reis et al., 2013).

2.4.2 Health outcomes

A certain level of exposure to air pollution is inevitable, whether a person is indoors or outdoors. Adverse health effects from air pollution have been identified regarding the respiratory, cardiovascular, nervous and reproductive systems and can lead to cancer. The evidence for these health effects is robust, however there are still knowledge gaps regarding the mechanism by which air pollutants affect human health, which pollutants should be treated with priority and the role of pollutant mixtures (WHO, 2013b, EEA, 2013, EPA, 2012, WHO, 2012, WHO, 2013a). In 2011 the WHO stated that some 235 million people suffer from asthma, the most common chronic disease among children (European Comission, 2010). According to the Asthma UK charity (Asthma UK, 2013) there are currently 368,000 people in Scotland receiving treatment for asthma while Coronary Heart Disease (CHD) kills around 8,000 people in Scotland each year (ISD, 2012). CHD is not only influenced by air pollution (Langrish et al., 2012) but also by other risk factors such as smoking, poor diet and lack of physical activity (ISD, 2012).

Reducing air pollution directly reduces adverse health effects and increases general well-being and the quality of life and improves public health. Furthermore, the monetary benefits due to reduced primary and secondary health care expenditures and absenteeism can, according to Pascal et al.

(2013) and Watkiss et al. (2005) be substantial and outweigh emission control costs by far.

Health effects from exposure to PM are broad but predominantly affect the respiratory and cardiovascular system (WHO, 2006). Direct effects from PM exposure from diesel exhausts include irritation of the nose and eyes, changes in the lung function, airway inflammation, headache, fatigue and nausea, while chronic exposure may cause symptoms such as cough, production of sputum and decrease in lung function (Sydbom et al., 2001). Particulate matter emitted by diesel engines, has recently been classified as a Group 1 carcinogen to humans by the WHO’s International Agency for Research on Cancer (WHO, 2012). This category means in the first instance that there is sufficient evidence of carcinogenicity in humans through the respective agent.

This categorisation is based on evidence that exposure to diesel exhaust is associated with an increased risk for lung cancer. In a recent press release the WHO stated that outdoor air pollution generally is carcinogenic to humans (Group 1) and causes lung cancer (WHO, 2013a).

With respect to fine particles ($PM_{2.5}$), neither short-term nor long-term studies give evidence for a threshold below which there are no adverse health effects from $PM_{2.5}$ exposure. Therefore any reduction of $PM_{2.5}$ will improve public health (WHO, 2013b).

The size of particles determines how deep they can penetrate into the respiratory system, where they cause damage or irritation through chemical and physical interactions with lung tissue (EEA, 2013, European Comission, 2012). The composition of the particles plays an important role as well. Rohr and Wyzga (2012) reviewed literature about fine PM components and health effects showing that health impacts in epidemiological studies are most strongly related to carbon-containing PM components. Toxicological studies imply an association with carbonaceous components too, but also suggest that several elements such as aluminium, silicon, and nickel are closely related to adverse health outcomes.

2.4.3 Susceptibility to air pollution

Not everyone has the same susceptibility to air pollution. As McKone et al. (2008) argue, there are significant differences between exposure and intake, intake and dose and dose and effect for different pollutants. Every person is different and individuals have a different health status, different activity levels, metabolic and breathing rates for example. All these factors can modify the individual's susceptibility and induce variations in health impacts between individuals who are experiencing very similar exposure to pollutants. A recent paper by Peled (2011) reviews the population groups at high risk. These groups include the elderly, infants and children, pregnant women and newborns, people suffering from respiratory, cardiovascular and other diseases and allergies, as well as deprived populations.

2.5 Methods and concepts for personal exposure assessment

2.5.1 Microenvironments

Most exposure studies apply the concept of microenvironments (MEs) to connect exposure to a specific, homogenous "space". An individual's whereabouts largely determine their exposure so it is important to know what time a person spent and where. The term microenvironment (ME) has been defined as

> “...*a chunk of air space with homogenous pollutant concentration*” (Duan, 1982, p. 305).

People move through a variety of MEs during their daily routines. For analysis it is necessary to categorise them into thematic groups with similar characteristics such as home, work or transport. These groups are a crucial element of structured questionnaires and time-activity diaries (TADs), relating activities to a spatial unit.

People spend around 20% of their time at work, school or other locations away from their residence and approximately 4% of time is spent in transit (WHO, 2005b). This time-activity pattern is reflected in the most commonly used MEs in exposure studies (e.g. Jantunen et al., 1998, Lai et al., 2004, Wu et al., 2005a): indoor home, outdoor home, other indoor/outdoor (work, school) and transport. Nevertheless, air quality within any ME may differ substantially depending on the location of pollution sources or the activities happening within the ME at that point in time. The home environment, where a substantial amount of time is spent, is an important ME with highly variable pollution levels due to the variety of sources and activities happening there. For ME measurements of the home environment commonly, only one monitor representing indoor exposure is combined with measurements from a monitor outside a subject’s house. The pollutant concentrations measured in the MEs are usually combined with time-activity information providing an insight into people’s whereabouts and activities. Microenvironmental measurements can be integrated with or compared to personal monitoring data to gain more information and validate the ME measurements (Harrison et al., 2002, Lai et al., 2004, Monn et al., 1998). This provides a comparatively detailed exposure assessment on the individual level.

Rodes et al. (1991) stress that ME measurements intending to characterise the room and personal measurements can be quite different, especially for shorter durations.

In many studies data from routine air quality monitoring network sites are incorporated for comparison and to investigate relationships between concentrations observed in MEs and personal measurements to test if the fixed-site monitor can be considered representative of the area of interest (Gulliver and Briggs, 2004, Physick et al., 2011, Piechocki-Minguy et al., 2006, Wu et al., 2005a).

Often study designs focus on a single ME which is investigated in detail. The transport ME received particular attention in environmental exposure studies (Hertel et al., 2001b, Kaur et al., 2007, Knibbs et al., 2011, WHO, 2005a). A considerable amount of time, in general 1-1.5 hours per day (WHO, 2005a), is spent in the transport ME (including commuting to work and travelling for leisure).Road traffic, which includes vehicle exhaust, brake and tyre wear, and road abrasion is an important contributor to $PM_{2.5}$ concentrations too (Air Quality Consultants, 2012) which places a particular emphasis on this ME. As a result, some studies only focus on different aspects of the transport ME to gain detailed information about exposure (Thai et al., 2008, Kingham et al., 2013, Houston et al., 2013, Kaur et al., 2005). Single ME studies have the advantage of focussing in detail on specific situations within one ME. They do however lack the aspect of total exposure with respect to the exposome approach which is covered better in multi ME studies.

2.5.2 Report based approaches for time-activity data collection

An approximated or exact outline of the participants' movements and lifestyle to relate exposure to certain places, times, activities and habits are required depending on the study design and aim. This is becoming more and more important as we move away from a traditional low mobility society living in an area with stable living conditions to a much more mobile lifestyle (Rainham et al., 2010). Time-activity diaries and questionnaires are essential tools in personal exposure research as they are used to gain information about human behaviour and activities (Lioy, 2010). Both tools are relatively inexpensive and can be applied in manifold ways. In spite of these approaches being considered as a traditional tool for time-location studies, there are nevertheless concerns regarding recall bias and the reliability of TAD and questionnaires, hence it is necessary to test them before application (Freeman and Saenz de Tejada, 2002, Monn, 2001). These concerns are of a generic nature, but need to be taken into account. For instance confusing questions or questions framed in a way that leads the participants to answer in a particular direction can complicate their use or introduce bias. Difficulties can also arise through the language barrier for non-native speakers which can affect the reliability of results (Elgethun et al., 2007). Bias can also be a problem when people need the assistance of the researcher to complete the forms. To encourage participants to fill in the forms without getting bored, time requirements for the survey process need to be kept low (Crosbie, 2006, Freeman and Saenz de Tejada, 2002, Freeman et al., 1999). Brevity should also help to reduce recall bias and increase reliability (Klepeis et al., 2001).

The format is also crucial for the design and use of TADs and questionnaires. Using an open format gives the participants the opportunity to record activities and other information in their own words. Often a more structured format where activities and MEs are pre-grouped is preferential to ease the evaluation of data collected (Crosbie, 2006). TAD and questionnaires require literacy, a sense of time and a certain amount of commitment, thus it is useful to train the participants in using them (Elgethun et al., 2007, Freeman and Saenz de Tejada, 2002, Freeman et al., 1999). This is particularly the case for questionnaires presented on personal digital assistants (PDAs) and other electronic devices such as smart phones.

The concept of self-reported TADs can be laborious for the participant as a tight record has to be kept. The active cooperation of the participants in the monitoring process has to be fostered and interference with the participants' usual behaviour and lifestyle needs to be reduced to a minimum. The aim is to facilitate the process of "tracking" the person's movements, for example using Global Positioning System (GPS) signal receivers.

The classic questionnaires and TADs are in paper format. Recently however, small electronic devices such as smart phones or PDAs have been used for these purposes, with the data recording becoming more flexible in space and time (Ohmori et al., 2005) and minimising the burden on participants (Dons et al., 2011). The use of such electronic devices is becoming more common and widespread. Wu et al. (2005a) for instance provided PDAs to their participants to record activities every 15 minutes over two weeks. Dons et al. (2011) used a small handheld computer to record the participants' activities and whereabouts, using GPS receivers for coordinate tracking. Ohmori et al. (2005) developed a GPS-enabled mobile phone based activity diary survey system to collect data and compared this method with data collected by classical paper format surveys with the result that the time-lag in data entry as well as the time needed to fill in the TAD is reduced. Since the mobile phone used in this study included a GPS receiver the device also directly reads and logs the location. Shareck et al. (2013) developed an activity location questionnaire using a mobile phone with integrated GPS. Volunteers would display their GPS track with a specific online application; this prompted them to recall the locations they visited throughout the day. The authors conclude that this new questionnaire can be applied as alternative or complementary to the GPS receivers and traditional surveys used in health and place research.

Usually a questionnaire has to be filled in only once during the study period. Most TADs are accompanied with questionnaires to collect supporting information about the participants, their residence, workplace etc. Well structured and precise, online questionnaires which require a few mouse clicks only, are a viable and low-impact option. Electronic communication also enhances direct contact between researchers and participants. In order to get satisfactory response rates, Crosbie (2006) note that it appeared to be necessary to stay in contact with the person during the process of the study. Therefore face-to-face-interviews instead of - or in combination with - electronic questionnaires can be considered as a reliable method. Electronic devices and communication can also be used to remind participants to fill in questionnaires, for instance by contacting them via telephone, text message or email.

In summary, the use of TAD and questionnaires can be critical, as a fair amount of commitment is required from the participants to fill it in regularly and reliably. The information needed has to be chosen carefully, questions need to be concise, non-ambiguous, easy to understand and to answer. Hence a well structured, short format is best suited. Consequently, development is moving away from the classic paper format towards the use of portable electronic devices and internet based survey forms. As the reviewed literature implies, the overall goal is the facilitation and simplification of the survey process. The implementation of electronic internet-based TADs and questionnaires has advantages such as more flexibility for the participant, reducing time needed for data input (which is also prone to human error) and the availability of the data straight after completion (Wu et al., 2011). The data is also saved electronically.

2.5.3 GPS – objective time-activity data

In several recent studies GPS receivers have been used for tracking movements of people in space and time (e.g. Houston et al., 2011, Elgethun et al., 2003). This method provides “objective” time-activity data and can help reduce the intensity of keeping TADs (Wu et al., 2012). Nevertheless, special attention has to be paid when aiming to link data from GPS devices and TADs to determine a person’s location. Associating these two datasets is problematic as it requires the conversion of geographic coordinates from the GPS receiver into descriptions of real locations and activities. Time mismatches between the two datasets are an issue and the common way to match data is to process them manually which is time intensive (Mavoa et al., 2011, Wu et al., 2012). In addition not all study participants may be familiar with or keen on using electronic devices and the application of advanced communication technology may result in anxiety and misuse, potentially limiting the applicability of these methods (Bricka et al., 2012).

2.5.4 Monitoring air pollution

2.5.4.1 Fixed-site measurements

Traditionally data from fixed-site air quality monitoring networks has been used to assess human exposure to air pollutants. Such monitoring sites are usually part of a national network and tend to provide a large quantity of data for a wide range of pollutants, albeit for one point in space. Typically annual average concentration maps are created from monitoring data through the application of interpolation techniques, or statistical models. With this derived pollution surface, pollutant concentrations can be spatially related to a population or to a particularly susceptible subpopulation such as asthma patients, children or pregnant women (Harrison et al. 2002, Nethery et al., 2008a, Nethery et al., 2008b). Allocating a population to a monitoring site is most suitable for large population studies regarding outdoor air (Chow et al., 2002). Compared to real exposure scenarios such an aggregated approach is however unavoidably affected by assumptions implicit in the application of this indirect method (Cattaneo et al., 2010, Hertel et al., 2001a). Exposure assessment based on averaged measurements artificially diffuses pollution and operates on aggregated demographic data. This is naturally problematic for personal exposure assessment as it neither provides a representative measure of an individual’s personal exposure nor does it reflect real-world activity patterns (Rodes et al., 1991, Setton et al., 2011).

2.5.4.2 Personal monitoring

All human activities have a spatial and temporal component and can therefore be described as a path (Rainham et al., 2008, Thrift, 1977). Thus personal exposure assessment requires not only the pollutant concentrations in the environment through which a person is exposed but also information about the person's time-activity patterns (Sabel et al., 2009). The traditional tool to record such a path, as well as additional information, is TADs which have to be filled in by the participants (section 2.5.2).

The key factor to understand the causal chain of exposure related health impacts is to know when and where a person has been exposed to which concentration. The aim of studying the heterogeneity of individual exposure is to draw conclusions for larger populations. It has to be kept in mind, however, that complex links between exposure and health effects exist. Personal exposures of individuals in a population can be lower, equal or higher than those derived from ambient pollutant concentrations (McKone et al., 2008) for a specific location (e.g. the residence of an individual).

Recent developments in electronic communication and sensor design enable personal monitoring in many different ways and offer in particular opportunities for citizen science. Citizen science involves lay people in the process of collecting data, with a specific focus on the involvement of and engagement with non-scientists. It covers a wide range of potential applications and approaches (Irwin, 1995), including the collection of environmental information (for instance about air pollution levels, biodiversity, seasonal events or species occurrence) thus contributing to expanding knowledge about the topic of interest (Roy et al., 2012, Tweddle et al., 2012). The added value of citizen science methods is that a substantial amount of data can be collected across a large geographic area without having to resource field work experts. Citizen science also engages volunteers in environmental research, raises awareness about the environment and human (including the citizen scientists' individual) influences on it, thus educating and enabling, providing a basis for informed behavioural change (Roy et al., 2012).

In the case of monitoring personal exposure to air pollution, pollutant of interest may directly affect the health and well-being of the volunteers themselves. Furthermore, the spatio-temporal variability that needs to be captured by observations makes it a well-suited application for a citizen science approach. In addition to environmental data, contextual information about the volunteers themselves, their activities, habits and whereabouts can be collected and analysed. This may, however, introduce issues with confidentiality and identifiability of individuals, as discussed in Steinle et al. (2013). The ease of data collection methods, which need to be designed to minimise substantial disruptions to volunteers, is vital for citizen science approaches. This is even more relevant as, in the case of personal exposure to air pollution, the volunteer may well be study subject and observer at the same time, depending on the project design. Approaches that are specifically targeted to decrease the burden of entering data in TADs and questionnaires, as well as the form factor, weight and operation of the monitoring equipment, are of particular interest.

One example of citizen science engagement in an air pollution monitoring pilot study is the *iSPEX* project in the Netherlands which made use of smart phones with their inbuilt geolocation technologies and a simple optical device to measure aerosol concentrations in the atmosphere (ISPEX, 2013). Another study, making use of the large number of smart phone users worldwide, aimed to collect geolocation and physical activity data and was conducted in Spain (de Nazelle et al., 2013). The data collected was processed and linked with street-scale maps of nitrogen dioxide (NO_2) concentrations to estimate population level exposure.

2.5.4.3 Pollution monitors for personal monitoring

An essential part of all exposure studies is the development and application of suitable monitors for the respective pollutant concentrations. The basis for the development of specific personal exposure, time-budget and health studies which developed since the late 1970s (Ott, 1982) were occupational/industrial studies and the portable and wearable monitors developed (e.g. Sherwood and Greenhalgh, 1960). These monitors were not yet capable of sampling, storing and manipulating data. Wallace and Ott (1982) describe in their paper *"Personal monitors – a State-Of-The-Art survey"* the issue of manually writing down large quantities of data and the development of a personal CO monitor with an internal data-logging system to successfully generate personal exposure data. Meanwhile a wide range of portable, personal monitors as well as stationary monitors either for individual pollutants or multi-pollutant concentrations have been developed and applied in research (section 2.5.4.5).

In general, personal monitors should be portable and not interfere with the person's usual behaviour and habits throughout the day. They should be lightweight and battery operated (or passive) as well as robust, user friendly and flexible (Branis, 2010; Lippmann and Lioy, 1985; Monn, 2001; Nieuwenhuijsen, 2000; Wallace and Ott, 1982). Many devices are now capable of measuring air pollutant concentrations at resolutions ranging from seconds to minutes attaining acute short-term or peak exposures to be measured reliably in time (Adams et al., 2009). This is not viable with personal monitors collecting time-integrated concentrations, especially passive samplers, which tend to miss peak exposures but provide chronic exposure information (Lawless et al., 2012). In addition, passive samplers are known to lack accuracy. Their advantage, however, is that they are comparatively inexpensive, do not require power and can be worn on outer clothing (Branis, 2010, Monn, 2001). Despite substantial achievements and developments in sensor design, many air pollution monitors are still not sufficiently sensitive regarding their capacity to obtain highly selective multi-pollutant measurements outside of laboratories (Committee on Human and Environmental Exposure Science in the 21st Century et al., 2012).

2.5.4.4 Purpose and challenges of personal monitoring

The traditional approach for assessing personal exposure to air pollutants is depicted in Figure 2-2. Personal exposure is derived from a person moving within the changing concentration field. The synchronised measurement of air pollution and the individual's movement is implemented either with one integrated device or several sensors which are running parallel, with a trend towards the use of GPS-enabled devices (section 2.5.5). Data from personal monitoring studies is also used as input to and for the validation of exposure models (e.g. Dons et al., 2014, Gerharz et al., 2009, Gulliver, 2005, Hertel et al., 2001b, Hertel et al., 2001a).

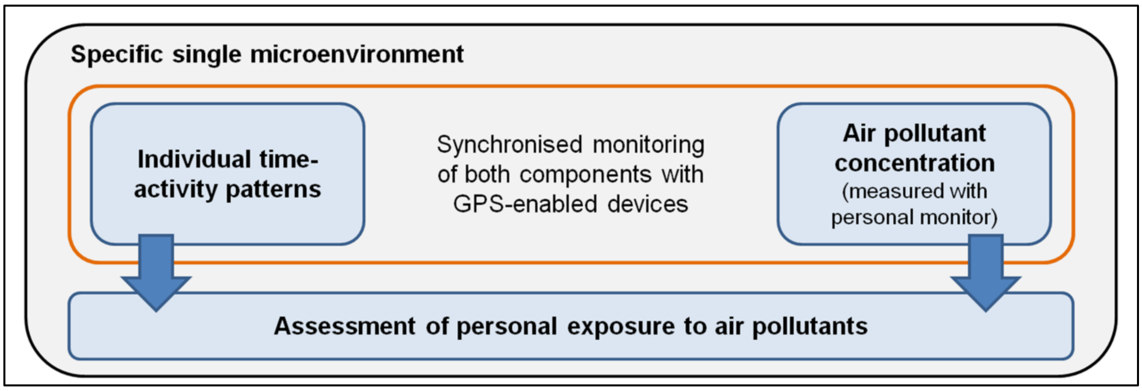


Figure 2-2 Conceptual model illustrating the traditional approach for the assessment of personal exposure to air pollution (Steinle et al., 2013).

Personal monitoring studies which are cost-, time- and labour-intensive are often conducted as non-representative pilot studies (Dons et al., 2014). Derived exposure estimates form part of the bigger picture with the aim to eventually contribute to or improve Health Impact Assessment (HIA) and policy advice (Quigley et al., 2006). According to Flachsbart (2007), the direct approach provides the most accurate exposure estimates because the actual exposure of people during their activities is surveyed, rather than calculations from static concentration data from fixed-site network monitors. Lawless et al. (2012) stress that this is only the way though if exposure misclassification is minimised and confounders that cause misinterpretation of the data are reduced, both through the implementation of measures and strict compliance about how to wear the monitors. The authors define “wearing compliance” as how well a participant is wearing the personal monitoring in accordance with the sampling protocol.

The issue of behavioural changes of the participants when wearing a monitor is avoided when researchers or volunteers follow scripted activities in certain locations which are representative for high exposure situations (Lioy, 2010). Such a scripted study design might also improve wearing compliance. In single-participant studies where the only participant is usually the researcher (e.g. Cole-Hunter et al., 2012; Greaves et al., 2008) compliance and behavioural changes are avoided.

2.5.4.5 Example studies

Studies using different methods, approaches and monitors to assess personal exposure to a variety of air pollutants are described below. The studies reflect the possibilities available to study personal exposure to a variety of air pollutants. Each study with its individual set of tools and methods provides a part of the total exposure picture. Based on a review of this literature, a pilot study is developed with the aim to bring together those individual parts into a wider picture of the total exposure as a snapshot of a persons' exposome.

Passive samplers

Monn et al. (1998) used passive nitrogen dioxide (NO_2) samplers worn on outer clothing within the chest-head region and were exposed for one week each. Personal measurements were only carried out in the first week of the month-long monitoring period. The reason given for this is that participants need to be much disciplined in order to carry out the personal sampling and it is laborious on the participants to wear the equipment on a daily basis. Additionally stationary monitors indoors (in the bedroom) and outdoors (in close proximity to the home) measured ambient concentrations for these respective MEs (home indoors, home outdoors). Information on the characteristics of the accommodation, occupational exposure and personal habits was available but no information was given on the method for data collection for all participants. Since NO_2 concentrations were measured averaged over one week, no time–activity information was collected. In this study a strong relationship between personal exposure and indoor concentration levels was observed.

Piechocki-Minguy et al. (2006) developed a new passive sampler to measure personal exposure to NO_2 in four MEs. The sampler consisted of a porous cartridge which is fitted in a protective cylindrical box. The sampler was deployed in two campaigns, with volunteers providing information on home and work location, home characteristics and their lifestyle in a questionnaire. Personal exposure was measured over two periods of 24 hours, once on a weekday, once on the weekend. Each person received a sampler including four porous cartridges. Each cartridge was for one of the following MEs – home, other indoor, transport, outdoors – and had to be changed every time the person moved to a different ME. The respective times of the changeover had to be recorded in a TAD. Additionally, each home NO_2 concentration value was taken from a nearby fixed-site monitor considered representative of the neighbourhood in which the home was located, to evaluate if personal exposure could be predicted based on fixed-site concentration data. Correlations were weak which led the authors to suggest that fixed-site monitors are poor predictors for personal exposure to NO_2 at home. In this study, the highest levels of NO_2 were found in the transport ME, followed by outdoors, other indoor and the home.

Physick et al. (2011) measured NO_2 with passive samplers attached to the outer clothing at chest height and compared the measured data with results based on modelling methods. Data was collected over four two-day periods. To allow for precision checking, two sets of two passive samplers were worn at all times. One set was measured NO_2 over the 48 hours period. The other set measured NO_2 in certain MEs (home, work, transit between work and home, other). Volunteers kept TADs with times of arrival/departure in and from different MEs, details of cooking and heating appliances, usage times and also recorded information about open doors and windows. Additionally, samplers were placed outside the volunteer’s homes and workplaces and only exposed when the person was present in the respective environment. Measurements were compared to hourly observations from the nearest fixed monitoring station. The highest exposures and variability were measured when people were in transit, with the highest value measured by a cyclist (42ppb).

Active samplers

Kaur et al. (2005) measured $PM_{2.5}$, ultrafine particle counts (UPC) and carbon monoxide (CO) concentrations with personal monitors at a street canyon intersection in Central London. The measurements were conducted by four volunteers who collected samples three times a day, along two different routes by walking, cycling, bus, car or taxi. For measuring $PM_{2.5}$, a high-flow personal sampler connected to a pump which was carried in a rucksack sampled airborne particles onto a filter. The sampling head was worn on the lapel or on the rucksack strap. Start and end time of the measuring period were recorded with a dictaphone using synchronised stopwatches. Particle counters measured UPC with a 1 second resolution. The UFP counters were either handheld at waist height of an adult, placed on a seat of the vehicle used for travelling or attached to the bicycle crossbar with the inlet on the handlebar, explicitly representing the breathing zone of children. Combined CO and temperature monitors measured with a 10 second resolution. These monitors were also strapped to the lapel or rucksack strap. In addition, $PM_{2.5}$ and CO hourly averages from two AURN network sites (urban background and kerbside) were compared to personal measurements and found to be relatively poor predictors of the exposure that an individual experiences. Findings indicated that the mode of transport as well as route and timing had an effect on the exposure to the pollutants.

A similar approach to Kaur et al. (2005) was applied by Cattaneo et al. (2010) for measuring personal exposure in Milan. Active monitors measuring PNCs for ultrafine particles (UFP), fine particles and coarse particles with a 30-second resolution were strapped to the participant's thorax. The samplers for measuring the gaseous pollutants CO (passive sampler measuring continuously) and O_3 (1-minute resolution) were placed within the breathing zone. Monitoring took place on five consecutive working days. The participants followed a standardised route including major and minor streets, an office ME and a park, and used different modes of transport. Instead of tracking time explicitly, a certain amount of time was allocated and prescribed for the different elements and activities along the route. Parallel to these personal measurements, the pollutants were also sampled as “individual exposure” within 3 m vicinity of the subject. This was done with the so-called mobile monitoring unit, a trolley containing a variety of monitors and weighing about 25kg. Results showed that there are significant differences between individual and personal exposure to coarse particle counts and CO. PNCs of fine and ultrafine particles measured in the breathing zone as well as in the vicinity of the subject, however, do not show significant differences which the authors explain by the low space variability sand lower velocity compared to PM10.

> *“These findings suggest that future experimental studies dealing with human exposure to PM_{10} or its finer fractions could be carried out measuring the individual exposure without losing accuracy with respect to breathing zone (personal) measurements.”* (Cattaneo et al., 2010, p. 377).

Gulliver and Briggs (2004) measured different size fractions of PM in the transport ME by applying wearable monitors which were carried on the chest while walking or placed on the front passenger seat when sitting in the car. Two prescribed routes were used for monitoring during peak traffic times. Comparisons were made between the transport modes by particle size fraction and vice versa as well as between the transport ME and concentrations from a nearby fixed monitoring site. Results show that, on average, observed PM_{10}

concentrations were higher during journeys made by car than walking. With increasing distance to the location of the fixed monitoring site, a declining representativeness of the concentrations observed at that location was noted compared to the direct measurement of journey-time exposure.

Wu et al. (2005a) measured PM exposure of children with direct reading personal nephelometers (light-scattering devices for measuring suspended particulates, (see Wu et al., 2005b). Concentrations inside and outside the homes of study participants were measured with stationary monitors and concentration data from a nearby fixed monitoring site were used for comparison. A PDA was applied as an electronic TAD with a 15 minute resolution. Pollutant concentrations were measured once a minute over a period of two weeks. During the study, the subjects were visited daily to collect data, as well as to check and calibrate the instruments. Personal concentrations observed were higher than the concentrations measured at the centrally located fixed monitoring site as well as the stationary monitors outside and inside the home. The children received a large part of their total exposure in the school ME despite the fact that they spent more time in other MEs.

Most of the studies discussed above applied active monitoring devices often comparing them to nearby routine fixed-site monitors or stationary monitors in a specific local ME, with the concordant result that neither fixed-site nor ME monitors can be regarded representative for personal exposure. This highlights the need for personal monitoring studies, but also identifies areas for further development and provides a basis for improvements in study design and sensor technology. Most of the studies presented above also focus on the transport and urban MEs, which have a high density of both population and pollution sources. Few studies of the presented include different MEs where in some cases highest concentrations of the respective pollutants have been measured in the transport ME (Physick et al., 2011, Piechocki-Minguy et al., 2006). Other studies show strong correlations between personal exposures and indoor MEs (Monn et al., 1998) or highlight that a large part of total exposure is received in one specific indoor ME only (Wu et al., 2005a).

All the studies described above show the variety of exposure to air pollution in different MEs and for different situations. To account for total of exposure over a lifetime towards the exposome concept, it is necessary to collate these components of exposure by assessing personal exposure in the full heterogeneity of MEs. For future personal exposure research it is thus strongly recommended to include all MEs visited throughout a personal daily routine.

2.5.5 GPS enabled personal monitoring

2.5.5.1 GPS technology and receivers

The Global Positioning System (GPS) offers a freely accessible technology to determine real-time geolocation of individuals for use in personal exposure research. GPS receivers log location and time simultaneously and thus enhance the recording of time-activity patterns. As Rainham et al. (2008) state, wearable GPS receivers can be used to derive a more complete picture of the different places that influence each individuals' well-being.

The worldwide navigation and positioning system technology GPS is based on satellite positioning and is freely accessible. A very basic explanation of GPS technology is given based on U.S. EPA (2003). GPS operates by measuring the time delay of radio signals transmitted from approximately 24 satellites orbiting the earth. The position of these satellites can be accurately determined as they are placed in precise orbits. Each satellite carries atomic clocks with nanosecond accuracy to time the signals sent to earth. The constellation of the satellites provides four to eight signals that can be received simultaneously from any point on earth at all times. There are also five ground control segments which serve as uplinks to the satellites and make adjustments if required to orbits and clocks. To determine the location of the GPS receiver on earth, the time signals sent from four or more satellites are compared to the time it reached the GPS receiver on earth. Precision of the coordinates reported by the GPS receiver varies based on the receiver design as well as on the signal strength and potential signal blockage. Elgethun et al. (2003), for instance, used GPS units integrated in clothing that had spatial resolution root mean square errors between 3 to 3.4 m outdoors and 5.7 to 5.9 m inside a wood-frame house.

Questionnaires, TADs and interviews are the traditional methods used to collect time-activity data in exposure studies. In several small, non-representative studies, GPS technology and receivers have been successfully applied in conjunction with these traditional methods, with the aim to facilitate the observation/monitoring of human time-activity patterns to a certain degree (section 2.5.2). GPS is not a standalone tool as it only provides information on location and time and not about the pollutant of interest. However, using such active locating devices in combination with active pollutant sensors allows measuring and consolidating concentration, location and time directly without requiring the participant’s intervention. As Lioy (2010) discusses, a well designed integration of GPS with personal pollution monitors, ME measurements as well as activity and behaviour information can enhance exposure research by identifying specific personal exposure situations and profiles towards changing environmental influences, which differ from other individuals as well as the population average.

GPS based approaches have flexibility as advantage over static approaches where the person’s residence or a static area functions as surrogate for the person’s time-activity pattern. By operating at the individual rather than the aggregated level, the application of GPS for collecting personal time-location data while moving in the changing concentration field reduces the so-called modifiable area unit problem (MAUP) (Openshaw, 1984). The MAUP describes the fact that using arbitrary boundaries, for instance administrative areas such as postcode areas or Council Areas, to aggregate cases may introduce bias as the results can be sensitive to changes in the size and shape of boundaries (Järup, 2004, Flowerdew et al., 2008, Sabel et al., 2013).

GPS technology enables the collection of large spatial datasets, but these are not immediately usable for analysis. The raw GPS data requires further processing to extract locations and paths and become meaningful for analysis (Thierry et al., 2013). GPS data also serves as input for exposure models which are based on individual movement patterns or routes (Davies and Whyatt, 2009, Gerharz et al., 2009).

Requirements for GPS receivers in exposure or any other human mobility tracking studies are manifold (Rainham et al., 2008). A small and lightweight design is required. The receiver needs to be able to log and store a sufficient amount of data at reasonable temporal resolution and to transmit it to a receiver when a wired or wireless connection can be established. A long battery run-time is required and the receiver needs to operate passively so that the person who is tracked does not have to interact during the tracking. A fast response to the first–fix and after the signal was lost is required too. The resolution needs to be as accurate as possible and also precise in built-up environments.

2.5.5.2 Example studies

A series of non-representative personal exposure studies described below made use of GPS technology for monitoring people's movement in the changing air pollution field. Like the examples in section 2.5.4.5 the studies are introduced to demonstrate the possibilities and achievements of these studies for personal exposure research whereby every study contributes individual parts to the total assessment of exposure.

Zwack et al. (2011) investigated the contribution of local traffic to PM concentrations in street canyons of Manhattan. GPS receivers tracked the participant's movements along designated walking routes at specific times. Temperature, relative humidity and 1-minute averaged pollutant levels of UFP and $PM_{2.5}$ were measured with equipment carried in a backpack. Measurements were also taken in Central Park to investigate the effects of distance from the street canyons on ambient concentrations observed. Additional 1-minute temperature and relative humidity measurements from a stationary meteorological station on a rooftop in the street canyon were recorded. Volunteers carrying the backpack had to keep a log-sheet recording traffic flow characteristics. One implication of the study was that stop-and-go traffic in these busy street canyons increased UFP and $PM_{2.5}$ concentrations by approximately 10% compared to low traffic levels.

A similar approach was used by Boogaard et al. (2009) who measured PNC, $PM_{2.5}$ and noise while cycling and driving in a car. Sampling took place along 12 predefined routes. Since the shortest way was chosen for each of the transport modes, they did not cover the same route. The pollutant monitors were placed in a backpack (cycling) and behind the driver seat (in-vehicle) with the inlets near the breathing zone. Several potential predictor variables such as GPS coordinates, road type, traffic intensity as well as passing cars and mopeds were collected to explain the variability in exposure during cycling. For in-vehicle journeys only exact time and GPS coordinates were recorded. In this study PNC and $PM_{2.5}$ exposure of car drivers was slightly higher than exposure of cyclists.

Portable personal monitoring devices are a fast evolving field and also incorporate everyday devices such as mobile phones. Kingham et al. (2013) for instance used mobile phones for which a customised logging application was developed to record GPS coordinates, sound and photos. In their study in Christchurch simultaneous measurements of PM_{10}, $PM_{2.5}$, PM_1, UFP and CO were made during the morning and evening commute by car, bus and bicycle on pre-defined routes. GPS coordinates were plotted on maps with colour coding for the different concentration levels. Relative low population density and traffic congestion in Christchurch compared to other cities, where similar studies took place, resulted in commuters being exposed to lower levels of CO. However, levels of PM_1 and UFP show similar levels to those recorded by other studies elsewhere. Results showed that people commuting by car are exposed to the highest average levels of CO and UFP.

GPS receivers have also been applied in combination with portable aerosol monitors in a study in Sydney (Greaves et al., 2008) with the aim to investigate pedestrian exposure to $PM_{2.5}$ in busy traffic MEs. Meteorological data from a nearby routine measurement site and traffic volume were collected or computed for the respective monitoring periods morning, lunchtime and evening. Personal concentrations were compared to levels measured at a nearby fixed monitoring site. Data was collected in two directions on the prescribed study route. A voice recorder was used to record events, or specific circumstances which potentially could increase the $PM_{2.5}$ concentrations. Average concentrations were higher in the morning than at lunchtime or in the evening. Results from the study route were 40% higher than concentrations from the routine monitoring station. Keeping in mind the difference in temporal resolution, the authors report a reasonable correlation between these two measurements ($r = 0.6$).

Thai et al. (2008) investigated exposure to a variety of PM size classes along designated bicycle routes during the morning rush hour, applying particle counters and GPS receivers on a specifically instrumented bicycle. GPS coordinates were logged at a 10-second resolution and synchronised with PM measurement from a fixed monitoring site in the area. Results show that PM_{10} varies in concentration along the route depending on land use. Higher concentrations were measured along construction sites and where road dust is resuspended. UFP were highest in areas with high traffic volumes while PM_3 showed a homogeneous concentration for the full length of route.

A similar set up was used by Cole-Hunter et al. (2012) who investigated exposure to inhaled PNC on bicycle commutes in Brisbane. A specifically designed measurement bicycle was built and cycled along different commuter routes leading into central Brisbane. Some routes were closer, some further away from the actual traffic during the morning rush hour. PNC and particle diameter of UFP were measured, additionally UFP concentration was measured at a monitoring station on top of a building. A small and portable GPS unit with a 4-second resolution was applied. With UFP being recorded at 16-second resolution, only the fourth GPS log was allocated to each UFP log. The heart rate was recorded during commutes, as well as meteorological data, recorded with a lightweight monitor, and compared to data from the Australian Bureau of Meteorology for analysis. Notes were taken post-commute about specific circumstances, anomalies and weather observations. Results indicate that cycling along a route further away from traffic reduces the exposure to PNC levels significant (p= 0.012 for total mean PNCs). The inhaled particle count is mainly determined by the actual ambient PNC rather than the cyclist's physical effort.

In a study from Belgium (Dons et al., 2011) eight couples were observed, one individual being a homemaker, the other partner being in full-time employment, thus both having very different time-activity patterns. The aim was to investigate the impact of these time-activity differences on personal exposure to black carbon (BC) over a week. A portable monitor measuring BC in 5-minute intervals was used and could be carried in the participant's own backpack or handbag with the inlet exposed to the air. GPS coordinates were recorded on a PDA that also served as a device to record the TAD. Questionnaires were handed out at the beginning of the monitoring period. A stationary monitor was installed outside the house to provide simultaneous observations for the outdoor ME near the home. Results show that differences between the households are larger than between the individuals of one household, highlighting the challenges of up-scaling from individual to population exposure. In addition findings emphasised the relevance of studying everyday exposure over several days:

> *"Differences in exposure between members of a family originate from differences between their time-activity pattern and the corresponding locations visited."* (Dons et al., 2011, p. 3597).

In a similar study to Dons et al. (2011), Buonanno et al. (2014), assessed exposure to and dose of UFP for a group of 24 couples, the men being full-time workers and the women being homemakers. Over 48 hours ultrafine particle counts were measured every 16 seconds with the monitor worn on the belt or placed in the bedroom. The participants also had to provide time-activity information. Results show that women are exposed to higher average exposures of PNCs. The authors relate this to cooking activities. In addition, the authors highlight that

> *"The difference between the personal exposure of a full-time worker versus a homemaker of the same household amounts to more than 50% with the homeworker being more exposed with respect to the full-time worker."*
> (Buonanno et al., 2014,.p. 906).

This is in line with the findings of Dons et al. (2011) that individual time-activity patterns drive personal exposure.

Gerharz et al. (2009) collected GPS data and information from TADs and questionnaires which have been combined with $PM_{2.5}$ concentrations from existing data sources and models to derive a novel indoor and outdoor model. The resulting daily average exposures of the profiles derived show a strong influence of individual behaviour. In a further step the model has been deployed as a web service allowing lay people to assess their own exposure risk depending on their activity profile (Gerharz et al., 2013). For this step time-activity data has been enriched by video records (Broich et al., 2012). Uncertainties in results are discussed in Gerharz et al. (2013).

2.5.5.3 Performance of TAD and GPS for time-activity data collection

Differences in survey reported and GPS recorded trips for a 24 hour period were investigated by Bricka et al. (2012) using data from the 2009 Indianapolis regional household travel survey. In their conclusions the authors recommend the use of both a GPS receiver and traditional time-activity survey methods to complement each other. However, the authors also highlight the fact that not all individuals are "*...technology savvy...*" (Bricka et al., 2012, p. 87) therefore the use of traditional survey methods is recommended as a preferred option for some population groups.

Houston et al. (2011) studied the significance of underreported trips and locations in Los Angeles when using recall-based TAD and questionnaires for exposure assessment. GPS tracking was carried out for 10 to 14 days, with time-activity logs being completed for three weekdays. Participants also completed a general survey, received training and a follow-up interview was conducted. The data resulting from this study provided insight in the difference introduced by the different methods and improved the amount and quality of time-location data in comparison to collecting data solely through TADs.

2.5.5.4 Potential and limitations of GPS technology for personal monitoring

The feasibility of using GPS receivers for tracking individuals in their everyday environments has also been studied by Adams et al. (2009), Elgethun et al.

(2007, 2003), Phillips et al. (2001) and Rainham et al. (2008) who were assessing methodology, potential and limitations when using GPS receivers for exposure assessment, respectively for the validation of TADs. The main challenge when using GPS devices is that the signal from the satellites can often not be received in indoor environments or near certain materials, such as steel–reinforced constructions, body panels and other electrically conductive material (Nuckols et al., 2004, Phillips et al., 2001).

Adams et al. (2009), being aware of GPS receiver issues, developed a high resolution, space and time-referenced method for personal sampling of PM, including a GPS receiver and a temperature sensor. All devices logged data at 10-second intervals and were carried in a backpack. A key issue was the GPS signal quality, therefore the positioning capability of the commercial GPS receiver was evaluated beforehand against U.S. National Geodetic Survey benchmarks. Six indoor reference positions were set up to improve signal quality. By utilising to temperature differences and comparing against known ambient conditions, it could be determined if the person was in- or outdoors. Data recorded from all three monitors were transcribed and stored in a database by matching the associated timestamp from each instrument. The GPS receiver used in this study performed with better accuracy than initially expected. No signal loss was detected outdoors or in a wood-framed single story residential structure. In a concrete building, however, the signal was lost in windowless rooms, yet it could be regained nearly instantaneously when moving to a room with windows or when leaving the building. The authors concluded that the most up-to-date customer grade handheld GPS receivers have a much better capability to receive signal indoors, compared to previous versions which is likely due to the use of high-sensitivity GPS microcontrollers.

The authors however also mention that substantial further sensitivity gains may not be available in the near future. Thus, alternative and supplementary technologies such as a GPS signal repeater or radio-frequency-identification (RFID) for improving positioning indoors should be considered. Although the temperature sensor worked well as an indicator for distinguishing between indoor/outdoor, alternatives to consider could be light sensors or the strength of the GPS signal received.

As alternatives to GPS technology, other studies suggest ultrasound (Allen-Piccolo et al., 2009) or small cameras which not only help locate the environment in which the person has been, but also record behaviour objectively (Broich et al., 2012),.

There are certain factors which limit accuracy and operability of GPS receivers such as (overseas) military control over GPS satellites, although new commercial GPS satellite networks are launched which will not be subject to military control. However, as Rainham et al. (2008) point out, these factors are unavoidable or lie beyond the researcher’s control. Nevertheless, most of these influences are usually measurable and well known and can thus be taken into account when studies are designed. In the future we might also consider clothes with in-built sensors (Van Laerhoven et al., 2002) as a logical extension of the ideas presented by Elgethun et al. (2003).

In summary, the studies discussed above are covering three main areas. One area concerns the investigation of transport and urban MEs. Several studies investigate the compatibility of GPS data and TAD data to track time-activity patterns. The third research area covers the improvement of sensor technology for exposure research. The focus on the transport ME in these studies does, similar to the non-GPS based approaches, not sufficiently address everyday exposure across all MEs visited. Few studies only (e.g. Gerharz et al., 2009, Dons et al., 2011, Buonanno et al., 2014) focus on individual behaviour and the influence on personal exposure, covering several environments a person spends time in during a day. Ongoing developments in monitor design improve the feasibility for personal exposure studies. However, study designs have to evolve to adequately utilise the potential of flexible monitors with high spatiotemporal resolution, data storage and communication capability.

2.6 Discussion & Conclusions

There is no gold standard or best practice for monitoring air pollution with personal monitors. As it stands, the variety of devices and study designs is vast, reflecting the current fast development in this research area and the many possibilities offered through recent technological improvements. Personal monitors provide the most accurate data on actual personal exposure as they allow the measurement of pollutant concentrations as close as possible to a person's breathing zone. Comparative measurements between personal monitors, fixed-site monitors and stationary ME monitors indicate substantial differences in concentration and thus establish a preference for the use of personal monitoring techniques to collect individual exposure information reliably.

2.6.1 Personal exposure monitoring – the bigger picture

Growing evidence of adverse health effects from exposure to air pollutants requires progressing and improving air pollution monitoring techniques, as well as risk, exposure and health impact assessment tools. Personal monitoring studies are one vital building block to advance personal exposure research as a basis for public health policy, interventions and measures. Exposure research is the basis for identifying sources and exposure pathways in people’s everyday life which will help to prevent and to reduce the risk of exposure. However, it is clear that major reductions of air pollutant emissions have already been achieved and further reduction will be more challenging and with slow progression.

Personal exposure studies contribute to the knowledge about exposure pathways and risks and at the same time also have the potential to educate and increase people’s awareness of environmental health issues (Roy et al., 2012). Awareness of how environment, human health and quality of life are interlinked can be increased, especially if the devices and tools can be applied for citizen science studies.

2.6.2 Burden of volunteers

Personal monitoring studies rely on volunteers carrying the monitoring equipment and taking actions to record and report activities. Interference of the personal monitoring device with the person’s everyday habits should thus be kept to a minimum, especially if lay people are carrying the devices in non-scripted studies or citizen science projects. Regardless of how miniature and non-intrusive monitoring equipment and TADs become, their application will require a substantial commitment from study participants. Being part of such a study therefore needs to be rewarding and informative for the participant, which could be achieved by providing feedback based on the collected data about the person’s own exposure. The data has to be made accessible to the volunteers and presented in an easy to understand way, as for instance demonstrated by Semple et al. (2013).

2.6.3 Expanding personal exposure to everyday environments

Based on the literature and example studies discussed in this chapter the conclusion is that the conventional study designs applied are sufficient to assess the exposure situation in a specific single ME or for prescribed routes primarily. Only a few studies expanded the assessment of exposure to a variety of MEs during everyday situations. In order to gain information about exposure in all MEs a person moves in during a specified time period with the aim to contribute knowledge to exposome research, the simulated approach has to be taken a step further. Studies now need to be expanded to include the observation of personal exposure in everyday environments. Thus, in a recent publication (Steinle et al., 2013) a novel conceptual model has been proposed (Figure 2-3), reflecting the potential of the new developments in personal monitoring discussed in section 2.6 and taking account of cause-effect models and the way they integrate context (section 2.3). This new model incorporates latest technological and methodological developments and goes beyond the traditional approaches as outlined in Figure 2-2. It integrates the full heterogeneity of MEs for personal exposure assessment, including context, by establishing a methodology to conduct personal monitoring without gaps. In order to up-scale from the individual to a population wide assessment further research is required and needs to include models to connect the data collected by personal monitoring to behaviours and environmental factors of larger populations. By including exposure as people experience it through their daily/every day routine, a more realistic assessment of total exposure can be achieved. Taking into account context, which includes economic, social, environmental determinants and lifestyle factors can, in particular in connection with TADs and questionnaires, provide additional socio-economic, demographic and environmental information that may affect health effects based on potential exposure. The overall aim of personal exposure studies is to gain knowledge about the individual exposure and context, as a basis to ultimately scale up to population wide exposure estimates, for instance by modelling. This is a core requirement for improving population health.

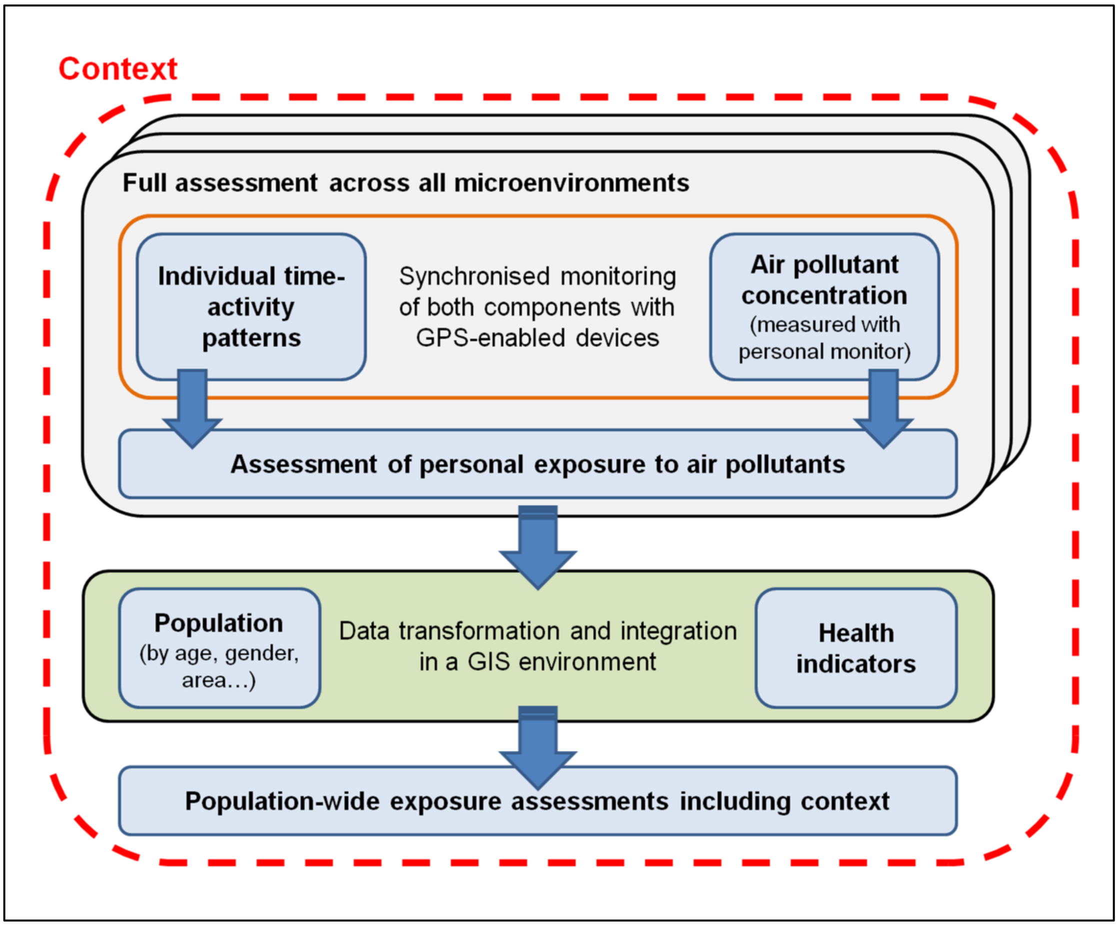


Figure 2-3 Novel conceptual model for the assessment of individual and population-wide exposure to air pollution including effects (health factors) and context (Steinle et al., 2013).

As mentioned earlier there is no gold standard method in place for personal exposure research. This conceptual model however can support research in providing the framework for proposing research questions, develop and implement future exposure studies. In the same way as the mDPSEEA and eDPSEAA models (section 2.3) this is a conceptual model designed as a tool to think with (McIntosh et al., 2007).

It is of vital importance that new technologies and monitoring solutions which are now mature enough will be applied in future studies. At the same time it is time to move away from the single ME approach and apply the devices and tools available in a greater context, i.e. in people's everyday life to take account of the heterogeneity of MEs and exposures. This is of particular importance if the personal exposure data is used as input for exposure models.

Monitoring air pollution and tracking human activity patterns has progressed considerably in recent years. Improvements are required with regard to the incorporation of an expanded environment, improvements in sensor design and monitoring methods to allow for a bigger variety of pollutants to be monitored indoors and outdoors. With respect to GPS-enabled monitoring approaches it is time to design integrated devices fit for purpose, logging location, time and environmental variables simultaneously. This can substantially improve the accuracy of the data collection and subsequent analysis, especially for citizen science application and when dealing with large amounts of data.

2.6.4 Privacy or confidentiality concerns

Environmental monitoring data is required to generate robust evidence and builds the basis for the development of effective environmental and public health policies. It is done by national bodies and research institutions but also partly by volunteers (who may be called citizen scientists in certain applications) who, for instance, change over samples at an air quality monitoring site or monitor a species occurrence (BTO, 2013). Volunteers who get involved sometimes already have a pre-existing personal interest in the topic which encourages them to be part of the research community (Mackechnie et al., 2011).

Like all personal assessment studies, personal exposure to environmental air pollution does rely on measurements of the state of the environment and in equal shares on tracking individuals, their activity patterns and behaviour. It is thus based on the willingness of individuals to take part in the research and reveal details of their personal activity and environment. In our modern society concerns of being constantly tracked and observed are more present than ever with people being increasingly under surveillance. CCTV cameras, smart phones, and loyalty cards are just a few examples of ways our movements and habits are recorded, often without our knowledge or consent.

Personal exposure study design needs to record an individual's activities, habits and personal circumstances. This could be seen as an infringement of personal space and territory, so the potential for misuse of personal exposure datasets is reduced by the anonymisation of data, a dedication to good practice and the implementation of secure data storage when handling individual datasets. With these precautions taken, it is proposed that the disadvantages for an individual taking part in the study are outweighed by the advantages gained through personal exposure studies for air quality improvement and health protection for the individual as well as for the general population

The necessity to monitor exposure to air pollution during people’s daily routines was identified through reviewing a wide range of historic and current approaches for the assessment of personal exposure to a variety of air pollutants, The selection of suitable tools and methods from the vast pool of possibilities outlined above was based on the study approach and the funding available. This included the need to deploy a suitable and practical pollutant monitor for active data logging, with high temporal resolution and sufficient ruggedness. Based on the review, the decision was made that a GPS tracker on its own would not be able to fulfil the requirements of time-activity pattern data collection, in particular as contextual information would be missing. For practicality, commercial availability, cost and confidentiality reasons technologies such as cameras, smart phones or radio-frequency identification (RFID) were not adopted for this pilot study. Thus classic methods utilising time-activity diaries and questionnaires (in this case collected online via web based forms) were identified as suitable tools, enhanced by interviews with study participants after their monitoring periods.

3 Materials and Methods

This chapter outlines the materials and methods used in this study. More information about the data collection approach and data processing and analysis methods is presented in individual chapters where appropriate.

3.1 Approach

3.1.1 Study design and area

Following the rationale of the conceptual model (Figure 2-3) a small scale pilot study to test the feasibility of a portable monitoring solution for particle number counts (PNC) was set up. The objective of this pilot study was, in the first instance, to establish a new personal exposure monitoring approach and test its feasibility for monitoring constantly across the full heterogeneity of microenvironments visited.

Monitoring personal exposure to air pollutants requires a portable monitoring solution. Since the objective is to monitor PNC around the clock in all visited MEs, a non-scripted, multi microenvironment study design has been selected. This is only possible with the help of volunteers who agree to carry the portable monitoring equipment with them during their daily routines and activities.

The study area is Scotland, a country with highly heterogeneous environments. It stretches from the border with England in the South (Gretna is located at 54.994997 N, -3.067108 W) up to the Shetland Islands (Lerwick is located at 60.155823 N, -1.144569 W).

The climate in Scotland is strongly influenced by the Gulf Stream and the prevailing westerly winds from the Atlantic. The West coast and Western

Islands are under maritime influence, resulting in seasonally high rainfall in autumn and early winter and annual mean temperatures of around 9˚C. The East of Scotland is sheltered from the western winds and thus in comparison drier, but also colder with mean temperatures varying between 6 and 9˚C depending on the proximity to the coast and topography. The Northwest of Scotland is on average the windiest region of the UK and along the West coast high rainfall occurs especially in autumn and early winter (Met office UK, 2013b).

Phase 1 of data collection for the pilot study was conducted in November when daylight hours in Scotland vary between ~6 ½ (minimum for Shetland) and 8 ½ (maximum for Edinburgh). In May, when the second stage of fieldwork took place, daylight hours are in the order of ~15 ½ (minimum for Edinburgh) and 18 ½ (maximum for Shetland) hours (UK weather, 2014).

Scotland's' population was 5,313,600 (estimated) on 30 June 2012 (GROS, 2013b). The Central Belt, between the two most populous settlements of the country, Edinburgh and Glasgow, is densely populated with a high level of infrastructure (see Figure 3-1). Large parts of the country are, however, rural and much less populated and have comparatively less infrastructure and industry (Steinle et al., 2011). According to national statistics (GROS, 2013b) the Eilean Siar (Western Isles) and Highland Council areas had a population density of only 9 people per km^2 in mid-2012, while Glasgow City had 3,407 people per km^2 with the average being 68 people per km^2, across the whole of Scotland.

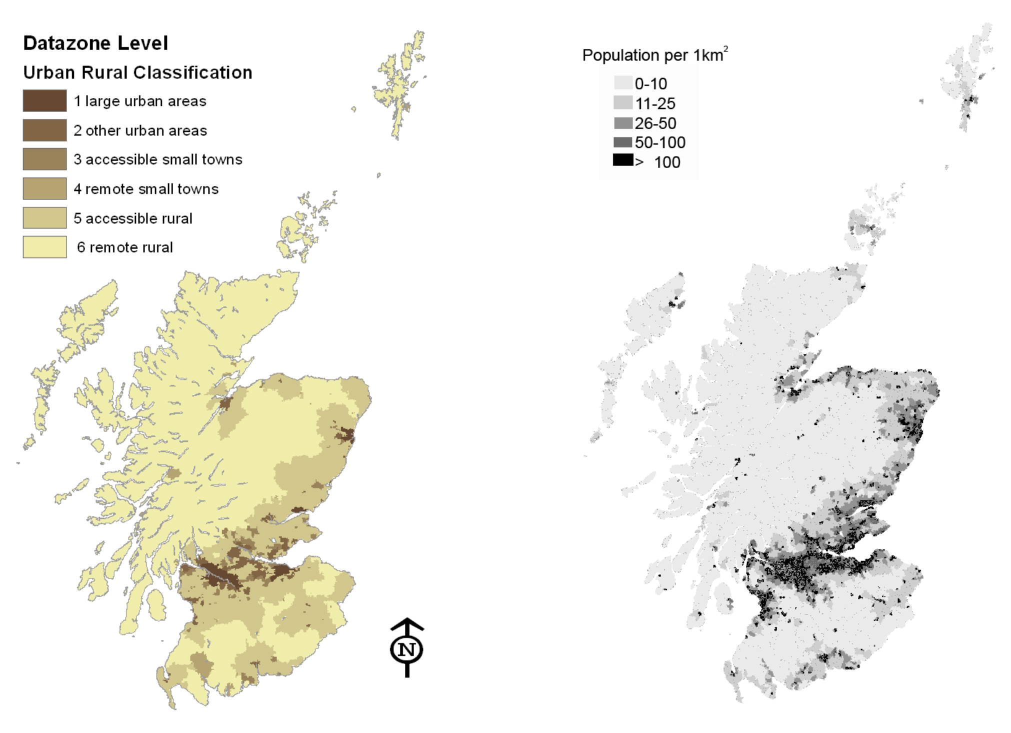


Figure 3-1 Scottish Government Urban Rural Classification 2009/10 (left) and population density (1×1 km) based on 2009 midyear estimates (right) on data zone (DZ) level (see section 3.3.3) (Steinle et al., 2011).

Since this pilot project has a focus on personal exposure monitoring, the definition of a suitable study area depends on where people are most likely to be moving during their monitoring period. This is mainly the area around the Scottish capital, Edinburgh, located at 55.9531 N, -3.1889 W, which has a population of 482,640 (estimated population on 30 June 2012 (GROS, 2013b)) and the adjacent council areas, East-, Mid- and West Lothian, where most of the volunteers participating in this study live and work. However, there are also profiles covering journeys reaching far up North to the Highlands and the Western Isles, as well as South across the border to England (Figure 3-2).

Figure 3-2 Map of Scotland (OS raster Miniscale) showing all the GPS tracks from the fieldwork phases 1 and 2. Note that the GPS tracks are comprised only of logs that have accompanying Dylos data. Also shown are the Centre for Ecology & Hydrology (CEH) where the researcher and most of the volunteers are working and the locations of the fixed site monitoring station Auchencorth Moss and St. Leonards which are part of the national monitoring network (chapter 4).

In Scotland, no single source dominates the emission of primary $PM_{2.5}$. The three most important sources according to a recent report on $PM_{2.5}$ in Scotland (Air Quality Consultants, 2012) are road transport, domestic combustion and industry, accounting for about 70% of total Scottish emissions. Moreover, atmospheric dispersion model results indicate that particuate matter concentrations in the UK overall are dominated by $PM_{2.5}$ components originating from emissions of precursor substances (ammonia, nitrogen dioxides and sulphur dioxide) outside the UK (Vieno et al., submitted). Annual mean background concentrations range from 3 to 11 $\mu g/m^3$ across Scotland, with highest concentrations occuring in the densely populated urban areas of Edinburgh and Glasgow, but also more generally across the Central Belt between those two cities and to the North along the east coast up to Aberdeen. Background concentrations describe the pollution levels away from sources and are thus representative for large areas.

3.1.2 Volunteers

A non-representative group of study participants was recruited from the institute the researcher is based at: Centre for Ecology & Hydrology (CEH, Figure 3-2 and Figure 3-3). Despite being a non-representative group of society, the volunteers all have different daily activity patterns which were sufficient to test the feasibility of a new methodology. A call to staff and students with information about the project and its objectives provided was issued by email to identify volunteers. CEH is located in a rural environment in Midlothian, Scotland. This offers the opportunity to monitor exposure for a group of people sharing a common workplace from which their profiles radiate out in different directions to their residences and other activity spaces (Figure 3-3.).

The advantage of both researcher and volunteers being based in the same institute is that the turnaround time between measurements is reduced. It is also easy for the researcher and volunteers to stay in contact during and after the monitoring period. Just one volunteer was unrelated to CEH. This person was based in Edinburgh city centre had a different work environment. In fact this person never left the urban area of Edinburgh during the monitoring period.

Individuals who expressed interest in participation were contacted. The time and details for each monitoring slot were discussed with the participants and the project details and equipment handling were explained when the monitoring pack was handed out to them. In total 17 individuals volunteered for this pilot study and collected personal exposure data at least once and in some cases up to five times. More detail on the study population is given in section 6.3.1.1.

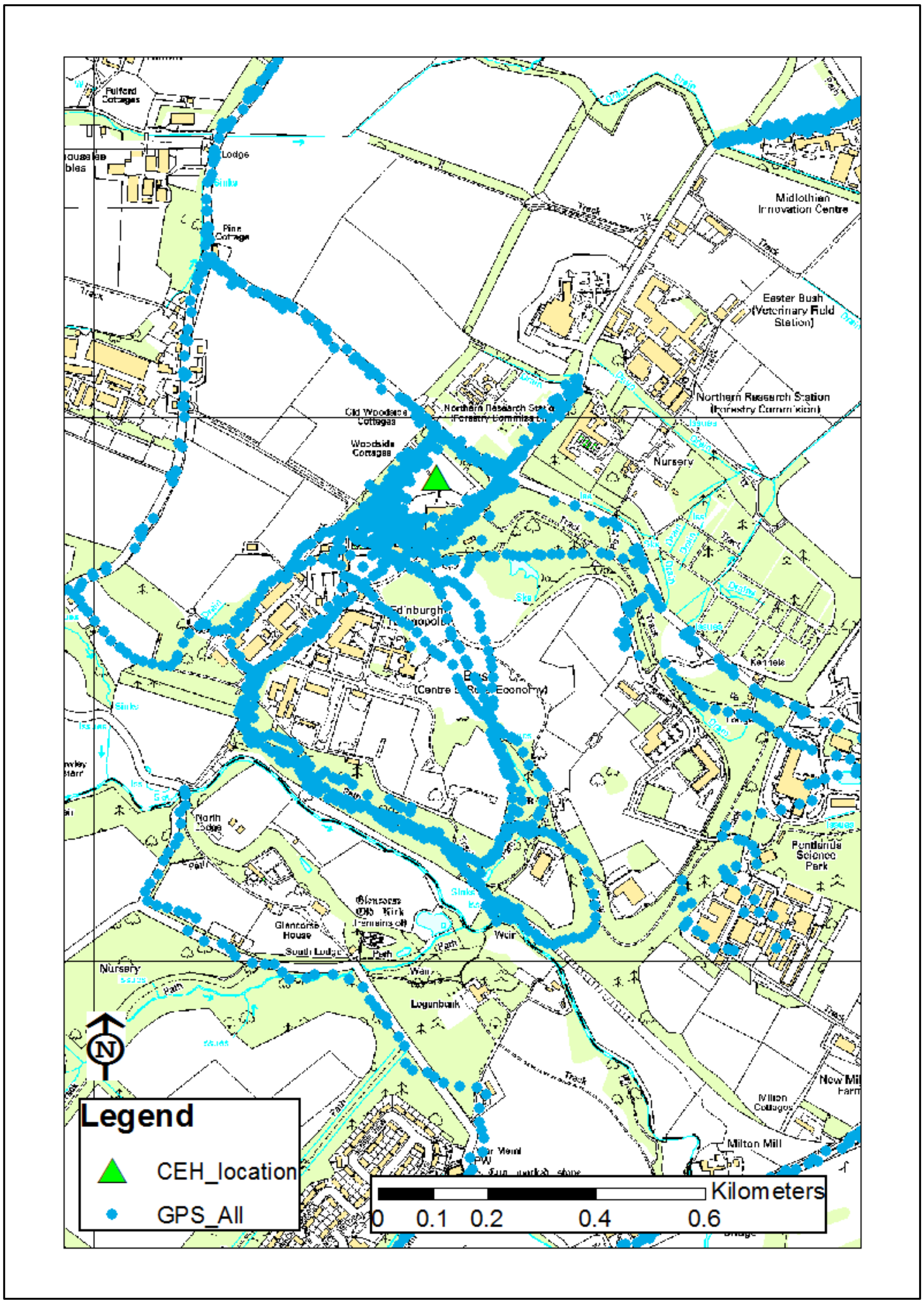


Figure 3-3 Map (OS raster 1:10.000) showing the common workplace of most volunteers, CEH (Centre for Ecology & Hydrology, green) and the GPS tracks (blue) of volunteers. Note that this map shows all GPS data including the logs which have no accompanying Dylos data. Confidential GPS logs, i.e. logs that are close to the individual's private residences have been removed.

Contains Ordnance Survey data © Crown Copyright and database right [2013].

3.2 Devices and tools applied

3.2.1 Particle monitor – Dylos DC 1700

To measure particle number concentrations (PNC), the Dylos DC 1700 monitor (Dylos Cooperation, Riverside, California, USA) was used. In the following we refer to this instrument as the Dylos or 'the monitor' interchangeably. It is a particle counter based on light-scattering technology and has been developed for indoor air quality monitoring for households. In contrast, many other commercially available air quality monitors have been developed primarily for industrial environments and occupational health monitoring applications. The Dylos has been used and evaluated, by Semple et al. (2012, 2013) regarding exposure to second-hand smoke (SHS) and by Northcross et al. (2013) comparing the performance of the Dylos against other commercially available particle monitors (both for chamber and ambient environments). At approximately £270, the Dylos is relatively cheap compared to other particle monitors such as the SidePak AM510 (~ £2,500) or the DustTrak (~ £3,200). Both instruments are commercially available from TSI Inc, Shoreview, Minnesota, USA.

The Dylos does not directly provide particle mass concentration, but outputs the number of particles counted per cubic foot of air (1 cubic foot = 28.32 litres), ensuring constant air flow by a fan channelling air through the measurement chamber. The Dylos logs particles in two size classes (>0.5 µm “small” and >2.5 µm “large” aerodynamic diameter) with a sampling frequency of once per minute. The lower detection limit is stated by the manufacturer to be at 0.5 µm particle diameter. The instrument is provided with proprietary software (Dylos Logger version 1.6) to download and display data.

On a full battery charge, the Dylos runs for approximately 6 hours. Regaining a full charge takes much longer while the Dylos is monitoring and plugged into mains power, than when it is switched off. The built-in memory can store approximately one week of data when sampling continuously i.e. one log per minute. Once the memory is full, the Dylos continues to operate, but starts overwriting the oldest samples.

The Dylos is an easy to operate instrument with one button to switch it on/off and two more buttons to adjust settings. Its low weight (~500 g) and relatively small dimensions (~12×20×8 cm) make carrying the instrument easy (Figure 3-4). Note that when the Dylos is running on continuous mode, no actual PNC readings are displayed, but a generic message (“logging data”) is shown which has the advantage that volunteers cannot get distracted or adjust their behaviour according to or to avoid high PNC readings.

The monitor was originally designed for indoor use and so is not water- or splash-proof. A detailed evaluation of the Dylos performance follows in chapter 4.

3.2.2 GPS Trackstick

A GPS receiver to track the movement of study participants was used in combination with the particle counter to relate observed particle concentrations to time and location. GPS receivers are available in many varieties for handheld use, for instance for leisure activities (walking, climbing) or for professional use. The GPS Trackstick (Telespial Systems Inc, Burbank, California, USA) was selected for this study because of the small form factor (~10×3×2 cm), low weight (~82 g) and the ease of use with one button operation only (Figure 3-4).

The GPS Trackstick records date, time, longitude and latitude, altitude, temperature, status, course, GPS fix and signal quality approximately every 10 seconds, depending on signal quality.

Applying the GPS in combination with the Dylos provides spatiotemporally resolved particle number counts for personal exposure research.

3.2.3 Monitoring pack

With the key features of the Dylos being its low weight and reasonably small size, it has been considered to also be well suited for use in a personal monitoring study. A small hiking backpack with elastic cord attachments and side pockets to attach/carry the instruments (Figure 3-4) has been adapted. To avoid the interface buttons on the Dylos being pushed accidently while it is strapped onto the backpack, a protective plastic cover has been fitted covering the buttons, while allowing users to switch the device on and off with a pen. To secure the monitor an adjustable Velcro strap is used. To charge the Dylos, the device can simply be plugged into the mains electricity supply without having to detach the monitor from the backpack. Four monitoring packs were assembled to allow for parallel data collection and also to increase flexibility in handing out the devices and collect as much data as possible in the given time frame. The backpack had also space for additional batteries, charger, power plug, notebook, instruction leaflet and an official letter from CEH explaining the reason and purpose of the monitoring study with the contact details of the researcher.

The design of the monitoring pack and the fact that the Dylos is not water- or splash-proof, yet needs to be worn exposed to ambient air, restricts its outdoor use to dry weather conditions or sheltered/indoor use only.

Figure 3-4 The monitoring pack - the Dylos monitor is strapped onto the backpack with the inlet and fan exposed to the air. The GPS is placed in the side mesh bottle pocket.

3.2.4 Time-activity diary, follow-up meeting and questionnaire

A TAD was created from scratch based on the reviewed literature and implemented as a web form accessible from any device with internet access (Table A 2). It was tested with volunteers before the actual data collection and adjusted based on user feedback between Phase 1 and Phase 2 of data collection (section 5.3.1.2.). In addition, volunteers were given a 24-hour matrix on paper and were encouraged to take their own notes during the day and later transfer their notes in the web form.

TAD and GPS data were reviewed after the monitoring pack was returned and discussed in follow-up meetings with the study participants. Follow-up meetings were mandatory and conducted as informal meetings with the volunteer to look at and talk through their personal data. In those meetings additional temporal and spatial details could be added, and ambiguities or gaps in the TAD clarified. This proved to be a vital step as the TAD can only be fairly generic, necessitating the follow-up meetings to explore detailed issues afterwards. These meetings had to take place as soon as possible after the monitoring period while memories were still fresh and to aid recall.

A questionnaire was designed as a web form accessible from any device with internet access. Volunteers were asked to fill in this questionnaire once during the pilot study. It includes questions about the individual's living conditions, the household the person is living in, building and neighbourhood characteristics and other contextual factors (Table A 1).

3.3 Data collection and processing

3.3.1 Data collection, extraction and processing

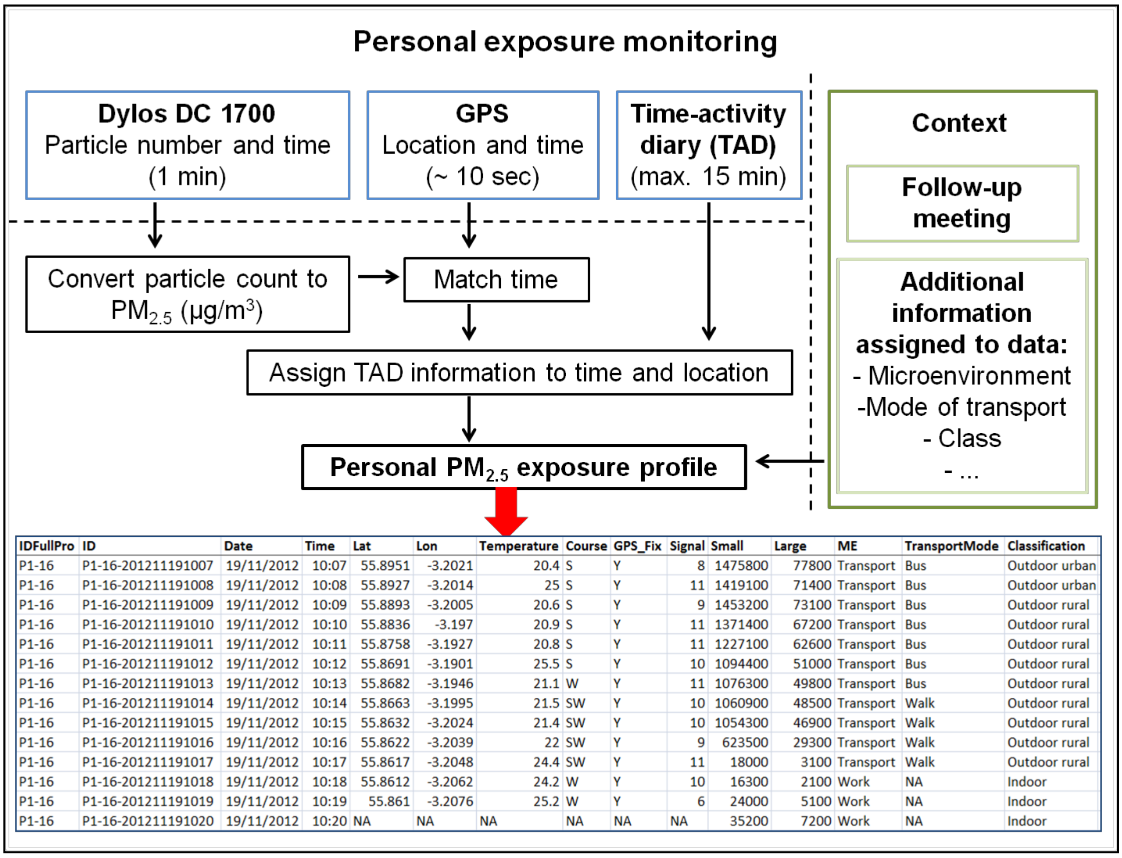
Data was collected for two periods during autumn/winter 2012 – namely Phase 1 or P1 - and during spring 2013 (Phase 2 or P2). Overall 17 volunteers collected 35 individual profiles. This is both a manageable number and covers sufficient activities to assess the variability of individual exposure.

Once the monitoring pack was returned, data was downloaded from the Dylos with the propriety software as particles per cubic foot (1 cubic foot = 28.32 litres). Data was exported as an ASCII text file and visually checked for bad data or data gaps before being further processed. The GPS data was downloaded with the propriety Trackstick manager software and exported as a .csv file.

TADs were exported and talked through with the volunteer during the mandatory follow-up meeting.

Figure 3-5 describes the process designed to ensure consistent data analysis and provides an overview on the characteristics of the different datasets. Data processing methods have been developed and MEs and transport modes defined based on data collected in Phase 1 and consistently applied to data collected during Phase 2. Differences in the logging time steps between the particle measurements (1 min) and the GPS log (~10 sec) tracks require careful processing of the data. To match the timestamps of both devices a method was developed utilising the FME (Feature Manipulation Engine, (Safe Software Inc., 2014) to match the GPS to the respective Dylos timestamps (at every full minute). FME software provides the opportunity to develop work flows based on so called ‘workbenches’ where a sequence of individual processing steps can be linked. The workbenches are self-documenting with transformer tools and variable flows graphically linked, ensuring a processing audit trail for all datasets. In this process date and time are also split into two separate variables. Dylos logs without a matching GPS-originated timestamp i.e. indoor logs and where the GPS did not log due to reception problems or battery life, are kept in the dataset.

The matching of “hard” GPS coordinates and timestamps with “soft” real locations and times as noted in the TADs has to be done manually. The resulting new dataset, comprising GPS data, PNC and TAD information displayed as excel graphs with TAD information added as text was then discussed and approved with the volunteer in a follow-up meeting. These mandatory follow-up meetings have to happen as soon as possible after the monitoring equipment is returned as memory fades quickly.



IDFullPro	ID	Date	Time	Lat	Lon	Temperature	Course	GPS_Fix	Signal	Small	Large	ME	TransportMode	Classification
P1-16	P1-16-201211191007	19/11/2012	10:07	55.8951	-3.2021	20.4	S	Y	8	1475800	77800	Transport	Bus	Outdoor urban
P1-16	P1-16-201211191008	19/11/2012	10:08	55.8927	-3.2014	25	S	Y	11	1419100	71400	Transport	Bus	Outdoor urban
P1-16	P1-16-201211191009	19/11/2012	10:09	55.8893	-3.2005	20.6	S	Y	9	1453200	73100	Transport	Bus	Outdoor rural
P1-16	P1-16-201211191010	19/11/2012	10:10	55.8836	-3.197	20.9	S	Y	11	1371400	67200	Transport	Bus	Outdoor rural
P1-16	P1-16-201211191011	19/11/2012	10:11	55.8758	-3.1927	20.8	S	Y	11	1227100	62600	Transport	Bus	Outdoor rural
P1-16	P1-16-201211191012	19/11/2012	10:12	55.8691	-3.1901	25.5	S	Y	10	1094400	51000	Transport	Bus	Outdoor rural
P1-16	P1-16-201211191013	19/11/2012	10:13	55.8682	-3.1946	21.1	W	Y	11	1076300	49800	Transport	Bus	Outdoor rural
P1-16	P1-16-201211191014	19/11/2012	10:14	55.8663	-3.1995	21.5	SW	Y	10	1060900	48500	Transport	Walk	Outdoor rural
P1-16	P1-16-201211191015	19/11/2012	10:15	55.8632	-3.2024	21.4	SW	Y	10	1054300	46900	Transport	Walk	Outdoor rural
P1-16	P1-16-201211191016	19/11/2012	10:16	55.8622	-3.2039	22	SW	Y	9	623500	29300	Transport	Walk	Outdoor rural
P1-16	P1-16-201211191017	19/11/2012	10:17	55.8617	-3.2048	24.4	SW	Y	11	18000	3100	Transport	Walk	Outdoor rural
P1-16	P1-16-201211191018	19/11/2012	10:18	55.8612	-3.2062	24.2	W	Y	10	16300	2100	Work	NA	Indoor
P1-16	P1-16-201211191019	19/11/2012	10:19	55.861	-3.2076	25.2	W	Y	6	24000	5100	Work	NA	Indoor
P1-16	P1-16-201211191020	19/11/2012	10:20	NA	NA	NA	NA	NA	NA	35200	7200	Work	NA	Indoor

Figure 3-5 Flowchart showing the data processing. Individual data sets are merged, additional contextual information is added to enrich personal exposure profiles.

Based on the recorded data, additional contextual information (Figure 3-5 green box on the right) is added. This includes:

- Time of the day (morning 06:00 – 11:59, afternoon 12:00-17:59, evening 18:00-23:59, night 00:00-05:59).
- Day of the week (Monday-Sunday)

- Microenvironments (MEs) (section 3.3.2)
- Comments
- Transport mode (*Bus, Bicycle, Car, Ferry, Train* and *Walk;* section *3.3.2*)
- Class (*Indoor, Outdoor rural, Outdoor urban*) (section 3.3.3)

Each profile has been coded with an ID based on the fieldwork phase P1 or P2 and the number according to the alphabetical order of the volunteers' names: P1-01, P1-02 etc. Moreover every data point has an individual ID based on the profile code and the timestamp (Figure 3-5).

Data where the Dylos was carried in backpacks, panniers or handbags or was left in cars or at home while the person was away was discarded as non-valid for the purpose of personal exposure assessment and was subsequently marked in the "comments" column and excluded from further analysis.

3.3.2 Microenvironments and transport modes

Based on the profiles collected during Phase 1 with concentration, location, time and TAD information, all locations and activity spaces visited by the volunteers during the monitoring period were analysed. Resulting from this analysis six MEs were identified (four indoor MEs and two outdoor MEs) into which all recorded locations could be allocated to analyse for time-activity patterns and exposure to particulate matter, namely

- *Home*
- *Work*
- *Public building* (shops, restaurants, sports centre, train station...)
- *Private residential building* (friends or partner's residence...)
- *Transport*

- *Outdoor other* (walking/cycling for leisure, spending time in a park...)

This is an important step in the analysis process as people are constantly on the move and hence exposed in many different environments and activity spaces with different pollution levels. Through a consistent application of the concept of MEs, activities can be related to a spatial unit, which serves as a space to refer exposure to and to a certain degree allows comparison between individual spatial units of the same ME category.

In this step the transport modes used by the volunteers during their monitoring period have been identified as follows and the respective transport mode was added to each individual data point.

- *Bicycle*
- *Bus*
- *Car*
- *Ferry*
- *Train*
- *Walk*

3.3.3 Classes

Each individual data point was assigned to one of the three following classes that are representative of a coarse allocation of personal activity spaces. This classification allows for distinction between different characteristic background pollutant concentrations and the association of observed particle number counts with indicative mass concentrations (section 4.4).

- *Indoor*

- *Outdoor rural*
- *Outdoor urban*

The class *Indoor* has been assigned to all data points which are in one of the four defined indoor MEs.

The outdoor classes have been assigned based on the collected GPS data and the Scottish Government Urban Rural Classification (URC) from 2009/10 (The Scottish Government, 2010). The URC classification aims to help develop the understanding of specific issues that may commonly affect urban, rural and remote locations in Scotland. It acknowledges the fact that issues such as transport, health and education can have a particular impact on the population of rural communities and provides a consistent way to define urban and rural areas in Scotland (The Scottish Government, 2010). This classification is based on the Scottish Governments definition of rurality that defines settlements with a population of 3,000 or less as being rural. Drive times from settlements with 10,000 or more people are used as parameter to define areas as remote or accessible (Table 3-1). The URC is available as 6-fold and 8-fold version. For this study the 6-fold version has been used.

Table 3-1 The 6-fold Urban Rural Classification (URC) defines urban and rural areas based on population numbers. Drive times from settlements with more than 10,000 people are used to distinguish between remote and accessible areas within Scotland (The Scottish Government, 2010).

Class	Class Name	Description
1	Large Urban Areas	Settlements of over 125,000 people.
2	Other Urban Areas	Settlements of 10,000 to 125,000 people.
3	Accessible Small Towns	Settlements of between 3,000 and 10,000 people and within 30 minutes drive of a settlement of 10,000 or more.
4	Remote Small Towns	Settlements of between 3,000 and 10,000 people and with a drive time of over 30 minutes to a settlement of 10,000 or more.
5	Accessible Rural	Settlements of less than 3,000 people and within 30 minutes drive of a settlement of 10,000 or more.
6	Remote Rural	Settlements of less than 3,000 people and with a drive time of over 30 minutes to a settlement of 10,000 or more.

The dataset applied for this study is the URC classification on data zone level. Data zones are geographical units with an approximate population between 500 and 1,000. These data zones nest within Council Areas and as far as possible meet the criteria of compactness and homogeneity, and also respect other boundaries e.g. the physical environment. There are 6,505 data zones in Scotland. Since the data zones are based on population numbers they cover smaller areas in densely populated regions while data zones in the Highlands can cover vast areas. In densely populated regions the data zone geography provides a very detailed picture of the respective information displayed (The Scottish Government, 2004).

The URC dataset is available from the Scottish Neighbourhood Statistics website (www.sns.gov.uk, 2011). The data zones are classified in categories 1-6 (**Table 3-1**). For the purpose of this study categories 1-4 were summarised into urban and 5-6 into rural (**Figure 3-6**).

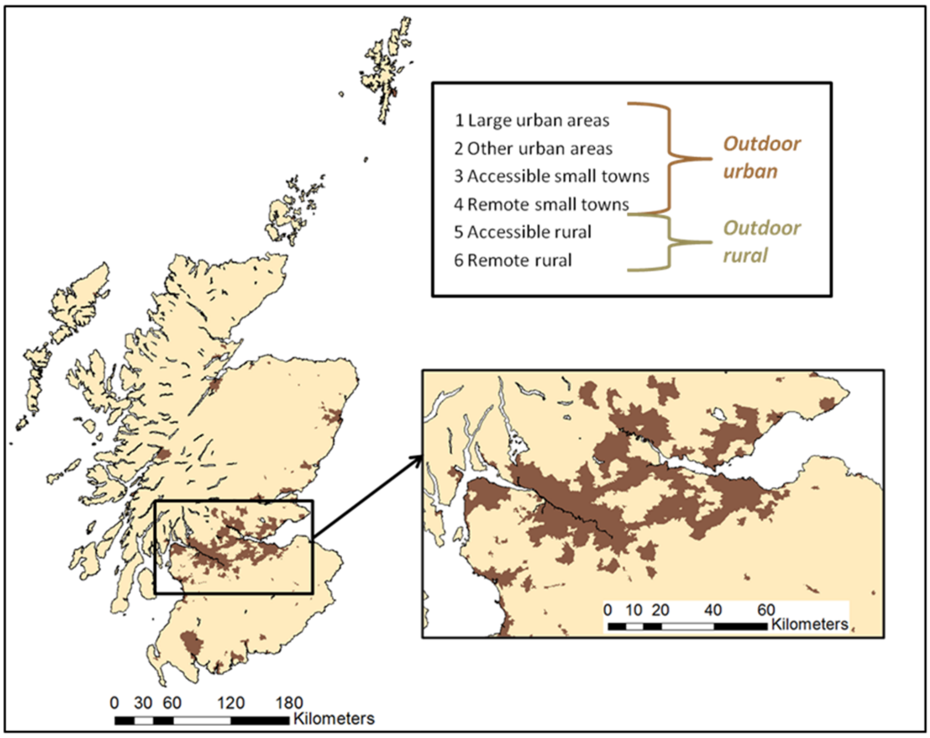


Figure 3-6 Map of Scotland showing the distribution of *Outdoor urban* and *Outdoor rural* areas on data zone level. The small map on the right shows the Central belt of Scotland which is densely populated and has a high degree of infrastructure. The two classes have been aggregated based on the 6-fold Scottish Government URC 2009/10 for application in this thesis.

A dedicated FME workbench has been developed to assign the GPS points that have been recorded by volunteers to the respective class. The URC map has been overlaid with the GPS points to determine the category of the data zone within which the GPS point was located. At the same time the 6-fold classification is already summarised into the two classes *Outdoor rural* and *Outdoor urban* as shown in Figure 3-6. Data has been displayed and visually assessed in ArcGIS 10.1 (ESRI, 2013).

Where no GPS data was available an assessment based on the route description from volunteers and the URC map has been made.

3.3.4 Confidentiality - issues with GPS data

For confidentiality reasons GPS data has been post-processed to exclude all logs in the vicinity of volunteer's *Home* addresses and other *Private residential buildings* from the resulting output tables and maps in this study. To do so all GPS logs recorded within postcode sectors that included *Home* or *Private residential building* MEs have been excluded.

The postcodes for the volunteer's homes were collected in the questionnaires. Therefore the easiest way to exclude data was to determine the coordinates of the *Home* location and put a spatial buffer around this point. Because the postcodes for *Private residential buildings* people visited were not available a different method has been chosen. The postcode sectors for *Private residential buildings* were determined based on the nearest GPS log, if GPS logs were available. Otherwise there was no need for this processing step. For future studies with bigger datasets it is recommended to explore further which geospatial techniques could be applied to remove confidential GPS data while provide as much GPS cover as possible.

Postcode sectors are the first four digits of the postcode e.g. EH26. The area covered by these varies a lot, as postcodes are allocated based on population numbers and in less densely populated areas may reflect a large area. This is the downside of this approach because GPS points that are within the postcode sector but not nearby the *Home* or *Private residential building* are automatically excluded as well.

On the other hand, due to the typical size of postcode sectors in the study domain, it cannot always be guaranteed to provide sufficient confidentiality, for instance, if the coordinates logged fall within an urban area where postcodes cover smaller areas. Thus it was assessed if an additional buffer around the postcode sectors would be required to provide data protection. Due to the overall small size of urban postcode sectors in the study domain, applying buffers to all home locations in this study would result in removal of most GPS logs in the Edinburgh City area. For all but one volunteer, the protection of home location was deemed sufficient with the use of postcode sectors only, however, for future studies, this needs to be considered, in particular with larger populations in urban areas.

The processing has been done with FME and ArcGIS software and is depicted as a flowchart in Figure 3-7. In a first step all GPS logs were tested for correctness, meaning that all logs that had longitude and/or latitude values outside the study area boundaries and also all data with no GPS logs (NAs) were excluded and saved in a separate file (*False/NA*) from the true GPS logs (*True*). In the *False/NA* dataset all GPS data i.e. latitude, longitude, altitude, temperature, signal etc. was set to “NA” to provide confidentiality but kept the accompanying Dylos and contextual data within the dataset. Both datasets (*False/NA* and *True*) were output as text file and as spatial data (points) for visualisation in ArcGIS. Transforming text into a spatial dataset is done with FME but requires the “NA” values for longitude and latitude temporarily to be set to blank as the tool doing the transformation cannot handle “NAs”.

In a next step the relevant *postcode sectors (PC)* were extracted from the full dataset, which is publicly available from the General Register Office for Scotland website (GROS, 2013a). Relevant postcode sectors are those within which either a *Home* or a *Private residential building* was located. These *postcode sectors* were used as base to test which GPS logs (*True*) were within the respective sectors. For this step the spatial datasets, postcode polygons and GPS points, were used as input files. A spatial filter was set up to test which postcode sectors “contain” *True* GPS logs*.* GPS logs that passed this spatial filter lie within the *postcode sectors* and therefore have to be set to “NA” to provide confidentiality. This data was saved as a new dataset called *Passed*. GPS logs that failed the spatial filter are located outside the *postcode sectors* and remained as they are (*Failed*). Both datasets were output as text and spatial data.

In a final step all three datasets, *False/NA*, *Passed* and *Failed,* were merged into one text file and additionally converted into a spatial dataset to visualise the GPS tracks. All spatial datasets were assigned the correct spatial reference, projected and visualised in ArcGIS.

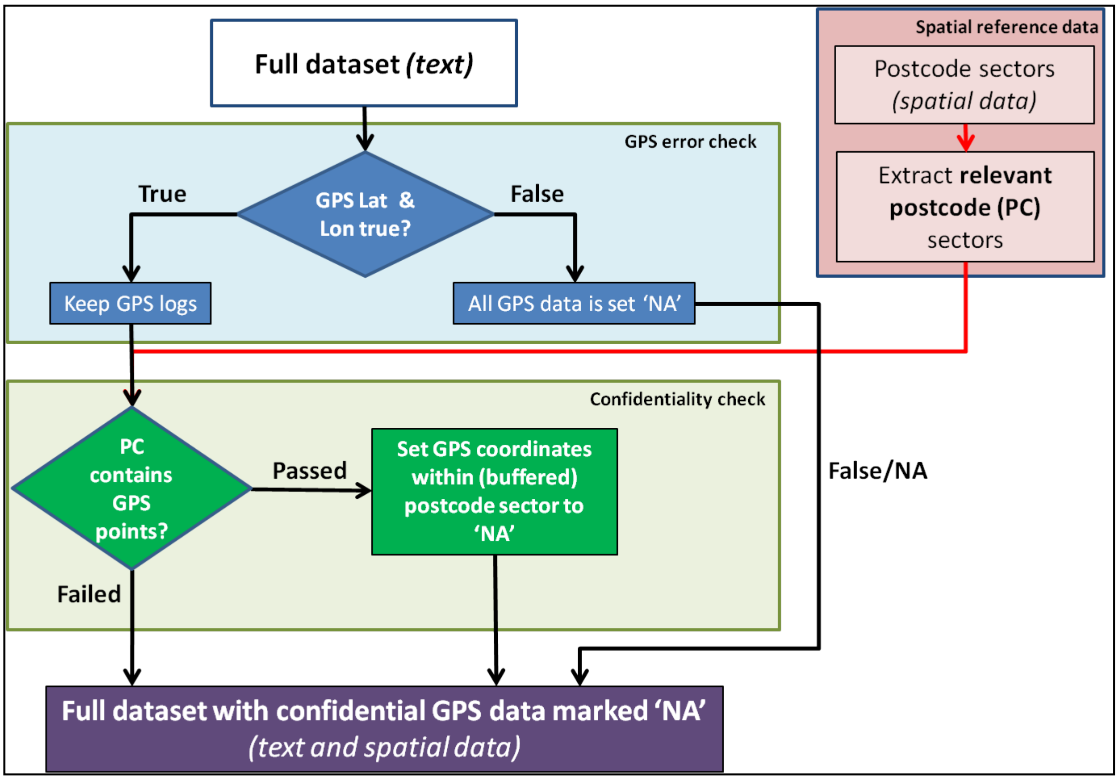


Figure 3-7 Flowchart showing the method with which GPS points collected during fieldwork phases 1 and 2 that are confidential have been excluded from the dataset.

3.3.5 Distance between features

Distances between the volunteer's home's, the work place and the two fixed site monitoring stations from the national automatic urban and rural network (AURN) have been calculated (Table 6-9). This has been done based on the geographic coordinates taken from the Scottish air quality website (Scottish Air Quality, 2013) for the monitoring stations as well as for the work place location at the CEH (here the station Bush Estate located outside the building is used) and the postcodes for the individual home addresses compiled with the questionnaires. The latitude/longitude coordinates for the respective postcodes have been derived with the help of a freely accessible web tool (http://www.townscountiespostcodes.co.uk, 2014). Based on these coordinates, the actual calculation has been done with the ArcGIS Point distance tool, which provides the direct line distance. The distance has been calculated as the crow flies therefore actual distances travelled are underestimated.

3.3.6 Functions to derive particle mass concentration depending on class

As described in section 3.2.1 the Dylos does provide the measured data as particle number counts (PNC). However, ambient fine particulate matter levels are however usually expressed in $PM_{2.5}$ ($\mu g/m^3$) particle mass concentration, for instance in air quality guidelines. Following Semple et al. (2012, 2013) we developed two functions to derive particle mass concentration for the classes *Outdoor urban* and *Outdoor rural*. This was done based on the data collected during the evaluation of the Dylos which has been assigned an individual chapter in this thesis (chapter 4). The monitor was co-located with the reference instruments at an urban background station and a rural station in the vicinity of Edinburgh. Results show good agreement for both locations and are the basis for the functions derived. For the class *Indoor* we applied the function derived by Semple et al. (2013) based on second-hand smoke exposure in real-life settings.

The tools and methods described in this chapter have been selected based on the literature reviewed, as discussed in chapter 2. The application and performance of individual tools and methods is evaluated in the following chapters. Chapter 4 focuses on the performance of the Dylos particle counter in outdoor environments, while in chapter 5 the feasibility and limitations of all methods and tools required for data collection, as well as the actual monitoring process are evaluated. Chapter 6 concerns the actual monitoring results and how this fits in with the tools and methods applied.

4 Evaluation of the Dylos DC 1700 for personal exposure assessment in indoor and outdoor environments

In this chapter the evaluation approach to assess the performance of the Dylos against the TEOM-FDMS reference instruments is described. Functions derived based on this evaluation to convert measured particle number counts into predicted $PM_{2.5}$ mass concentrations are introduced.

4.1 Introduction

In this chapter the performance and evaluation of the Dylos against reference instruments that measure $PM_{2.5}$ mass concentration is discussed. The measurement and assessment of exposure to $PM_{2.5}$ is challenging, because of the nature of particles, their formation, evolution and their variability in size and composition (section 2.2.1). The European Standardisation body CEN outlines reference methods for particulate matter measurements in standard EN14907:2005 (CEN, 2005) employing a manual gravimetric approach, while the Dylos provides a count of the numbers of particles for a given sampling volume (PNC) in two different size classes (section 3.2.1).

The Dylos has recently been applied in different settings, both indoors (Semple et al., 2012, 2013) and outdoors (Northcross et al., 2013). Its response has been evaluated against the TSI SidePak optical aerosol monitor providing data in mass concentration in chamber experiments with second-hand smoke (Semple et al., 2012) as well as in people's home environments (Semple et al., 2013). Northcross et al. (2013) evaluated the Dylos integrated into a system called the Berkley Aerosol Information Recording System (in chamber and ambient experiments) against the TSI DustTrak, a commercially available photometer providing aerosol mass. All three studies have confirmed a reliable representation of particle numbers by the Dylos. For the purpose of this study the Dylos has been applied in mixed indoor and outdoor settings. As the pilot study has been conducted in both rural and urban conditions, it is necessary to evaluate the Dylos performance against reference instruments in both an urban and rural outdoor settings in order to test the first hypothesis as listed in section 1.2:

a) The portable particle counter Dylos DC 1700 is a viable instrument for personal air quality monitoring, providing robust, reliable results when compared to reference instruments in outdoor settings.

4.2 Methods

4.2.1 Reference methods

The reference standard for measuring ambient $PM_{2.5}$ mass concentration is a manual gravimetric method (CEN, 2005). The gravimetric method is based on the mass difference of filters onto which the PM is sampled onto. In practice however, manual methods are not able to provide fast, continuous measurements as required for monitoring networks. Hence, the use of automatic instruments designed to provide equivalent results (equivalence is defined according to the Guide to the Demonstration of Equivalence, (European Commission, 2010)) is permitted by EU legislation (CEN, 2013) for the measurement of $PM_{2.5}$ in a regulatory context. Such methods, however, introduce uncertainties to the already complex task of monitoring $PM_{2.5}$ (Air

Quality Expert Group, 2012). The instrument applied throughout the UK Automatic Urban and Rural Network (AURN) is a Filter Dynamic Measurement System (FDMS) which is based on a Tapered Element Oscillating Microbalance (TEOM) and will from now on be referred to as reference instrument or TEOM-FDMS. Its performance has been extensively evaluated in the equivalence programme for monitoring of PM in the UK (Harrison et al., 2006). The accurate measurement of PM is a demanding task and notoriously difficult because of factors such as semi-volatile compounds and variations in water-content (Thai et al., 2008) which leads to the understanding that:

> *"...the $PM_{2.5}$ metric... [does] not correspond to definite physical or chemical components of the air, but is in effect defined by the measurement method." (Air Quality Expert Group, 2012, p. 39).*

In comparison to PM_{10}, uncertainties in $PM_{2.5}$ data are inherently larger because the absolute mass of $PM_{2.5}$ is smaller, which makes the variations in the mass of the filter more significant (Brown et al., 2006). Furthermore decreasing ambient $PM_{2.5}$ concentrations may result in smaller PM mass that is sampled onto the filters, thus uncertainty in the accuracy of weighing the filters becomes relatively more significant over time (Brown et al., 2006). In measurement method comparison studies it is regularly reported that the $PM_{2.5}$ fraction is underreported by the TEOM-FDMS, which is to a large extent due to the volatilisation of semi-volatile particles and can result in zero and negative values (Ayers et al., 1999, Charron et al., 2004, Cyrys et al., 2001, Air Quality Expert Group, 2012). In fact, values down to -4 $\mu g/m^3$ are considered valid in the ratification process and as the report on $PM_{2.5}$ in Scotland (Air Quality Consultants, 2012) discusses, this negative offset suggests that the concentrations measured are too low for the TEOM-FDMS instruments which have issues with volatile material being lost from the filters. This report relates the issues with the TEOM-FDMS measurements specifically to the Auchencorth Moss site which means:

> *"If the rural concentrations are, in reality, too low, then the estimated urban increment will be too high".* (Air Quality Consultants, 2012, p. 23)

When looking at the data from the two fixed site monitoring stations which have been used for data analysis in chapter 6 it becomes obvious though that negative and zero values are recorded by the TEOM-FDMS at both Auchencorth Moss and St. Leonards. This suggests that the aforementioned issues occur at both sites, affecting the comparison of Dylos measurements with reference observations.

The TEOM-FDMS is based on complex technology, making it relatively maintenance-intensive and resulting in data gaps due to downtimes. Substantial effort is required to ensure that output data is internally consistent and also comparable with the manual gravimetric reference method. Significant data rejection is, however, not unusual and measuring $PM_{2.5}$ remains a challenge (Air Quality Expert Group, 2012).

4.2.2 Evaluation approach

For this study it is necessary to evaluate the Dylos performance concerning its ability to measure levels of $PM_{2.5}$ in the environment and temporal trends. To achieve this, a co-location approach was taken. The Dylos was set up for 5 day periods next to TEOM-FDMS instruments which are operated routinely at a rural and an urban background site of the national Automatic Urban and Rural

Network (AURN). By evaluating the performance in both urban and rural outdoor environments, we later derive functional representations to translate PNC into indicative $PM_{2.5}$ mass for the outdoor microenvironments according to the classification of data collected.

In the greater Edinburgh area, two $PM_{2.5}$ monitoring sites, both part of the AURN, are suitable for the evaluation of the Dylos (Figure 4-1**)** for their location relative to the study area):

1. Auchencorth Moss (55.792160 N, -3.242900 W): The Co-operative Programme for Monitoring and Evaluation (EMEP) of the UNECE Convention on Long-range Transboundary Air Pollution Level II Supersite (Torseth et al., 2012) located in a rural environment approximately 10 km south of Edinburgh on an transitional lowland peat bog (Figure 4-1). This site is also part of the Scottish Automatic Rural Network.
2. St. Leonards (55.945589 N, -3.182186 W): This Scottish Automatic Urban monitoring station is located within a small park area in the south side of Edinburgh with the nearest main road being approximately 35 m away (Figure 4-1). The site is classified as *urban background*, which means that it is located in an urban area away from major sources, broadly representative of city-wide background conditions.

Full details on both sites, pollutants measured, measured data and statistics can be found on the UK air website (DEFRA, 2014).

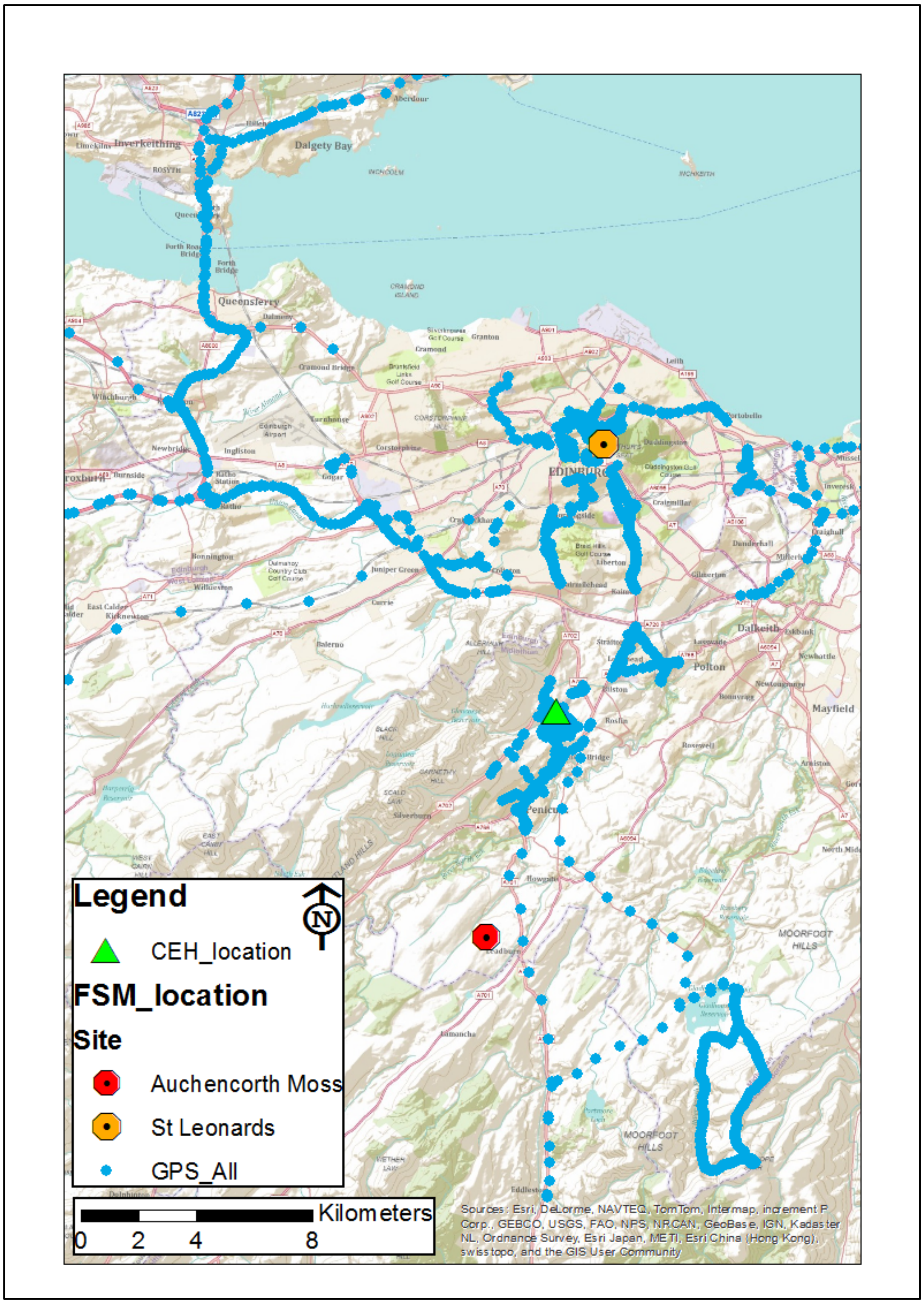


Figure 4-1 Map showing the rural fixed site monitoring station Auchencorth Moss in the South and the urban background station St. Leonards in the North in relation to CEH and volunteers GPS tracks from all profiles (covering both fieldwork periods).

At both sites the reference instrument operated and used for the comparison is the TEOM-FDMS system (Thermo Fisher Scientific Inc., USA). Additionally an *OSIRIS Airborne Particle Monitor* (Turnkey Instruments Ltd., UK) and a MARGA - *Monitor for Aerosols & Gasses in Ambient Air* (Methrom Applikon B.V., Netherlands), were deployed at St. Leonards and Auchencorth Moss respectively during the co-location periods and data from these instruments was used for supporting comparisons.

Each co-location study was conducted over a period of five days from 10th to the 15th of April 2013 (Auchencorth Moss) and 30th September to 4th October 2013 (St. Leonards). In both cases, the Dylos was set up outdoors, protected from direct precipitation and running on mains power. The duration was chosen to fit the maximum data storage capacity of the Dylos of approximately six days. In both periods, weather conditions were mixed with windy and rainy periods alternating with dry sunny spells. It should be noted that the setup was not intended to replicate a full equivalence test to certify the Dylos according to the Environment Agency's *Performance Standard for Indicative Ambient Particular Matter* (MCERTS (Environment Agency, 2009)) as the focus of this study is the assessment of the relative contributions of different MEs and activities on people's individual exposure, not to establish a reference method. Nevertheless, the evaluation method and results are robust for the microenvironments directly represented by the co-location situations (urban and rural background respectively). Further co-location and evaluation studies are required to derive functional relationships between PNC and indicative PM mass in other environments and situations, which is being addressed for future studies.

The data was also analysed for potential correlation between the measurements and temperature and relative humidity, however no relationship could be identified. The individual Dylos instruments have also been tested by direct comparison, showing very good agreement.

4.3 Results

Data from the Dylos and the reference instruments which were co-located in two different environments were analysed with respect to reliability and robustness.

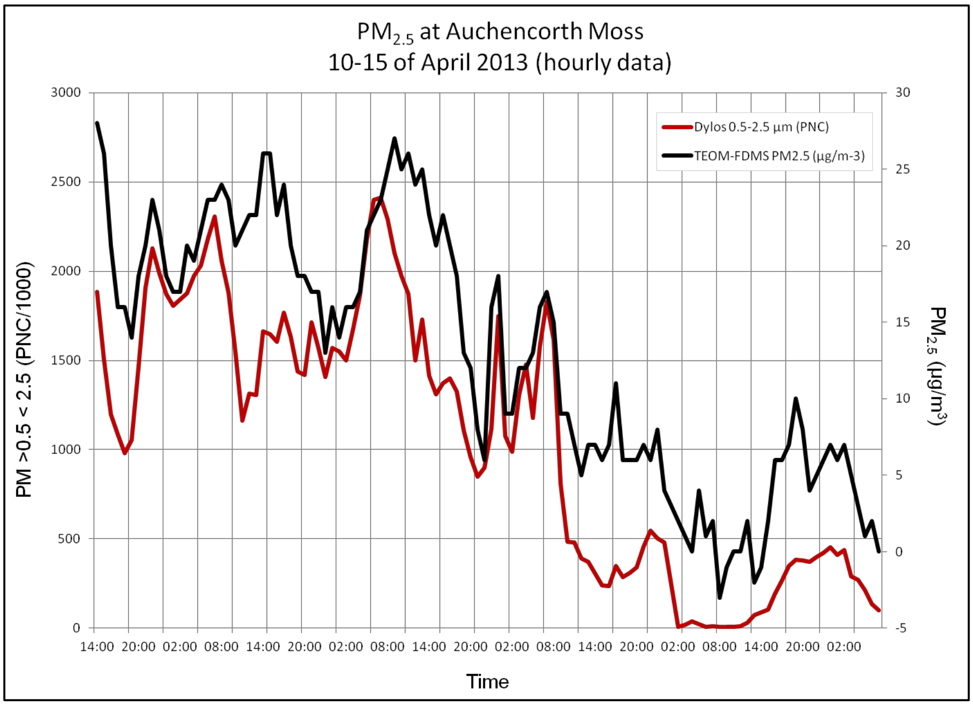


Figure 4-2 Auchencorth Moss TEOM-FDMS hourly data (µg/m^3) and Dylos hourly data (PNC) calculated from 1-mintue logs during the co-location period 10-15/04/2013

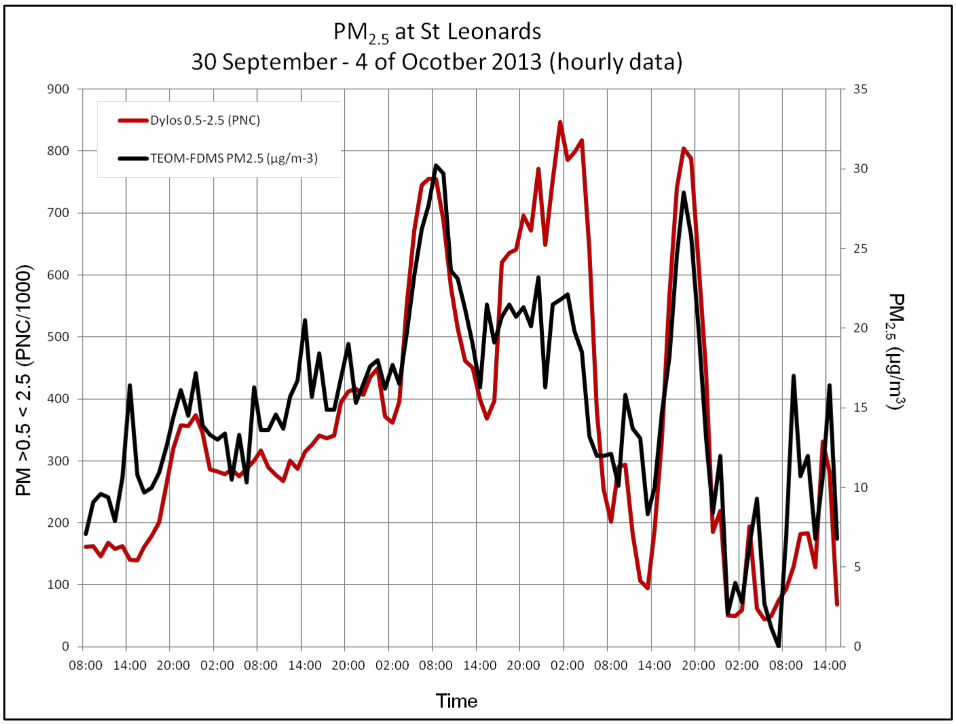


Figure 4-3 St Leonards TEOM-FDMS hourly data (µg/m^3) and Dylos hourly data (PNC) calculated from 1-mintue logs during the co-location period 30/09/-04/10/2013

The TEOM-FDMS instruments at both sites output data as hourly averages (also as daily values at Auchencorth Moss measured with the Partisol sampler (Thermo Fisher Scientific Inc., USA)). Therefore the Dylos observations were processed to calculate hourly averages from the data collected at 1-min resolution (Figure 4-2 and Figure 4-3).

Figure 4-4 displays the scatter plots for the standard major axis regression of the Dylos and TEOM-FDMS hourly data at both locations chosen for this field experiment. The correlations between the Dylos and TEOM-FDMS at both monitoring sites are good: R^2 = 0.9 at Auchencorth Moss and R^2= 0.7 at St. Leonards. Similar results (not displayed here) were found for the MARGA at Auchencorth Moss (R^2=0.8) in April and the OSIRIS at St. Leonards (R^2=-0.6) in October respectively.

The TEOM-FDMS data routinely undergoes quality control and has to be ratified before it is officially released to the public (e.g. on the Scottish Air Quality website). For this co-location study, quality-controlled data from the TEOM-FDMS for the October measurements at St. Leonards were directly obtained from the local site operator, Bureau Veritas prior to the official release of the data.

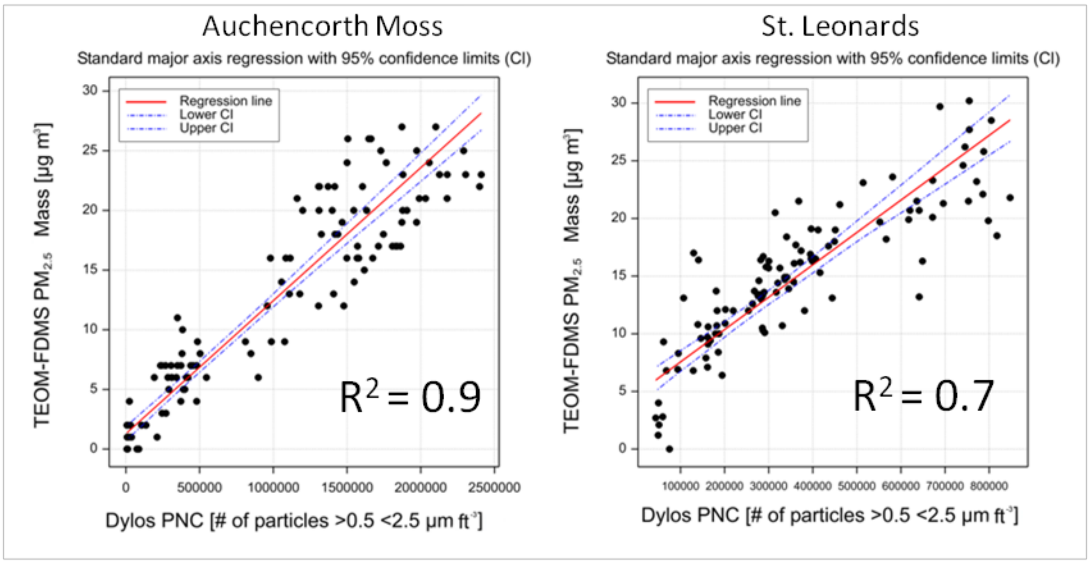


Figure 4-4 Comparison of hourly-average Particle Number Counts (PNC, # ft^{-3} for particles between 0.5 and 2.5 µm) from the Dylos monitor and $PM_{2.5}$ Particle Mass (in µg/m^3) from the TEOM-FDMS instruments at Auchencorth Moss (left) and Edinburgh St. Leonards (right).

The correlation for PNCs and temperature at Auchencorth Moss is relatively high R^2 = 0.78. This strong correlation coefficient (R^2 value) can be explained by a change in weather conditions (primarily wind speed (from ~5 m/s to ~15 m/s) and direction (from E/SE to predominantly S/SW) – resulting in decreasing temperatures and PM concentrations towards the end of the co-location period. It is therefore thought that the correlation between PNCs and temperature does not reflect a causal relationship, which was confirmed by identifying the composition of the PM aerosol mass concentration measured by the MARGA (cf. Twigg et al., 2014). This data (Figure 4-5) shows a substantially larger contribution of SO_4^{2-} and NO_3^- in the first part of that period, indicating a dominating influence of long-range transport from continental Europe.

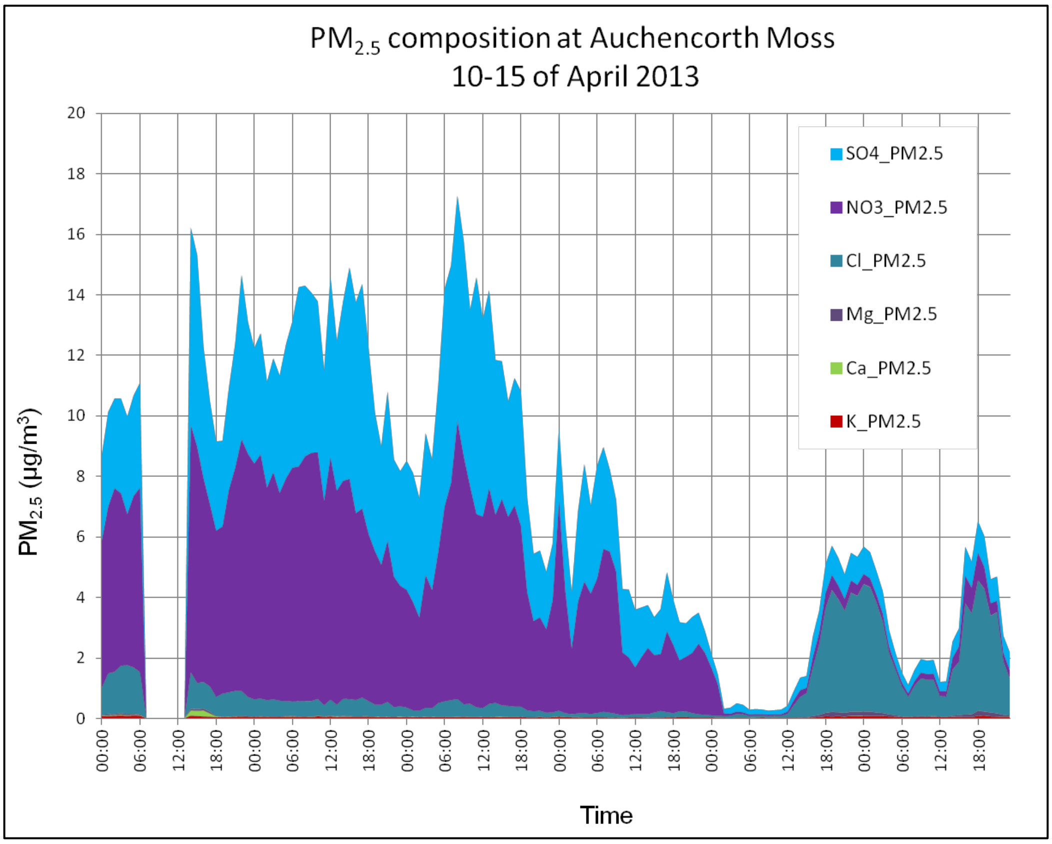


Figure 4-5 $PM_{2.5}$ composition for the period 10-14th of April 2013 at Auchencorth Moss. Note that this is preliminary data which has not been ratified yet. Due to a problem with the instrument, Na^+ and NH^{4+} measurements in the $PM_{2.5}$ size range are missing in this graph.

This analysis suggests as well, that the PNC data from the two particle size bins (“small” (> 0.5 µm) and “large” (> 2.5 µm)) measured by the Dylos may be used to investigate ratios between “large” and “small” particle numbers and thus identify source footprints, such as the long-range transport vs. local emissions ratio in the Auchencorth Moss data. A more in-depth analysis of this matter is under way and is in preparation for publication.

4.4 Deriving indicative $PM_{2.5}$ mass concentration from particle number counts

One output of the evaluation process is the development of two functions to derive $PM_{2.5}$ mass concentration from the PNCs monitored with the Dylos during this pilot study. This is a great opportunity since the collected data is in PNC but required as $PM_{2.5}$ mass concentration to be comparable to the measurements done with the TEOM-FDMS. Air quality guidelines and health metrics also refer to particle mass concentrations and not PNCs.

Based on the good agreement between reference instrument (see Figure 4-4) and the Dylos, two distinct functions have been developed to calculate $PM_{2.5}$ mass concentration from the measured PNCs. These functions are applied to all measurements made with the Dylos in outdoor environments. The functions are allocated according to the type of class the person has spent time in (section 3.3.3). Table 4-1 displays the functions derived by (a) Semple et al. (2013) which is applied to all *Indoor* environments, as well as the functions derived for (b) *Outdoor rural* (based on the data from Auchencorth Moss) and (c) *Outdoor urban* (based on the data from St. Leonards).

The indoor function was derived from Semple et al. (2013) with 34 samples collected in smoking and non-smoking households. Homes with open fire places were excluded. The measurement instruments were placed in the main living area and data used for the regression analysis was randomly selected from the full dataset.

Table 4-1 Functions to calculate indicative $PM_{2.5}$ (in µg/m^3) from Dylos hourly-average PNC (in particles per cu ft).

Environment	**Function**	**Source**
(a) Indoor	$PM_{2.5} = 0.65 + 4.16\times10^{-5} \times [PNC] + 1.57\times10^{-11} \times [PNC]^2$	*Semple et al. (2013)*
(b) Outdoor rural	$PM_{2.5} = 1.291 + 1.114\times10^{-5} \times [PNC]$	*this study*
(c) Outdoor urban	$PM_{2.5} = 4.748 + 2.807\times10^{-5} \times [PNC]$	*this study*

Figure 4-6 shows the trends and absolute values of indicative (predicted) $PM_{2.5}$ derived from the Dylos PNC and the observed TEOM-FDMS $PM_{2.5}$ data. For both sites the comparison shows a good agreement between the TEOM-FDMS data and the predicted Dylos data with the observed and predicted values following the same pattern. In the first part of the data from Auchencorth Moss, the exceptionally high values influenced mainly by long-range transport show a lot of fluctuation which is picked up slightly differently by the Dylos compared to the TEOM-FDMS. The difference between the instruments becomes less pronounced towards the end of the co-location period, when strong winds and local particle sources dominated. Note the strong downward trend in concentrations at Auchencorth Moss after approximately 70 hours which is as discussed in section 4.3 down to a change in weather conditions.

The predicted Dylos data for St. Leonards follows the observed data generally well, with the nature of the urban background station and the slight difference in inlet height for the TEOM-FDMS (on the roof of the cabin) and the Dylos (1 m above ground) may account for the differences displayed. Trends and peak timing and magnitude are well captured, however the Dylos appears to have a higher cut-off concentration, i.e. detection limit than the TEOM-FDMS.

Table 4-2 compares, for each site, the maximum, minimum, mean and median values for $PM_{2.5}$ mass concentrations directly measured by the TEOM-FDMS with the indicative $PM_{2.5}$ derived by applying the functions displayed in Table 4-1 to the Dylos PNC. Both for maxima and mean/median values, the predicted values are close to the observations. The minimum concentration observed by the TEOM-FDMS reach zero which are not replicated by the predicted values, but it is unlikely that zero concentrations will be observed in reality. Zero and even negative values are however a feature of the TEOM-FDMS instruments, in fact the ratification process allows negative concentrations down to -4 µg/m^3 (Air Quality Consultants, 2012).

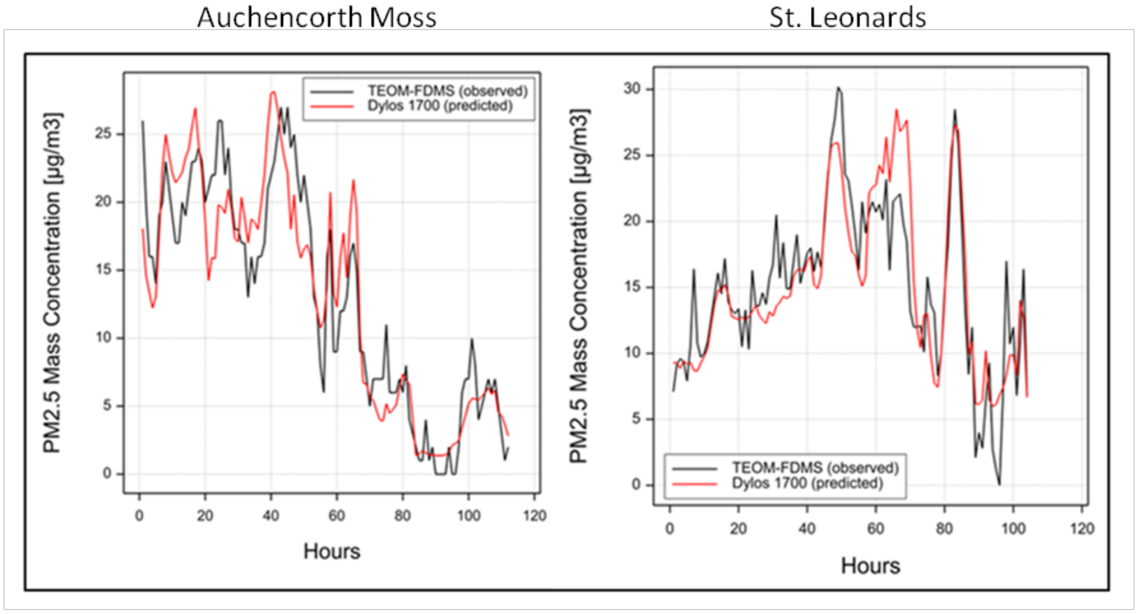


Figure 4-6 Comparison of indicative hourly-average $PM_{2.5}$ mass concentrations "predicted" by the Dylos vs. the TEOM-FDMS observed concentrations in **µ**g/m^3 for Auchencorth Moss (*Outdoor rural*, left) and Edinburgh St. Leonards (*Outdoor urban*, right) as a result of applying the functions presented in Table 4-1. Both the trends and absolute values of indicative $PM_{2.5}$ derived from the Dylos PNC ("predicted") agree well with the TEOM-FDMS $PM_{2.5}$ ("observed").

Table 4-2 Comparison of observations with the TEOM-FDMS and Dylos predictions applying the functions presented in Table 4-1 at both co-location sites (based on hourly values).All values in µg/m^3.

Statistic	Auchencorth Moss		St. Leonards	
	TEOM-FDMS *observed*	Dylos *predicted*	TEOM-FDMS *observed*	Dylos *predicted*
Mean	13.0	13.0	15.1	15.1
sd	8.2	8.2	6.2	6.2
Median	13.5	14.0	14.9	13.8
Minimum	0.0	1.4	0.0	6.0
Maximum	27.0	28.1	30.2	28.5
Range	27.0	26.8	30.2	22.6

4.5 Discussion & Conclusions

The primary purpose of this study is the development of a methodology for personal exposure monitoring in a variety of microenvironments. The reliable performance of the Dylos against other particle monitors has been proven in chamber experiments, indoor and outdoor settings in previous studies (see section 4.1). However an evaluation in different outdoor environments in the study area for this thesis is required to assess the instrument's performance in those specific geographic settings. Referring back to the aim, "*The portable particle counter Dylos DC 1700 is a viable instrument for personal air quality monitoring, providing robust, reliable results when compared to reference instruments in outdoor settings*", here, it has been demonstrated that the Dylos can provide robust and reliable indicative measurements of $PM_{2.5}$ in outdoor environments which compare well against standardised EU reference instruments. This evaluation is taking into account that the measurement of PM is inherently difficult and the reference instruments are prone to inherent, technologically driven uncertainties, which is reflected in the output. Knowing how the Dylos performs in relation to those instruments is vital for the application in future studies, including the development of new, integrated sensor packages based on similar technology, as well as providing a test bed for data handling and analysis.

When applying a personal monitoring approach, the ability to distinguish between different environments is the basis for analysing the data for certain environmental influences. Furthermore the national monitoring networks provide measurements from different environments to account for the influence of sources and environmental conditions on the pollutant concentration. Merging those two ideas in an approach where personalised PNC are converted to particle mass concentrations based on where the person has spent time is therefore a logical consequence. The Dylos PNCs converted into particle mass concentrations are indicative by design, but provide data at a higher spatio-temporal resolution than is available from national AURN data.

The evaluation of the Dylos and the subsequent development of functions to transform PNC into $PM_{2.5}$ mass concentration are reassuring the capability of measuring ambient PM. Results are showing good agreement between the two units of measurement. However, it should be kept in mind that using the Dylos or any other non-reference air pollution monitor is not aiming to establish equivalence with reference methods for measuring PM, but should be seen as a portable tool to generate indicative concentration measurements.

The approach presented here adds to the ongoing scientific discussion - *information content versus instrument precision* - which has intensified since low cost portable pollution sensors have become increasingly available. The results look promising and certainly raise the value of the Dylos low-cost particle counter for personal monitoring in a mixed indoor and outdoor setting. We thus have confidence for our purposes (chapter 5 & chapter 6) that the Dylos particle counter will perform within acceptable bounds for our study.

5 Assessment of a methodology for personal monitoring in a variety of microenvironments

This chapter assesses the feasibility of the study approach taken and monitoring system applied. The performance and synergy of individual tools during the pilot study is evaluated as is the development and application of data processing methods. The discussion includes future potentials and applications of methodology and study design.

5.1 Introduction

With the overall aim of the thesis being to improve knowledge about exposure to particulate matter in people’s everyday lives a method needed to be determined, which was feasible in a real-life study setting. This requires a portable, non-intrusive monitoring solution that is sufficiently sensitive for measuring ambient air pollution, which is at the same time robust enough to be carried around. When working with lay people easy operation is required. If the method is assessed regarding its suitability for citizen science applications, the cost factor needs to be relatively low to ensure that a suitable number of monitors and other equipment can be developed or purchased. The whole approach of personal monitoring also involves dealing with volunteers or citizen scientists, explaining the equipment and collecting information in the form of TADs and questionnaires. The turnaround time between collecting, processing and examining the data with the volunteers needs to be kept to a minimum to ensure maximum recall of activities. The alignment of personal data collected from the volunteers and objective, measured data in a meaningful way and its interpretation is challenging and requires the development of routines to reduce bias and allow for quality control.

In this chapter the methodology and study design developed and applied in a pilot study to assess personal exposure to particulate matter in Scotland are evaluated based on the hypotheses listed in section 1.2, specifically discussing:

b) Method and study design applied are feasible for monitoring personal exposure to particulate matter in everyday microenvironments.

Feasibility in this context relates not only to the performance of the technology and the data analysis approach, but covers the whole process from recruiting the volunteers to interpreting the data and providing feedback.

5.2 Methods

5.2.1 Personal monitoring solution

For this small scale pilot study, a non-scripted, multi ME study design was selected where people were instructed to pursue their usual activities and habits, as elaborated in section 2.6.1.3.

The personal monitoring task in this study required a portable or wearable monitoring solution which not only measures pollutant concentration but at the same time records geolocation data.

For monitoring particle number counts (PNC), we used the Dylos as described and evaluated in more detail in section 3.2.1 and chapter 4. With the key features of the monitor being its low weight, reasonably small size and the ease of handling it, it is well suited for use in personal exposure measurements. It provides PNCs >0.5 µm and >2.5µm aerodynamic diameter which need to be converted to $PM_{2.5}$ particle mass concentration in order to be directly comparable to reference air pollution monitoring data and limit or target values set by air quality legislation.

The geolocation data was recorded with a GPS receiver, the GPS Trackstick (section 3.2.2), which was chosen for this study because of the small form factor and the ease of use. Unfortunately it was not possible to integrate concentration and geolocation measurements in one device to get a mutual timestamp, as currently no commercial devices exist that fulfil all requirements as laid out in 2.6.1.3. Thus the datasets had to be combined after the data collection. Together with the GPS, the Dylos was attached to a small backpack. Four of these monitoring packs were built to allow for parallel data collection and flexibility enabling the volunteers to decide when it suited them best to take a monitoring pack.

To carry out the measurements with the monitoring packs, 17 volunteers from the Centre for Ecology & Hydrology (CEH), where this PhD project has been carried out, were recruited. Data was collected in two phases between September - December 2012 (Phase 1) and May 2013 (Phase 2) to cover two seasons and identify potential differences in time-activity patterns and concentrations.

A TAD and a questionnaire were prepared as online web forms. For the TAD people were encouraged to take their own notes in a prepared 24 hour matrix or use their own notebooks during the monitoring and later transcribe this information to the web form. It was recommended that volunteers look at the TAD beforehand to familiarise themselves with.

In mandatory follow-up meetings volunteers were shown the data they recorded. Volunteer and researcher discussed the data and open questions from both sides in these meetings. The volunteer was asked to provide feedback concerning the monitoring period, the monitoring pack, the individual devices, issues and other observations regarding the project.

Monitoring pack, TAD and questionnaire were all tested before the actual data collection by additional volunteers and the researcher. Valuable feedback especially regarding the TAD and questionnaire was received and incorporated before the actual data collection phases started. Despite this amendments were made to the web forms during the pilots study.

5.2.2 Data processing

Data was downloaded and processed as describe in section 3.3.1 to create a data file with GPS and PNC data and TAD information. This personal exposure profile dataset with concentration, location, time and TAD information was analysed and the activity spaces the volunteers had visited during the monitoring period extracted. Based on the GPS data and the Scottish Government Urban Rural Classification as well as TAD information each data point was allocated a class to allow for distinguishing between the characteristic background pollutant concentrations (section 3.3.3).

Six distinct MEs were identified to analyse time-activity patterns, lifestyle and exposure differences (section 3.3.2). This is an important step in the analysis process as people are constantly on the move and hence exposed in many different environments and activity spaces with different pollution levels. Places or in this case MEs, have a dynamic influence on health because certain places are more or less relevant to human wellbeing which is again determined by the length of time and how regular time is spent in those particular places (Rainham et al., 2008).

Transport modes used by volunteers during their monitoring period were assigned alongside with other contextual information (section 3.3.1). Functions to derive particle mass concentration from the measured PNC in outdoor urban and rural environments were developed and applied. A function to derive $PM_{2.5}$ mass concentration for indoor environments was developed by Semple et al. (2013) and was applied to the data collected in indoor MEs in this study.

5.3 Evaluation of the feasibility of methodology and tools applied

5.3.1 Approach

5.3.1.1 Study design and interaction with volunteers

Study participants were typically asked to take the monitoring equipment for a minimum of two days, the maximum profile length was six days. Unlike as discussed by Lawless et al. (2012) there was no set sampling protocol to assure wearing compliance to guarantee relatively comparable circumstances for each profile collected. Instructions on how and when to carry the backpack were deliberately kept flexible to allow people to make their own decisions about whether it was feasible to take the monitor with them or not, as this is part of the second aim as listed in section 1.2:

a) Assessment of a methodology for personal monitoring in everyday microenvironments.

Given the exposed design of the monitoring pack (section 3.2.3) volunteers were instructed to cover the Dylos to protect it from rain. It was down to the volunteer to decide when the monitor had to be covered or not. At any time when the monitor was still sampling while in a backpack or covered by a pannier, the data recorded was deemed invalid and had to be excluded, as no uninhibited air flow could be assumed. Because of this, some of the profiles collected have gaps of a few minutes (e.g. P1-12, P2-04, P2-06), while others contain mainly indoor measurements (e.g. P1-03, P1-18).

In indoor environments people were instructed to leave the monitor static in one place, plugged in to mains power as the device only has a battery life of roughly six hours and needs to be fully charged to ensure battery lifetime long enough for commutes and non-stationary activities. When the monitor was moved within the home ME, for instance from the kitchen to the living room this had to be recorded in the TADs. Some participants, however, decided to carry the monitor with them in these environments all the time e.g. P2-05 (section 6.3.4.4). This was noted in the accompanying TADs, as well as discussed in the follow-up meeting. Instructions to leave the monitor stationary are not ideal with regard to monitoring in or near the breathing zone. The data in this study were however, aggregated into specific MEs which represent a space with homogenous pollutant concentration. Studies looking at the spatial variability of particles in homes also found that inter-room transport minimises the variability of particle levels between rooms quickly after a source event happened (Jones et al., 2007, Wallace et al., 2008) which was also seen in some of the profiles in this study e.g. P2-05 (section 6.3.4.4). It is therefore assumed for this pilot study that exposure is the same within an indoor ME, be it the same room or the same building. The author cautions against assuming that these results accurately reflect the exposure an individual experienced when being permanently in the vicinity of the source or in a different room behind closed doors as seen in one of the profiles discussed in chapter 5 (P2-02, section 6.3.4.6). Information about where the monitor was placed in the respective indoor ME was collected to potentially allow for source identification within indoor MEs.

Generally, the instructions given to volunteers seemed to work well, but occasionally additional questions regarding the handling of the devices occurred after first steps with the equipment. Since researcher and volunteers were all, apart from one person, based at CEH this was straightforward to deal with in a brief meeting.

Common errors during the pilot study were related to the battery life of the Dylos i.e. it was forgotten to charge the device overnight/when somewhere stationary for a longer period of time (e.g. P1-01, P1-07 and P2-05). As a result, some profiles have data gaps, for instance during transport as people realise they forgot to charge the Dylos when they depart from home.

Occasionally participants forgot to switch the GPS receiver on or back on after a longer period had been spent indoors. The integration of GPS and air quality monitor to create a common timestamp in combination with a strong power supply could substantially reduce the occurrence of these errors.

It was left to the volunteers to decide when it was feasible or suitable to take the monitor with them. Main reasons for leaving the monitor behind are related to the exposed design of the monitoring pack during activities involving water splash (surfing P1-06), precipitation (P1-03, P1-18) or the noise of the fan (P1-17, P1-14). Although this has not been explicitly noted or expressed in TAD and follow-up meetings in this study, other studies (Lawless et al., 2012) have identified the possibility of embarrassment causing the volunteers to leave the monitor behind. Some profiles have gaps when the person went to the gym or a party and left the monitor at home. This may not only be related to practicality issues, but also to embarrassment. Volunteers reported back that they have been stared at when wearing the monitor in public places which may impact on the person’s comfort and alter their behaviour. As stated in section 2.6.1.2 taking part in a personal monitoring study will always involve a certain degree of intrusiveness and a certain burden for the volunteer is unavoidable.

Interaction with the volunteers was relatively straightforward since they were all, apart from one person, staff or students from the same research institution as the researcher. Handing over and returning the equipment was easy as people could be directly approached without having to arrange specific meeting points. Meeting face to face was therefore the preferred way of communication and meetings could be arranged at short notice before, during and after the monitoring period. The proximity of volunteers and researcher also allowed a certain flexibility should a volunteer have to shift their monitoring period at short notice. This is of course a special feature of this pilot study and other studies where the researchers and volunteers are from the same institution (e.g. Delgado-Saborit, 2012) or in single participant studies (e.g. Greaves et al., 2008). This has to be incorporated and taken into account, however, when planning a bigger study where researchers and participants are not based in the same location and do not know each other, as it is likely to be logistically more challenging and more time-consuming.

For future studies the aim should be to set up a second follow-up meeting once the data has been analysed, to provide and inform the volunteer with their individual exposure profile and potential consequences with respect to adverse health impacts and well-being, as done by Semple et al. (2013) for instance. Informing the public and rewarding the volunteers for their participation is an important part of exposure studies, which rely on people interested in the topic and who are willing to participate as volunteer and study subject.

5.3.1.2 Time-activity diaries, follow-up meetings and questionnaires

The TADs are an important source of information. Times and locations as well as specific activities could be allocated to measured PNCs and matched to GPS logs. Volunteers took notes at varying degrees of detail on the timing of activities which were discussed in the mandatory follow-up meetings. These meetings proved to be a very important source of additional information. For example, one person had a distinctive peak in their profile which could not be immediately explained in the TADs. During the follow-up meeting the person remembered that they had visited the train station to collect tickets during the respective week but could remember neither the exact date nor time. The receipt from the ticket machine, however, clearly identified date and time of this activity (P1-17 section 6.3.4.3). “Landmarks” such as doctor’s appointments or theatre visits helped the volunteers remember their activities, and receipts from shops or other occasions also helped to determine the exact times of activities and places visited. Generally any kind of time stamped data can provide useful context for pinning down time-activities and location which then can be matched with the measured air quality data.

Feedback on the TAD from volunteers during the first pilot phase was used to improve its design and to rephrase questions in order increase clarity for the web form applied in Phase 2 (Table A 2). In Phase 1 the *“other (please describe)”* option was often used to add additional information about the volunteers whereabouts in free text. Therefore a space for *“notes”* was added in the TADs to enable them to add additional information, which was received positively by the volunteers. Based on the feedback, the question about the amount of time spent doing a certain activity has also been edited to *“from when…until when”* the respective activity lasted which improved the allocation of activities to concentration data substantially.

The time resolution used in the TAD was 15 minutes, however volunteers often kept more detailed temporal information in their own notes and transcribed this information to the web form later as free text. Here issues occurred with the 15 minute time step introduced for the online TADs: it had been viewed as being not sufficiently detailed as the duration of activities often lies in-between. This caused mismatches when transcribing handwritten notes into the web form. Additionally, providing information about start and end date/time of the monitoring period caused confusion. This section was therefore removed for Phase 2 and only the date of the monitoring day for which the TAD was filled in had to be provided. When talking through the data during follow-up meetings it became apparent that it is difficult to accurately track activities in shared accommodation, as observations are influenced by activities of dwellers other than the volunteer. This aspect is not easily captured in TADs and volunteers often found it challenging to adequately recall and report on all activities in the accommodation.

One person provided the TAD information only as plain text in an email, while another person provided only sparse information in paper format. In both cases more information was extracted during the follow-up meetings. It has also be noted that the TADs for the “end” days of the monitoring period are often not provided as people basically only get up and commute to work where the monitoring equipment is returned. This information was again provided in the follow up meeting.

In Phase 2 there were some issues with the web form regarding the monitoring date which was sometimes shifted by one day. Extra care had to be taken when processing this information to match it with GPS and pollution data.

The researcher’s impression was that volunteers preferred to write their own notes in free text and use the free text options in the web form to add this information. This allowed the volunteer to write down exact times, activities and other information regardless of any categories provided. The web form was then used to match the data with the GPS and PNC data before the follow-up meeting. Here often inconsistencies with the 15 minute time step and the temporarily more detailed notes in the free text “notes” box were noted. Therefore the follow-up meetings were crucial to revise and clarify time-activity information. Naturally, these follow-up sessions needed to occur as soon as possible after the measurement period to aid maximum memory recall. Some volunteers had to be reminded and urged to take part in these follow-up meetings. However, in this study where researcher and volunteers were based in the same building the meetings could be arranged easily without much organisational effort. Generally though arranging such meetings with every individual volunteer is time-consuming, especially because the actual meeting itself did not last very long (in the order of 15 minutes). For a larger scale project the aspect of collecting time-activity and contextual information will have to be reconsidered to improve the ease of use for the volunteer and the information content for the researchers. Electronically aided TAD or voice recorders as applied in other studies (e.g. Kaur et al., 2005) should be considered.

The questionnaires used in Phase 1 were substantially revised based on feedback from volunteers, edits in the TADs and experience. So were information about the transport mode and questions about the use of the monitoring equipment removed as this is already covered in the TADs on a day-to-day basis. The questionnaires applied in Phase 2 were therefore shorter and less time-consuming to fill in which contributed to reducing the burden of the volunteers. All necessary information was still in the edited web form which was important as people who took part in Phase 1 did not have to fill in another one, unless they have moved house in between the fieldwork phases, which was the case for one person. Data from the questionnaires was required for characteristics of the study population but also to gain information about contextual factors which could potentially influence PNC and exposure pathways such as housing and neighbourhood characteristics.

Some people did not fill in all categories of the question *“Home-location characteristics - Is your home within range of one of the following features? Please choose the approximate category”* (Table A 1). Where data was missing the author assessed the distance based on geographic data and answers from volunteers living in the same area.

5.3.2 Monitoring devices

5.3.2.1 Particle counter

Considering the Dylos is designed for indoor use, it was taken out of its comfort zone by applying it in a mixed indoor/outdoor setting. Handling and operation of the Dylos is relatively straightforward with no calibration or programming required, which makes it an attractive choice for personal exposure research where lay people are handling the devices (Semple et al., 2012). So does the simple and lightweight design with one button to switch it on/off. Both the low noise fan and the easy operation are in line with the requirement of being able to apply the monitor across the full diversity of MEs visited which we put forward in the conceptual model discussed in Steinle et al. (2013) and section 2.6.1.3. The comparatively low unit cost is also a key advantage of using the Dylos for personal exposure and citizen science studies where a sufficient number of sensors are required for simultaneous data collection. Extracting data from the Dylos is straightforward with an USB-to-serial adapter and the provided software. Finally, the temporal resolution of 1 log per minute allows for detailed assessment of the variability of ambient PNCs and subsequently particle mass concentration in time, and - in combination with GPS and TAD data - in space.

Being based on a light-scattering device, the Dylos measures particle number counts. The lower detection limit of the Dylos is described by the manufacturer as being at 0.5 µm particle diameter. With this cut-off the analysis misses out on UFP which are potentially more harmful to human health (section 2.4) and have a large variety of sources in both indoor and outdoor environments. Nevertheless the Dylos’ performance against reference instruments was evaluated (chapter 4) based on the application of functions to transform PNC into $PM_{2.5}$ µg/m^3. This transformation is required to get the data in a unit generally used by other instruments applied in personal exposure research (2.5.4.5 and 2.5.5.2), reference instruments and air quality guidelines.

The limitations of using the Dylos are partly due to the fact that it is originally designed for indoor use and therefore not waterproof, which restricts its use during rain and for any activity involving potential water splash. Volunteers protected the monitoring pack in backpacks or panniers during rain and data recorded during this period had to be excluded. There were a few other situations where it was not possible or not comfortable for the volunteer to carry the monitoring pack. This includes vigorous activities like running where the pack has been left at home or in the car. Although being a low noise instrument compared to the e.g. the TSI SidePak AM510, it has been considered too noisy for certain MEs and activities, in particular in the bedroom. Generally the monitor was placed in living or dining rooms, kitchens or studies; only one person took it to the bedroom during the night (P2-04). Secondly the device was considered as being too noisy for events such as concerts or theatre visits. These are, however, restrictions which lie in the nature of the activity and apply for most instruments using an active airflow.

The built-in battery life of the Dylos lasts for approximately six hours which results in data gaps when people are on the move a lot, without the opportunity to plug and recharge the monitor in between. For longer monitoring periods it also needs to be considered that the Dylos can only store 10,000 log entries in its built-in memory, which corresponds to ~6.9 days, subsequently overwriting the oldest logs. First tests with a polymer battery pack (Intocircuit Power Castle Powerbank 26,000 mAh) which outputs 12 V at 1 A, as well as 5V via USB extends the Dylos' lifetime away from mains power to about 27 hours but adds 670g weight to the pack and additional costs of ~£80.

While the Dylos is small and lightweight enough to be used as a personal monitor it would be preferable if the size could be further reduced and the form factor improved. Integration with the GPS receiver would also be more than beneficial to any personal monitoring approach.

5.3.2.2 GPS

The GPS Trackstick applied in this study is small, lightweight and easy to carry and provides high resolution spatiotemporal data. The minimalistic one button design on the one hand makes handling it relatively easy but on the other hand causes handling errors. Generally the GPS covered the outdoor movements very well, logging a point approximately every 10 seconds depending on signal quality. In-built up environments, especially in streets with high buildings which block the sky, the GPS receiver was struggled with getting enough signal coverage. As GPS receivers generally struggle with signal strength in indoor environments, and to preserve battery life, volunteers were instructed to switch the GPS off when they reached their destination and spent longer time periods indoors. Location information for these periods was based on the TADs and in particular on discussions during the follow-up meetings. This worked reasonably well, however occasionally volunteers forgot to switch the GPS back on. The GPS receiver also takes a few minutes to a find signal again once losing it due to obstruction or when switched off. Hence the first few minutes of the tracks after leaving an indoor or built-up environment are often not covered, although they can be traced with TAD information. Note that as described in section 3.3.4 the GPS logs in the vicinity of *Home* and *Private residential buildings* have been set to “NA” in this thesis for confidentiality reasons and to keep at the same time, the data point which includes the concentration and contextual information in the dataset. Therefore the beginning and/or end of many tracks are not displayed in this thesis.

The manufacturer reports a battery lifetime of between three days and eight weeks depending on battery type, signal strength and power mode. However, we occasionally experienced issues with unexpectedly short battery lifetimes, which may be related to signal acquisition issues indoors. This is partly due to the minimalistic design of the GPS which does not provide a read-out. Battery and signal status are both indicated by a small LED which is not clearly visible and led to occasional handing errors as the status of the GPS was unclear. The LED flashes green when the device has signal and red when it does not have signal. This seemed to confuse volunteers occasionally as they thought a red flashing LED meant the batteries were low on power (this actually is indicated by solid red – Super Trackstick or alternating red/green Trackstick II). A clearer indication of the battery status and remaining lifetime would be beneficial. Occasionally there was also confusion about the status of the device due to it being labelled as 1 (on) and 0 (off) next to the power switch. This resulted in missing data. The advantage of not having a display is the same as with the Dylos (section 3.2.1): volunteers do not worry about “wrong” data displayed and the likelihood of them adjusting their behaviour is reduced.

5.3.2.3 Monitoring pack

The design of the monitoring pack allows the instruments plus additional equipment such as the mains adapters, batteries, charger, notebook and other belongings to be carried all in one backpack. Using a backpack also provides flexibility in the way the monitoring pack is carried e.g. on the back, front or over the shoulder or strapped onto a bigger backpack depending on the person's preference, comfort and specific activity. This setup has proven to be feasible for most MEs and activities as it had been postulated in the conceptual model (Steinle et al., 2013) and section 2.6.1.3.

Limitations arise due to the non-waterproof design of the pack or the inconvenience of carrying the monitoring pack for the volunteers. One person for instance mentioned that it was too much to carry and handle when picking up their child from nursery and therefore the monitor was left in the car.

With respect to the location of the monitoring pack we are aware that measurements were not taken from within the breathing zone (within 30 cm of nose and mouth as postulated by Nieuwenhuijsen (2000)). It was left to the volunteers to decide how to wear the monitoring pack to reduce the burden of a prescribed setup. Usually the monitoring pack was carried lower down the torso, mainly on the back, occasionally over the shoulder or in front of the body. When stationary it can be placed anywhere and thus the measurements are not taken from a standard height. This simplification is not likely to substantially affect measurements however, as Cattaneo et al. (2010) found that concentrations of fine and ultrafine particles measured in the breathing zone as well as near the subject do not show significant differences. With this in mind, and the fact that this research is interested in the variability of concentrations between MEs and not the actual dose received, the back-carried solution and the added comfort and ease of use are of more relevance for testing the feasibility for personal monitoring and citizen science applications, than the potential for insignificant differences by not positioning the device in the breathing zone. Future developments of smaller, integrated devices aim to allow for easier ways to measure within the breathing zone.

5.3.3 Data collection, processing and interpretation

5.3.3.1 Phase 1 – September – December 2012

Twelve volunteers collected 19 personal exposure profiles of different length over the months September to December 2012, with the bulk of data being collected in November. Five individuals took the monitoring equipment with them twice, one person three times. The completeness of the profiles with regard to the monitor recording for the full time period and the GPS recording at all times when outdoors, varies based on technical issues and human errors, as well as on the activities undertaken, MEs visited and weather conditions. Out of 62 days in which people conducted monitoring only seven have full 24 hour coverage, due to issues with battery life and charging, the feasibility of carrying the monitor for certain activities as well as the fact that start and end days do not provide full 24 hour coverage. Altogether, 15 out of 19 profiles are comprised of more than 24 hours of data.

It was not specified which activities or locations should be monitored and people could volunteer for taking the monitor when and for how long it suited them best, regardless of their plans. Therefore profiles from Phase 1 included between two and six days of monitoring. This phase included six weekend profiles and one holiday profile (days of arrival/departure as well as one day during the holiday have been monitored). All volunteers in this phase were working at the same place, CEH, although not all profiles include the work ME.

Data from Phase 1 were the basis for developing, testing and improving data processing steps as well as defining MEs and transport modes which were then applied to Phase 2 data as well.

5.3.3.2 Phase 2 – May 2013

For Phase 2 twelve volunteers were recruited, of which seven had already been involved in Phase 1. Data was collected in May 2013 and is comprised of 16 profiles of different length. Two volunteers completed two monitoring periods, one person three. Out of 50 days that people had a monitor with them, six have the full 24 hour coverage. The number of profiles comprising more than 24 hours of data is 15 out of 16 which was an improvement specifically aimed for.

For this phase it was more difficult to recruit volunteers due to the time of year as many people were away (holiday, fieldwork season) and also the novelty of being part of this project may have worn off. People also might have felt uncomfortable wearing the monitoring pack or it was inconvenient for them carrying it in Phase 1 and therefore decided not to take part in Phase 2. It was specifically aimed to cover 24 hours without gaps in Phase 2, thus only four profiles include weekends and no holiday profiles were recorded. The profiles are hence generally shorter, often just about the requested 24 hours. The longest a person had the monitoring pack with them was six days although this profile has many data gaps due to the weather conditions and activities conducted.

Detailed analysis and discussion of the data derived in the two phases follows in chapter 6.

5.3.3.3 Data Processing

The first step, matching the PNC as measured by the Dylos with the GPS data was done with a FME workbench developed for this purpose. This step has been automated as far as possible to both ensure consistent data quality and reduce the time required for recurrent processing tasks. Issues arise with the different time and date formats provided by the two devices, and also the way the device management software handles date and time formats. Because of this the date and time always have to be checked and, in most cases, converted before the actual merging process takes place. All data has been analysed with a FME workbench incorporating all the steps. Meanwhile a better routine dealing with date and time has been developed and applied to later analysis steps.

Matching real locations, times and activities noted by volunteers with the objective data recorded by the GPS receiver was challenging. Issues of time shifts between GPS log, TAD and more detailed notes have been described in section 5.3.1.2. The matching of MEs and timestamp and, in a further step, the transport mode is based on the evaluation of the author and this matching had to be conducted manually, introducing a potential for handling error or bias. This contextual interpretation of the data is crucial but at the same time difficult, subjective and to a certain extent crude. Categorising some locations into specific MEs is not immediately obvious (section 5.3.3.4). Often the time-activity information is not detailed enough or does not exactly match the GPS data to identify clearly when the change between two MEs happened. This resulted in periods of uncertainty or ambiguity, where decisions had to be made on assignments to one or the other ME. In the following this will be referred to as "grey areas".

Based on the lessons learned from Phase 1 and the development of analysis methods, more detailed and targeted specific questions were introduced into the TADs as well as in the follow-up meetings, to reduce bias and ambiguity and to increase the information content gained with data collection at the same time. In the long run, small USB cameras, smart phones for ad hoc TAD entries, voice recorders and other techniques improving the GPS signal (in particular indoors) and the detail of time-activity information respectively could help overcome some of these issues (Steinle et al., 2013). It is also worth mentioning that research is going into the automation of such data matching e.g. Mavoa et al. (2011) who looked at matching GPS data and travel-diaries automatically with sequence alignment algorithms.

Data where the monitor has been left in cars, at home or was covered in bags to protect it from rain has been marked under “comments” and has been excluded from further analysis

5.3.3.4 Microenvironments, transport mode and class

The choice of MEs has been based on the data collected in Phase 1 of this study as well as on MEs commonly used in research (section 2.5.1). The process of identifying suitable MEs to aggregate all activity spaces had to be done manually and was entirely based on the author’s interpretation. All locations recorded by volunteers in Phase 1 were listed and assigned to a suitable group. While the indoor MEs were relatively easy to interpret with a clear cut-off of which location fits into which ME, the *Outdoor other* and *Transport* ME required more discussion. It is clear that the ME approach introduces a certain amount of generalisation. The great advantage of the detailed TAD information derived is that the dataset still allows individual activities and locations to be distinguished.

Outdoor other also includes transport, namely when a person has been walking or cycling for leisure, in comparison to walking or cycling to get from place A to place B. This does of course not apply when the person is using a motorised transport mode, like the train, for leisure activities. Therefore it occurs that the same trip - the person cycles somewhere for leisure (*Outdoor other*) and takes the train to return (*Transport*) covers two different MEs. As a result of this categorisation the amount of cycling and walking in the dataset is actually higher than the data reflects, due to this ME allocation (Table 6-8). *Outdoor other* also includes a mix of indoor and outdoor environments in a few cases where people have been strolling around the city centre, and visiting variety of shops but did not take detailed notes of when they have been inside the building and the GPS data was insufficient to determine their location.

The MEs *Home* and *Private residential building* are generally the same type as a private residential building is nothing else than someone else's home. However, it was considered important to distinguish between those two activity spaces which are naturally at different locations. The activities in *Private residential buildings* are also slightly different from the *Home* environment. For example when people have been invited for dinners or parties with a group of people present larger than would be the case at *Home* which can influence a person's exposure.

Within the *Transport* ME each data point has been assigned the respective transport mode (*Bus, Bicycle, Car, Ferry, Train* and *Walk*). Difficulties arise here when a switch between transport modes has happened e.g. a person *Walk*s to the bus stop, takes the *Bus*, gets off the bus and *Walk*s to their destination (e.g. P1-03 section 6.3.4.2 and P2-16 section 6.3.4.5). As mentioned earlier, time shifts between GPS, TAD and detailed notes taken by the volunteers made it difficult to exactly assign the switch between transport modes. When there was conflicting or inconclusive data on the exact time of the switch an assessment based on the researchers knowledge of the area was made.

The assignment of data points to the respective classes relies firstly on the assignment of MEs. All indoor MEs fall into the *Indoor* class. To distinguish between *Outdoor rural* and *Outdoor urban* the Scottish Government Urban Rural Classification map has been used together with the available GPS data (section 3.3.3). The matching between GPS and URC map is made using a FME workbench and works well as long as the data is within the borders of Scotland. One profile included a train journey to England. In this case a crude assessment based on the knowledge of the area and the GPS points displayed together with Ordnance Survey (OS) maps in ArcGIS was conducted. When no GPS data was available an assessment based on TAD was made.

The idea behind the three classes is based on the differences in background concentrations in those three environments. Despite air exchange, indoor spaces are distinctively different from outdoor spaces and hence exposure in indoor MEs is different as well, as concentrations present a combination of influx of outdoor air and indoor sources (including the personal cloud).

5.3.3.5 Transformation of PNC into particle mass concentration

The Dylos measures PNC in the two size bins “small” (>0.5 µm) and “large” (>2.5 µm). This labelling is not intuitive as the “small” size class includes “large”.

To directly compare with other measurements, the units have to be transformed into $PM_{2.5}$ particle mass concentration. This makes the interpretation of the data much easier as it is the unit commonly used for air quality legislation. Reference instruments also operate and deliver results in particle mass, as exposure effect relationships and air quality limit values are expressed in $\mu g/m^3$. The functions applied to the measured data are shown and discussed in chapter 4.

The actual transformation of the PNC into $\mu g/m^3$ is based on the classes to which the individual data points have been assigned to (section 3.3.3). Firstly the $PM_{2.5}$ fraction of the PNC is calculated by subtracting “large” PNC from the “small” PNC to derive a count of all particles > 0.5 and < 2.5 µm in aerodynamic diameter. Then the functions are applied. The whole process is done within one FME workbench. Deriving $PM_{2.5}$ $\mu g/m^3$ based on the class i.e. taking into account the coarse activity spaces, adds another layer of detail to the personal exposure assessment process.

5.4 Discussion & Conclusion

A methodology to collect high resolution (both temporally and spatially) data on human exposure to fine particulate matter was developed and tested. The purpose of the pilot study was to test the feasibility of the individual components, and the applicability of devices and other tools when handled by volunteers, the process for the collection of contextual data, interaction with the volunteers, data processing and analysis steps.

With respect to the hypothesis *“Method and study design applied are feasible for monitoring personal exposure to particulate matter in everyday microenvironments”* the monitoring equipment applied has proven to be feasible for the purpose of this pilot study - exposure monitoring across the full variety of MEs in people's daily lives. The monitoring pack could be taken to almost all MEs visited daily and is suitable for most activities. The main restrictions are related to wet weather conditions and the coverage of activities where the monitoring pack is considered as being too noisy or not wearable, but also to the overall burden of wearing the monitoring pack during daily routines. These criteria – size and weight, ruggedness, non-intrusive design - will apply to a large number of currently available, active air pollution monitors. Despite the limitations outlined above, the ease of use and low-cost of the monitoring pack make it specifically attractive for studies where many monitors are required and where lay people are handling it, for instance in citizen science applications.

Considering this, the field tests conducted with the Dylos in outdoor environments (chapter 4) reinforce its adequate performance in reproducing both the level and variability of ambient particle numbers. Being also portable and wearable it is a viable solution for collecting indicative particulate matter concentrations to assess the spatial and temporal variability of personal exposure in comparison to static approaches based on fixed monitoring site data. The same accounts for not wearing the monitor within the breathing zone. Altogether personal monitoring studies are based on a trade-off between instrument precision, wearing compliance and information content, and it is down to the study aim and purpose where the focus is set. Further research needs to focus on improvements regarding devices and study design, with the aim of allowing for a seamless coverage of all MEs and activities, while reducing the burden to study participants.

Further research is also needed to improve the data processing. This is partly related to further advancements in hardware and technology (e.g. provide harmonised time stamps or delivering data via wireless communications or the internet) but also to tools and study design to collect time-activity information and interpret the collected data respectively. Extraction and processing methods with a substantial manual component are feasible for this small scale pilot study only. In larger scale applications, the amount of data collected will increase substantially and this requires a thoroughly tested and suitable method of processing and analysing the data, including quality control and visualisation. Automated routines for as much of the data processing as possible are required to take this approach further. FME software workbenches provide a powerful tool for data analysis and have already proven to be feasible for individual steps in the data processing. The software enables the design of self-documenting, graphical data flows and process diagrams, quality assessment and control, and flexibility of output generation combined with a transparent audit trail and reproducible, reusable data infrastructures. While this will be relatively straightforward to implement for some parts of the data processing and analysis chain, it is unlikely that automatic processing will be viable for steps such as the actual definition of MEs and the assignment of individual data point to the MEs.

These steps very much depend on further improvements in collecting time-activity data, as well as requiring expert judgement by the researchers, which are not easy to implement in automated routines. As a first step the integration of air quality monitor and GPS receiver will ease the data handling procedure and aid accuracy of the data set, while at the same time reducing the burden to study participants. First and foremost a clearer structure i.e. structured TADs with preset text options, if the study aim is to improve data processing is required to improve the design and application of TADs. This however comes at a cost of potentially receiving less detailed information, as free text entries are usually more informative. Such a trade-off between information detail (information as free text) and easier to process datasets (structured TADs with preset answer options) needs to be evaluated depending on the study aims and the overall setup of the study, including the tools used (e.g. if cameras are used, TADs need less detail on environmental context).

The further development of devices for GPS tracking will be the basis for improving and potentially farther automating the data analysis and contextual interpretation of time-activity patterns. This is however inherently difficult and requires careful evaluation of the data available. In terms of automating the whole process of matching GPS with time-activity information, the application of more objective tools such as cameras or video would be preferable as it reduces bias or misclassification introduced by volunteers taking notes of their own activities and locations. This means, on the other hand, that additional contextual information usually provided by the volunteer in a classic TAD will be lost. As highlighted by Rainham et al. (2010), the researcher needs to be mindful of issues related to data confidentiality as well as potential bias introduced by non-compliance of the participant.

Using the approach introduced in this thesis as a basis for further development into a more widely applicable method, for instance in a citizen science context, could increase both the quality and quantity of data collected on personal exposure to air pollution and thus improve the characterisation of exposure patterns. This requires a working, well structured study design considering all facts from the recruitment of volunteers, over the data collection, extraction and processing. It would further benefit the development and validation of exposure models, in particular supporting the development of up-scaling parameters to larger populations, and informing the design of representative personal exposure studies. However, it should not be forgotten that it requires a lot of commitment and a certain burden for the volunteer to take part in such a study.

Results from this pilot study show that it is difficult to attract a reasonable number of volunteers for a small scale pilot study with the methodology and study design at the current state, let alone a representative or citizen science study without offering more than just an interpretation of and feedback on personal data. Miniaturisation of the devices, integration with devices generically used already by a wider population (e.g. smart phones) and a development in the way time-activity information is collected could improve this. The way the study output is prepared for the volunteer and published, e.g. in the form of a quantitative air quality information, sheet, leaflets and other public information with more general results and advice for exposure reduction and health protection can also help to make personal monitoring more attractive .

In summary, collecting personal exposure data can be relatively straightforward if individuals can be encouraged to take part in such a study, but processing and interpreting the individual components into a comprehensive exposure dataset is an ongoing challenge. The more data one collects, i.e. the higher the spatiotemporal resolution, the better the data processing and analysis infrastructure has to be.

6 Personal exposure in a variety of microenvironments – results from the pilot study

In this chapter, the results from the pilot study and the study design are presented and discussed. This includes the monitoring pack as introduced in chapter 3 and is based on the evaluation in chapter 5.Time-activity patterns and neighbourhood characteristics of the study population are presented and $PM_{2.5}$ concentrations measured put into context. A number of individual exposure profiles are discussed in detail emphasising the variety of contextual influences affecting the ambient concentrations measured and the high level of detail that can be obtained with the methodology applied.

6.1 Introduction

“Profiles” in the context of this thesis refer to individual datasets, monitored at different times and for different lengths by individual study participants. Direct comparisons as often done in scripted studies, where profiles have common features, are therefore not possible. Time-activity patterns and concentrations are compared here between the two monitoring phases in winter 2012 and spring 2013. Individual profiles and exposure situations are discussed in detail. The results are evaluated in relation to the methodology applied and their inherent spatiotemporal component to test the hypothesis as listed in section 1.2, specifically:

c) Depending on environment, personal time-activity patterns and other contextual factors, exposure to air pollution is notably different between individuals, which can be revealed by personal monitoring.

Indicative particle mass concentrations have been derived from directly observed particle number counts (PNCs), based on the method and functions explained in chapter 4. From now on this is referred to as $PM_{2.5}$ ($\mu g/m^3$).

6.2 Methods

The methods applied to prepare and analyse the data have been introduced in chapter 3 and evaluated in chapter 5.

Statistical analyses, data summaries and graphs have been generated with Microsoft Excel software (Microsoft Office, 2014). Summary statistics were calculated with the R *psych* package (R Project, 2013). Profile plots have been designed with the R *ggplot2* package, while the R *openair* package (Carslaw and Ropkins, 2012) was applied to plot the time series of measured AURN data and modelled meteorological data.

For preparing, transforming and integrating different spatial and non-spatial datasets the FME software has been used (Safe Software Inc., 2014).

ArcGIS version 10.1 software has been applied for transforming and displaying spatial and temporal data and calculating the distance between two spatial reference points (ESRI, 2013).

6.3 Results

The number of data points deemed valid for analysis, as explained in section 3.3.1, are shown in Table 6-1. These are the Dylos 1-minute data points that have each been assigned to a specific ME, a transport mode and a class. Note that not every data point has a related GPS log, for instance indoor locations and outdoor locations where GPS reception issues prevented a GPS fix to be established. Summary statistics for Phase 1, Phase 2 and individual profiles can be found in the Appendix at the end of this thesis.

Table 6-1 Overview of data recorded during the pilot study including basic descriptive statistics. Each data point relates to 1 minute as recorded with the Dylos.

	P1	**P2**
Number of profiles	19	16
Number of Dylos data logs (minutes)	50,162	43,331
Shortest profile (minutes)	450 (P1-01)	1,422 (P2-05)
Longest profile (minutes)	5,079 (P1-14)	6,254 (P2-01)
$PM_{2.5}$ concentration range (max-min)	236.4 µg/m^3	264.3 µg/m^3
mean	5.8 µg/m^3	9.0 µg/m^3

6.3.1 Study population and time-activity patterns

6.3.1.1 Study population

The age of the volunteers in Phase 1 was between 27 and 61. Nine of the volunteers were female and three male. One person was a smoker (smoking outdoors only). One person suffered from asthma. All volunteers considered themselves as being healthy at the time of the study.

Four people lived in shared accommodation and seven people in family homes one person was a single occupant. Households had between one and five occupants with the average being two persons per household.

In Phase 2 volunteers were between 25 and 61 years of age. Note that seven volunteers took part in Phase 1 already (these are marked in Table 6-2). Eight volunteers were female, four were male. No smoker was involved. One person suffers from asthma, doesn't use a bronchodilator. All volunteers considered themselves as being healthy. Four people lived in shared accommodation, five were in family homes and three lived in single occupancy. There were between one and five persons per household, with the average being three.

6.3.1.2 Perception of the environment

Distance of the Home ME from certain features

In the questionnaire (Table A 1) study participants were asked to provide information about how far away their home is located from certain features. It should be noted that definitions of the features were deliberately not provided and the assessment was thus based on the volunteer's individual perception of their environment. With most residences being in urban areas the distance to major roads were generally not very far. Even less varied is the distance to parks and green space with all (P2) or almost all homes (P1) located within 1 km distance. In contrast to that most residences were located further away from industrial estates, as industrial areas tend to be located at the fringes of the city of Edinburgh. The distance of the volunteers residences to a farm varies between either being nearby (<1km) or further away (>5km) only two people noted the middle distance.

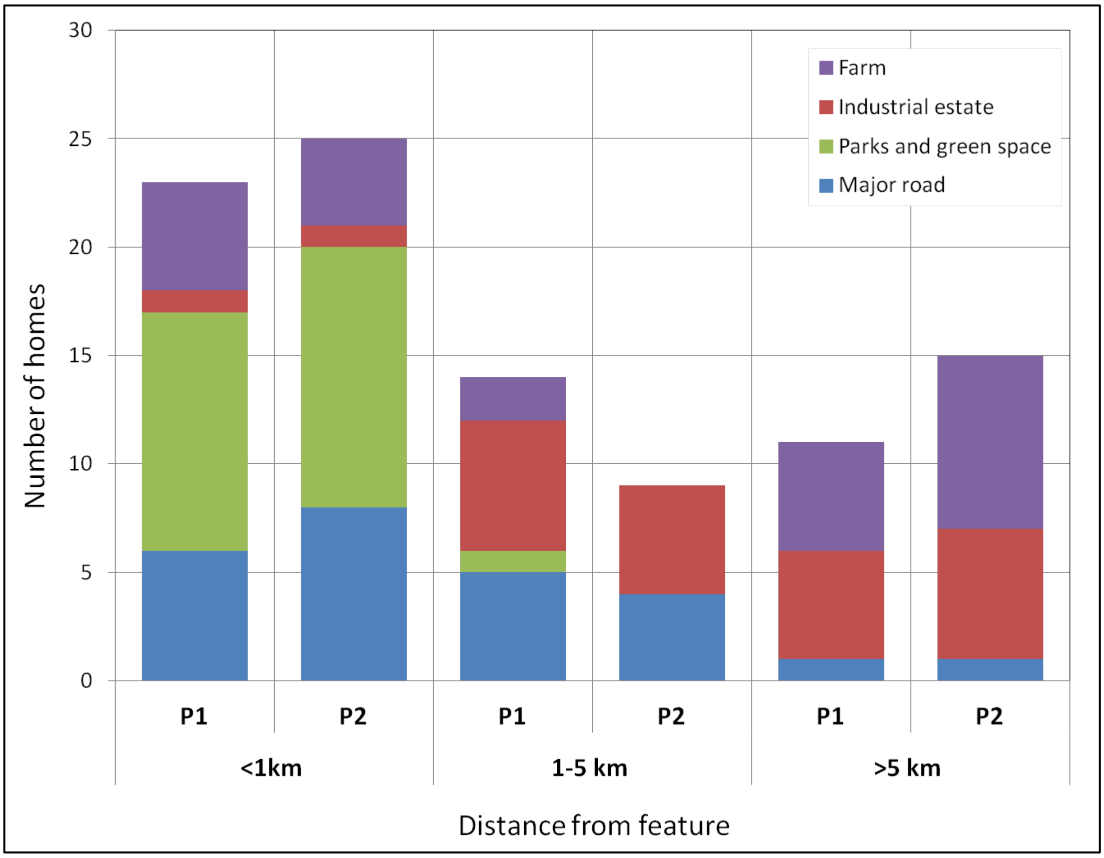


Figure 6-1 *“Home-location characteristics - Is your home within range of one of the following features? Please choose the approximate category.”* Answers extracted from the mandatory questionnaire volunteers had to fill in.

Location of the Home ME

According to the Scottish Government Urban Rural Classification (URC) from 2009/10 the majority of people live in what is classified as *Large urban areas* (Table 6-2). One person moved house between Phase 1 and 2, however within the same category. The work environment is located in category 5 – *Accessible rural*. Looking at the updated 2011/12 URC one residency from Phase 1 has changed category from *2 Other urban area* to *5 Accessible rural.* This will be discussed further down in this section.

People were asked to assess into which of the six categories their home fits. Recalling from section 3.3.3 the URC is based on population of the settlements and drive time between settlements. It has to be noted that the information in the questionnaire did not give details about the definition of the URC categories.

> "In your opinion, which of the following Urban-Rural Classification categories best describes the neighbourhood you live in? *Information*: *The Scottish Government uses the so called Urban-Rural Classification for spatial analysis. The categories shown here are taken from the 6-fold version and describe 3 different types (urban area, small town and rural) with two varieties each (large/other, accessible/remote)."* Taken from the questionnaire in Table A 1.

Table 6-2 Individual profiles with the URC the volunteers saw their residence in and the actual URC class. Red indicates a mismatch in the URC self assessment – the person sees their neighbourhood as less urbanised. Blue indicates the person sees their neighbourhood as more urbanised. The type of heating and kitchen appliances are shown as well. URC classification is displayed in Table 3-1.

°took part in phase 1 as well

**Category according to URC 2011/12*

***The person noted the use of log fire in the TAD, but not in the questionnaire*

****This person has moved house between P1 and P2 data collection*

Profile	URC 09/10 (*URC11/12)	URC self-assessment	central heating	other heating	oven/cooker
P1-01	3	3	gas		electric
P1-02	3	3	gas		electric
P1-03	1	1	gas		electric/gas
P1-04	1	1	gas		electric/gas
P1-05	1	1	gas		electric
P1-06	1	2	gas	solid fuel	electric/gas
P1-07	2 (5*)	5	gas	solid fuel**	electric/gas
P1-08	1	2	gas		electric/gas

Profile	URC 09/10 (*URC11/12)	URC self-assessment	central heating	other heating	oven/cooker
P1-09	5	3	gas		gas
P1-10	5	3	gas		gas
P1-11	5	3	gas		gas
P1-12	1	1	gas	electric	gas
P1-13	2	3	gas	electric	electric/gas
P1-14	2	3	gas	electric	electric/gas
P1-15	1	1	gas		gas
P1-16	1	1	gas		gas
P1-17	2	3	gas		electric
P1-18	2	3	gas		electric
P1-19	1	1	gas		electric/gas
P2-01	1	1	gas		electric/gas
P2-02	1	1	gas		electric/gas
P2-03***°	1	1	gas		electric/gas
P2-04	1	2	gas		electric/gas
P2-05°	1	2	gas	solid fuel	electric/gas
P2-06°	1	2	gas		electric/gas
P2-07	1	1	gas		gas
P2-08°	2	3	gas	electric	electric/gas
P2-09°	2	3	gas	electric	electric/gas
P2-10	1	1	gas		electric/gas
P2-11°	1	1	gas		gas
P2-12°	1	1	gas		gas
P2-13°	1	1	gas		gas
P2-14°	2	3	gas		electric
P2-15°	1	1	gas		electric
P2-16°	1	1	gas		electric/gas

For ten volunteers, the answers given matched the official classification in URC 09/10 (Table 6-2). Seven volunteers however had differing answers. Interestingly all of these but one person perceived the area they live in as smaller as and less urbanised than the official URC category. These are mainly people living in residential areas within a *Large urban area* which are lacking major roads with high volumes of traffic, shops, industrial sites and other services.

Two residents of the same *Other urban area* settlement (P1-13 & P1-14, P2-08 & P2-09, P1-17 & P1-18, P2-14) perceived their home as an *Accessible small town* instead. This may be due to its proximity to Edinburgh City which makes it feel more like a suburb of Edinburgh rather than an independent town.

One person perceived their neighbourhood as being larger and more urbanised (*Accessible small town*) than categorised by the URC (*Accessible rural*) (P1-09, P1-10 & P1-11). This settlement is well connected and has plenty of local services which give it a small town feeling even though its actual population is way below the 10,000 threshold.

The biggest mismatch was recorded in P1-07 which is categorised as *Other urban area* but the volunteer perceives it as *Accessible rural.* In the updated URC 2011/12, the location has actually been reclassified as *Accessible rural*, which may be coincidence, but does now better match the volunteer’s perception. The reason for this reclassification is not explained in detail in the URC 2011/12 report (The Scottish Government, 2012) but may be due to a change in the settlement boundaries i.e. this was previously part of a bigger settlement and is now recognised as an individual settlement. Considering the average concentrations at *Home* for profiles that are classified as being located in *Other urban area*, relatively high mean values have been recorded for P1-07 (Table 6-3 middle) suggesting that influences other then the location within a certain URC class influence the $PM_{2.5}$ concentration. These influences will be discussed in more detail in section 6.3.3.5. There was no data available for the *Home* ME in *Accessible rural* homes (P1-09, P1-10 and P1-11) as these are all profiles where the person spent time away from *Home*.

Looking at the average concentrations for each URC class the *Large urban areas* (left) have the highest concentration and the *Accessible small town* (right) the lowest. This is, as described for P1-07 above, unlikely to reflect the location within the URC class though as numbers between individual profiles vary a lot. It is more likely that the variability in the *Home* concentrations is mainly driven by indoor sources and activities in each profile, while outdoor background concentrations of the surrounding areas contribute to a lesser extent. In case of the *Large urban area* there are two profiles which have distinctive concentration peaks due to cooking activities (P2-02 and P2-05) which introduce bias in the calculation of the average values.

In any case the profiles on which this analysis is built on have not been derived with the intent to identify similarities in exposure between the same URC classes. To do this and to assess if the URC classification could indeed serve as a proxy for variations in $PM_{2.5}$ levels, more data in representative locations would need to be collected, possibly with stationary measurements inside and outside the respective *Home* MEs to determine influx of outdoor concentrations.

Table 6-3 Tables showing the mean values for the *Home* ME split by the URC 2009/10 category the home is located in.

Left - *Large urban area (1);* Middle - *Other urban area (2);* Right - *Accessible small town (3)*

profile	$PM_{2.5}$ mean ($\mu g/m^3$)	URC 09/10 (*URC11/12)
P1-03-Home	2.1	1
P1-04-Home	3.0	1
P1-05-Home	4.1	1
P1-06-Home	11.4	1
P1-08-Home	2.7	1
P1-12-Home	6.3	1
P1-15-Home	12.6	1
P1-16-Home	8.1	1
P1-19-Home	6.7	1
P2-01 Home	14.14	1
P2-02 Home	46.85	1
P2-03 Home	8.22	1
P2-04 Home	4.87	1
P2-05 Home	32.20	1
P2-06 Home	6.13	1
P2-07 Home	7.95	1
P2-10 Home	3.54	1
P2-11 Home	4.70	1
P2-12 Home	8.14	1
P2-13 Home	3.18	1
P2-15 Home	7.37	1
P2-16 Home	17.82	1
Average	**10.1**	

profile	$PM_{2.5}$ mean ($\mu g/m^3$)	URC 09/10 (*URC11/12)
P1-07-Home	6.4	2 (5*)
P1-13-Home	2.8	2
P1-14-Home	3.9	2
P1-17-Home	3.1	2
P1-18-Home	7.7	2
P2-08 Home	4.55	2
P2-09 Home	2.19	2
P2-14 Home	4.78	2
Average	**4.4**	

profile	$PM_{2.5}$ mean ($\mu g/m^3$)	URC 09/10 (*URC11/12)
P1-01-Home	3.1	3
P1-02-Home	4.4	3
Average	**3.8**	

Results from asking people about their home location illustrate that people have different perceptions of their neighbourhood which might be due to one or several factors other than actual population density or distance to certain features. Factors influencing an individual's perception may be the intensity of road traffic, access to green space, or the amount of residential areas as compared to industrial or commercial areas, access to services, or how well developed the community is and how involved an individual is in the community.

Perception of exposure

These factors might also influence perception of air quality and exposure. In the TADs, study participants were asked for each recorded day what level they thought their exposure to air pollution was (*high, medium, low*) (Table A 2).

In Phase 1 two people stated *high* for individual days, while all other days have been perceived as *medium* or *low* exposure (note: one person did not provide the information on both days, another person did not provide the information on days where there were issues with the monitoring device and hence no PM data could be collected). The two days with *high* included long distance travel by train for one person and time spent in the city centre by another person. Seven people had the same level for all monitoring days. Based on the TAD information provided study participants appear to associate higher levels (i.e. *medium* and *high*) of exposure with spending time in motorised transport (commute to work as well as long distance travel), cycling, walking or generally spending time in the city centre, spending time in public buildings where many people are present and, to a lesser extent, cooking and baking activities.

In Phase 2 all volunteers chose *low* or *medium* (note: one person did not provide answers, one person provided answers for one day but not the other).

Seven people had the same level for all monitoring days. The remaining volunteers, similarly to Phase 1, seemed to generally associate higher levels (i.e. *medium*) with time spent in or around motorised transport, city centres and public places (restaurant/pub visits).

Looking at the actual mean values (Table 6-4) there is no agreement between the measured values and the perception people had of their exposure on the given days. The mean values for days on which volunteers noted *low* exposure range between 1 and 19 μg/m^3 while for days where *medium* was noted, the range is between 2 and 38 μg/m^3. *High* exposure which was chosen only for two days of the whole pilot study covers days with $PM_{2.5}$ mean values of 3 and 5 μg/m^3, corresponding to a substantially lower actual exposure than perceived This highlights the issue of human sensors not being well tuned to provide an accurate measure of exposure to air pollution and it is thus difficult for individuals to be aware of levels of pollution that may affect their health, while not being high enough to be directly noticeable.

Table 6-4 $PM_{2.5}$ mean value for individual days of each profile calculated from the 1-minute data are shown along with data from the TADs regarding volunteer's perception of exposure on the respective day.

Profile	Date	number of data points	$PM_{2.5}$ mean ($\mu g/m^3$)	What do you think was your personal exposure to polluted air today?
P1-01	07/11/2012	60	4	-
P1-07	08/11/2012	471	8	-
P1-06	12/11/2012	555	10	-
P1-05	14/11/2012	102	4	-
P1-04	21/11/2012	1,025	3	-
P1-18	17/12/2012	346	8	-
P1-18	19/12/2012	360	6	-
P1-18	20/12/2012	1,059	9	-
P2-14	10/05/2013	151	2	-
P2-03	13/05/2013	619	5	-
P2-02	20/05/2013	124	10	-
P2-02	21/05/2013	1,440	16	-
P2-01	22/05/2013	705	4	-
P2-02	22/05/2013	1,250	47	-
P1-09	08/10/2012	413	3	Low
P1-08	08/11/2012	617	3	Low
P1-06	09/11/2012	447	8	Low
P1-07	09/11/2012	1,167	8	Low
P1-10	09/11/2012	345	3	Low
P1-06	10/11/2012	1,343	6	Low
P1-07	10/11/2012	1,239	5	Low
P1-10	10/11/2012	1,440	4	Low
P1-06	11/11/2012	1,440	16	Low
P1-07	11/11/2012	1,195	10	Low
P1-10	11/11/2012	1,440	6	Low
P1-07	12/11/2012	269	3	Low
P1-10	12/11/2012	805	4	Low
P1-02	14/11/2012	1,304	4	Low
P1-03	14/11/2012	810	2	Low
P1-12	15/11/2012	1,310	6	Low
P1-12	16/11/2012	717	6	Low
P1-14	16/11/2012	553	6	Low
P1-19	16/11/2012	368	19	Low
P1-16	18/11/2012	1,440	8	Low
P1-19	18/11/2012	1,440	8	Low
P1-04	19/11/2012	580	2	Low
P1-16	19/11/2012	621	4	Low
P1-19	19/11/2012	687	2	Low
P1-04	20/11/2012	1,440	4	Low

Profile	Date	number of data points	$PM_{2.5}$ mean ($\mu g/m^3$)	What do you think was your personal exposure to polluted air today?
P1-11	20/11/2012	475	5	Low
P1-14	21/11/2012	734	2	Low
P1-18	18/12/2012	940	4	Low
P2-11	06/05/2013	739	4	Low
P2-12	06/05/2013	329	10	Low
P2-07	07/05/2013	379	15	Low
P2-08	07/05/2013	770	5	Low
P2-12	07/05/2013	1,112	6	Low
P2-08	08/05/2013	1,440	6	Low
P2-07	09/05/2013	960	5	Low
P2-08	09/05/2013	1,428	4	Low
P2-05	10/05/2013	916	7	Low
P2-08	10/05/2013	605	2	Low
P2-03	11/05/2013	1,373	9	Low
P2-09	11/05/2013	510	1	Low
P2-09	12/05/2013	1,301	1	Low
P2-09	13/05/2013	1,440	3	Low
P2-15	13/05/2013	606	7	Low
P2-06	14/05/2013	1,429	12	Low
P2-09	14/05/2013	590	3	Low
P2-15	14/05/2013	851	5	Low
P2-06	15/05/2013	1,429	2	Low
P2-10	15/05/2013	1,440	3	Low
P2-16	19/05/2013	614	17	Low
P2-16	20/05/2013	850	19	Low
P2-13	22/05/2013	912	6	Low
P2-13	23/05/2013	554	3	Low
P1-09	29/09/2012	409	5	Medium
P1-09	04/10/2012	399	2	Medium
P1-15	05/11/2012	421	2	Medium
P1-01	06/11/2012	390	2	Medium
P1-15	06/11/2012	1,210	3	Medium
P1-15	07/11/2012	756	3	Medium
P1-13	08/11/2012	702	3	Medium
P1-08	09/11/2012	883	3	Medium
P1-13	09/11/2012	722	3	Medium
P1-03	12/11/2012	812	3	Medium
P1-05	12/11/2012	193	4	Medium
P1-02	13/11/2012	390	4	Medium
P1-03	13/11/2012	1,315	4	Medium
P1-05	13/11/2012	1,440	4	Medium
P1-12	14/11/2012	774	4	Medium
P1-02	15/11/2012	582	5	Medium

Profile	Date	number of data points	$PM_{2.5}$ mean ($\mu g/m^3$)	What do you think was your personal exposure to polluted air today?
P1-16	16/11/2012	410	5	Medium
P1-14	17/11/2012	1,390	5	Medium
P1-16	17/11/2012	1,215	5	Medium
P1-19	17/11/2012	1,438	5	Medium
P1-14	18/11/2012	1,063	5	Medium
P1-17	19/11/2012	509	5	Medium
P1-14	20/11/2012	754	5	Medium
P1-18	21/12/2012	672	5	Medium
P2-11	05/05/2013	736	5	Medium
P2-04	08/05/2013	737	5	Medium
P2-07	08/05/2013	932	6	Medium
P2-14	08/05/2013	805	6	Medium
P2-04	09/05/2013	726	6	Medium
P2-05	09/05/2013	506	7	Medium
P2-14	09/05/2013	751	8	Medium
P2-03	10/05/2013	418	8	Medium
P2-09	10/05/2013	346	9	Medium
P2-03	12/05/2013	1,181	10	Medium
P2-06	13/05/2013	587	11	Medium
P2-10	13/05/2013	914	11	Medium
P2-10	14/05/2013	1,430	12	Medium
P2-06	16/05/2013	847	12	Medium
P2-01	17/05/2013	647	15	Medium
P2-01	18/05/2013	1,062	20	Medium
P2-01	19/05/2013	960	20	Medium
P2-01	20/05/2013	1,440	25	Medium
P2-01	21/05/2013	1,440	38	Medium
P1-14	19/11/2012	585	5	High
P1-17	20/11/2012	1171	3	High

Based on the TAD information the study participant's perception of exposure is affected by the individual's perception of the environment as a whole. The natural environment as well as built-up environment, and social and economic differences between the urban and rural space influence people’s idea of their exposure. So does the amount of time spent in motorised transport. This might be due to peoples existing knowledge that motorised transport has always been a well known source of air pollutants. A few people relate higher exposure to public places which are naturally busier than a home or other private environment.

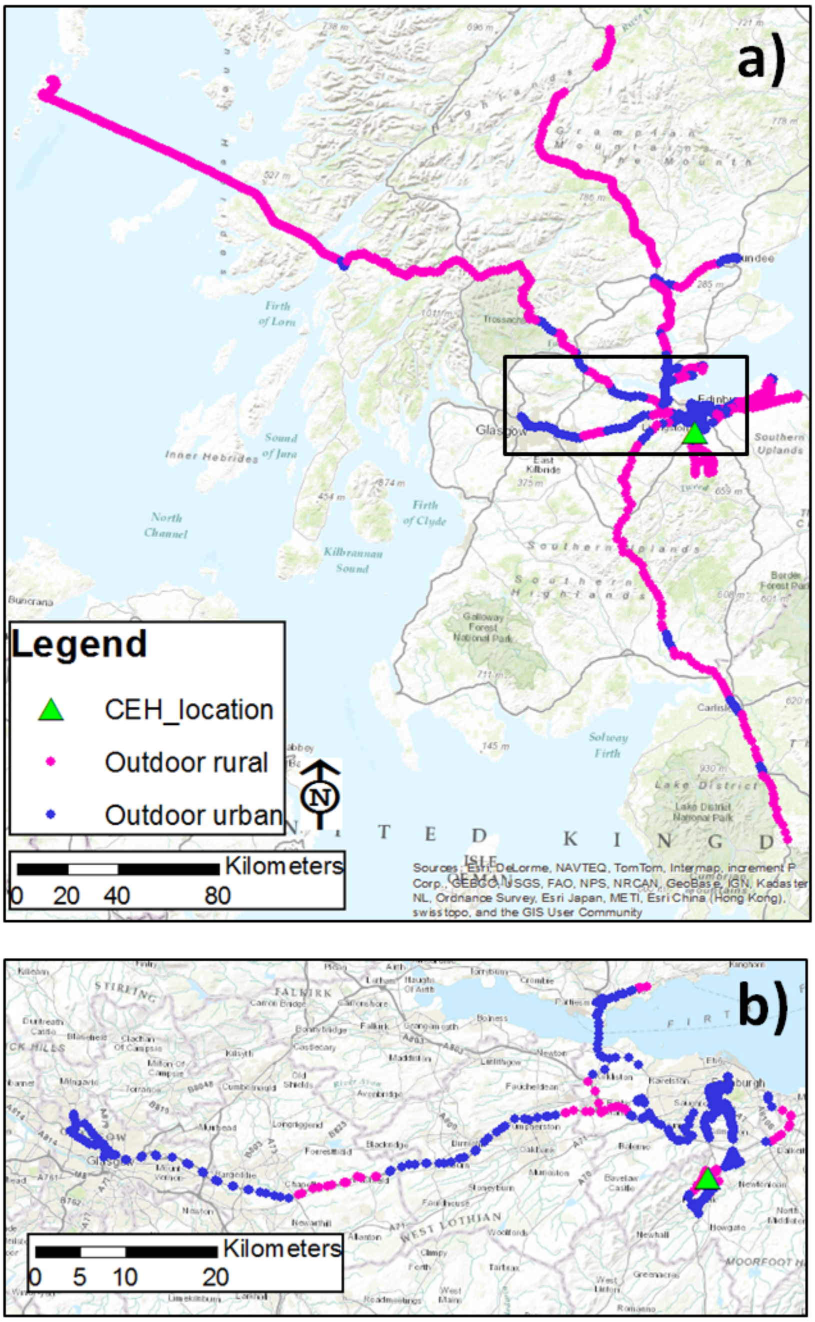
Study participants perceived their neighbourhood in a similar way – for example, lively places with access to a large range of services have been perceived as “more urban” than residential areas with less services.

6.3.1.3 Time activity patterns

A detailed table with all individual profiles and the number of data points (minutes) spent per ME, transport mode and class can be found in the Appendix (Tables B2 and B3). This chapter only shows summary tables relevant to the detailed discussion of results.

Classes

The majority of time in Phase 1 was spent *Indoors*, which is in line with the European average of 90% (Fernandes et al., 2009) (Table 6-5). Given the geographic location of the study area (Edinburgh is located at 55.9531 N,-3.1889 W,) and that the monitoring in Phase 1 happened during the winter months with cold and wet weather dominating and short daylight hours these results are consistent with other studies (section 3.1.1). Time spent in *Outdoor rural* environments is strongly influenced by weekends spent in rural Scotland and long work related journeys through rural Scotland and England **(**Figure 6-2a).



Sources: Esri, DeLorme, NAVTEQ, TomTom, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), swisstopo, and the GIS User Community

Figure 6-2 Map showing the GPS logs which have an assigned $PM_{2.5}$ value from volunteers in fieldwork Phase 1 (a) and fieldwork Phase 2 (b) and the respective class: Outdoor rural and Outdoor urban. The location of CEH, the “work” environment for most volunteers is displayed as well. The black box highlights the area shown in (b).

For Phase 2, for which data was collected during May 2013, the weather is generally drier and milder and the daylight hours much longer than in winter (section 3.1.1). However, May 2013 was a wet and relatively cold month with rainfall of 118 mm and a mean temperature of 8.1˚C (Met office UK, 2013a). Despite the long daylight hours, the time spent outdoors was much less in Phase 2 compared to Phase 1. This is however unlikely to be related to the adverse weather conditions alone, but also reflects the composition of the profiles. Phase 2 consisted mainly of weekdays where the majority of time is spent *Indoors* due to work. The time and activities allocated to the two outdoor classes are pretty much limited to the commute to work. Most people live in urban areas and the commute to the work place, which is located in a rural area, only incorporates short distances within data zones classified as rural (Figure 6b).

Table 6-5 Percentage of time spent per class for the full dataset Phase 1 and Phase 2. Due to rounding the values do not sum up to 100%.

% time spent per class	P1	P2
Indoor	86.8	93.6
Outdoor rural	6.7	1.1
Outdoor urban	6.5	5.4

Looking at individual profiles and individuals showing marked differences in how their time is split between indoor, outdoor rural and outdoor urban (please note the difference in recording length of the profiles which ranges from 7:30 hours to 104:14 hours) it becomes obvious how this pilot study confirms existing data with a European average of 90% of the time spent in indoor environments (Table 6-6). Furthermore the data shows that the time spent outdoors is mainly located in urban areas. It should be noted that the two outdoor classes largely consist of time spent in transport and not actually time spent outdoors. In extreme cases where the time spent indoors is >97%, the time spent outdoors is down to transport only, i.e. only the commute to and from work and short distances to/from a pub or other location (P1-13, P2-01 and P2-11) or when the weather restricted outdoor use due to the transport mode i.e. cycling or walking (P1-03 and P1-18).

Profiles with less than 75% of the time spent indoors are an exception and listed below:

- P1-02 - the person was on fieldwork in the rural highlands; outdoors includes drive time and the actual time spent outdoors.
- P1-09 - the person was on holiday and recorded the arrival and departure day which includes long distance travel through rural Scotland and one holiday day where the majority of time was spent outdoors cycling and walking.
- P1-11 - the person travelled for work through rural Scotland.

Table 6-6 Table showing and the number of data points (n), the time and percentage of time spent in Indoor and Outdoor rural and urban environments for each profile.

Profile	n	Full profile duration (hh:mm)	Indoor (%)	Indoor (hh:mm)	Outdoor rural (%)	Outdoor rural (hh:mm)	Outdoor urban (%)	Outdoor urban (hh:mm)
P1-01	450	7:30	77.6	5:49	9.3	0:42	13.1	0:59
P1-02	2,276	37:56	74.9	28:25	19.0	7:13	6.1	2:18
P1-03	2,937	48:57	98.4	48:11	0.2	0:7	1.3	0:39
P1-04	3,045	50:45	93.8	47:35	1.8	0:56	4.4	2:14
P1-05	1,735	28:55	90.1	26:3	1.7	0:30	8.2	2:22
P1-06	3,785	63:5	85.2	53:43	4.2	2:39	10.6	6:43
P1-07	4,341	72:21	91.3	66:2	3.5	2:30	5.3	3:49
P1-08	1,500	25:0	88.9	22:14	3.3	0:49	7.8	1:57
P1-09	1,221	20:21	4.3	0:52	82.3	16:45	13.4	2:44
P1-10	4,030	67:10	88.4	59:21	8.5	5:43	3.1	2:6
P1-11	475	7:55	63.4	5:1	27.2	2:9	9.5	0:45
P1-12	2,801	46:41	94.1	43:57	0.9	0:25	5.0	2:19
P1-13	1,424	23:44	97.0	23:1	0.4	0:6	2.6	0:37
P1-14	5,079	84:39	82.3	69:38	4.4	3:43	13.3	11:18
P1-15	2,387	39:47	91.1	36:14	4.7	1:53	4.2	1:40
P1-16	3,686	61:26	85.3	52:24	10.1	6:12	4.6	2:50
P1-17	1,680	28:0	87.4	24:28	2.2	0:37	10.4	2:55
P1-18	3,377	56:17	98.1	55:13	0.8	0:27	1.1	0:37
P1-19	3,933	65:33	88.5	58:0	3.7	2:27	7.8	5:6
P2-01	6,254	104:14	97.1	101:14	0.3	0:16	2.6	2:44
P2-02	2,814	46:54	95.7	44:53	0.0	0:0	4.3	2:1
P2-03	3,591	59:51	92.5	55:20	0.8	0:30	6.7	4:1
P2-04	1,463	24:23	93.4	22:47	2.8	0:41	3.8	0:55
P2-05	1,422	23:42	92.2	21:51	4.1	0:58	3.7	0:53
P2-06	4,292	71:32	95.1	68:3	0.8	0:33	4.1	2:56
P2-07	2,271	37:51	93.2	35:17	1.0	0:23	5.8	2:11
P2-08	4,243	70:43	95.4	67:27	0.9	0:38	3.7	2:38
P2-09	4,187	69:47	95.0	66:16	0.5	0:23	4.5	3:8
P2-10	3,784	63:4	87.8	55:22	0.2	0:8	12.0	7:34
P2-11	1,475	24:35	97.2	23:54	0.0	0:0	2.8	0:41
P2-12	1,441	24:1	90.7	21:47	4.1	0:59	5.2	1:15
P2-13	1,466	24:26	85.9	21:0	4.4	1:5	9.6	2:21
P2-14	1,707	28:27	96.4	27:26	1.2	0:21	2.3	0:40
P2-15	1,457	24:17	93.6	22:44	2.1	0:31	4.3	1:2
P2-16	1,464	24:24	83.3	20:20	0.7	0:10	16.0	3:54

Microenvironments

Table 6-7 provides a split of the time recorded in all six MEs identified in this study. *Indoors* is split into four different MEs, with the time spent in the *Home* environment dominating in both phases.

Phase 1, which includes seven profiles covering weekends and also holidays, shows more time spent in *Public* and *Private residential buildings* due to people spending weekends away visiting friends for instance. These seven profiles account for the bulk of time spent in *Outdoor other* environments (82%) while the time spent in *Outdoor other* on a normal working day is negligible or does actually not exist (three profiles only, accounting for 18%). Altogether ten profiles include a considerable amount of time spent in *Outdoor other.* Only two profiles have less than an hour spent outdoors. The longest time, with 410 minutes spent in *Outdoor other* is the holiday profile where the person has been walking and cycling outdoors most of the monitoring day. Outdoor activities include long-lasting activities like hikes, bicycle tours and gardening but also walking the city centre, dog walking, walking at lunchtime, waiting at bus stops (if this has specifically been noted in the TAD). Weekend profiles comprise the described outdoor activities plus time spent in cafes, restaurants and pubs, shops, friend’s houses, hotels and other public buildings which do not or in much more limited amounts occur on weekdays. The weekends covered in Phase 1 do, however, also include long distance travel which, unless it is travel for work, does not typically occur on weekdays. This longer travel distances have an impact as well on the time spent in the *Transport* ME.

As Phase 2 mainly covers weekdays (five profiles only include weekend days) the profiles recorded are generally much shorter and do not contain long distance travel. Therefore also the time spent in *Public* and *Private residential buildings* e.g. people spending the weekend away, is comparatively less than in Phase 1 while the share of time spent at *Work* and especially *Home* is higher than in Phase 1. Whilst the time spent at W*ork* increased only by 2.5%, *Home* is where people spent the time instead of being in *Transport*, *Private residential* or *Public buildings*. The time spent outdoors is negligible with nine profiles including time spent outdoors of which only one profile has more than an hour recorded outdoors. The activities classed as O*utdoor other* in Phase 2 include waiting at a bus stop, walking around the city centre or taking walks at lunchtime or evenings as well as dog walking which compared to the activities in Phase 1 are much shorter.

Table 6-7 Percentage of time spent per ME in Phase 1 and Phase 2. Due to rounding the values do not sum up to 100%.

% time spent per ME	P1	P2
Home	57.9	70.4
Work	14.7	17.2
Public building	10.2	5.5
Private residential building	4.1	0.4
Transport	9.6	5.5
Outdoor other	3.5	0.9

Transport mode

In Phase 1 the *Car* is the dominant transport mode for everyday use, followed by *Bus* and *Walk*. *Ferry* and *Train* are only used for leisure or work related travel and over relatively long distances hence the large amount of time spent in those transport modes. As mentioned earlier the weekend profiles also have an impact on the *Car* category with longer distances driven.

Walk is the dominant transport mode in Phase 2 with all but one profile spending time in this transport mode. In comparison in Phase 1 only 10 out of 19 profiles have recorded data in the *Walk* category. This is followed by *Car* and *Bus*. The *Bicycle* is used more despite the cold spring. The *Train* is only used for work related travel over longer distances.

Table 6-8 percentage of time spent in the respective transport modes within the *Transport* ME in Phase 1 and Phase 2.

% time spent per transport mode	P1	P2
Bicycle	4.9	9.8
Bus	17.0	18.9
Car	47.1	28.5
Ferry	11.8	NA
Train	7.2	12.2
Walk	12.0	30.6

It has to be remembered that some profiles are only snapshots of days rather than full monitoring over several consecutive days due to e.g. battery life or feasibility issues. In Phase 1 people visited between two and six MEs, in Phase 2 between 3 and 6 MEs during their monitoring periods. Some volunteers provided more detailed information than others, hence the level of detail to which time-activity patterns could be broken down to is different from profile to profile.

6.3.2 Distance between features

Georeferenced data has been used to calculate the distance between the volunteers' residence locations and the fixed-site monitoring stations at St. Leonards and Auchencorth Moss as well as the work place CEH respectively (section 3.3.5). CEH is located roughly in the middle (direct line) between the two fixed site monitors from the AURN network which do measure $PM_{2.5}$ in the greater Edinburgh area (distance to Auchencorth Moss is 8.1 km, to St. Leonards 9.4 km). The workplace is the ME where overall people spent the second largest amount of time (Table 6-7). Located in a rural environment, the values recorded at Auchencorth Moss are seen as representative in this study and not the urban background site St. Leonards. In fact the nearby AURN station Bush Estate is classified as rural, but does not provide PM measurements.

Looking at the representativeness of the AURN sites for people's homes where they in summary spent most of their time (Table 6-7) the distance between residences and monitoring stations varies substantially (Table 6-9). The majority of homes are located within Edinburgh City and a maximum of 5.4 km away from St. Leonards, with a couple homes being only 700-800 meters away (P1-19 and P2-01). The longest distance accounts for the home location of P1-08, which is located in the greater Glasgow area and therefore closer to an AURN kerbside site (Glasgow kerbside) there. Another home (P1-07) is located in the Perth area and therefore closer to Grangemouth, an industrial background site. Other homes outside Edinburgh city are about 10-13 km away from the urban background station and closer to Auchencorth Moss (P1-09, P1-13, P1-17).

Table 6-9 Distances from the volunteer's home address to the fixed site monitoring stations Auchencorth Moss and St. Leonards, and the work environment CEH. Note that distances are measured as a direct line between the two coordinates.

*This persons *Work* environment is not at CEH

Profile	Distance (km) *Home* to Auchencorth Moss	Distance (km) *Home* to St. Leonards	Distance (km) *Home* to CEH
P1-01, P1-02	30.5	13.7	22.7
P1-03, P1-04	15.5	2.4	7.5
P1-05	16.5	2.8	8.8
P1-06, P2-05	19.8	5	11.8
P1-07	70.8	55.5	63.8
P1-08, P2-06	68	70.4	69.2
P1-09, P1-10, P1-11	8.9	9.7	2.6
P1-12	14.5	3.6	6.7
P1-13, P1-14, P2-08, P2-09	4.2	13.3	4
P1-15, P1-16, P2-11, P2-12, P2-13	16.4	1.2	8.4
P1-17, P1-18, P2-14	4.3	13.3	4.1
P1-19, P2-15, P2-16	16.9	0.8	8.7
P2-01	16.9	0.7	8.8
P2-02*	17.4	1.3	9.4
P2-03	14.9	3.2	7
P2-04	13.9	5.4	6.1
P2-07	19.5	2	11.4
P2-10	16.5	1.2	8.4

With the majority of time spent at work during a weekday, applying the $PM_{2.5}$ values from the fixed site monitor nearest to the *Home* ME is not sufficient but requires personal monitoring (as postulated in the second hypothesis (section 1.2), which presents one of the key shortcomings of the home location approach for population exposure assessment. Firstly, the *Home* environments are between 2.6 and 69.2 km away from the *Work* environment. Secondly the *Work* ME is located within a rural environment, which is not adequately represented by an urban background station which is - in addition - about 9.4 km away. For homes closer to Auchencorth Moss, however, it is questionable if a rural station (which is by definition distanced as far away as possible from roads, populated and industrial areas (Scottish Air Quality, 2013) can be used as representative for concentrations in a town classified as *other urban* area or *accessible rural*.

Furthermore, the specific locations of AURN sites are chosen to represent certain ambient concentrations i.e. urban background or rural. And as the section about time-activity patterns and the individual profiles (6.3.4) shows, people are constantly on the move and spend substantial parts of their day away from the *Home* ME. The distance of the individuals' actual activity spaces in relation to their residence location (here only the distance from the Work ME is shown as an example) support the case for individual monitoring to assess personal exposure on a much more detailed level. Most relevant is that the concentrations are measured in the direct vicinity of the person, or at least in the same building. Secondly, the concentrations are measured at higher temporal resolution (in this pilot study 1- minute), allowing for a more detailed analyses of source contributions and variability when moving through different MEs.

When comparing daily values between those profiles which cover 24 hours with the data from the two fixed monitoring sites (calculated from the hourly TEOM-FDMS values) it becomes obvious that concentrations resulting from personal monitoring are on average higher. Moreover does the table (Table 6-10) show the difference in average concentrations measured with a personal device between two individuals (P1-06 & P1-10, P2-01 & P2-02) or the similarity (P1-16 & P1-19).

In the latter case the profiles were recorded on a Sunday and both individuals spent a certain amount of time outdoors walking in accessible and remote rural environments (P1-16) and accessible rural (P1-19). In both cases a fair amount of cooking and cleaning occurred in the *Home* ME.

The most obvious explanation for the difference in average concentration between P1-06 and P1-10 on Sunday the 11th of November is that P1-10 was recorded entirely in remote rural areas of the Highlands while P1-06 was recorded in Edinburgh and East Lothian which covers a mix of urban and rural areas. In addition, the person in P1-06 was cooking, visiting restaurants and pubs, cycling and using the train while P1-10 consists mainly of quiet activities in indoor environments and some travel by car.

P2-01 and P2-02 have been recorded on a Tuesday and both individuals spent the entire 24 hours in Edinburgh City. P2-02 shows an unexplained extremely strong increase of PM in the evening (section 6.3.4.6) which strongly influences this daily average value. P2-01 is almost entirely (98%) recorded in a shared accommodation. Despite the flat being only about 700m away from the St. Leonards monitoring site the daily averages differ by 6 µg/m^3. Interestingly the day before (P2-01 20th of May 2013) is one of the two cases only where the Dylos average is lower than the St Leonards measurements over 24 hours. This is however at the tail end of a high pollution episode which is explained in more detail in section 6.3.4.5.

In section 6.3.4 individual profiles are discussed and assessed in relation to measurements from the two fixed site monitoring stations (if possible).The data is however also used to show where there is no relation between the two datasets.

Table 6-10 The daily means for the days which have 24 hour Dylos measurements, in comparison to calculated daily means (based on hourly TEOM-FDMS values) for Auchencorth Moss (ACTH mean) and St. Leonards (ED3 mean). Additionally the split between the time spent indoors and outdoors is shown as percentage.

Profile	Date	Dylos mean (µg/m^3)	ACTH mean (µg/m^3)	ED3 mean (µg/m^3)	% time spent Indoor	% time spent Outdoor
P1-10	10/11/2012	4	1	4	100	0
P1-06	11/11/2012	16	0	5	85	15
P1-10	11/11/2012	6	0	5	93	7
P1-05	13/11/2012	3	0	0	93	7
P1-16	18/11/2012	8	1	3	73	27
P1-19	18/11/2012	8	1	3	82	18
P1-04	20/11/2012	4	2	3	91	9
P2-08	08/05/2013	6	13	15	93	2
P2-09	13/05/2013	3	2	3	99	1
P2-10	15/05/2013	3	1	5	97	3
P2-01	20/05/2013	20	NA	24	100	0
P2-01	21/05/2013	12	5	6	98	2
P2-02	21/05/2013	16	5	6	97	3

6.3.3 Concentration characteristics P1 and P2

The whisker plots in Figure 6-3 illustrate the variability of $PM_{2.5}$ concentrations between the individual profiles arising from places visited and activities done by the individual volunteers. The upper end of the box ("hinge") corresponds to 3rd quartile, the lower end to the 1st quartile. The median (2nd quartile) is depicted as a horizontal blue line inside the box. The upper whisker extends from the hinge to the highest values which is within 1.5 * IQR of the hinge. IQR is the inter quartile range or distance between the 1st and 3rd quartiles. The lower whisker extends from the hinge to the lowest values that is within 1.5 *IQR. Outliers are plotted as black points and represent data beyond the end of the whiskers. The variability of profiles derived by the same person on different days can be seen based on the colour coding that indicates profiles derived by the same individual.

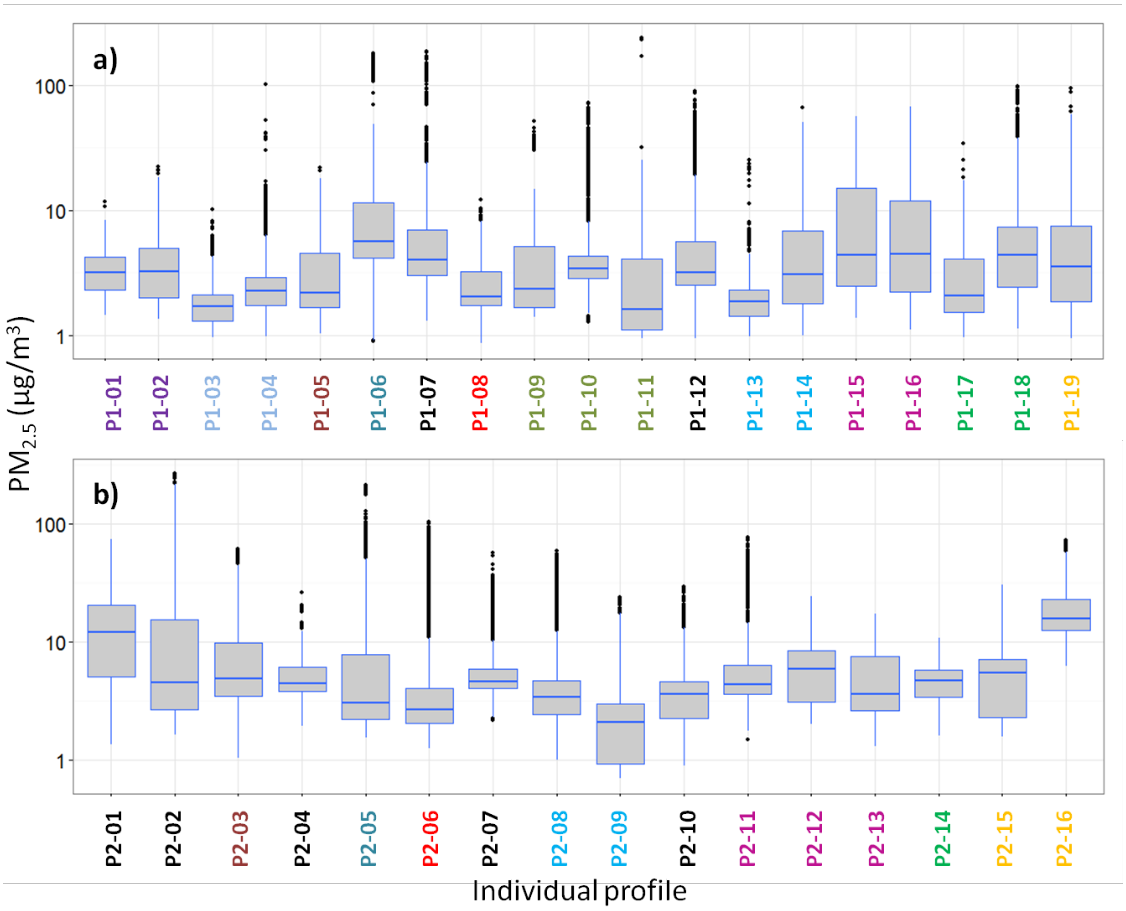


Figure 6-3 $PM_{2.5}$ (μg/m^3) for each individual profile from Phase 1 (a) and Phase 2 (b). The colours indicate profiles that have been generated by the same volunteer. Profiles in black show individuals that only generated one profile.

The profiles in P1 have medians (Figure 6-3a) varying between 1.6 μg/m^3 (P1-11) and 5.7 μg/m^3 (P1-06) while the means vary between 10.6 μg/m^3 (P1-06) and 1.9 μg/m^3 (P1-03).

For Phase 2 (Figure 6-3b) the medians are between 15.7 µg/m^3 (P2-16) and 2.1 µg/m^3 (P2-09). The means in Phase 2 vary between 29.6 µg/m^3 (P2-02) and 2.5 µg/m^3 (P2-09).

Maximum values for both fieldwork phases are mainly related to cooking and baking activities which are known to create high PM levels (Abdullahi et al., 2013) and increased movement in the direct vicinity of the monitor that have been reported in the TADs and follow-up meetings. Usually when people noted in their TADs that they get ready to leave a place, arrive somewhere, or have moved the monitor the PNC has increased. This is notably different to times spent in an ME doing quiet activities and therefore interpreted as movement in the vicinity and handling of the monitor likely causing the resuspension of (household) dust and also influenced by the personal cloud. Here movement can relate to the volunteers themselves but also to other people or pets in the vicinity. Since these movements and handling increases occur regularly when a switch between MEs happens, increased concentrations within the “grey areas” (section 5.3.3.3) can bias the results for one to the other ME as in bias the top end of the measurement range in that ME.

Peak concentrations have almost exclusively been measured in *Indoor* environments and can be predominantly related to indoor sources and human activities, which have been identified in other studies to cause events of high concentration but short duration (Ferro et al., 2004). Notably, an outdoor peak is recorded in front of a burger grill and therefore is also related to cooking activities. Minimum values have mainly been recorded *Indoors* at home during quiet activities and overnight, at a small sports centre and the work environment but also in individual profiles during *Transport* and *Outdoor other* activities in *Outdoor rural* areas.

A selection of individual profiles will be discussed in more detail in section 6.3.4. Concentrations in the individual MEs are discussed in the following two sections.

6.3.3.1 Phase 1 – concentrations per ME

In the following the $PM_{2.5}$ concentrations in the individual MEs shown in Figure 6-4 are discussed.

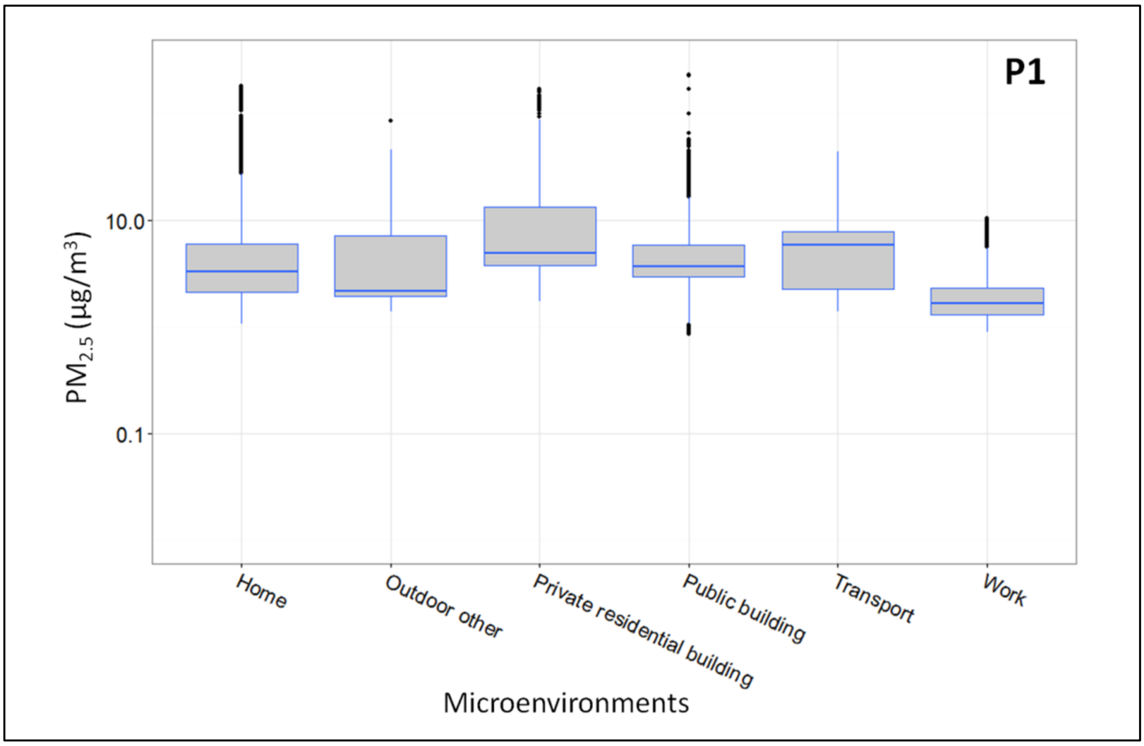


Figure 6-4 $PM_{2.5}$ statistics per Microenvironment for data collected in Phase 1. The whisker plots show the variability of concentrations in the six microenvironments.

The *Work* environment (included in 17 profiles) has the smallest range, i.e. maximum minus minimum concentration, of $PM_{2.5}$ (9.6 µg/m^3) whereby highest concentrations are related to increased movement in the vicinity or actual handling of the monitor when people arrive or leave their office (maximum ~10 µg/m^3). The work place itself is mainly an office environment with a few labs and does not have typical indoor sources like a canteen for instance. It is also located in a rural environment with generally low ambient $PM_{2.5}$ concentrations.

It is followed by the *Transport* ME which is included in all profiles with a range of 42.6 µg/m^3. Here the lowest concentrations (minimum 1.4 µg/m^3) have been recorded while cycling, on a bus or in a car in either urban (non-rush hour) or rural areas.

Outdoor other (Figure 6-5) (included in 10 profiles, range 85.6 µg/m^3) has lowest concentrations (minimum 1.4 µg/m^3) recorded in rural areas of the Scottish Highlands and Islands and near the work place e.g. P1-02, P1-09, P1-10, P1-14 and P1-15 in Figure 6-5. The higher concentrations in *Outdoor other* (maximum ~87 µg/m^3) have been recorded at the Farmers Market in front of a burger grill (P1-19) and the concentrations in this ME are therefore strongly influenced by this one specific event. Higher concentrations have also been recorded around the city centre (P1-14 and P1-17, Figure 6-5) and when getting home (P1-07, “grey area” – when moving from car to the home) and when working in the garden (P1-07).

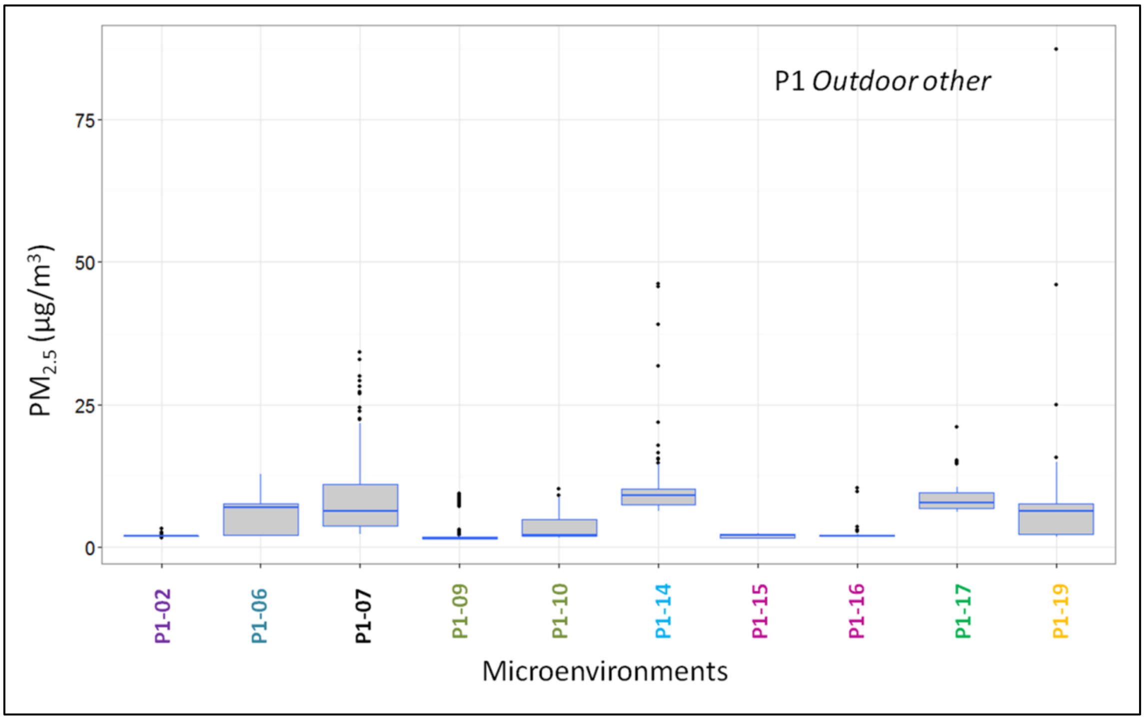


Figure 6-5 Profiles of fieldwork Phase 1 which include the *Outdoor other* ME

The *Home* ME (Figure 6-6 b) is included in 16 profiles and has a wide range (184.8 μg/m^3) with the lowest values all recorded throughout the night and the early morning hours, before the start of human activities (minimum 1 μg/m^3). The higher concentration levels (maximum 185.8 μg/m^3) that have been recorded related to either cooking activities (P1-06, P1-12, P1-19 in all three cases it was frying), increased movement in the vicinity of the monitor e.g. when people get ready to leave the house or pets are moving in front of the monitor causing resuspension (P1-07), or are unexplained (P1-18). Analysing the whisker plots for each profile (Figure 6-6 a) it becomes obvious that the wide range is driven by peak concentrations while the minimum values are spread relatively evenly between 1 and 2 μg/m^3.

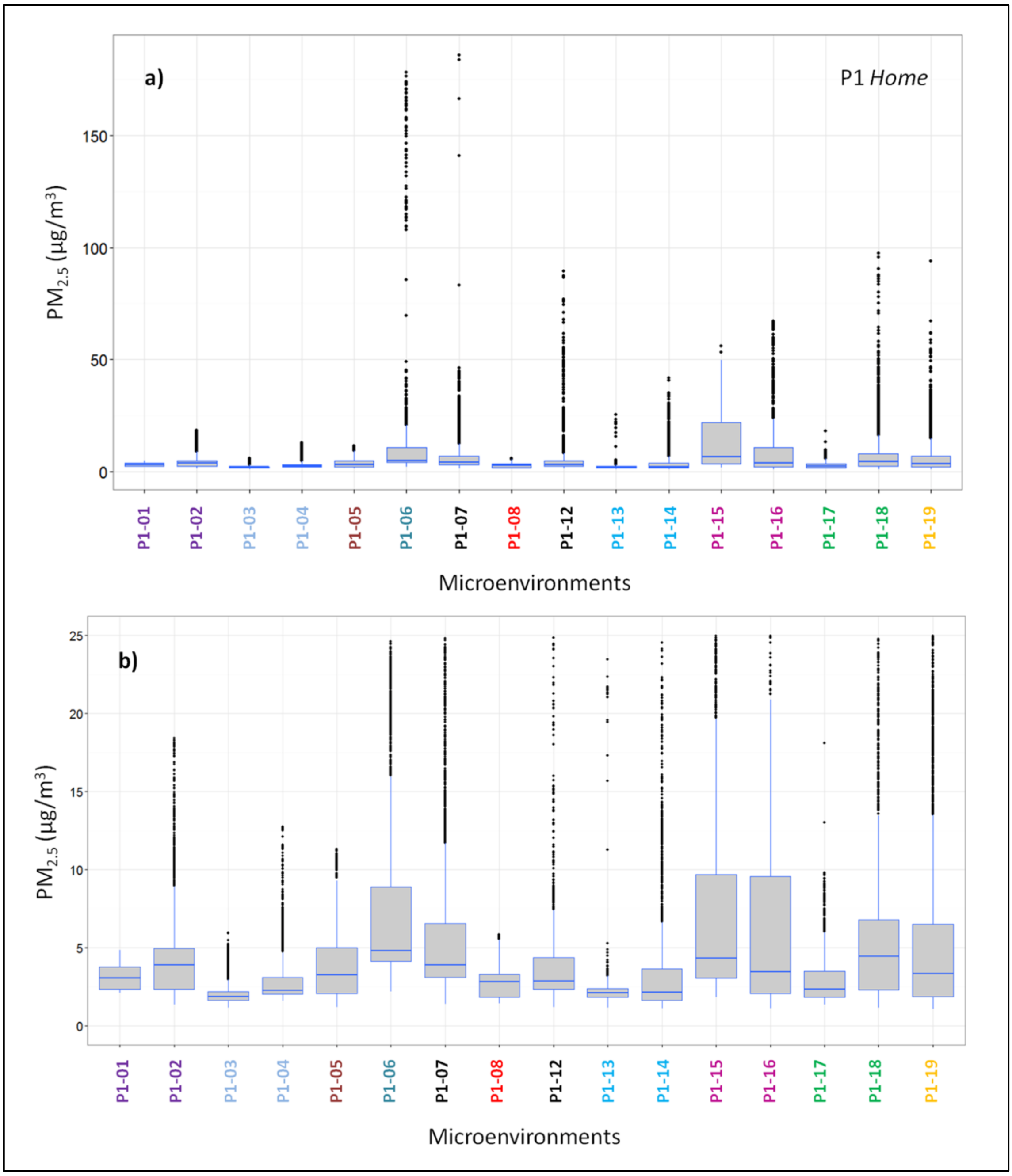


Figure 6-6 Profiles recorded in fieldwork Phase 1 that include the *Home* ME. a) showing the full range of concentrations - b) showing the profiles between 0-25 µg/m^3

The *Private residential building* ME (Figure 6-7) has a similarly wide range (169.6 µg/m^3) which is to be expected as this ME is of more or less of the same characteristic as the Home ME. One of the profiles (P1-07) recorded PM$_{2.5}$ concentrations of up to 171.4 µg/m^3 during cooking) which strongly influences the range of this ME especially since it has only been visited by four volunteers. Profiles P1-14 and P1-16 have small ranges of ~16 µg/m^3 while P1-10 has a wider range of peak concentrations reaching up to 72 µg/m^3 when the person moved the monitor across the room.

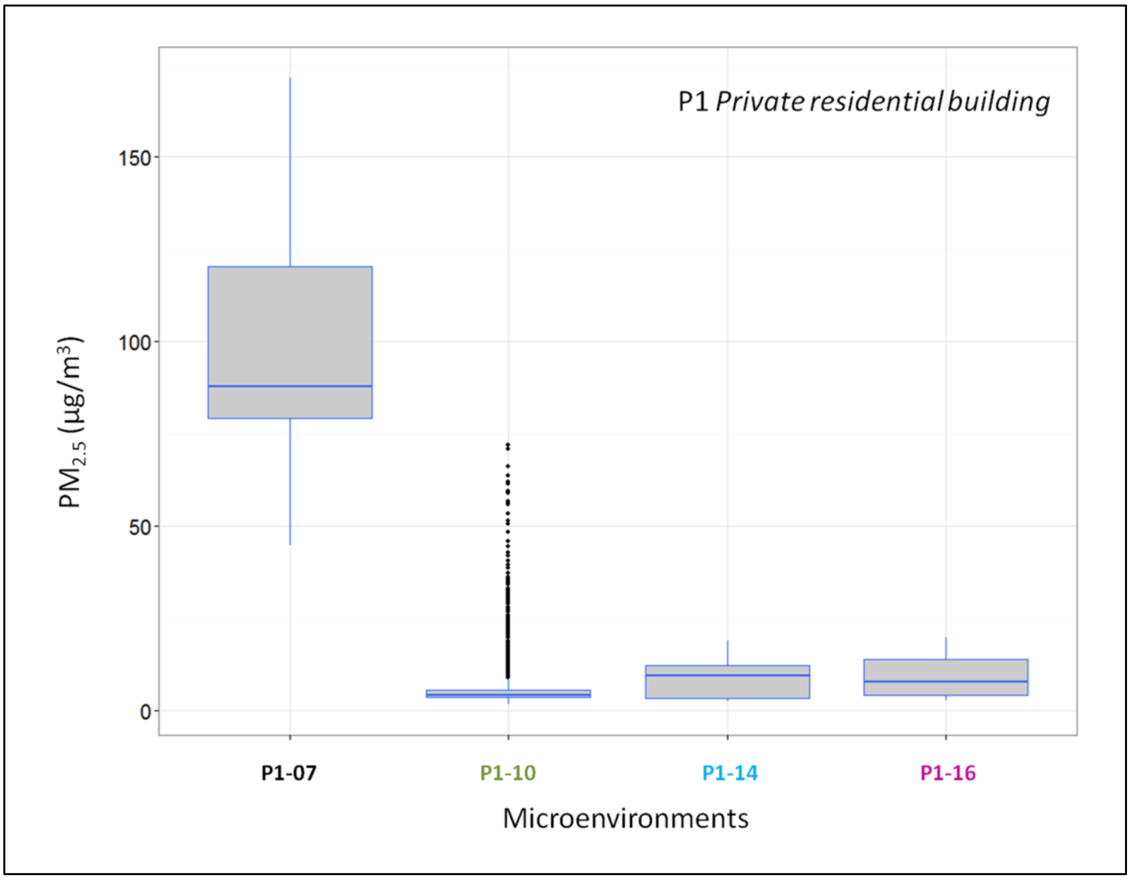


Figure 6-7 Whisker plots showing the variability in concentrations recorded in *Private residential buildings*.

The widest range (236.4 µg/m^3) has the *Public building* ME which is included in 17 profiles. Individual profiles tend to have a fairly small range for this ME apart from P1-04 and P1-19 which have a very wide range that influences the overall range of the profiles. *Public buildings* include a large variety of buildings and activities for instance a small sports centre where the minimum (0.9 µg/m^3 in the actual sports hall) as well as the maximum (~236.4 µg/m^3 in the changing room) have been recorded (on separate days by different individuals). The top end of the range has been recorded in a dry cleaner's shop, a cafe and a theatre. The lowest concentrations were recorded in a shop and a post office.

6.3.3.2 Phase 2 – concentrations per ME

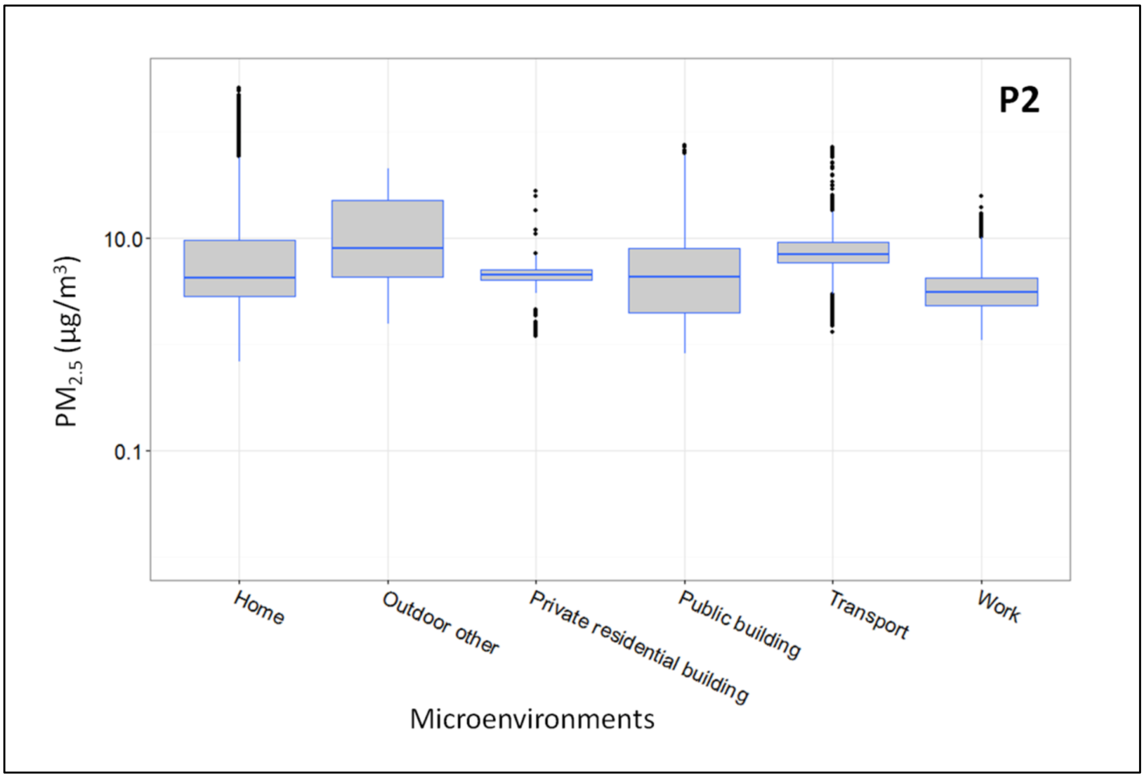


Figure 6-8 $PM_{2.5}$ statistics per Microenvironment for data collected in Phase 2. The whisker plots show the variability of concentrations in the six microenvironments.

In the following sections the $PM_{2.5}$ concentrations in the individual MEs shown in Figure 6-8 are discussed.

In Phase 2 it is also the *Work* ME (which is included in 14 profiles) that has the smallest range (23.9 µg/m³), however remarkably wider than in Phase 1 (9.6 µg/m³). Maximum concentrations in the *Work* ME are related to monitor handling and increased movement in the vicinity of the monitor, for instance when the volunteer moved through the building wearing the monitoring pack, opening and closing doors which is likely to have caused resuspension of particles (maximum 25 µg/m^3, P2-08 Figure 6-9). An exception is P2-16, which is discussed in more detail in section 6.3.4.5. P2-13 shows a wider inter-quartile range than other profiles in this phase with concentrations recorded in the afternoon being higher than those recorded in the morning; no specific reason could be identified for this difference though.

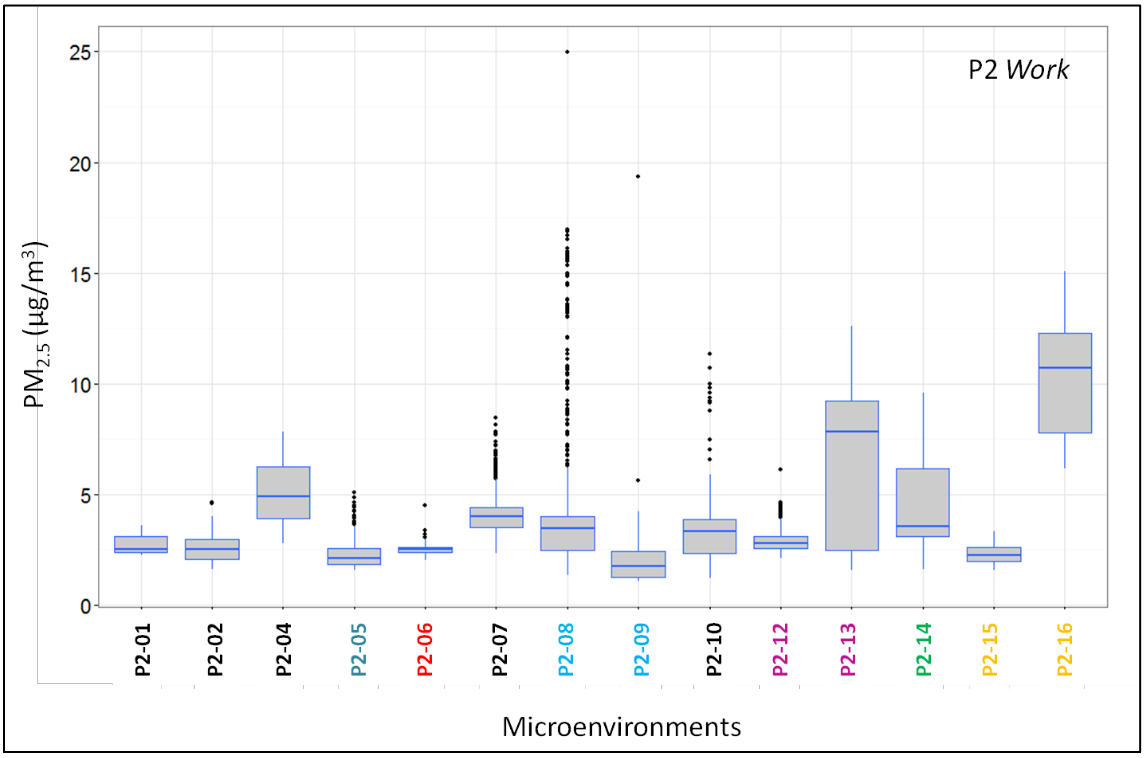


Figure 6-9 Profiles recorded in fieldwork Phase 2 that include the *Work* ME.

Transport (Figure 6-10), which is included in all profiles has a range of 71.7 µg/m^3. The maximum concentrations of 73 µg/m^3 were recorded during a bus journey (P2-16 and section 6.3.4.5). Other increased concentrations are related to the beginning of a car journey and is interpreted as handling the device or moving when getting into the car (P2-03 and P2-08). Other peak concentrations are often related to the beginning or end of journeys where movement and handling are likely to influence the Dylos measurements and might as well be subject to unclear cut offs between two MEs, resulting in "grey areas" and therefore still inside a building for instance. Lowest concentrations (minimum 1.3 µg/m^3) have been recorded during walking, bus and car journeys in rural areas.

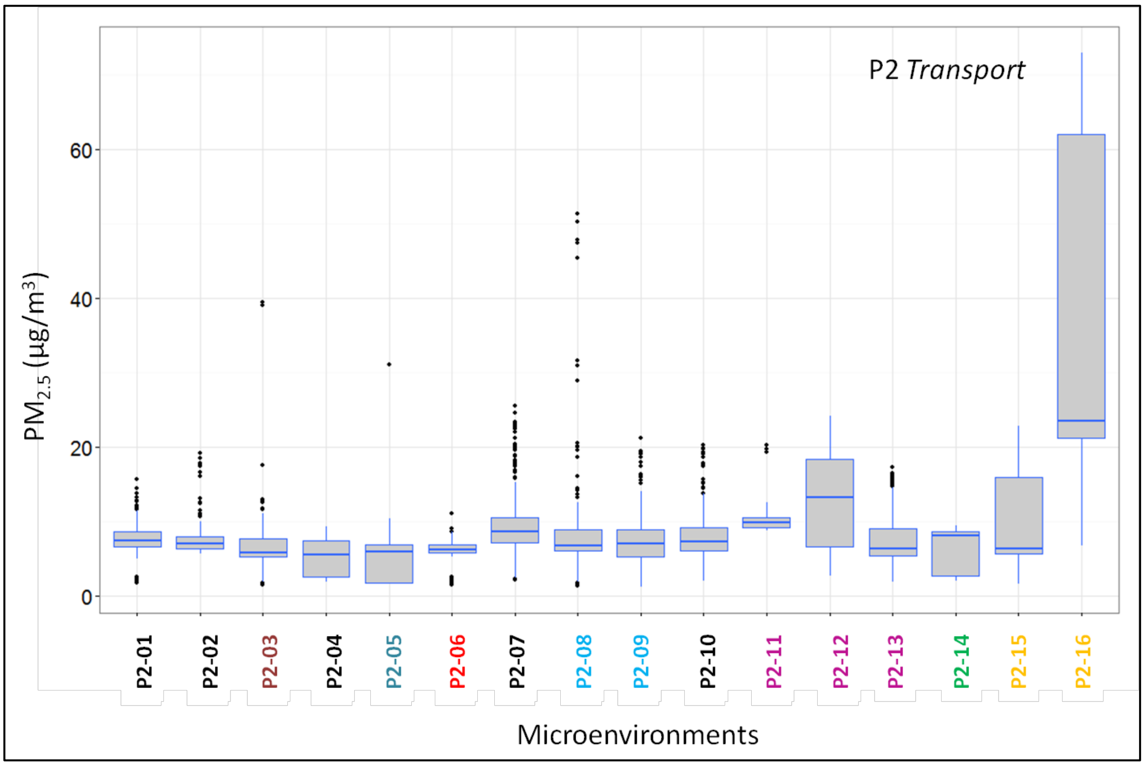


Figure 6-10 Profiles recorded in fieldwork Phase 2 that include the *Transport* ME.

The *Outdoor other* ME has been visited by nine study participants during Phase 2 and has a range of 43.8 µg/m^3. Lowest concentrations (minimum 1.6 µg/m^3) have all been recorded when going for a walk near the *Work* environment (P2-05, P2-12, P2-13) in a rural environment. Highest concentrations are related to handling the monitor when getting on and off a bus and probably involves movement and handling of the monitor when sitting down/getting up; and waiting at a bus stop in the city (P2-16, section 6.3.4.5). The maximum is related to the burning of food and has been recorded when the person left the flat (P2-05, section 6.3.4.4). Due to the difficulties in pinning down the exact change of MEs this might actually still have been measured inside the building.

Every profile in Phase 2 included the *Home* ME which has the widest range of all MEs in either fieldwork phase (264.3 µg/m^3). This is down to a huge variety of activities taking place and sources existing in this ME. However there are also a couple of specific activities with very high concentrations that strongly influence the range. Low concentrations have been recorded during quiet activities or in the late evening/night and early morning hours when none or very limited human activity happened (minimum 0.7 µg/m^3). Peak concentrations are all related to cooking and baking activities or unexplained and relatively long lasting. Baking (with a badly maintained oven (P2-02)) and chargrilling (P2-05) result in very high peak concentrations of 265 µg/m^3 and 211 µg/m^3 respectively which only very slowly decrease and infiltrate other rooms beyond the kitchen despite ventilation and closed doors (sections 6.3.4.4 and 6.3.4.6).

The *Private residential building* ME has again only been visited by four individuals. The range of 26.8 µg/m^3 is much smaller compared to Phase 1 (169.6 µg/m^3) which was strongly influenced by one individual cooking event. The maximum concentration of 28 µg/m^3 is related to getting ready to leave the place and therefore probably due to handling and moving about in the vicinity of the monitor, causing resuspension of particles. Generally levels are relatively low due to quiet activities.

The *Public building* ME (Figure 6-11) which has been visited by 13 volunteers has a range of 75.3 µg/m^3. Lowest $PM_{2.5}$ concentrations have been recorded in a shop, a conference centre and in a church (minimum 0.8 µg/m^3). Highest concentrations (maximum 76 µg/m^3) are related to concerts (P2-08), a changing room (P2-05), movement from tiding up and cleaning (P2-08) as well as pub visits where food was prepared and consumed and many people are present (P2-11). The spread of concentrations in this ME reflects the variety of actual public buildings, sources and activities.

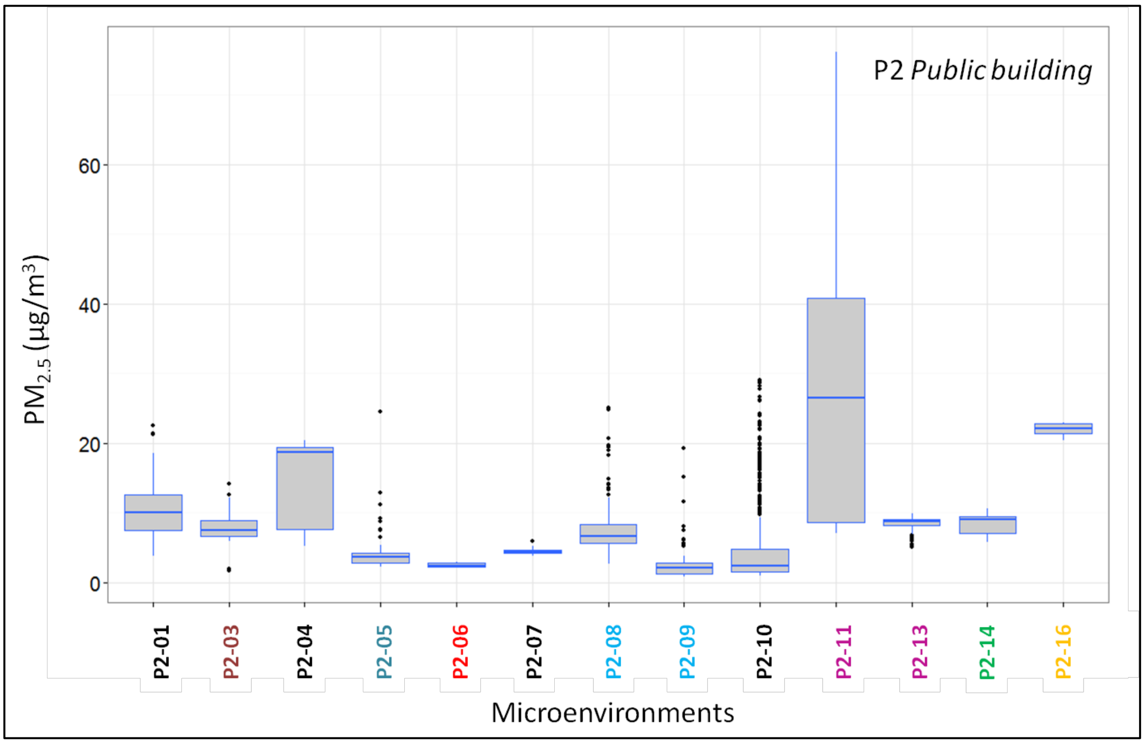


Figure 6-11 Profiles recorded in fieldwork Phase 2 that include the *Public building* ME.

6.3.3.3 Concentrations per class

Table 6-11a shows summary statistics for $PM_{2.5}$ concentrations in the three different classes as predicted with the functions derived in chapter 4 (for comparison reasons Table 6-11b shows the statistics for PNCs (>0.5 and <2.5 µm) as recorded with the Dylos). The pattern for the three different classes is the same in Phase 1 and Phase 2: *Indoor* has the widest range of $PM_{2.5}$ concentrations. This is due to the large variety of sources and activities in the indoor environment where peak concentrations are recorded during cooking and baking activities as well as when many people are about and unexplained. *Outdoor rural* has the smallest range, median and mean values as it is (when compared to *Indoors*) a fairly uniform environment where the person is either in transport or outdoors. Mean values in Phase 2 are all higher than in Phase 1. This is driven by a number of peak concentrations in Phase 2 which also cause a wider range in *Indoor* and *Outdoor rural.* The *Outdoor urban* range is wider in Phase 1 which is influenced by the peak measurement in front of a burger grill.

Table 6-11 Descriptive statistics for $PM_{2.5}$ concentrations ($\mu g/m^3$) (a) and PNC (>0.5 and <2.5 μm) (b) per class in Phase 1 and 2

	P1						P2					
a	**mean**	**sd**	**median**	**min**	**max**	**range**	**mean**	**Sd**	**median**	**min**	**max**	**range**
Indoor PM2.5 ($\mu g/m^3$)	5.8	9.8	3.1	0.9	237.3	236.4	8.9	19.2	4.0	0.7	265.0	264.3
Outdoor rural PM2.5 ($\mu g/m^3$)	2.5	1.3	2.1	1.4	17.0	15.6	3.1	2.7	2.3	1.3	22.5	21.1
Outdoor urban PM2.5 ($\mu g/m^3$)	8.9	4.5	7.8	5.0	87.2	82.3	10.8	8.4	7.7	4.8	73.0	68.2

b	**mean**	**sd**	**median**	**min**	**max**	**range**	**mean**	**sd**	**median**	**min**	**max**	**range**
Indoor PNC (# of particles/ft^3)	123,596	234,604	59,200	4,900	5,687,570	5,682,670	199,018	461,361	79,800	900	6,355,300	6,354,400
Outdoor rural PNC (# of particles/ft^3)	106,652	119,708	71,500	8,800	1,408,800	1,400,000	163,993	246,617	87,700	1,700	1,899,600	1,897,900
Outdoor urban PNC (# of particles/ft^3)	148,271	158,556	107,400	8,300	2,939,000	2,930,700	213,994	300,078	105,900	100	2,431,300	2,431,200

6.3.3.4 Concentrations per transport mode

Table 6-12 displays the different transport modes in the two outdoor classes which show distinct differences. The data shows firstly, that the *Bus* is the transport mode with the highest mean concentrations in both phases and both environments, this is followed by *Walk* (except in phase 2 *outdoor urban* where *Bicycle* has a higher mean value), *Car* and the *Bicycle* which has the lowest mean concentration (except in phase 2 *outdoor urban* where the *Car* has the lowest mean value).

Secondly, the *Outdoor rural* means are much lower than *Outdoor urban* mean concentrations revealing the difference between ambient urban and rural background concentrations.

Thirdly *Outdoor urban* and *rural* means in Phase 2 are higher than in Phase 1, except *Car* and *Walk* in *Outdoor urban*. Especially the maximum (and mean) concentrations for *Bicycle* and *Bus* in Phase 2 *Outdoor urban* are much higher than *Outdoor rural* and than comparable values from Phase 1. This is in one case likely due to handling/moving as the person arrived at their destination within the respective timeframe (*Bicycle,* P2-07). In the other case (P2-16) it is partly influenced by the prevailing wind direction bringing in air masses from the European continent but also calm and humid conditions preventing turbulence and therefore limiting air exchange within the boundary layer and partly due to local transport emissions (*Bicycle* and *Bus,* P2-07 and P2-16).

Table 6-12 Descriptive statitscs of $PM_{2.5}$ concentrations per transport mode and class. Please note that only the regularly used transport modes are displayed - *Train* and *Ferry* have been excluded from this table.

P1	TPM	n	mean	sd	median	Min	max	range
Outdoor rural	Bicycle	42	2.1	0.5	2.0	1.4	3.5	2.1
	Bus	139	4.3	3.9	2.8	1.4	17.0	15.6
	Car	1,263	2.2	0.6	2.1	1.4	7.8	6.4
	Walk	99	2.3	1.7	2.0	1.4	12.6	11.2
Outdoor urban	Bicycle	196	7.6	1.5	7.3	5.0	11.5	6.5
	Bus	682	10.4	6.3	8.3	5.0	44.0	39.0
	Car	1,075	7.9	2.3	7.3	5.1	22.7	17.6
	Walk	479	9.0	3.7	7.9	5.1	36.0	30.9

P2	TPM	n	mean	sd	median	Min	max	range
Outdoor rural	Bicycle	33	2.5	0.7	2.3	1.6	4.3	2.7
	Bus	71	4.9	4.8	3.4	1.5	22.5	20.9
	Car	169	2.8	2.2	2.1	1.5	19.6	18.1
	Walk	78	3.1	2.8	2.1	1.3	20.9	19.6
Outdoor urban	Bicycle	202	12.5	6.4	9.3	5.8	25.5	19.8
	Bus	381	15.2	14.7	9.6	4.8	73.0	68.2
	Car	511	7.8	5.4	6.7	5.3	51.4	46.1
	Walk	652	8.1	3.2	7.2	4.8	34.3	29.6

6.3.3.5 Concentrations influenced by type of heating & kitchen appliances

In the questionnaires volunteers had to provide information about the heating system and the type of oven and cooker installed in their homes (Table 6-2). With all volunteers having gas central heating no conclusions can be drawn as to whether different heating systems affect indoor particulate levels differently. A few people used additional heating methods, e.g. two homes used electric, and two used solid fuel appliances. One person (P1-07) used a log fire as recorded in the TAD (the person did not mention this in the questionnaire though). As the profile in Figure 6-12 shows, concentrations increased sharply when the fire is lit and decrease relatively quickly after the initial lighting.

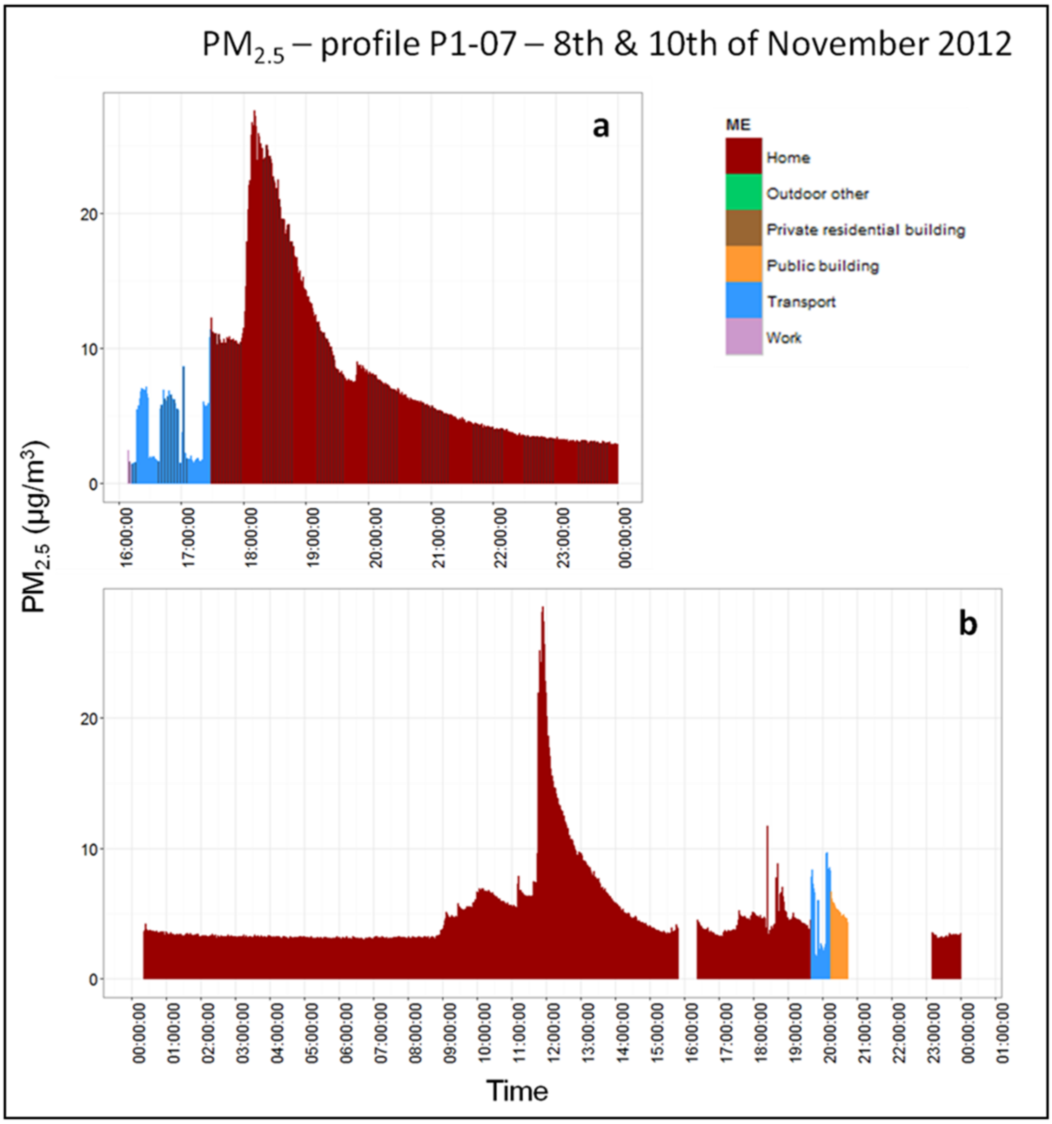


Figure 6-12 Graph showing the $PM_{2.5}$ data with 1-minute resolution while a log-fire is lit. The person in profile P1-07 lit a log fire on two days during their monitoring period. This can be seen in the *Home* ME where distinctive peaks appear as soon as the fire is lit at ~18:00 on the 8th and at 12:00 on the 10th of November. On both days concentrations drop to levels before the fire was lit within the hour. Data collection started on the 8th of November (a). Data gaps on the 10th of November (b) are due to the Dylos running out of power.

Regarding kitchen appliances, the only measure that can be analysed is the concentrations in the *Home* ME (Table 6-13). However this has to be looked at carefully because, as discussed in sections 6.3.3.1 and 6.3.3.2, there are a variety of sources and activities in the *Home* ME which make it difficult to relate differences in concentrations to the type of hob or oven used. $PM_{2.5}$ emissions from cooking are expected to be mainly affected by the actual type of food and not the use of an electric or gas hob (compared to biomass or solid fuel use which will contribute more to the total concentration) (Abdullahi et al., 2013).

The data in Table 6-13 are the same as shown in Table 6-3 but on this instance split by the type of oven/cooker available in the respective households. Mean values vary substantially between the individual profiles and suggest influences other than the type of cooking fuel the hob and/or oven are operating on.

Table 6-13 Tables showing the $PM_{2.5}$ mean values (µg/m^3) for the *Home* ME split by the type of oven/cooker.

Profile	**$PM_{2.5}$ mean (µg/m^3) (with electric oven/cooker)**
P1-01-Home	3.1
P1-02-Home	4.4
P1-05-Home	4.1
P1-17-Home	3.1
P1-18-Home	7.7
P2-14 Home	4.78
P2-15 Home	7.37
Average	4.9

Profile	**$PM_{2.5}$ mean (µg/m^3) (gas oven/cooker)**
P1-12-Home	6.3
P1-15-Home	12.6
P1-16-Home	8.1
P2-07 Home	7.95
P2-11 Home	4.70
P2-12 Home	8.14
P2-13 Home	3.18
Average	7.3

Profile	**$PM_{2.5}$ mean (µg/m^3) (electric oven/gas cooker)**
P1-03-Home	2.1
P1-04-Home	3.0
P1-06-Home	11.4
P1-07-Home	6.4
P1-08-Home	2.7
P1-13-Home	2.8
P1-14-Home	3.9
P1-19-Home	6.7
P2-01 Home	14.14
P2-02 Home	46.85
P2-03 Home	8.22
P2-04 Home	4.87
P2-05 Home	32.20
P2-06 Home	6.13
P2-08 Home	4.55
P2-09 Home	2.19
P2-10 Home	3.54
P2-16 Home	17.82
Average	9.97

6.3.4 Discussion of individual profiles and exposure situations

Each profile shows the personal exposure data of the respective participant, and since all profiles were recorded by an individual pursuing their own daily activities, profiles are not directly comparable between individuals even for the same time and day. A location that all study participants but one have in common is the workplace which means that in most cases, the work indoor environment is comparable. The urban background concentration levels for Edinburgh as measured at the St. Leonards fixed monitoring site represent the nearest reference concentration data for 11 of the individuals, who have their residential address in Edinburgh. The other six individuals have their home address in other areas where the Auchencorth Moss site or other AURN sites are closer (section 6.3.2). In the case of the weekend/holiday profiles individuals have been exposed to an entirely different background level to their residence.

In the following individual profiles and the variations of measured concentrations across the MEs visited within these profiles are displayed, analysed and discussed.

Following this, specific exposure situations of individual profiles are discussed in more detail. Here, all cases show (an) individual day(s) taken from a comprehensive profile. The y-axis changes from profile to profile according to the concentrations measured the x-axis depending on the length of the profile recorded on the respective day.

For comparison the hourly $PM_{2.5}$ values recorded at the two local fixed-site stations of the AURN which are also used for the evaluation of the Dylos in chapter 4 are shown for the respective days on which measurements were conducted. One is an urban background station (Edinburgh St. Leonards), the other a rural station (Auchencorth Moss). The data is provided on the Scottish Air Quality website (Scottish Air Quality, 2013) through the Open Air application which also provides modelled wind speed and direction data (Carslaw and Ropkins, 2012). There are issues with data quality resulting in zero and negative values at both sites which are inherent to the measurement method and devices applied (chapter 4) and essentially indicates very low concentrations. While the TEOM-FDMS data has undergone quality control and is ratified, it represents measurements of particulate matter concentrations based on an accepted reference method, which results in zero or negative particle mass concentrations. It is highly unlikely that such concentrations do occur in reality, which highlights that such observations need to be viewed with care and can affect the comparison of different measurement methods.

Additional weather data used in this chapter is provided by Dr. Massimo Vieno, taken from the weather station on the roof of one of the University of Edinburgh buildings in Edinburgh (University of Edinburgh, 2013) (55.922450 N, -3.1724447 W) and represents the meteorological conditions in Edinburgh with sufficient accuracy for this pilot study.

6.3.4.1 Variability of concentrations across the MEs visited within a profile

Profile P1-07 shows how individual events and activities can influence the whole profile and affect summary values. P1-07 has a range of 184.6 µg/m^3. Looking at the spread of concentrations across the six MEs the volunteer has visited over 5 consecutive days it is the *Private residential building* that dominates concentration levels with a mean concentration of 101.5 µg/m^3 over a period of 42 minutes. This high concentration value is entirely driven by a cooking event at a friend’s house and corroborates findings from other studies that cooking can cause high concentrations and exposures (Abdullahi et al., 2013). Note that the monitor ran out of power hence the recording of this event only lasted for 42 minutes, while it can be assumed that concentrations stayed high for a longer period as seen in other profiles (section 6.3.4.4). Furthermore, the *Home* ME does stand out in this profile with maximum concentration peaks of up to 185.8 µg/m^3 within a period of 5 minutes (black dots). This short term peak occurs when people and two dogs were getting ready to leave the house, which is in line with the findings by Ferro et al. (2004) that human (and in this case pet) activity can generate short term high PM concentration events. It is these short term peaks that strongly influence the range of the overall profile. The mean concentration value for *Home* is at 6.4 µg/m^3 and as a summary measure integrating over a longer time period is not able to reveal short term peaks such as those just described. All other MEs display much smaller concentration ranges.

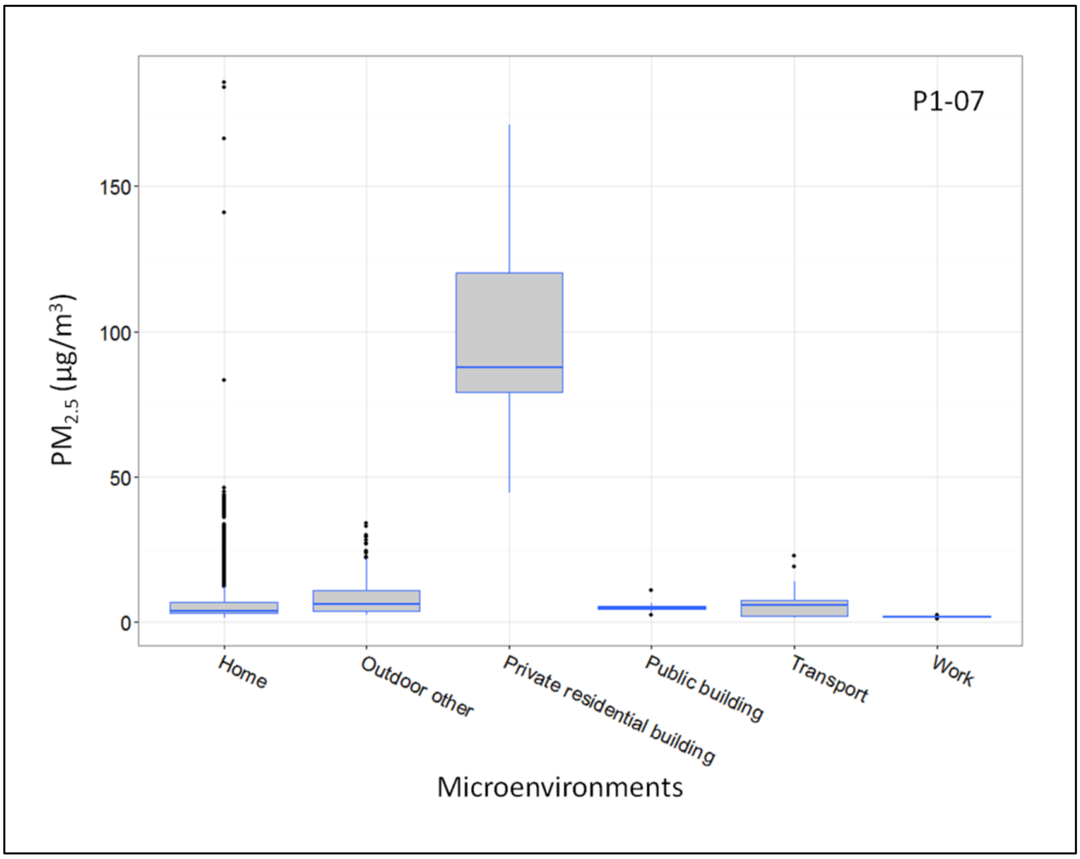


Figure 6-13 Concentrations per ME of profile P1-07.

Similar to profile P1-07, the volunteer recording P1-14 also spent time in all six MEs over six consecutive days. Unlike P1-07, though, the concentrations encountered across the MEs are much more uniform and have a much narrower range of 65.4 μg/m^3. The highest concentration (66.4 μg/m^3) is recorded in the *Public building* ME which was after a theatre show finishes and people leave and therefore is likely to have been caused by resuspension and the personal clouds of people moving about. The *Work* ME has the smallest range in both profiles.

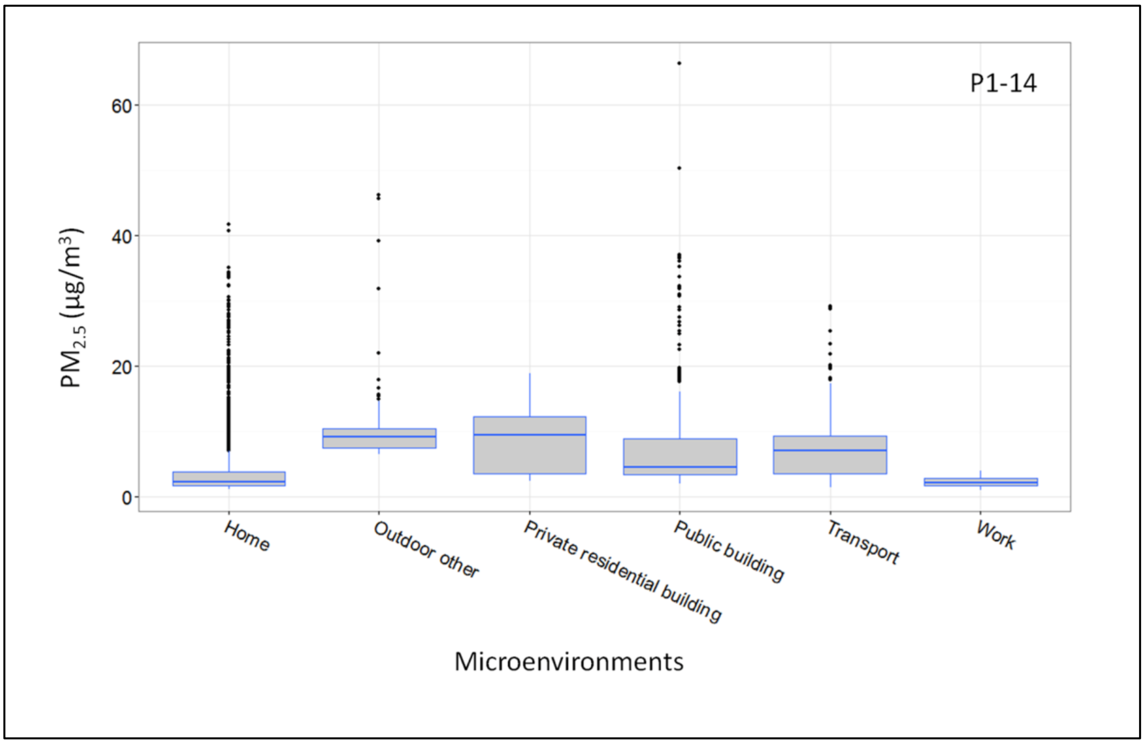


Figure 6-14 Concentration per ME of profile P1-14.

6.3.4.2 Example P1-03 and P1-05 -generally low concentration and weather/transport mode related data gaps

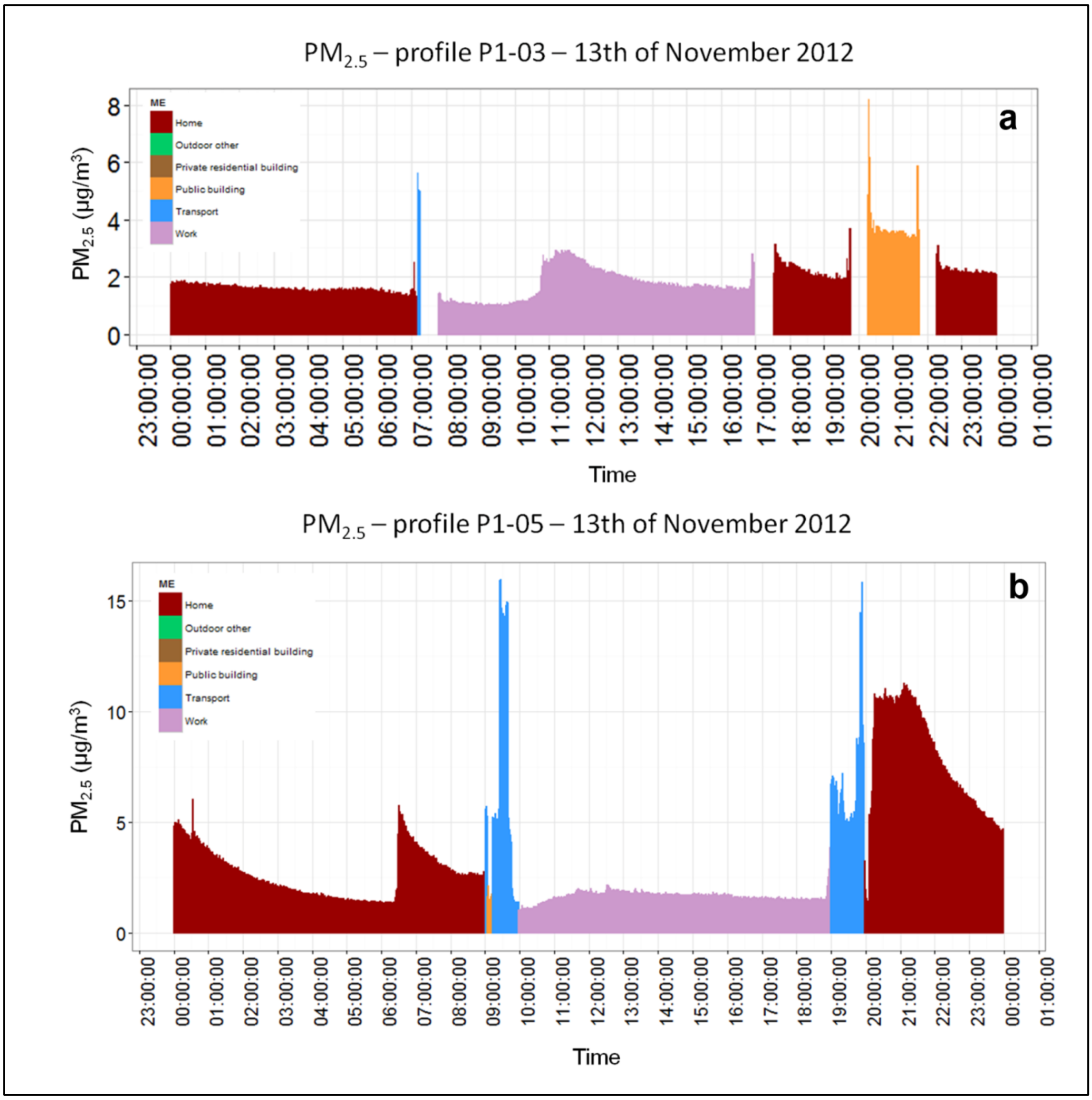


Figure 6-15 a) Profile P1-03 showing data collected with 1-minute resolution on the second day of a monitoring period. $PM_{2.5}$ concentrations are generally low with the maximum being 8.2 µg/m^3. Part b) shows the second day of P1-05 which has been recorded on the same day as the second day of P1-03. Concentrations are generally low for both profiles; however a different, individual pattern can be distinguished between them.

The person recording the profile depicted in Figure 6-15a lives in central Edinburgh and commutes to *Work* by *Bicycle,* the distance measured as a direct line between *Home* and *Work* is 7.5km. Due to rain the monitor had to be covered half way through the journey in the morning (~7:00-7:30) and for the entire return journey (~17:00). The increase of concentration at the *Work* place around 11:00 is at the time when staff came back to the office after a seminar. The monitor was left in the office which was shared by four people, on the floor next to the person's desk. The gaps in the evening were due to rain when the person was walking to their destination. The short-term increase (note that concentrations are still <10 μg/m^3) at the beginning and end of the visit to the *Public building* ME where the person attended a dance class are likely due to the volunteer and other people arriving, moving about and getting ready to leave, which created turbulence and caused resuspension of particles. During the class the monitor was located at the side of the room where levels remained low (<4 μg/m^3). This suggests that only movement in the direct vicinity of the monitor causes increased levels that are picked up by the monitor. A similar observation has been made in a sports hall where people played badminton and the monitor was located at the side, recording low values throughout. Note that there are only very limited GPS recordings available for this profile because the monitoring pack was not used outdoors due to adverse weather conditions.

Figure 6-15b shows data recorded on the same day as for P1-03 displayed in Figure 6-15a. This person also lives in the urban environment of Edinburgh and commutes to the same *Work*place (distance 8.8km). Notable differences are the higher levels at the *Home* and *Transport* MEs. The increase at *Home* around 6:00 might be caused by the volunteer's cat. In the morning the person *Walk*ed to the bus stop, briefly calling in at a post office. The second part of the commute was by *Bus.* Here the highest concentrations of about 16 μg/m^3 were recorded in the first half of the bus journey (see pink dots on the GPS location map in Figure 6-16). *Work* is, like in Figure 6-15a, characterised by low concentrations with values <2 µg/m^3. This person is located in an open plan office with people frequently coming and going. Movements in the open plan office seem however not to be picked up by the Dylos which was placed at the person's desk in the far corner of the room, away from the door. This further supports the assumption that only movement in the direct vicinity of the Dylos leads to a measurable increase in particle concentrations. The return journey in the evening follows a different route and is done by *Car, Bus* and the last leg by *Walk*ing. When *Walk*ing along a main road the highest values of this journey (~12-14 µg/m^3) are observed. The detailed information in the TAD provided by the volunteer made it possible to distinguish between exposure situations along main roads, minor roads or away from roads. These values are not shown on the GPS map (Figure 6-16) due to confidentiality reasons, as they are in close proximity to the volunteer's home. In the evening (~20:00-21:30) cooking and cleaning increased concentration levels at *Home* to just over 10 µg/m^3 for a short period, slowly decreasing again over night.

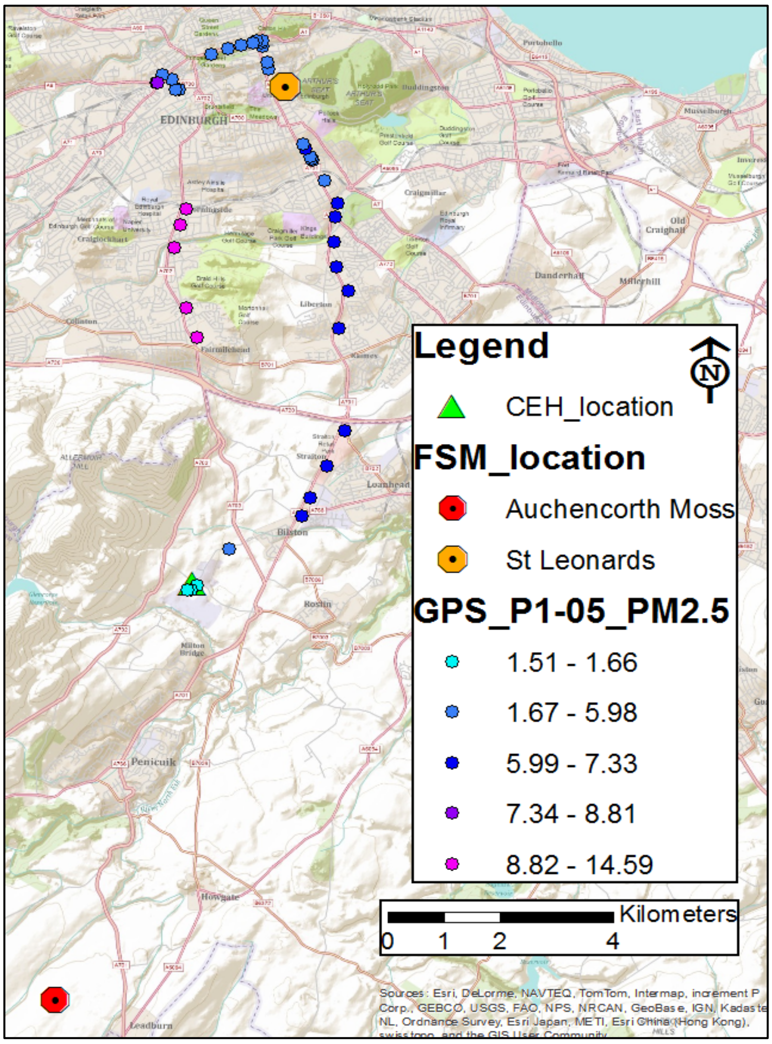


Figure 6-16 GPS tracks of P1-05 showing the $PM_{2.5}$ concentration (µg/m^3) logged once per minute. Note that only confidential GPS points are shown, in particular indoor MEs do not have GPS logs. Also shown are the locations of the fixed site stations St. Leonards, Auchencorth Moss and the location of CEH. Highest concentrations (pink dots) occurred during a bus journey, lowest (turquoise dots) near the workplace

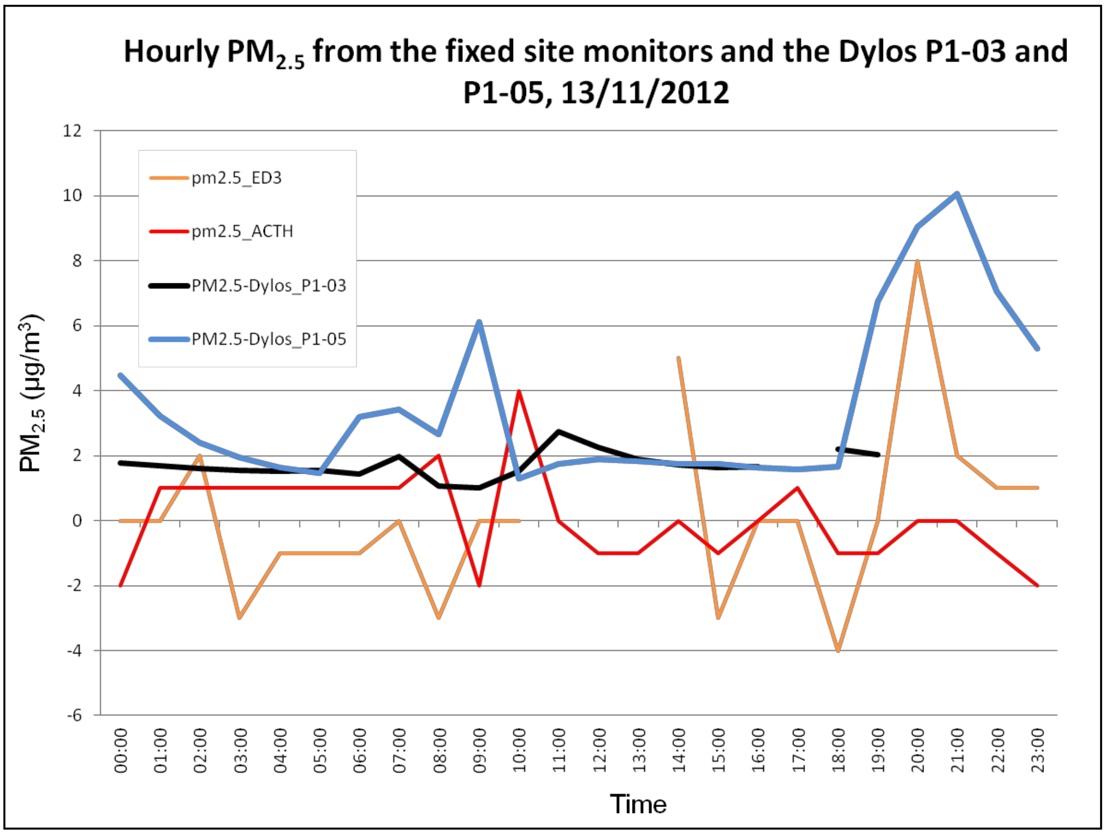


Figure 6-17 Hourly PM$_{2.5}$ data from the two fixed site monitoring stations Auchencorth Moss and Edinburgh St. Leonards and hourly values derived from the personal Dylos measurements for the two profiles recorded on the 13th of November. The daily mean recorded at Auchencorth Moss was 0 µg/m^3, a value unlikely representing real world concentrations, but is due to the measurement method (section 4.2.1). Note that there is no measured daily value provided for Edinburgh St. Leonards.

The hourly PM$_{2.5}$ values recorded at the urban background station (PM2.5_ED3) are either negative or zero during the night and the morning, which are in line with the low values recorded at *Home*. When the volunteers were at *Work* the values measured at the rural station (PM2.5_ACTH) varied between negative values and 4 µg/m^3 while the daily mean was recorded as 0 µg/m^3. This corresponds to the low values measured by both volunteers at the workplace (~9:00-18:00). In the evening hours the urban levels vary between negative concentrations and a maximum of 8 µg/m^3 at 21:00. This increase of PM$_{2.5}$

concentrations form roughly 19:00 onwards is due to traffic and is in line with the higher concentrations measured when the volunteer was walking along a main road (~19:40-20:00, PM2.5_Dylos_P1-05, blue line). All together the low concentrations measured at both sites are in line with the generally low concentrations in both profiles recorded over the 24 hours. Generally the low levels between personal and stationary measurements agree, however it is only the personal measurements that can capture and make visible the fine details of concentration changes.

The volunteers were asked to provide information in the TADs about the weather on the monitoring days. For this day the volunteers reported rain/a bit of rain, cloudy and 10˚C. This corresponds to the fact that the monitor could not be used outdoors in one of the profiles and the relative humidity of ~70-90% increasing to 100% in the evening, measured at the weather station at the University of Edinburgh.

6.3.4.3 Example P1-17 - variety of concentrations across different MEs and noise related data gap.

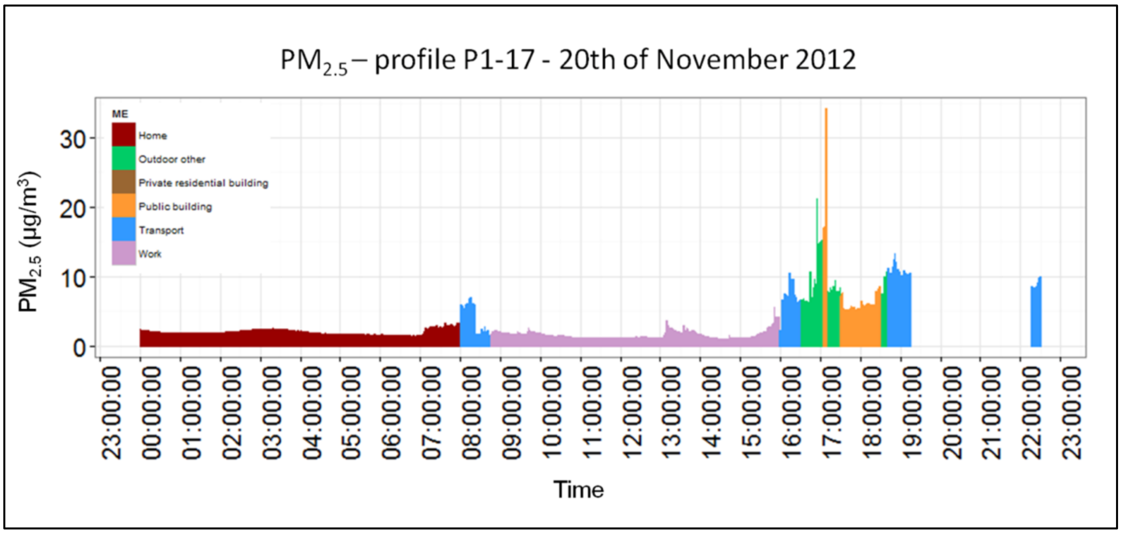


Figure 6-18 Data from one day of profile P1-17, showing $PM_{2.5}$ concentrations with 1-minute resolution and the five MEs the volunteer visited during the day in different colours.

Figure 6-18 shows the personal variation in exposure to $PM_{2.5}$ as recorded in P1-17 on the 20th of November 2012. The person visited all but the *Private residential building* ME during the day. The profile starts at *Home* located in a large urban area, where the person stayed until ~ 08:00 and concentrations are generally low. *Transport* to *Work* (~08:00-08:45) was done by running with the monitor carried on the front. The first part of this journey was in a mainly urban area but avoiding the main roads before the route leads out into the countryside. As the W*ork* ME is located in a rural, low pollution environment, concentrations measured do not exceed 6 µg/m^3. All other *Transport* activities were conducted by car (~16:00-16:20, ~18:40-19:15 and ~22:15-22:30) with up to four passengers and show slightly higher concentrations which can be due to the actual transport mode, the location of the *Outdoor urban* environment and the movement and personal cloud contribution of the people in the *Car*. *Outdoor* *other* comprised walking around Edinburgh city centre which shows variability in concentrations. *Public buildings* visited were a train station (~17:04-17:10) which is a busy and unique environment covered by a roof, but with both trains and taxis inside the station contributing emissions that would otherwise only be found outdoors. This visit results in a short term peak concentration of ~34 µg/m^3. Since January 2014, the station is closed for private cars and taxis and only authorised vehicles can enter (BBC News, 2014). While this was introduced due to security concerns, it should have a positive effect on air quality inside the station compound. After leaving the train station, the person spent some time in a cafe (~17:30-18:30). The data gap (~19:15-22:15) is due to the volunteer visiting a concert for which the monitor was considered as being too noisy and was therefore left in the car.

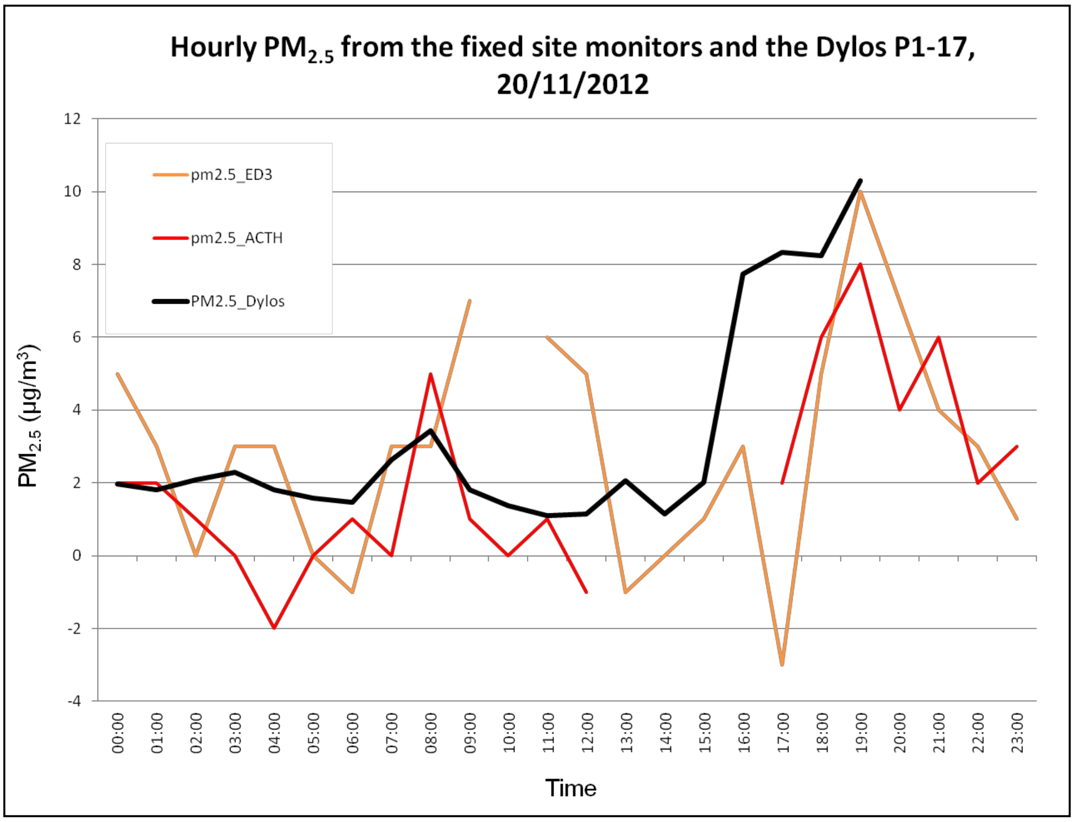


Figure 6-19 Hourly PM$_{2.5}$ data from the two fixed site monitoring stations Auchencorth Moss (PM2.5_ACTH) and Edinburgh St. Leonards (PM2.5_ED3). The daily mean recorded at Auchencorth Moss was 2 µg/m^3.

Hourly values derived from the personal Dylos measurements for the 20th of November (PM2.5_Dylos) are shown as black line. On this day no GPS data has been recorded.

Hourly $PM_{2.5}$ concentrations measured at the rural station Auchencorth Moss (PM2.5_ACTH) and the urban background station St. Leonards (PM2.5_ED3) for the 20th of November 2012 are shown in Figure 6-19. This person lives in an urban area between the Auchencorth Moss site and the *Work* environment (4.3 km to Auchencorth Moss, 4.1 km to *Work* and 13.3 km to St. Leonards) and it is thus suggested that measurements from St. Leonards are not representative for the persons *Home* ME. During the night concentrations at both sites were low and included zero and negative values. In the morning concentrations at Auchencorth Moss picked up and reach 5 μg/m^3 by 9:00 before they dropped down to zero and negative values again. After that there was a data gap until 18:00 due to instrument issues. The large number of zero and negative values at Auchencorth Moss during the day indicate very low concentrations and correspond to low values measured both in the *Home* and *Work* environment.

The urban background concentrations measured at St. Leonards are at 1 μg/m^3 at 16:00 when the person left work and headed into Edinburgh city centre. Concentrations increase to 3 μg/m^3 before they reached a negative value again and then showed a peak of 10 μg/m^3 at 20:00. Edinburgh St. Leonards measurements between the hours of 16:00 and 22:00 varied a lot and did not correspond well with the Dylos measurements highlighting the difficulties of assessing personal exposure based on fixed-site monitoring. The increase in the evening between 19:00-20:00, which occurred on all evenings discussed in this chapter, was probably due to evening rush hour traffic emissions.

According to the volunteers' notes it was a dry day which is in line with the weather parameters from the station at Edinburgh University, with temperature varying between 8 and 13˚C and relative humidity between 60-90%.

6.3.4.4 Example P2-05 - Long lasting high concentrations due to cooking

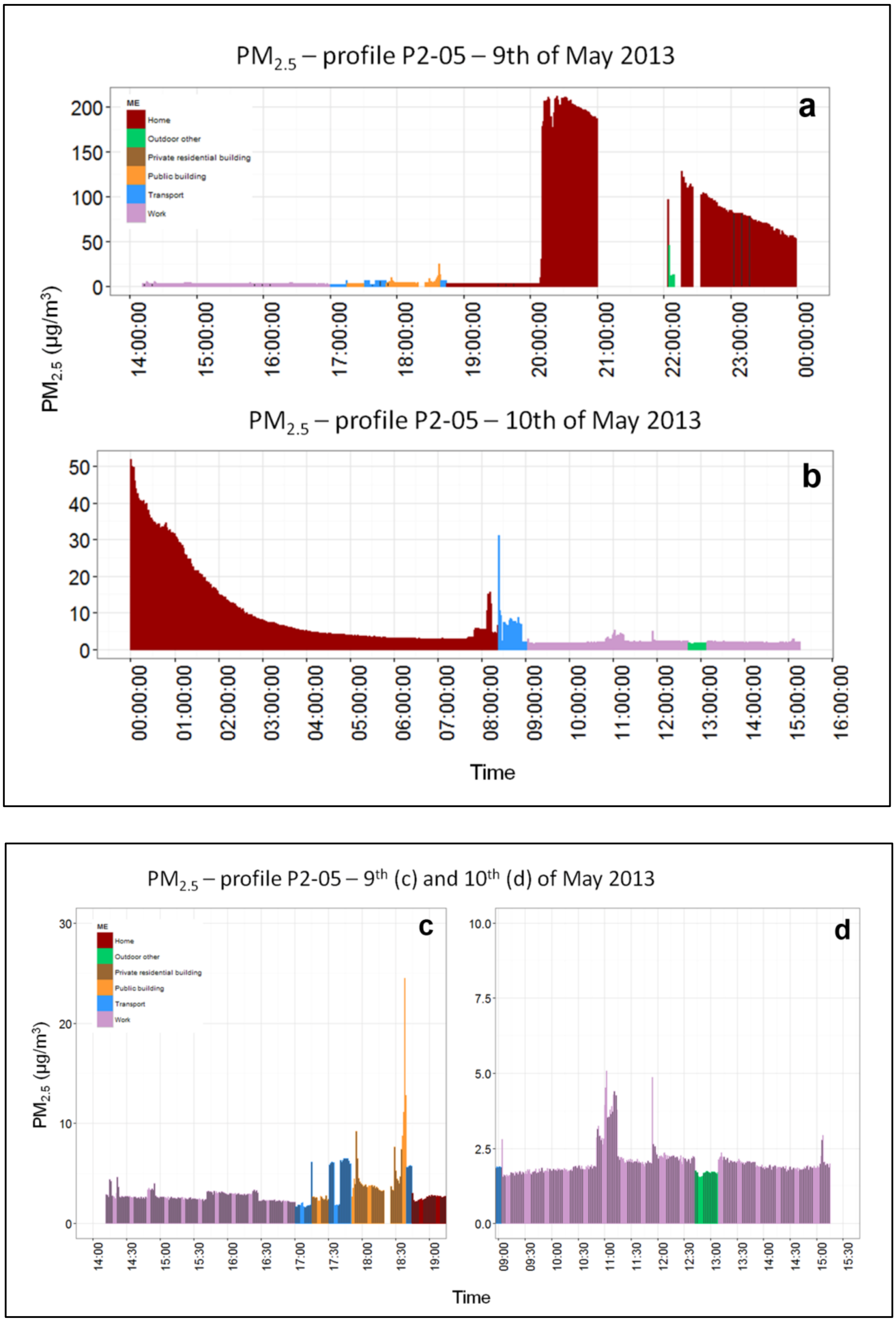


Figure 6-20 PM$_{2.5}$ concentrations (1-minute resolution) on two consecutive days. While concentrations are generally low, there are notably higher concentrations in the *Home* environment (a and b). This profile also illustrates differences in the very low concentrations at the *Work* environment due to movement (c and d). Data gaps on the 9th of May are due to leaving the Dylos in a locker in the swimming pool (~18:20) and a flat battery (~21:00-22:30).

The profile extract shown in Figure 6-20 is an example for increased concentrations at *Home* due to a cooking event, which is broken down into different stages as follows:

a) On the evening of the 9th of May the volunteer has been at *Home* chargrilling food in the kitchen commencing at ~20:00. The kitchen filled up with smoke quickly and concentrations increased rapidly to values >200 µg/m^3. The extractor fan was turned on and the window opened. Note that the kitchen door was open, so when the person moved from the kitchen to the living room at around 20:21, carrying the monitoring pack with them, concentrations remained high, in fact the maximum concentration of 211 µg/m^3 is reached at 20:24. The Dylos then ran out of battery power and was not monitoring consistently until the person returned from a short period in *Outdoor other* and plugged the monitor in at 22:16. Note that the concentrations were still high inside (~110 µg/m^3) when the person returned *Home*.

b) The concentrations stayed high in the *Home* ME and decreased only slowly overnight, falling below 25 µg/m^3 after 1:15 on the 10th of May. The volunteer perceived this as is reflected in their TAD "*... I did fill my kitchen with smoke char grilling before I remembered to open window and turn on fan... probably lingered most of night."*

c) On the 9th of May levels in the *Work* environment were generally very low. Differences can however be seen between a quiet lab where gas samples are handled (~14:30-14:50 and 15:00-15:35) and a busy lab where soil samples are processed (~14:50-15:00 and 15:35-16:25). The impact of human activity when moving around the building and changing rooms is nicely shown in this dataset. The gap in the evening (~18:20) is when the person went to a public swimming pool and had to leave the Dylos in a locker for a short period. Levels observed in the swimming pool were low, with short term peaks at the beginning and end of the visit due to handling. The person noted that the changing room visited at the end was very busy and probably there were a lot of aerosol sprays in the air.

d) Levels in the *Work* environment on the 10th of May were generally low, however differences were picked up by the monitor when the person went to the common room for tea break (~10:46-11:00) and when moving around the building opening doors. This is likely due to movement and activity in the direct vicinity of the monitor causing short term increases of PM levels due to turbulence and resuspension.

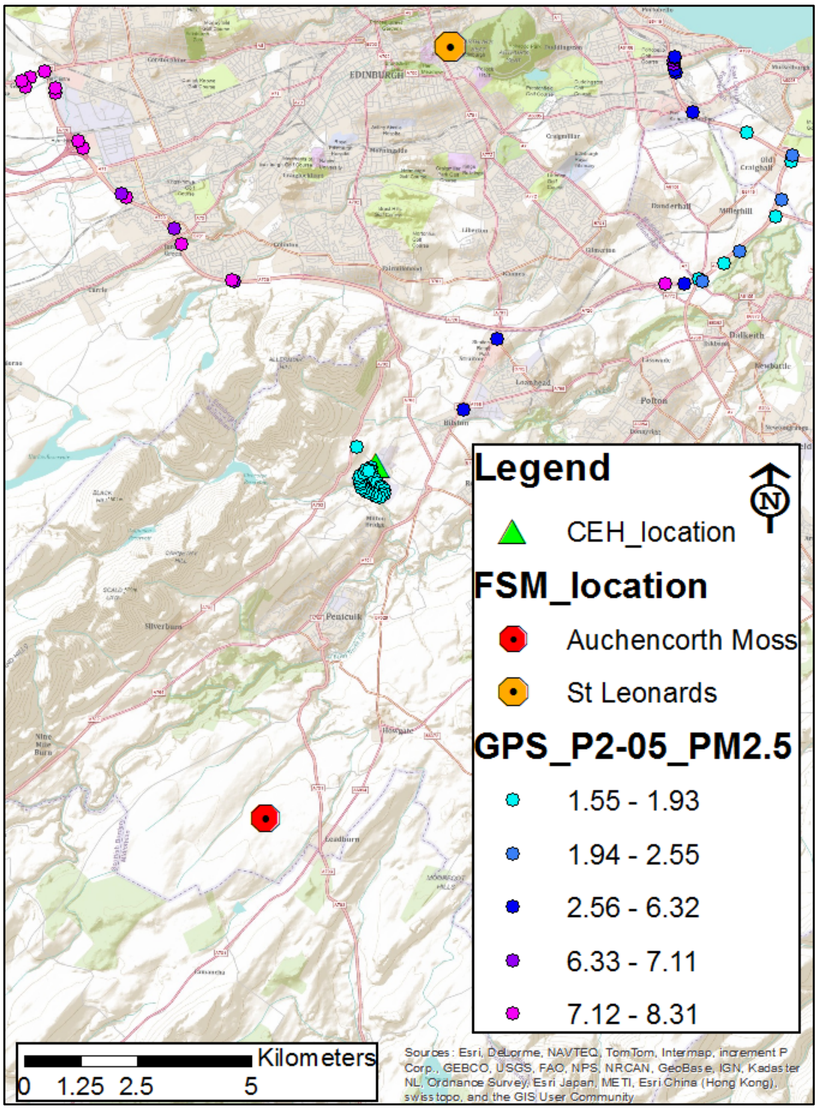


Figure 6-21 Map showing the GPS tracks of P2-05 and the respective $PM_{2.5}$ concentration (µg/m^3) logged once per minute. Also shown in the map are the locations of the fixed site stations St. Leonards, Auchencorth Moss and the location of CEH. Concentrations during the journey in the evening of the 9th of May are lower (blue and turquoise dots, East) while concentrations are highest on the city Bypass during the morning rush hour of the 10th of May (pink and purple dots, West). Lowest concentrations have been recorded during a walk at lunchtime (turquoise dots, South). Note that the concentrations shown in this map do not exceed 8.3 µg/m^3.

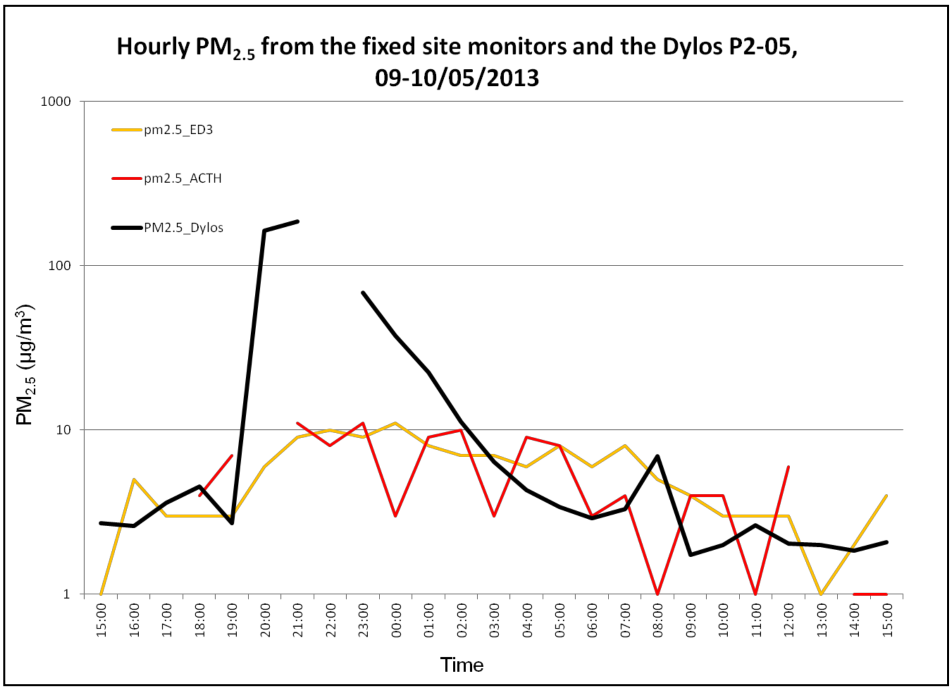


Figure 6-22 Hourly $PM_{2.5}$ data from the two fixed site monitoring stations Auchencorth Moss (PM2.5_ACTH) and Edinburgh St. Leonards (PM2.5_ED3) and hourly values derived from the personal Dylos measurements (PM2.5_Dylos) for the period 9-10th of May. Daily means for Auchencorth Moss were 4 µg/m^3 on the 9th and 3 µg/m^3 on the 10th of May. The data is presented on a logarithmic scale to accommodate peak concentrations arising from the cooking, thus negative values recorded at Auchencorth Moss are not shown.

The urban background data increases in the evening of the 9th from ~19:00 onwards which is probably due to traffic (Figure 6-22). A change in wind direction to N/NE during the evening is in line with an increase of $PM_{2.5}$ levels at both St. Leonards and Auchencorth Moss around 21:00. Note that this is not correlated with the increase in Dylos measurements, which is entirely due to the cooking event, but rather due to long-range transport contributing to increases in rural and urban background concentrations. This highlights the specific challenges in applying fixed-site measurements to an individual that is not only moving in space and time but is also exposed to local and indoor sources which cannot typically be resolved by a single point measurements.

6.3.4.5 Example P2-16 - Elevated background concentrations due to long-range transport and atmospheric conditions

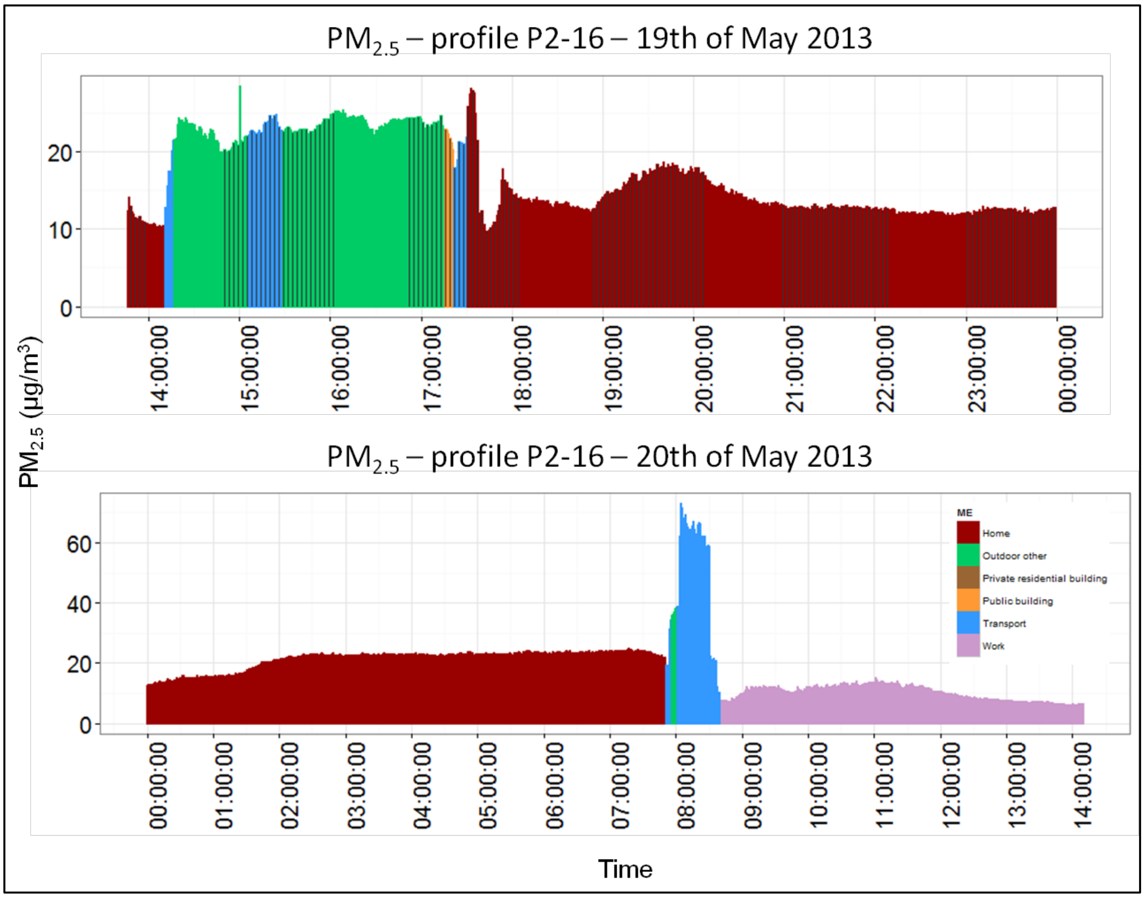


Figure 6-23 The profile shows $PM_{2.5}$ concentrations on two consecutive days with 1-minute resolution. All data is recorded in an urban environment until the person commutes to *Work* on the 20th of May.

The profile extract shown in Figure 6-23 has been mentioned in this chapter before as it stands out with constantly elevated concentrations in all MEs visited which are due to an incoming air mass from the North-East and very stable atmospheric conditions leading to accumulation of air pollutants in the boundary layer:

a) The volunteer spent the afternoon of the 19th of May in Edinburgh city centre where a bicycle rally was taking place (*Outdoor other, Transport* and *Public building*). For this bicycle rally the roads along which the person cycled in the city centre were closed for motorised traffic just before the cyclists went through. Urban background concentrations seem to be notably higher than in other profiles recorded in the urban environment (e.g. Figure 6-15) resulting in constantly elevated levels of ~20-25 $\mu g/m^3$ in *Outdoor other* and ~12-25 $\mu g/m^3$ at *Home*.

b) During the night of the 20th of May *Home* background concentrations increased and stayed high at ~20 $\mu g/m^3$ in the morning hours. While waiting at the bus stop and during the actual bus journey to work in the morning concentrations increased to over 60 $\mu g/m^3$. Such high concentrations have not been recorded in any other bus journey during this pilot study. Note that in the *Work* environment which is in a rural area with few built-up areas around it, concentrations were lower than in the urban environment (~10 $\mu g/m^3$), but on average higher than usually observed during this pilot study.

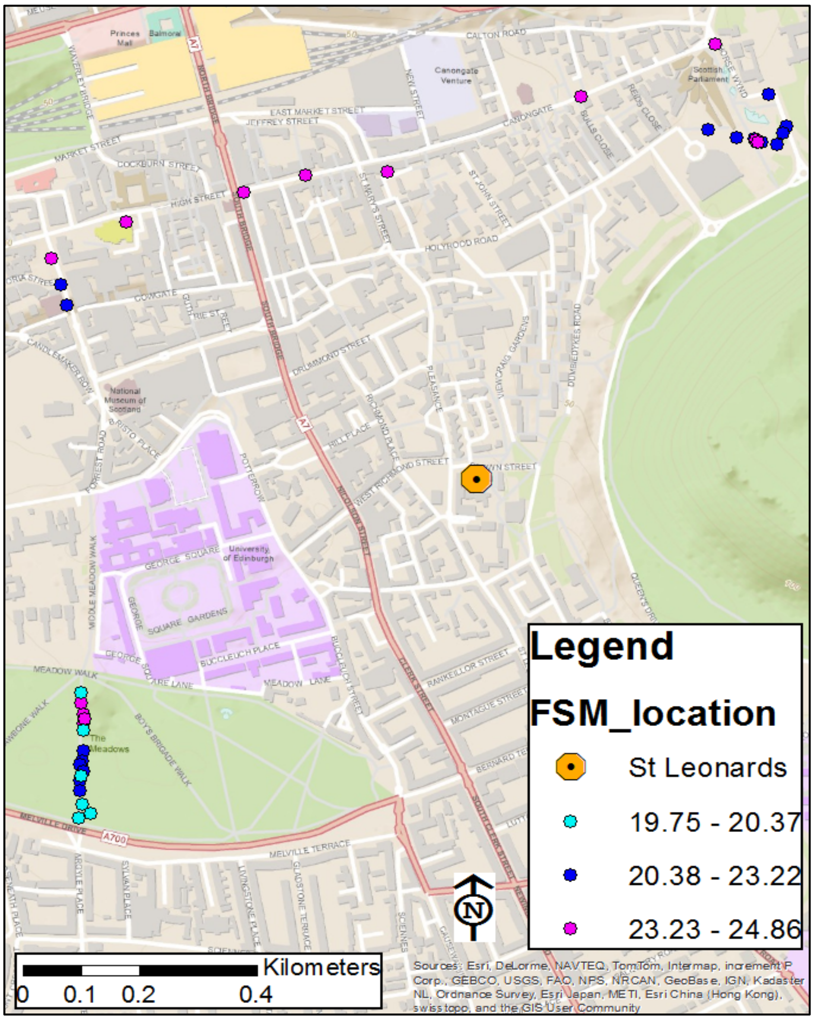


Figure 6-24 The map shows the GPS track of P2-16 on the 19th of May (there was no GPS data recorded on the 20th) and the respective $PM_{2.5}$ concentration (µg/m^3) logged once per minute. Note that due to the small range of concentrations the data has been grouped in three classes only. Also shown in the map is the location of the fixed site station St. Leonards. The mix of concentrations in the park is when the volunteer was walking up and down the park where hundreds of cyclists were gathering, stopping and chatting with people. Highest concentrations (pink dots) have been recorded when the group of cyclists went through the city centre which was closed off for traffic and when the rally came to an end and all cyclists gathered.

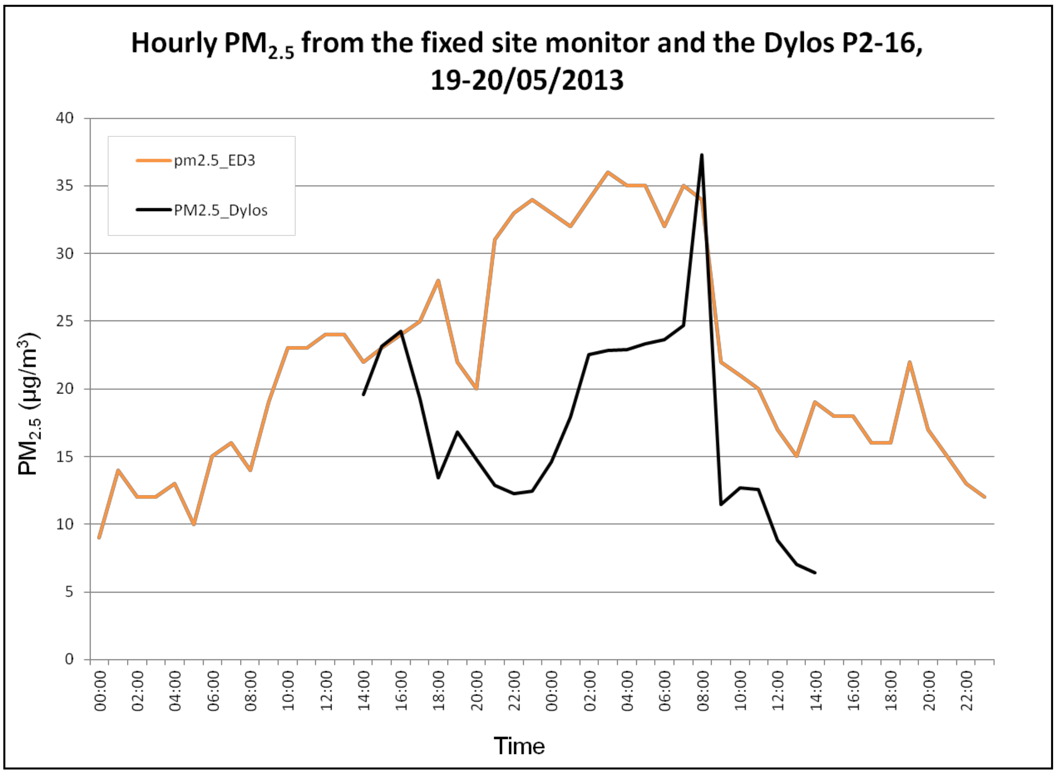


Figure 6-25 Hourly $PM_{2.5}$ data from the fixed site monitoring station Edinburgh St. Leonards (PM2.5_ED3) and hourly $PM_{2.5}$ values derived from the personal measurements with the Dylos (PM2.5_Dylos, black). Hourly data for the rural station Auchencorth Moss is missing for these dates, a daily value is however provided at 11 µg/m^3 on both days. Note that the personal $PM_{2.5}$ data only covers the hours between 13:00 until 15:00 on the following day. Hourly urban background data and the daily mean are however depicted for the full 48 hours to show the build up of $PM_{2.5}$ concentrations.

Levels at St. Leonards, which in this case was only 700m away from the person's residence, increase from 14 µg/m^3 at 9:00 to 28 µg/m^3 at 19:00 on the 19th of May. Which means by the time the personal measurements started urban background levels were already elevated at 24 µg/m^3. Hourly values then dropped for two hours to 22 µg/m^3 and 20 µg/m^3 respectively before concentrations increased again overnight to reach a peak of 36 µg/m^3 at 4:00 in the morning. This overnight increase is also picked up by the personal measurements (black line and Figure 6-23).

For the hours 7:00-8:00 on the morning of the 20th of May, which was when the person commuted to *Work* by *Bus*, hourly mean values at St. Leonards were still at 32 µg/m^3 and 35 µg/m^3 respectively. The steep decline in the Dylos data shows the difference between the urban environment and the rural environment where the work place is located. Concentrations recorded at *Work* are higher than in other profiles recorded with values between 6.2 µg/m^3 and 15.1 µg/m^3. Unfortunately hourly data for the nearby rural background station is missing for those days. The daily mean recorded with a different device is available though and is reported at 11 µg/m^3 on both days, which is much higher than on any of the other days discussed in this chapter. Preliminary data from the MARGA (section 4.2.1) deployed at Auchencorth Moss for the two day period 19-20/05/2013 shows how large the relative contribution of SO_4^{2-}, NO_3^- and NH_4 of the total $PM_{2.5}$ is. These pollutants are characteristic for long-range transport episodes bringing in polluted air masses from continental Europe. Generally, air masses from Northern and Eastern Europe are associated with contributing to the highest $PM_{2.5}$ concentrations in Scotland and there is also evidence for air masses coming in from the South that have passed over large land areas in England and, previously, continental Europe, contributing secondary aerosols formed from precursors emissions from these respective regions (Air Quality Consultants, 2012).

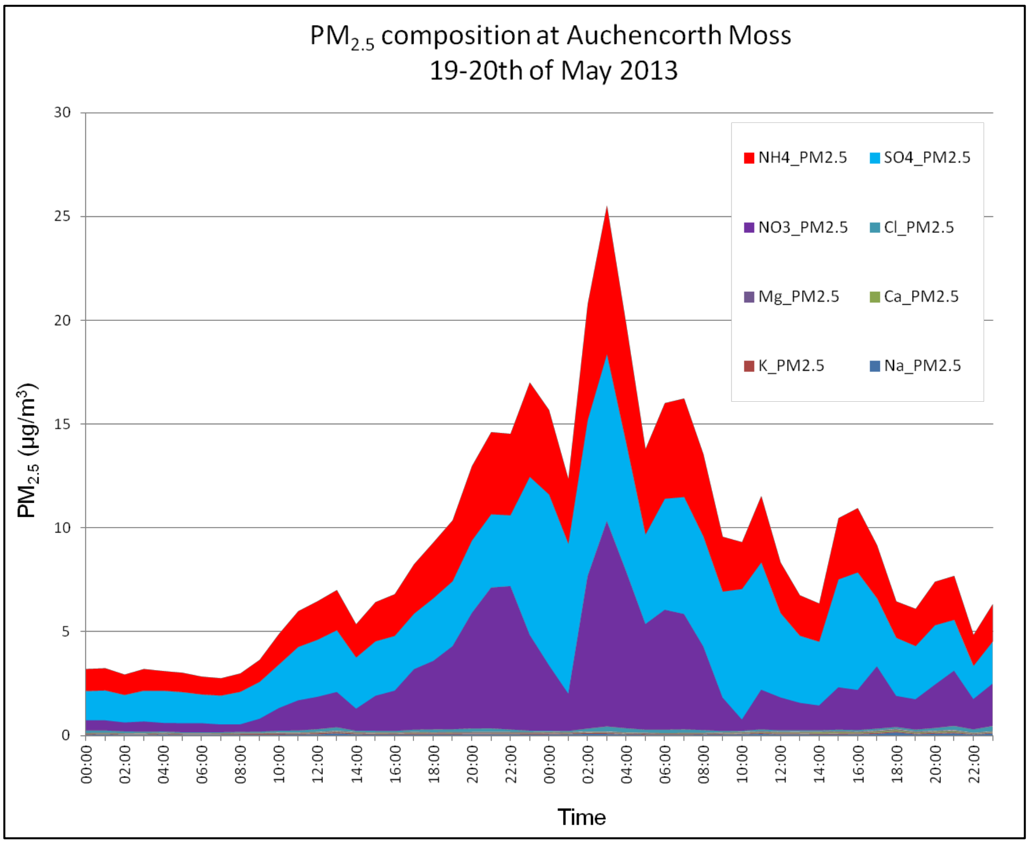


Figure 6-26 Hourly data recorded with the MARGA at Auchencorth Moss showing the $PM_{2.5}$ composition on the two days when P2-16 was recorded.

Urban background levels and the personal measurements on these two days are much higher than on other monitoring days in this pilot study. Data for other pollutants measured at St. Leonards and the modelled wind speed and direction data (Figure 6-27) reveal that $PM_{2.5}$ had already been increasing from the 18th of May. This increase coincided with the wind coming from the East, which brought in air masses from continental Europe carrying a large amount of inorganic aerosols (Figure 6-26). The wind speed decreased steadily until midday of the 19th of May. A change of wind direction to more westerly winds in the afternoon brought a slight increase of wind speed and a short term drop of PM concentrations. Please note that the wind speed measured at the weather station on the Edinburgh University building stayed however between 0 and 4 m/s for the 48 hours which is much less in comparison to times when other profiles were recorded in May 2013, and is in line with the modelled data shown in Figure 6-27. Concentrations rose again during the evening hours and the night. The influx of air from the East plus relatively stable conditions, with slow wind speeds will have reduced mixing conditions in the boundary layer and prevented dispersion of pollutants from long range transport and local traffic emissions. This accumulation of pollutants was picked up by the personal monitor as well as at the fixed site station.

On the morning of the 20th of May the concentrations of $NO_{x,}$ which is a traffic related pollutant, showed a characteristic bump for the morning rush hour (Figure 6-27). Therefore it is likely that high personal exposure measurements during the commute to work can be attributed to traffic particle emissions, but a component of the observed concentration values is also still due to the tail end of the stable atmospheric conditions.

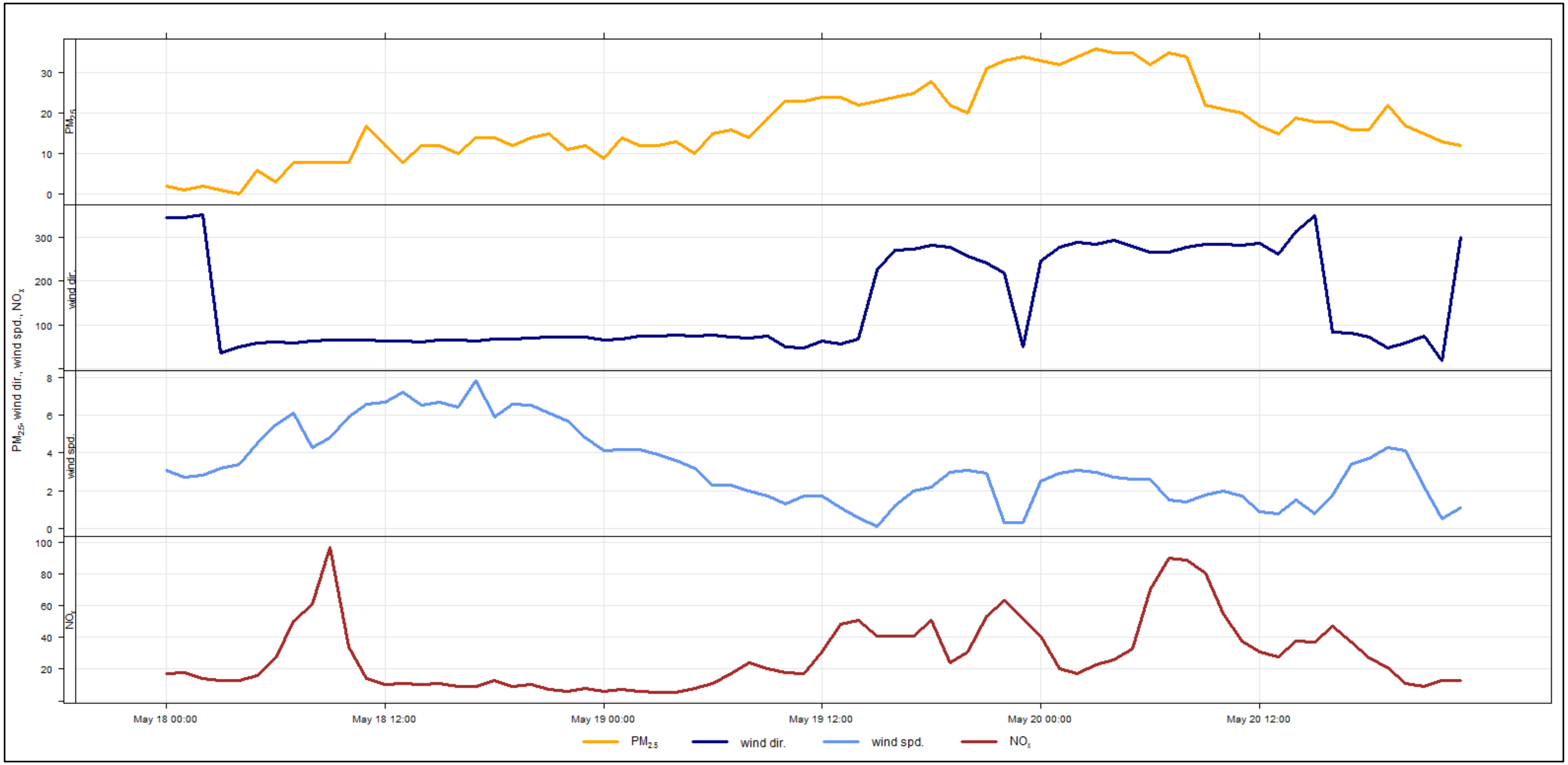


Figure 6-27 Time series for St. Leonards AURN station from 18-20th of May 2013 showing measured $PM_{2.5}$ and NO_x as well as modelled wind direction and wind speed.

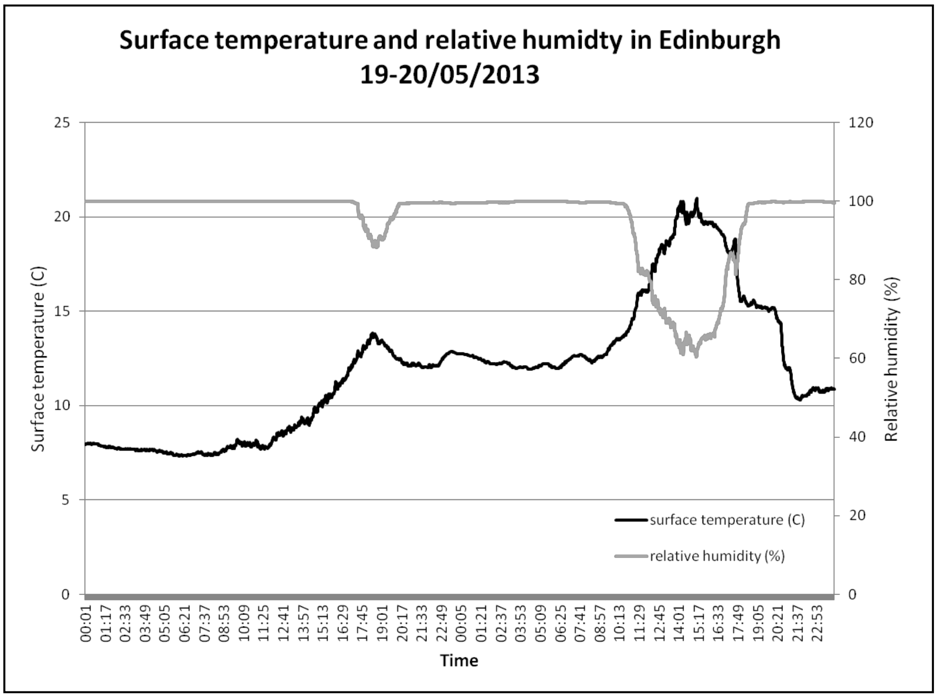


Figure 6-28 Surface temperature and relative humidity for the period 19-20/05/2012, logged once per minute. The data is taken from the weather station on the roof of one of the University of Edinburgh buildings (section 6.3.4), located in *Outdoor urban* and represents the weather parameters of the urban area well.

The weather conditions reported by the volunteer in the TAD during those two days were calm and mild with high humidity. The person also reported *haar* (coastal fog) on the morning of the19th of May which did not lift until lunchtime. This is reflected in the weather parameters measured at Edinburgh University (Figure 6-28) with relative humidity around 100% all afternoon of the 19th until ~17:00 when it dropped slightly. Overnight it reached the ~100% again until it dropped around midday of the 20th. The surface temperature increased from ~9˚C at ~14:00 to ~12-13˚C in the evening and stayed stable all through the night. On the 20th of May it increased from ~10:30 onwards to ~20˚C at 14:00.

High humidity, the mild weather and the low wind speed suggest that there was limited air exchange and dispersion of pollutants occurring, thus PM could accumulate to increased background levels in the urban (and rural) area. This will also have affected the $PM_{2.5}$ levels in the *Home* ME which had a mean of 17.8 µg/m^3. This is relatively high compared to profiles shown and discussed earlier (Figure 6-15), especially considering there were no specific high concentration events happening in the *Home* as in the profiles shown in Figure 6-29 and Figure 6-20.

This data supports the volunteer’s observations of the weather and the effect of pollution accumulation due to humid, calm and stable weather conditions.

6.3.4.6 Example P2-02 - Long lasting high concentrations - unexplained and due to baking

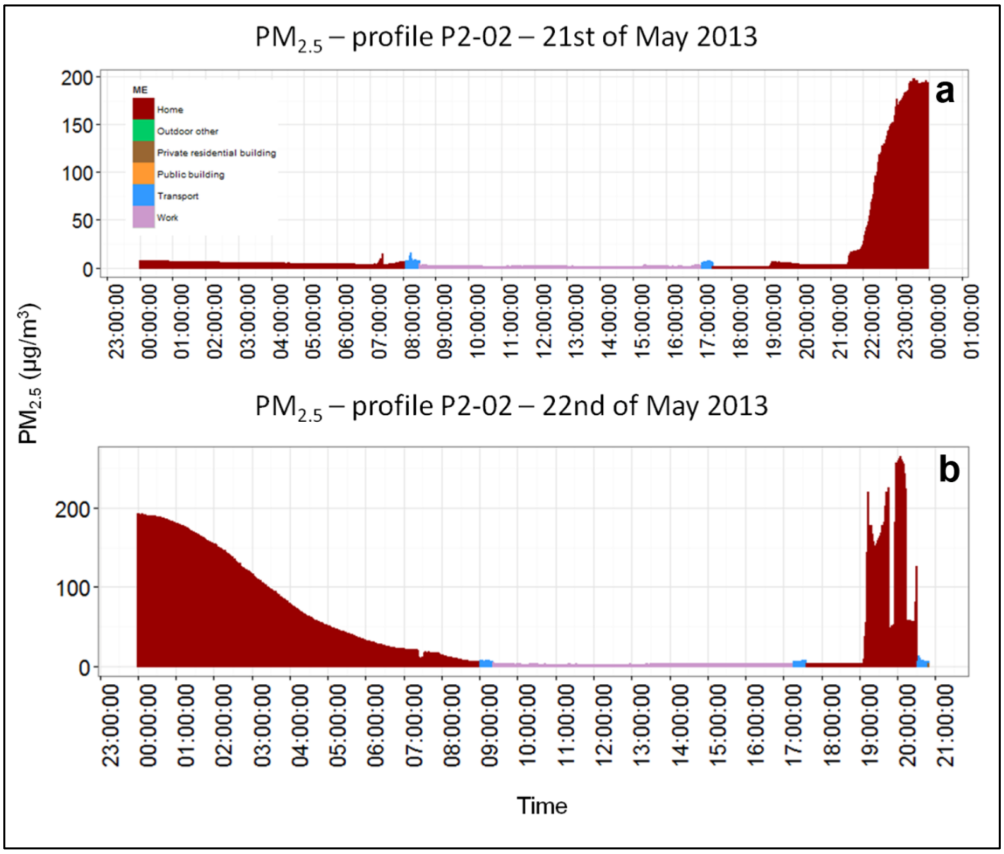


Figure 6-29 $PM_{2.5}$ concentrations (1-minute resolution) on two consecutive days. While concentrations are generally low, there are notably higher concentrations in the *Home* environment.

The data shown in Figure 6-29 is characterised by two distinctive high concentration events in the *Home* ME:

a) On the evening of the 21st of May concentrations increased from 21:30 onwards. The first small increase coincided with the person using a vacuum cleaner for a short period (~21:30-21:42). Afterwards the person was in the living room pursuing quiet activities with the monitor at their side. The strong increase from ~22:00 onwards remains unexplained. The person could not recall any event or activity that could have triggered such an increase in PM levels, neither by themselves nor by their flatmates. Neither were there any obvious outdoor sources or events that could explain the high concentrations. The maximum of 197.6 µg/m^3 was reached at 23:32. Please note that the concentrations stay high all through the night and only decrease very slowly. The monitor was placed in the living room overnight, otherwise it was with the person all the time.

b) On the 22nd of May concentrations were low, also note that concentrations in the *Home* environment have decreased to levels of <10 µg/m^3 after ~8:30. In the evening the volunteer did some baking (electric oven). The oven was opened for the first time around 19:08 which increased the concentration instantly to 24.5 µg/m^3, increasing further with the maximum concentration of 265 µg/m^3 occurred at 20:04. Note that this is much higher than the maximum recorded on the evening before. According to the volunteer the oven used for baking is more "*...like a charcoal burner*". The window was opened after the oven was opened for the first time and stayed open for the remaining time. The kitchen door was closed and no extractor fan was used. Sharp drops in concentration occurred when the person left the kitchen carrying the monitoring pack with them. Please note that concentrations are despite a closed kitchen door still at ~50 µg/m^3 outside the kitchen, which shows how PM levels even out between rooms by infiltration (section 5.3.1.1). Once the person left *Home* the concentration dropped instantly to 6.3 µg/m^3 while *Walk*ing in an *Outdoor urban* environment.

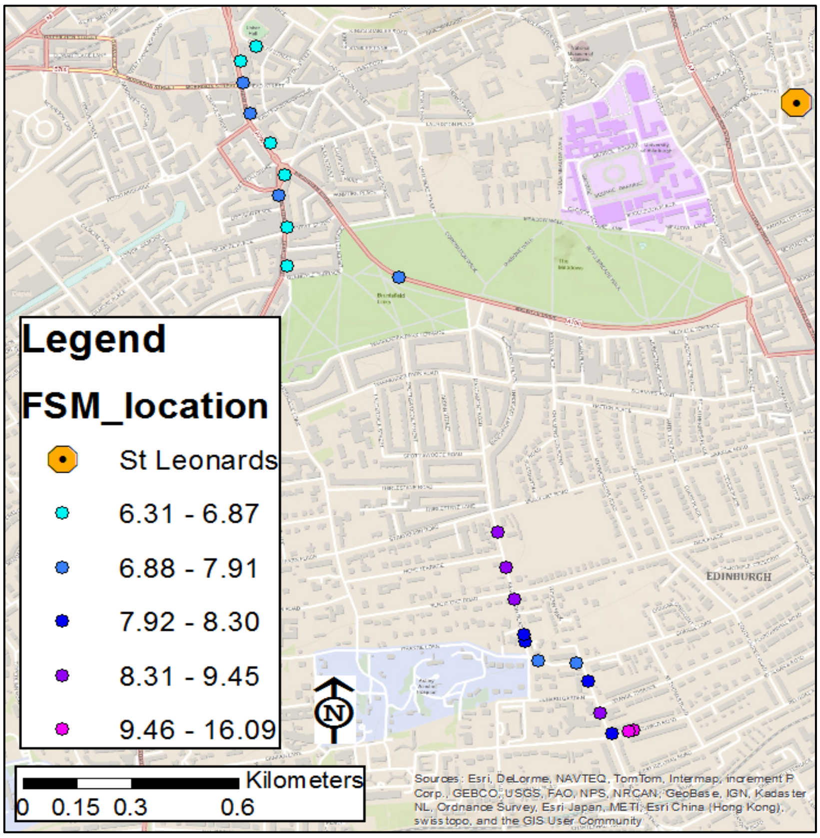


Figure 6-30 The map shows the GPS track of P2-02 on the 21st of May (there is no GPS data available for the 22nd) and the respective $PM_{2.5}$ concentration (µg/m^3) logged once per minute. The urban background station St. Leonards is shown as well. Lowest concentrations have been recorded while walking along a main road during the evening rush hour (northern track). Higher values have been recorded when driving in a car and walking during the morning rush hour (southern track).

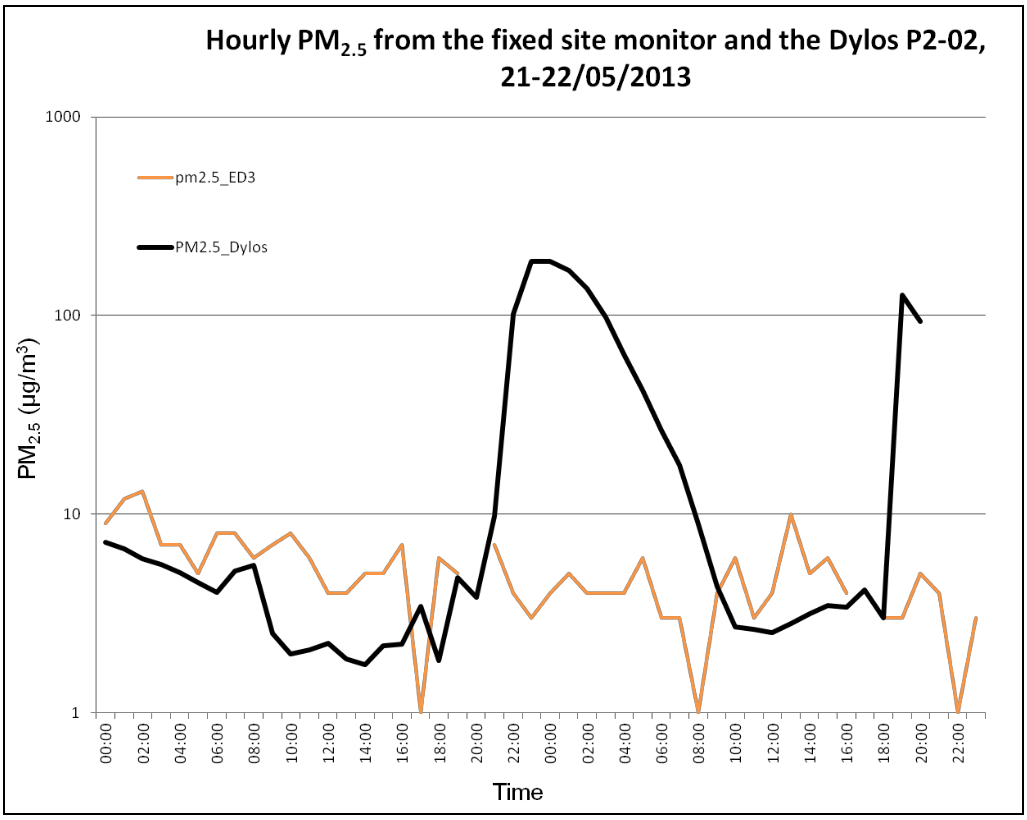


Figure 6-31 Hourly $PM_{2.5}$ data from the fixed site monitoring station Edinburgh St. Leonards (PM2.5_ED3). The black line shows the hourly values derived from the personal Dylos measurements (PM2.5_Dylos). The person spent all the time in Edinburgh City. This includes the *Work* ME. Note that the graph is shown on a logarithmic scale to accommodate the peak values thus negative values recorded at St. Leonards are not displayed.

The hourly concentrations recorded for the 21st of May at St. Leonards are shown in Figure 6-31 with the maximum concentration of 13 µg/m^3 measured at 3:00 (note that this is the day following the high $PM_{2.5}$ episode discussed in section 6.3.4.5) decreasing to levels between 4 µg/m^3 and 8 µg/m^3 during the day (6:00-18:00). The personal exposure measurements show decreasing concentrations overnight from ~7 µg/m^3 down to 4 µg/m^3 in the early morning which is in line with the urban background data. During the day, personal concentrations varied depending on the activity but generally stay below 10 µg/m^3.

The instrument at St. Leonards picked up the daily increase in the early evening due to traffic. Concentrations increased slightly after that to 7 µg/m^3 at 21:00 to 22:00 on the evening of the 21st and decreased thereafter to 4 µg/m^{3}and 3 µg/m^3 at midnight. Assessing ambient concentrations of NO_x for the same period, as well as the modelled wind speed and direction (Figure 6-32), there is no immediate explanation for the high and long lasting concentrations measured in the *Home ME* on this evening. Whatever caused the $PM_{2.5}$ increase in the flat was not driven by atmospheric or meteorological conditions, as neither the urban background station, nor the rural station (not shown in this graph) show similar behaviour. The source must be local, if not indoors.

On the 22nd of May hourly mean concentrations of $PM_{2.5}$ at the urban background station ranged between 4 µg/m^3 and 5 µg/m^3 overnight with a decreasing tendency (Figure 6-31). They showed an increase again from 6:00 and varied between 1 µg/m^3 and 10 µg/m^3 (at 14:00) during the day. Personal measurements stayed at notably higher levels (10-32 µg/m^3) at *Home* until ~8:30 due to the unexplained high concentrations. In the evening, background concentrations were low with values between 1 µg/m^3 and 5 µg/m^3 and showed an increase due to evening rush hour traffic emissions around 20:00. The volunteer did not report on the weather conditions in the TAD. The data from the weather station did not show any unusual pattern.

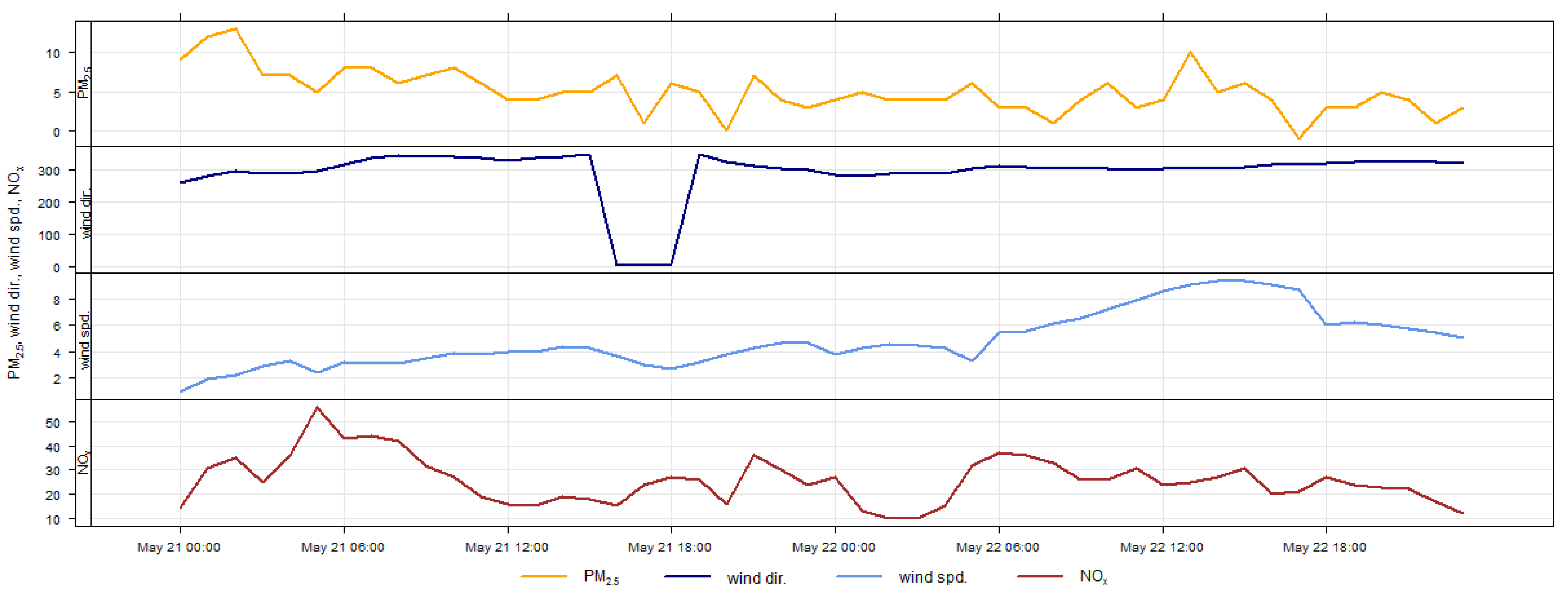


Figure 6-32 Time series for St. Leonards from 21-22nd of May 2013 showing measured $PM_{2.5}$, NO_x as well as modelled wind direction and wind speed.

6.4 Discussion

This pilot study was specifically set up to test, according to the first and second hypothesis (section 1.2), if the monitoring equipment can be considered feasible for robustly assessing personal exposure to $PM_{2.5}$ during everyday activities; and according to the third hypothesis, if the methodology is suitable to analyse the (causes for) differences in concentrations depending on lifestyle, time-activity patterns and other contextual factors. As an explorative study, its objective was to expand the scope of personal monitoring with currently available technologies (section 2.6). The dataset thus comprises data collected during a large variety of activities and in very different environments.

The study population has not been chosen to represent any specific subpopulation, but is simply based on the interest of the volunteer in the subject and available resources. Thus there is no balanced split between urban and rural neighbourhoods, with people living in rural areas being underrepresented (section 6.3.1.2). The neighbourhoods that volunteers live in are therefore relatively similar with respect to infrastructure and distance to certain features. Based on this the ambient background concentrations are also assumed to be relatively similar, although people's individual perception of their neighbourhoods varies (section 6.3.1.2). Most residences are located in the greater urban area of Edinburgh with only a few being further away and in different locales. The distance between the volunteer's homes and the two fixed-site stations Auchencorth Moss and St. Leonards varies a lot (section 6.3.2). Given the time-activity patterns with extensive commuting to work and travelling for leisure, the measurements from these sites cannot accurately represent personal exposure.

Regarding time-activity patterns (section 6.3.1.3), the data collected is comparable with findings elsewhere, e.g. the European average of 90% of the time spent *Indoors* despite the inclusion of weekend and holiday profiles which comprise more time spent outdoors. The split between the time spent in *Outdoor urban* and *Outdoor rural* environments shows that the majority of time is spent in urban areas of the Central Belt, where volunteers live. The rural environment which covers a vast area of Scotland is mainly visited on weekends or during holidays. In this study the exception is the workplace, which is in a rural area and shows very low concentrations both indoors as well as when people spent time outdoors in the vicinity of the workplace.

The variety of individual profiles and of profiles derived by the same person on different days is summarised in Figure 6-3. The analysis and discussion of individual profiles and exposure situations (section 6.3.4) supports the hypothesis stated in section 1.2. *"Depending on environment, personal time-activity patterns and other contextual factors, exposure to air pollution is notably different between individuals, which can be revealed by personal monitoring".*

The individual differences between profiles and in fact within profiles, depending on the exposure situation, highlight the importance and main purpose of deriving personal exposure measurements.

The variety of concentrations within individual MEs is also clearly illustrated. Since MEs generalise a certain number of individual activities there is a certain inherent variability of concentrations within each ME (section 6.3.3). Some MEs, like the *Home* or *Public building* have wider ranges because of the variety of activities, sources and exposure situations. While others like the *Work* and *Transport* ME are much more uniform. When looking at individual profiles and their spread of concentrations across the MEs visited (section 6.3.4.1) it becomes obvious though that individual events can cause very different spreads of ME concentrations between the profiles.

The same applies to the split between *Indoor, Outdoor urban* and *Outdoor rural*. *Indoor*s has the widest range of concentrations while *Outdoor rural* has the smallest (section 6.3.3.3). This is partly influenced by the background concentrations and atmospheric conditions, but also by the individual activities which are usually indoors, often causing very high concentrations. To a certain degree short-term elevated outdoor concentrations are probably caused by movement in the direct vicinity and handling of the monitoring equipment.

The data also shows that *Outdoor urban* means are consistently higher than the *Outdoor rural* mean concentrations for all analysed transport modes (section 6.3.3.4). In addition, it is shown that the mean concentrations in Phase 2 are generally higher than in Phase 1. This can be due to seasonal differences, but will primarily be influenced by individual exposure situations. In transport peak measurements are often caused by movement and handling at the beginning and end of journeys, which will influence the mean values.

Analysing individual profiles (section 6.3.4) shows that the methodology applied faces challenges in particular inherent to the devices applied, as already (partly) discussed in chapter 5. For instance, profiles often do not have full GPS coverage as the device does not get a signal fast enough after a cold start or after signal loss (e.g. P2-02) and therefore cannot resolve all movements and (especially) changes between indoor and outdoor environments. An additional challenge is presented by confidentiality issues, which require taking out a certain number of GPS logs in the immediate vicinity of study participant's homes to protect their identity, which in some cases (P1-03) reduces the number of usable, valid GPS logs to a very small number. Handling errors and issues with battery lifetime (P2-16 and P1-17) also limit the number of GPS points as discussed in section 5.3.2.2 .

Data gaps in monitoring ambient particle number concentrations (and subsequently $PM_{2.5}$) are due to adverse weather conditions (P1-03) or the noise level of the monitor (P1-17). Limitations of battery runtime and human errors i.e. forgetting to charge the monitor when stationary, introduce further data gaps (P2-05).

Regarding the interpretation of the results it is clear that not every activity, situation, source and the interaction between these different contributing factors that cause certain concentration levels can be unambiguously identified and used to conduct reliable source-apportionments for specific exposure situations. This partly depends on the degree of detail in the information the volunteer provides and the methodology of linking this contextual data with GPS and PM data, but is also due to the multiple complex influences contributing to (changes in) ambient PM concentrations. In other cases, such as the unexplained high concentration levels in P2-02, there is simply no obvious activity or source that can be related to the concentration increase. These challenges can be partly overcome by the generation of more detailed datasets; for instance including other size fractions, such as UFP and the actual physical characteristics and chemical composition of the particles. This additional information could enable more accurate and reliable source apportionments due to source fingerprints and thus further conclusions could be drawn.

As discussed in chapter 5, precise changeover times between MEs cannot always be determined, therefore logs in those “grey areas” (section 5.3.3.3) may be allocated to the wrong ME (e.g. P2-05). Ambiguity regarding the allocation of MEs could be reduced with an integrated device providing PM and GPS data with one common timestamp that would improve the alignment of objective, logged and subjective time-activity data provided by the volunteer. The use of cameras would be another option, providing time stamped photographic evidence of when a person was in a particular location. Collecting or recording time-activity data is a highly topical issue with many solutions and possibilities to work with (as discussed in chapter 2) and needs further investigation.

It is within these “grey areas” that increased PM levels have been interpreted based on time-activity information as handling and movement in the vicinity of the monitor. This is different from case to case (e.g. P1-03 and P1-05). Based on the researcher’s interpretation the data implies that movement in the direct vicinity of the monitor causes an increase in PNC ($PM_{2.5}$). This can be due to the disturbance of the air, causing turbulence and resuspension of particles. It is also possible that the personal cloud effect influences the PM levels.

The assessment of personal exposure data in this way can only provide a snapshot of the full exposure situation. Incorporating measurements for additional pollutants from fixed-site monitors, including meteorological parameters, can yield more insight into certain PM levels measured with the monitoring pack (e.g. P2-16).

6.5 Conclusions

Personal exposure monitoring provides a much greater insight into the highly variable concentrations of ambient pollution a person is exposed to during the course of day, or several days, as would be possible with static point measurements.

Personal exposure is as stated in the third hypothesis (section 1.2), driven by the individual's activities and habits. The approach taken in this study allows an in-depth analysis of individual exposure across a full set of MEs and activities over a short period of time. Enriching the $PM_{2.5}$ concentrations in space and time with contextual data regarding activities and broad environments as well as influences in the direct vicinity of the person (but caused by other individuals) highlight how varied individual exposure and the factors influencing it can be.

However, as the data analysis clearly indicates, personal exposure is also influenced by the environments the person spends time in and the other people present in these environments. The natural environment also influences the ambient concentrations and thus the personal exposure. Breaking the personal $PM_{2.5}$ exposure data down according to urban and rural environments highlights the difference which is also picked up by the routine background measurements made with reference instruments. Further investigations to better resolve the differentiation between urban and rural characteristics of the environment in personal exposure studies are recommended.

At the same time the environment influences people's perception of exposure to air pollution. With air pollution being difficult to see or notice, except when at really high levels (as for instance currently observed in Chinese cities), it is more the context and activities that influence people’s perception of exposure than actual sensory experience of pollutant levels.

Cooking and baking activities stand out in this pilot study with several profiles where these activities cause distinct peak exposures. General assumptions on cooking fuel or type of food cannot be derived from this study, as the data collection was not specifically targeted at such an analysis. The data collected for the *Home* ME can serve as an indication of exposure due to these activities, but is not sufficient for an in-depth analysis. The same accounts for the influence of the type of space heating. All households in this pilot study have gas central heating preventing any comparison, however, the impact of solid fuels used in a log fire can be seen in one profile (section 6.3.3.5).

Indoor environments are very interesting for a variety of reasons. People tend to spend a large amount of time in these environments and the range of pollution sources and exposure situations is substantial. In this pilot study the *Work* indoor environment was the same for all individuals (apart from one person, where mean values for their respective *Work* environment were however similar to the others) and despite having similar average concentrations, differences due to individual activities were revealed with the personal monitoring data.

In summary people are exposed to higher levels of PM in indoor environments where they also spend most of their time. However, how this affects human health is not only determined by time and dose, but also by the type of pollutant which with the approach applied cannot be determined.

7 General Discussion & Conclusions

This final chapter reflects on the findings of the study conducted and considers its implications for exposure research, public health and policy advice. The potentials and limitations of the methodology applied are discussed and recommendations for further studies in this research area are proposed.

7.1 Overview

This thesis describes the development and application of a methodology for monitoring personal exposure to fine particulate matter in a variety of microenvironments. The incentive behind studying personal exposure in everyday situations and microenvironments has been discussed, the motivation for the monitoring approach taken and study design applied have been outlined: to monitor personal exposure to $PM_{2.5}$ capturing the full heterogeneity of exposure situations in people’s daily lives (chapter 2).

The pilot study conducted has demonstrated how the methodology developed can contribute to the scientific debate about individual lifestyle and contextual factors affecting personal exposure. In particular it has highlighted that the low-cost monitoring approach chosen provides robust results to analyse individual exposure with a high spatiotemporal resolution across a variety of microenvironments.

The methodology applied has illustrated the complexity of individual exposure to a specific pollutant. Time-activity patterns and the general environment influence a person’s exposure as well as the activities of other people in their vicinity.

The information gained through personal monitoring studies, which naturally provides a high level of detail for a small sample size, sets the scene and provides a methodological basis for further studies. The results obtained can directly inform the design of larger-scale studies to underpin and deliver evidence for policy decisions regarding ecological public health and the development of air quality policies. Personal monitoring is just one component of a whole assessment process across a variety of disciplines aiming to quantify a person’s exposome. While personal monitoring - like any other monitoring method - cannot capture lifelong exposure to environmental influences on human health of every individual, it can, however, provide vital, detailed information for a short period of time. Such snapshots can, for instance, cover specific phases of development as suggested by Rappaport (2011) and include foetal development, early childhood, puberty and the reproductive years, but can also be targeted to monitor specifically susceptible or vulnerable population groups.

The level of detail derived by personal monitoring studies is hugely variable. By collecting contextual information about people’s environment and deriving specific functions for rural and urban background concentrations this pilot study distinguishes between urban and rural. Spickett et al. (2013) call this process “profiling” in their HIA and air quality standards approach for Australia. Profiling is one component of HIA which includes for instance urban and rural population attributes such as demographic information, housing and other living conditions, clearly distinguishing between those two environments.

7.2 Reflections on the performance of the particle monitor

According to the first aim "*Evaluation of the performance of a portable particle counter for personal air quality monitoring indoors and outdoors",* the particle monitor applied in the pilot study was evaluated against reference instruments in two different outdoor settings.

Findings from the co-location study between the Dylos and the reference instrument TEOM-FDMS leads to the following conclusions:

a) The two instruments, Dylos and TEOM-FDMS, agree well for both broad environments the co-location has been set up in.
b) The evaluation of the Dylos also outputs two distinctive functions for converting particle number counts to $PM_{2.5}$ mass concentration. Due to this step the data are provided in a comparable unit with reference instruments and air quality legislation and guidelines.
c) Analysing the data converted with these functions adds another layer of detail to the process by analysing the personalised data according to the broad environment it has been measured in.

This is the first study to evaluate the performance of the Dylos monitor in two different outdoor environments against UK reference instruments of the national automatic network. The co-location approach follows the concepts applied in earlier studies where the performance of the Dylos has been tested in chamber, indoor and outdoor environments for SHS and ambient exposures and against other devices regularly used in exposure studies.

The evaluation study in urban and rural Scotland delivers robust results, demonstrating the viability of using the Dylos monitor as a low-cost alternative to other commercially available instruments for exposure studies in a variety of environments.

Given the available instrumentation at the two co-location sites the Dylos' performance could be analysed and evaluated against further instruments. A key strength of this approach is the additional available data such as detailed elemental $PM_{2.5}$ data from the MARGA analyser (for Auchencorth Moss) and modelled meteorological data (for both sites).

The Dylos also picks up the heterogeneity of and changes in concentrations very well (Figures 4-2 and 4-3). The agreement between reference measurements and low-cost instrument also applies after the measured PNC have been converted to indicative $PM_{2.5}$ mass concentration for comparison reasons (Fig. 4-6).

The value of the Dylos lies in its price tag and relatively small form factor which allows a certain flexibility in measuring in mobile situations. While it is not a reference instrument and also cannot easily be worn within the breathing zone of the subject; it is suitable for relative measurements in the direct vicinity of the subject. Additionally the monitor performs well stationary as corroborated by the evaluation study, and can add spatial and temporal detail to routine measurements. No measurement method is able to replicate all aspects and details of every actual exposure situation and all methods have their challenges resulting in data gaps and rejection and operate with a certain degree of generalisation. With time, logistics and often cost making large-scale personal monitoring studies difficult; the application and validation of low cost monitoring solutions is crucial. The monitor applied in the pilot study and presented in this thesis is a low-cost particle counter, which is not primarily produced for scientific purposes, but is essentially a home appliance. Monitors such as the ones described by Mead et al. (2013) are developed specifically for the purpose of personal or high density network monitoring. These have been developed over years within research but are not yet commercially available. For further research it is necessary firstly to develop fit for purposes instruments and secondly produce them in a commercially available form at a price which makes it viable to purchase in larger numbers.

Results from this pilot study underpin the literature reviewed in chapter 2 in that national monitoring networks with their fixed site monitors at locations deemed representative for specific local or regional conditions are unable to accurately represent personal exposure. This has the implication that the fixed-site monitoring approach is inadequate for epidemiological studies, as Willocks et al. (2012) illustrate in their study from Scotland, which fails to find associations between PM_{10} and cardiovascular disease in Edinburgh and Glasgow for data covering the years 2000 to 2006. One possible explanation for the lack of association presented by the authors is that there was insufficient pollution data provided by the national network for time series studies, and a general lack of spatial detail due to the few available site locations. The authors therefore suggest an alternative study design based on measurements of health and pollution exposure on the individual level. Essentially highly accurate, but static routine measurements are not capable of capturing the real variability of pollutants, especially in urban areas (Mead et al., 2013) and indoor environments.

It is unlikely that the monitoring network in Scotland will be expanded and more monitoring sites will come online in the near future. On the contrary, due to fiscal constraints, there is a trend towards reducing the number of national monitoring network sites, as their operation and maintenance is cost- and labour intensive. The national network is not run for scientific reasons, but to comply with national and international regulatory requirements. This reduction in measurement sites could be compensated by integrating the use of low-cost and medium-cost sensor packages that can close the gaps and provide better spatial resolution in combination with reference instruments at fixed monitoring sites. A more integrated approach of mobile (both personal and otherwise e.g. public transport as platform) and fixed site sensors would be even better, as it would provide even more spatial coverage and account for the specific features of local environments. A dense network of sensors in urban areas for instance could increase the knowledge about spatiotemporal variability of pollutants in the complex urban environment as a basis for further exposure research.

In order to increase the quality of information gained from fixed-site and mobile monitoring an integration of devices which can determine the elemental composition of the particle mass (as for instance done by the MARGA at Auchencorth Moss) would be beneficial. Alternatively, devices with a range of size bins would help to derive basic analyses and allow the drawing of conclusions about the composition of the measured particle mass, and thus identify potential source fingerprints. In essence different ways of data collection such as personal monitoring and the combination with other methods as discussed in section 7.3 are the way forward. Beyond that recent and current developments in exposure research depend to a large extent on interdisciplinary collaborations especially between computer sciences, environmental and environmental health sciences but also with stakeholders and communities and the general public (e.g. de Nazelle et al. 2013, Mead et al.

2013, or the *Opensense (ETH Zurich, 2013), City-Sense* (NILU, 2012) and *iSPEX* (ISPEX, 2013) projects).

The monitoring solution applied in this study has proven to provide robust data for its specific purpose. In combination with data from the national AURN network the collected data can be analysed, and provides ambient concentration estimates for certain coarse environmental categories. This method could therefore be expanded based on a citizen science approach with personal monitoring equipment including co-location studies for the respective areas of data collection, if there are suitable monitoring sites available. This might be an issue as currently there are only five AURN site measuring $PM_{2.5}$ in Scotland. Nevertheless, following the example from this study, specific functions for the environments people spend time in could be derived. Despite being a rough categorisation based on few monitoring sites representing large areas of Scotland, the respective functions can provide exposure estimates on a more detailed level than the traditional exposure assessment based solely on measured concentration data from static fixed-site monitors, or personal monitoring without the distinction between urban and rural environments. The combination of static and mobile monitoring presented in this thesis is one promising option of integrating different methods for deriving exposure estimates.

7.3 Reflections on the development and application of a personal monitoring methodology

Devices, tools and study design were applied in a pilot study conducted in Scotland, split over two fieldwork phases, to assess its feasibility according to the second aim formulated in this thesis: "*Assessment of a methodology for* *personal monitoring in everyday microenvironments and its potential for citizen science applications".*

A group of non-representative volunteers were recruited for the pilot study collecting data while at the same time being study subject. Limitations of the applied devices, tools and study design have been discussed. The data collection process and the feedback from volunteers resulted in two main findings:

a) It is feasible for monitoring equipment to be taken to most MEs and for most activities. Still, improvements regarding air pollution monitor and GPS such as more practical design with respect to wearability and ruggedness and study design are required to upscale and improve the collection process.
b) Data processing and interpreting are time-consuming and in the current state feasible for a small scale study only. Further developments based on achievements regarding devices and tools (e.g. wireless data communication and integrated devices) and study design are required to make this approach applicable in a large scale study or for citizen science application.

This study applies a new approach of monitoring personal exposure to $PM_{2.5}$ in a variety of MEs over the course of several days. The novelty of this approach lies in the fact that measurements are taken across the full heterogeneity of places visited and activities conducted to gain as much insight as possible of a person's total exposure. This is important as people are constantly on the move and follow their own individual activity patterns, which determine their individual exposure. Analogue to the concept of the exposome, it is vital to take account of this variability and monitor pollution concentrations in as many situations as possible, providing a comprehensive snapshot of a person's daily exposure to $PM_{2.5}$. By doing so, this study gains insight into exposure situations previously not regarded in full sequence with other situations.

To achieve this, devices with a certain flexibility are necessary to provide robust results. The Dylos particle counter fulfils these requirements being small and lightweight and showing good agreement with reference instruments. Additionally the instrumentation is easy to use and has a small price tag, reducing the burden for the volunteers taking part and adding value for a citizen science approach where a large number of monitoring packs are required.

An integral part of this study approach is the collection of time-activity data which provides the necessary information to relate measured pollution levels to the respective circumstances. While the concept of MEs applied in this study is necessary to generalise data and analyse for time-activity patterns, the detail of information provided through time-activity diaries and in follow-up meetings allows the identification of individual situations, circumstances and spaces where (high) exposure occurs. It is possible to distinguish between different public buildings, the number of people around in a certain situation, and the transport mode to name a few. This level of detail is crucial and allows the detailed analysis of the reasons for high exposures to PM in both indoor and outdoor environments.

This study also allows for the distinction between urban and rural environments by applying respective functions to transform PNCs into particle mass, accounting for the different particulate matter components typically found in these environments. This novel approach adds a level of detail to the personal monitoring approach similar to the principle of having urban and rural national network stations providing detailed insight into different environmental compartments.

This thesis explores the possibilities and applications of a personal exposure monitoring methodology in a variety of microenvironments commonly visited. The methodology applied in this study is limited in the sense that it has been applied for a small group of volunteers who also know the researcher and work at the same institution. Furthermore, this study was explorative and hence no set study protocol was applied. On the contrary, the intention was to explore which part of the chosen methodology is feasible and where the challenges lie; and which of these, and for what reasons, can be regarded as critical. Much of the work presented here reflects the performance of individual tools and methods when applied in small scale pilot study.

The purpose of this pilot study was to test and provide feedback on the performance of the tools and study design applied. As an explorative study its aim was to expand the scope of personal monitoring to everyday situations. Thus the actual results derived are non-representative. The methodology developed includes tools to:

- Measure ambient PNCs in the vicinity of the individual
- Collect time-activity information for the individual
- Collect contextual information for the individual

The tools outlined above are commonly used in exposure studies but the way they have been combined and applied in this thesis is novel, as the focus is on constant monitoring throughout an individual’s daily activities seeking to capture as much of the total exposure as possible, across a complete set of microenvironments. This is in line with the conceptual models introduced in chapter 2 which explicitly include the natural, built and indoor environments in the assessment process in an attempt to capture the full exposure pathway, consequences and actions to intervene. Such models are aiming to help understanding of the relationships and links between the human and the environmental system.

The need for monitoring people’s exposure to environmental stressors in their daily life’s has grown over recent decades, for two key reasons:

- Shift in exposures due to changes in lifestyle
- Increasing evidence for adverse health effects from air pollutants on human health (and the combination with other environmental stressors)

As introduced in chapter 2 of this thesis exposure is a function of concentration and time and based on complex and intertwined relationships between the human and environmental system. The dataset collected with the personal monitoring method developed in this thesis is thus complex and concerns several dimensions which are:

- Changes in air pollution concentration in space and time
- Humans moving in space and time, showing individual behaviour
- The combination of the two first points
- The monitoring solution applied
- Data handling and processing

Regarding the first point, changes in air pollution concentration in space and time, personal exposure research involves atmospheric sciences including meteorological conditions and measurements methods for certain pollutants to determine the origin and fate of pollutants and pollutant mixtures. There is also a wide variety of models and tools such as trajectories available to investigate where and when pollutants occurred at which concentrations.

A huge variety of actual pollutant monitors are available for many pollutants, in different sizes, sensitivities and at different prices. However, they are still not sufficient regarding their capacity to obtain highly selective multi-pollutant measurements in real world circumstances (Committee on Human and Environmental Exposure Science in the 21st Century et al., 2012). The challenges for personal monitoring of air pollutants are requirements such as a practical, applicable and user-friendly form factor, and a robust and non-intrusive design which provides data with a resolution and quality as high as possible. Personal monitoring is therefore a trade-off between instrument precision, wearing compliance and information content. Conclusions from this study (chapter 5) support the importance of information content won with dynamic personal monitoring solutions over measurement accuracy provided by individual, expensive point measurements from fixed site monitors.

The second dimension, humans moving in space and time and showing individual behaviour, concerns time-geography to assess where, when and how humans move in space and time, including the methods and tools to do so. Methods to record movement and activities are available from very simple pen and paper approaches to electronically aided tracking tools and systems such as wireless communication, GPS location, radio-frequency identification, cameras. The achievements in the past decade have been immense in this area and have opened up many new possibilities in exposure research in fields, atmospheric sciences and time-geography. However, it is the combination of both – the constantly changing atmospheric conditions and humans permanently moving in space and time that makes exposure research complex.

The challenges lying ahead regarding the third and forth point, the combination of the two first points and the monitoring solution applied respectively, regard the sensitivity of the pollutant monitors. At the same time the monitors are required to be small and portable or wearable and ideally are capable of measuring multiple pollutants. The integration of methods and tools to aid data collection and reduce the burden on volunteers is also a major point driving personal exposure research. More generally, the objective of personal monitoring is to decrease the knowledge gaps regarding air quality, specific air pollutants and pollutant mixtures, human activities and adverse health effects by deriving improved exposure data with more precise information regarding the dimensions listed above. Such improved data can, according to the Committee on Human and Environmental Exposure Science in the 21st Century et al. (2012) provides more detailed information for risk assessments. This will eventually lead to the improvement of public health and ecosystem protection and policies which are the ultimate outcome of exposure research.

Regarding the data handling and processing (point five on this list), it is the large amount of data as well as the variety of data formats that requires attention. Personal monitoring with its high spatiotemporal resolution provides a large amount of data for each individual study subject or specific situation not only because pollutant data is required but also contextual data in order to allocate the pollutant concentration to certain environments and activities. This amount of data needs to be dealt with in a meaningful way for exposure analysis and requires the infrastructure to process and analyse the data to be in place. As this pilot study has shown it is challenging to merge and interpret the respective datasets to create the full profile. For this study (with a relatively small sample size) methods have been developed on the go and are not readily applicable for a large amount of data as some steps need to be done manually. It is necessary to explore further and develop methods and tools to automatically merge and process the data. This requires a clear structure of the input datasets. The level of detail derived from volunteers in this pilot study is likely to be not feasible to process large datasets. The data needs to be collected with a certain amount of generalisation to simplify the processing. In particular when the goal is to match TADs and GPS in a more automated process to reduce time-mismatches, the TADs must be in a clearly structured format restraining its information content somewhat. This became clear during the pilot study when the time-activity information was derived with TADs and during the follow-up meetings to generate the full profile dataset.

As evaluated in chapter 5 of this thesis, several steps in the process are only manageable in a small scale project and where direct contact and local knowledge are possible and available. Attention also has to be paid in order not to lose sight of the actual meaningfulness of, for instance geolocation or time-activity data, that can be easily collected and in large quantities using with GPS receivers or mobile phone apps. In other words, more data does not necessarily mean better data, as the data collected still needs to be dealt with in a meaningful way.

7.4 Application of and implications for personal monitoring

This personal monitoring study also strives to further understand the ambient concentration of $PM_{2.5}$ in our daily environments according to the third aim of this study: *“Assessment of the implications of individuals moving through the* *changing air pollutant concentration field on the applicability of air quality monitoring solutions".*

The measured results have been integrated with contextual data for analysis. Spatial and temporal data have been processed making use of GIS software and other processing and conversion software. Descriptive statistics have been applied to analyse data. Strengths and weaknesses of the data processing and methodology have been discussed. Findings show that:

a) Personal exposure to $PM_{2.5}$ is driven by the individual's activities and habits.
b) Personal exposure to $PM_{2.5}$ is influenced by the environment in its broadest sense, including contextual factors and the activities of other people in the vicinity of the study subject.
c) With the methods applied it is not possible to unambiguously identify every activity, situation, source and the interaction of these that cause certain concentration levels.

This study demonstrates the high level of detail that can be derived by personal monitoring approaches. Based on the novel study design incorporating the full heterogeneity of MEs and activities, a broad spectrum of contextual data has been gathered. This enables a comprehensive analysis of the interplay between measure pollutant concentrations, time-activity and the surrounding environment and circumstances in individual situations. During the analysis of the individual profiles it became evident how important the collection of detailed contextual data is, for example information about the number of people in the same room, certain activities happening in the vicinity of the person, or proximity to certain features such as roads or fireplaces. The data analysed highlights the variability of exposure situations, but also the difficulty in pinning down factors influencing specific events, as well as variations in the observed PM levels.

The explorative approach applied has also been analysed, evaluated and demonstrates issues with monitoring in certain environments due as much to practicality reasons as to the actual design of the tools and devices.

This study has not only illustrated to which detail an individual’s exposure can be analysed but has also shown that there are possibilities to work with people’s perception of the environment. This is especially interesting from an educational and consciousness rising point of view and should be further explored with respect to citizen science approaches and educational goals.

This study also highlights the importance of interdisciplinary collaborations to account for and analyse the full spectrum of data, which will be discussed in more detail in section 7.5. As discussed in chapter 4 the approach used in this study is not meant to replicate reference measurements but to improve the information content of personal exposure data. Since human health is affected by the actual pathogen through exposure but in particular by the whole environment the person is spending time in and other humans and their activities, personal monitoring includes contextual information. It is thus seen as the best way to collect exposure information for the individual. However personal monitoring is not intended to provide details for discussion of the issue of air quality and adverse health effects in its totality, but is limited to a small area, short periods and a small sample size, and is also often expensive and a burden to volunteers (Dons et al., 2014).

Furthermore, as Spickett et al. (2013) elaborate, air quality standards and guidelines exist to protect human health and the environment without enforcing unacceptable economic and social costs. However, such standards are not designed for indoor environments and do not take into account population subgroups which are potentially more susceptible to elevated pollution levels. Here personal monitoring of specific air pollutants and the assessment of exposure to these pollutants can provide more detail on exposure pathways and add to the exposome of an individual. The concept of the exposome is public health driven and aims to upgrade from the individual to a population. Thus personal monitoring studies help to increase the knowledge base upon which policy and public health decisions are made.

In that sense this study can only provide a snapshot of the total issue of air quality, adverse human health effects and the exposome. It does however feed into reducing knowledge gaps regarding the following key questions:

- Who is exposed and should be regarded in exposure assessment (and HIA) to protect them from adverse effects?
- Where are we exposed and thus where should we monitor (spatial resolution/coverage)?
- When are we exposed to potentially harmful concentrations?
- To what are we exposed and thus which pollutants or pollutant mixes need to be monitored/regulated?
- Are there any other contextual factors influencing either of the above questions?

The spatial resolution of exposure that personal monitoring approaches can provide is unique, but such high detail is often possible only across a small area. No other air quality monitoring or modelling method can currently resolve the individual interaction with the pollution space in a similar fashion. Personal monitoring generally also provides data at a high temporal resolution (unless passive monitors are used). This combined high spatiotemporal resolution makes personal monitoring a powerful method for collecting data at a high level of detail taking into account personal circumstances and activities which determine the variability of exposure for the individual.

This study specifically focused on the full heterogeneity of microenvironments in order to capture differences between those and also to get an insight into different spaces and activities, and their contribution to the variability of $PM_{2.5}$ concentrations. By doing so it has corroborated literature findings that personal exposure differs between individuals depending on a variety of contextual factors. Personal monitoring also provides a clear picture of concentrations in indoor environments. While the focus of air quality research is often primarily on outdoor air quality; indoor air quality, its contribution to personal exposure and relationships between indoor and outdoor concentrations play a vital role in exposure research. Results from this study have shown that firstly, people spend a large amount of time in indoor MEs and secondly, the levels of concentration measured in indoor MEs are highly variable from very low concentrations to short term peak concentrations much higher than typically observed in outdoor environments.

7.5 Outlook

The wide range of exposure studies conducted reflects the potential, as well as the limitations, of existing methods and approaches and their current developments. In this pilot study well established methods (TAD, questionnaire, the use of a personal monitor in specific MEs) combined with new tools and approaches (Dylos particle monitor, GPS, everyday MEs and situations) have been applied to further investigate and develop the potential of integrated, advanced methods for personal monitoring.

Personal monitoring is not a standalone tool and needs to be applied and assessed in combination with other methods and approaches. Here, the added value of modelled ambient pollutant concentrations and meteorological data in addition to measured concentration data from fixed–site monitors and observed weather parameters included in the analysis process has been demonstrated.

The approaches to integrate personal monitoring with other methods for exposure assessment and evolve it further are manifold. One option to achieve further progress with personal monitoring in the sense of increasing the spatial coverage and/or the sample size is the citizen science approach. A citizen science project relies on affordable and easy to handle equipment and a working infrastructure to process the data. Most importantly, however, volunteers are needed that are interested in the topic and willing to participate as citizen scientists, keeping in mind that they, depending on the study design, can also be study object at the same time. This study has shown that it is not straightforward to recruit large numbers of volunteers. Time-constraints, burden, confidentiality concerns and simply a lack of interest in the topic make it difficult to convince people to take part. A larger scale project, however, with a certain amount of publicity and most importantly educational aims could provide a win-win situation for individuals participating, scientific research and improving public health. Ideally such a project would engage with communities, stakeholders and interest groups to bring the topic to a wider audience, and to gain support and volunteers. The citizen science approach aims to increase the understanding of the issues, in this case how individual activities and habits contribute to pollution and determine individual's exposure, and therefore it also has an educational goal.

The data gained from this pilot study are limited in their transferability to other areas, pollutants or population groups. The integration of personal monitoring with modelling is an approach that has substantial potential for exposure science as it enables the assessment of exposure situations for large populations under a variety of circumstances, including the notoriously difficult assessment of exposure to pollutant mixtures. As the Committee on Human and Environmental Exposure Science in the 21st Century et al. (2012) state in their vision and strategy report, models form an essential part of exposure science as they can predict trends and help interpret data and observations. With the technological advances enabling the collection and generation of larger datasets, models are needed to extract meaningful data, summarise large datasets or on the contrary, upscale from a limited number of observations which may be subject to financial or feasibility constraints.

Dons et al. (2014) recently published a paper implementing and validating (with data from a personal monitoring campaign which had 62 participants) a model framework for personal exposure to black carbon. This framework has, according to the authors, the capability to firstly upscale to population wide exposure estimates and secondly to investigate the implication of those estimates for public health as postulated in the conceptual model introduced in chapter 2 (and Steinle et al. (2013)). The study from Belgium (Dons et al., 2014) reinforces the need for models to be validated with real-world personal monitoring data, be it the full dataset or just time-activity patterns as done in the model by Gerharz et al. (2013) albeit for a small number of individuals.

Models can also help to improve the $PM_{2.5}$ estimates for indoor environments, which often have to be estimated based on data available from central fixed monitoring sites and assumed transmission of outdoor concentrations into indoor environments. Hodas et al. (2014) refined and evaluated an outdoor-to-indoor transport model with the help of measured indoor and outdoor $PM_{2.5}$ data and air exchange rates to avoid using sparse outdoor data as surrogates for estimating indoor concentrations. Results suggest that not accounting for specific human activities such as heating or ventilation leads to bias in the predicted exposures to $PM_{2.5}$ at the individual level, however not at the population level. This model is according to the authors (Hodas et al., 2014) applicable for large epidemiological studies predicting exposure to $PM_{2.5}$ in the home environment. Such models have the potential to improve the assessment of indoor exposure in combination with personal monitoring data for instance.

Another approach to integrate personal monitoring with other methods for exposure assessment is to use a dense network of stationary monitors to characterise the concentrations in a specific environment. For such an approach the pollution concentration is provided as static data and integrated with the movements of humans in space and time. This avoids the limitations arising from personal monitoring regarding form factors, power supply and to a certain degree the burden of volunteers as only time-activity and contextual information are required. Mead et al. (2013) showed that small, low-cost gas sensors can provide high resolution urban air quality data for a longer period of time. This study also applied miniature sensors as mobile networks (pedestrians, cyclists and drivers) in order to derive short term personal exposure. This solves the problem of cost which generally limits the number of measurement stations. This study also demonstrates how one device can measure a variety of pollutants and provide geospatial information with one timestamp. The authors highlight that the longer term ambition is to extend this low-cost/high-density network approach as suitable sensing solutions become available, to other gases, PM and local micro-meteorology (Mead et al., 2013).

Alternatively ubiquitous sensing, referring to sensors that are already embedded in infrastructure, for instance in public transport vehicles, can be used for exposure purposes. The entire Lothian Buses fleet (which operates in Edinburgh and the Lothians) is fitted with GPS so that the vehicles can potentially be upgraded with pollution sensors and provide a mobile network. A variation of this approach is applied by a project in Zurich (ETH Zurich, 2013) which uses trams and buses for mobile sensing of air pollutants and other environmental parameters and two stationary sites form the national monitoring network providing high-quality measurements as reference (Saukh et al., 2013)

Ubiquitous sensing also makes use of smart phones and their inbuilt technologies for geolocating and wireless communication which are carried by billions of people around the world (Committee on Human and Environmental Exposure Science in the 21st Century et al., 2012) and therefore offers a cost-effective and non-intrusive way of data collection (de Nazelle et al., 2013). Therefore the citizen science approach can take advantage of the fast and ever-growing usage of smart phones and wireless communication which have the potential to provide large amounts of data usable for personal exposure assessment. Mobile phone and web applications have been used in a variety of projects to collect (for instance) time-activity information, prompt recall surveys, as an interface for measurements made with a wearable sensor that communicates wirelessly with the phone (Negi et al., 2011) in combination with modelled pollution data (de Nazelle et al., 2013) and even to measure aerosols directly as done in the *iSPEX* project (ISPEX, 2013)).

The current developments in communication techniques and sensing technologies also result in many individual projects that monitor one or the other environmental stressor, weather parameters or time-activity patterns. Such developments e.g. the so called Senspods (Sensaris, 2014) however are not yet technologically robust, and often lack appropriate evaluation and referencing to other instruments.

Accurately assessing exposure of the population or of individuals to air pollutants and other environmental stressors remains a challenge especially in urban areas, where the majority of the population is living. While it is essential to further develop and explore methodologies to conduct exposure and health impact assessment, in the longer term objectives need to contribute to reducing health care expenditures, improving public health and environmental protection which go hand in hand. The development and implementation of environmental protection measures may seem like a waste of resources to members of the public, hence it is necessary to inform the public and raise awareness of the links between public health, environment and the long-term benefits of strategies and policies. This can be done by highlighting the health care costs due to morbidity, respectively the economical costs of mortality due to air pollution related health effects and deaths, as done for instance by the *Clean air in London* campaign (Clean Air in London, 2012).

Future work should build on and utilise the advantages of already existing and emerging methods, while focusing on areas that need further development and validation. The applicability under different circumstances and at different scales is crucial to provide further insight into patterns and nature of exposure and public health issues.

Currently most methods are capable of measuring one or a small selection of common air pollutants only. The issue of health effects from pollutant mixtures, their dynamics in the atmosphere and their impacts requires further investigating.

Many developments in personal exposure research are dependent on further achievements in sensor design and disciplines such as microsystems engineering and computer science and links with environmental health sciences need to be improved. This highlights the need to work cross-disciplinary to fulfil the integration of the environmental and human systems as described in the eDPSEEA model (Reis et al., 2013).

7.6 Limitations

The tools, devices and methodology applied in this thesis provide a starting point to address issues and challenges regarding the quantification of human exposure to air pollution in everyday environments. They are not immediately applicable or transferable to other study areas and aims without further development and adjustments.

Firstly the study is limited to one pollutant and can only provide an indication for exposure to other air pollutants. While the monitoring equipment is functional and feasible, a better design with respect to wearability and reducing the burden could potentially improve measurement results, and also the number of volunteers involved. Further developments and research into other suitable monitors and tracking devices as well as technologies to record/collect time-activity patterns will, however, require a funded research project designed on a larger scale than was feasible for this thesis.

Given the fact that this is a pilot project without a substantial team behind it, the study is limited to a small number of volunteers who are almost all working at the same institution, thus considering a selective office work environment only. Urban areas are also over-represented in the dataset due to the residence locations of study participants. Data from rural areas remains mainly limited to weekend activities and therefore this study cannot adequately characterise exposure in everyday rural environments. Better spatial coverage and a more representative group of volunteers would be desirable and is essential for a study aiming to upscale to larger population groups.

The time for the data collection was limited to two seasons and it is anticipated that covering all seasons may result in different time-activity patterns and different meteorological circumstances, as well as daylight hours, thus potentially leading to different exposure profiles for individuals. Additionally, over the summer period, time-allocations would possibly have included less office and indoor hours and more time spent outdoors due to fieldwork and leisure activities. On the other hand the summer time would have been even more challenging with respect to recruiting volunteers due to holidays and activities that may not be conducive to wearing the monitoring pack.

7.7 Conclusion

In conclusion, this thesis has demonstrated that personal exposure monitoring is a viable method for improving the knowledge about individual level exposure to environmental stressors when compared to the predominant fixed monitoring site and aggregated approaches currently in the literature. As a methodology it is grounded on a compromise between instrument precision and information content.

While the degree of detail of the information gained by personal monitoring is very high, the scope is currently limited by the small sample size and limited spatial coverage that can be achieved with existing devices and methods. Thus it is necessary to expand the information generated from a small scale personal exposure study and further elaborate the approach towards other pollutants, pollutant mixtures and other contextual circumstances.

By exploring the feasibility of the method in everyday situations and across the full heterogeneity of microenvironments this pilot study already has taken a step in this direction. Furthermore it has shown that the application of a low-cost monitoring solution in combination with other monitoring and assessment methods provides robust and reliable exposure information.

The study has shown that individual exposure to $PM_{2.5,}$ and probably to other pollutants as well, is highly variable and identified the main contributing factors for this variability. It is recommended to further explore this variability across the full heterogeneity of microenvironments a person spends time in, especially with the aim to provide input for the development of models and a knowledge base for the development of air quality legislation.

8 Appendix

Webforms

Table A 1 Questionnaire in its modified form as used in Phase 2

Category	**Question**	**Answer options**
Participant		
	Name	*Free text*
	E-mail	*Free text*
	Age	*Free text*
	Sex	*Select:* - *Female* - *Male*
	Profession	*Free text*
	Your home postcode	*Free text*
	Do you smoke?	*Select:* - *Yes* - *No*
	If you smoke, how many cigarettes (or other tobacco products) do you smoke per day (on average)?	*Free text*
	Do you suffer from asthma?	*Select:* - *Yes* - *No*
	If you suffer from asthma, do you use a bronchodilator?	*Select:* - *Yes* - *No*
	How healthy do you consider yourself to be?	*Free text*
Your home		
	Which type of housing do you live in?	*Select:* - Terrace - Detached - Flat - Other *(please describe)*
	In your opinion, which of the following Urban-Rural Classification categories best describes the neighbourhood you live in? *Information*: *The Scottish Government uses the so called Urban-Rural classification for spatial analysis. The categories shown here are taken from the 6-fold version and describe 3 different types (urban area, small town and rural) with two varieties each (large/other, accessible/remote).*	*Select:* - Large urban area - Other urban area - Accessible small town - Remote small town - Accessible rural - Remote rural
	Which type of central heating is in your home?	*Select:* - Gas

		• Oil • Solid fuel (e.g. coal, wood, peat) • Electric
	Are there any other heating sources, if so what type?	*Select:* • Gas • Oil • Solid fuel (e.g. coal, wood, peat) • Electric
	What kind of oven/cooker do you have?	*Select:* • Gas oven/cooker • Electric oven/gas cooker • Electric oven/cooker
Household	What type of household do you live in?	*Select:* • Single occupant • Family • Shared house/flat
	Number of people in your household?	*Drop down menu:* 1...10
	How many people in your household are smoking?	*Drop down menu:* 1...10
	If there are smokers in your household, where do they tend to smoke?	*Select:* • Indoors • Outdoors
	Do you or any other person in your household have pets?	*Select:* • Yes • No
	If anyone has pets, what kind of pets and how many	*Free text*
Home-location characteristics - Is your home within range of one of the following features? Please choose the approximate category:	• Major road • Parks and green space • Industrial estate • Farm • Other features (please describe briefly)	*Select:* • <1km (0.6 miles) • Between 1 – 5km (0.6-3.1 miles) • >5km (3.1 miles)

Table A 2 Time-activity diary in its modified form as used in Phase 2

Category	**Question**	**Answer options**
Participant		
	Name	*Free text*
	E-mail	*Free text*
	Date for which this TAD is filled in	*Drop down menu:* year/month/day
Today's activities and places visited		
Transport Mode	Please describe from when until when have you been in the respective transport mode. Also describe form where to where you went	*Free text:* • car/taxi • bus • train • walking • cycling • motorbike • other mode *(please describe)*
Home-based activities	Please describe from when until when you have done which activity	*Free text:* • Cooking/baking (please also define the type of cooking (boiling, frying etc.) and existence of ventilation (window open, exhaust fan on etc.) • Cleaning • Quiet activities like resting, sleeping, reading, TV, working at a desk, other seated activities • TV, working at a desk other seated activities • Other activities *(please describe)*
Workplace	Please describe from when until when you have visited your work place	*Free text*
Other places visited during the day	Please describe from when until when you have visited the respective places	*Free text:* • Public building (e.g. library, museum, theatre...) • Private residential building (e.g. partners or friends home) • Shop/Supermarket • Gym/Sports centre • Restaurant/Pub/Cafe • Other places *(please describe)*
Outdoor activities	Please describe from when until when you have done the respective outdoor activities	*Free text:* • Go for a run/cycle ride/walk... • Fieldwork/gardening... • Playing/sports... • Other outdoor activity *(please describe)*
Contextual information	Can you give a short description of the general weather conditions today? (rain, wind, temperature)	*Free text*

	Were there any special occurrences, events, incidents that could have influenced ambient air quality conditions? Please comment	*Free text*
	What do you think was your personal exposure to polluted air today?	*Select:* • high • medium • low
	Notes	*Free text*

Data summary

Table B 1 Data summary – number (n) of data points collected in Phase 1 and Phase 2 split by microenvironment (ME), transport mode (TPM) and class.

		ME (n)						TPM (n)						Class (n)		
Fieldwork phase	**Total (n)**	**Home**	**Work**	**Public building**	**Private residential building**	**Transport**	**Outdoor other**	**Bicycle**	**Bus**	**Car**	**Ferry**	**Train**	**Walk**	**Indoor**	**Outdoor rural**	**Outdoor urban**
P1	50,162	29,020	7,396	5,088	2,067	4,836	1,755	238	821	2,338	514	347	578	43,571	3,353	3,238
P2	43,331	30,519	7,472	2,380	170	2,388	402	235	452	680		291	730	40,541	456	2,334
P1 & P2	93,493	59,539	14,868	7,468	2,237	7,224	2,157	473	1,273	3,018	514	638	1,308	84,112	3,809	5,572

Table B 2 Summary of data collected (number of data points (n)) in Phase 1 for each profile split by microenvironment (ME), transport mode (TPM) and class.

		ME (n)						TPM (n)						Class (n)		
Profile	**Total (n)**	**Home**	**Work**	**Public building**	**Private residential building**	**Transport**	**Outdoor other**	**Bicycle**	**Bus**	**Car**	**Ferry**	**Train**	**Walk**	**Indoor**	**Outdoor rural**	**Outdoor urban**
P1-01	450	349				101				101				349	42	59
P1-02	2,276	1,697	8			374	197			374				1,705	433	138
P1-03	2,937	1,429	1,361	101		46		26					20	2,891	7	39
P1-04	3,045	1,534	1,221	100		190			64	31			95	2,855	56	134
P1-05	1,735	988	566	9		172			112	14			46	1,563	30	142
P1-06	3,785	2,716	69	438		404	158		90	190		54	70	3,223	159	403
P1-07	4,341	3,708	172	40	42	258	121			258				3,962	150	229
P1-08	1,500	862	397	75		166				166				1,334	49	117
P1-09	1,221			52		759	410			245	514			52	1,005	164
P1-10	4,030		25	2,690	846	446	23			446				3,561	343	126
P1-11	475		183	118		174				174				301	129	45
P1-12	2,801	1,768	397	472		164		164						2,637	25	139
P1-13	1,424	714	632	35		43				43				1,381	6	37
P1-14	5,079	2,762	469	783	164	735	166		264	71		293	107	4,178	223	678
P1-15	2,387	1,776	394	4		159	54		102				57	2,174	113	100
P1-16	3,686	2,110	7	12	1,015	262	280		110	108			44	3,144	372	170
P1-17	1,680	862	538	68		150	62	22		82			46	1,468	37	175
P1-18	3,377	2,558	735	20		64				35			29	3,313	27	37
P1-19	3,933	3,187	222	71		169	284	26	79				64	3,480	147	306
	50,162	**29,020**	**7,396**	**5,088**	**2,067**	**4,836**	**1,755**	**238**	**821**	**2,338**	**514**	**347**	**578**	**43,571**	**3,353**	**3,238**

Table B 3 Summary of data collected in Phase 2 for each individual profile split by microenvironment (ME), transport mode (TPM) and class.

		ME (n)						**TPM (n)**						**Class (n)**		
Profile	**Total (n)**	**Home**	**Work**	**Public buil-ding**	**Private residential building**	**Trans-port**	**Out-door other**	**Bi-cycle**	**Bus**	**Car**	**Ferry**	**Train**	**Walk**	**In-door**	**Out-door rural**	**Out-door urban**
P2-01	6,254	5,891	73	110		180			73				107	6,074	16	164
P2-02	2,814	1,700	990		3	121				26			95	2,693		121
P2-03	3,591	3,192		83	45	261	10		79	90			92	3,320	30	241
P2-04	1,463	720	631	16		61	35			57			4	1,367	41	55
P2-05	1,422	738	515	58		80	31			77			3	1,311	58	53
P2-06	4,292	3,754	319	10		209				193			16	4,083	33	176
P2-07	2,271	1,237	760	120		154		154						2,117	23	131
P2-08	4,243	2,668	1,033	326	20	165	31			110			55	4,047	38	158
P2-09	4,187	3,482	150	242	102	179	32		82	29			68	3,976	23	188
P2-10	3,784	1,788	445	1,089		457	5		11	82		291	73	3,322	8	454
P2-11	1,475	1,250		184		41							41	1,434		41
P2-12	1,441	839	468			90	44		64				26	1,307	59	75
P2-13	1,466	739	397	124		153	53		73				80	1,260	65	141
P2-14	1,707	857	777	12		61				16			45	1,646	21	40
P2-15	1,457	779	585			93		43	35				15	1,364	31	62
P2-16	1,464	885	329	6		83	161	38	35				10	1,220	10	234
	43,331	**30,519**	**7,472**	**2,380**	**170**	**2,388**	**402**	**235**	**452**	**680**		**291**	**730**	**40,541**	**456**	**2,334**

Summary Statistics Individual Profiles (Phase 1)

Table C 1 Summary statistics for profile P1-01 split by microenvironments, transport modes and classes. n= number of data points, all values in µg/m^3.

	n	mean	sd	median	min	max	range
P1-01.PM2.5	450	3.4	1.5	3.2	1.4	11.7	10.2
Home	349	3.1	0.8	3.1	2.1	4.8	2.8
Transport	101	4.4	2.5	5.5	1.4	11.7	10.2
Car	101	4.4	2.5	5.5	1.4	11.7	10.2
Indoor	349	3.1	0.8	3.1	2.1	4.8	2.8
Outdoor rural	42	1.7	0.4	1.6	1.4	4.0	2.6
Outdoor urban	59	6.4	1.2	6.1	5.3	11.7	6.4

Table C 2 Summary statistics for profile P1-02 split by microenvironments, transport modes and classes. n= number of data points, all values in µg/m^3.

	n	mean	sd	median	min	max	range
P1-02.PM2.5	2,276	4.3	3.4	3.2	1.4	22.0	20.7
Home	1,697	4.4	3.3	3.9	1.4	18.4	17.1
Outdoor other	197	2.0	0.1	2.0	1.7	3.2	1.5
Transport	374	4.8	4.1	2.6	1.4	22.0	20.6
Work	8	2.3	0.9	1.8	1.6	3.9	2.3
Car	374	4.8	4.1	2.6	1.4	22.0	20.6
Indoor	1,705	4.4	3.3	3.9	1.4	18.4	17.1
Outdoor rural	433	2.2	0.6	2.0	1.4	6.5	5.1
Outdoor urban	138	9.0	3.9	7.9	5.1	22.0	16.9

Table C 3 Summary statistics for profile P1-03 split by microenvironments, transport modes and classes. n= number of data points, all values in µg/m^3.

	n	mean	sd	median	min	max	range
P1-03.PM2.5	2,937	1.9	0.9	1.7	1.0	10.1	9.2
Home	1,429	2.1	0.7	1.9	1.1	6.0	4.8
Public building	101	3.5	0.9	3.5	1.6	8.2	6.6
Transport	46	5.1	1.5	5.5	1.5	7.9	6.4
Work	1,361	1.5	0.5	1.3	1.0	10.1	9.2
Bicycle	26	4.7	2.0	5.4	1.5	7.9	6.4
Walk	20	5.5	0.2	5.5	5.2	5.8	0.6
Indoor	2,891	1.8	0.8	1.7	1.0	10.1	9.2
Outdoor rural	7	1.7	0.2	1.6	1.5	1.9	0.4
Outdoor urban	39	5.7	0.6	5.6	5.0	7.9	2.9

Table C 4 Summary statistics for profile P1-04 split by microenvironments, transport modes and classes. n= number of data points, all values in µg/m^3.

	n	mean	sd	median	min	max	range
P1-04.PM2.5	3,045	3.3	4.1	2.3	1.0	101.4	100.4
Home	1,534	3.0	1.9	2.3	1.6	12.7	11.2
Public building	100	11.4	13.7	9.2	3.3	101.4	98.1
Transport	190	9.4	7.9	9.0	1.4	41.3	39.9
Work	1,221	1.9	0.7	1.7	1.0	3.3	2.3
Bus	64	12.3	11.7	9.0	1.5	41.3	39.8
Car	31	4.5	2.8	2.8	1.8	8.9	7.1
Walk	95	9.1	4.1	9.7	1.4	17.0	15.6
Indoor	2,855	2.9	3.4	2.2	1.0	101.4	100.4
Outdoor rural	56	3.9	4.3	2.0	1.4	17.0	15.5
Outdoor urban	134	11.8	7.9	9.5	5.4	41.3	35.9

Table C 5 Summary statistics for profile P1-05 split by microenvironments, transport modes and classes. n= number of data points, all values in µg/m^3.

	n	mean	sd	median	min	max	range
P1-05.PM2.5	1,735	3.6	2.9	2.2	1.0	21.7	20.6
Home	988	4.1	2.6	3.2	1.2	11.3	10.1
Public building	9	1.6	0.3	1.7	1.2	2.1	0.9
Transport	172	7.3	4.1	6.7	1.4	21.7	20.3
Work	566	1.7	0.3	1.7	1.0	3.9	2.8
Bus	112	6.9	3.9	6.0	1.4	17.8	16.4
Car	14	6.3	1.3	6.6	2.2	7.1	5.0
Walk	46	8.8	4.6	8.3	1.4	21.7	20.3
Indoor	1,563	3.2	2.4	2.0	1.0	11.3	10.3
Outdoor rural	30	2.3	1.3	1.6	1.4	5.2	3.8
Outdoor urban	142	8.4	3.6	7.3	5.0	21.7	16.7

Table C 6 Summary statistics for profile P1-06 split by microenvironments, transport modes and classes. n= number of data points, all values in µg/m^3.

	n	mean	sd	median	min	max	range
P1-06.PM2.5	3,785	10.6	19.1	5.7	0.9	178.3	177.4
Home	2,716	11.4	22.3	4.9	2.2	178.3	176.1
Outdoor other	158	5.3	2.7	7.0	2.0	12.8	10.8
Public building	438	11.2	4.9	11.5	2.3	26.5	24.1
Transport	404	7.9	4.0	7.9	1.9	36.0	34.2
Work	69	1.5	0.5	1.5	0.9	2.9	2.0
Bus	90	10.2	3.1	8.9	7.2	21.6	14.4
Car	190	6.0	3.2	7.1	1.9	16.9	15.1
Train	54	5.8	2.9	7.1	1.9	14.7	12.8
Walk	70	11.6	3.7	11.1	8.4	36.0	27.6
Indoor	3,223	11.2	20.6	5.3	0.9	178.3	177.4
Outdoor rural	159	2.3	0.6	2.2	1.9	7.8	6.0
Outdoor urban	403	9.1	2.8	8.0	6.0	36.0	30.0

Table C 7 Summary statistics for profile P1-07 split by microenvironments, transport modes and classes. n= number of data points, all values in µg/m^3.

	n	mean	sd	median	min	max	range
P1-07.PM2.5	4,341	7.1	12.5	4.0	1.3	185.8	184.5
Home	3,708	6.4	8.2	4.0	1.4	185.8	184.4
Outdoor other	121	9.6	7.7	6.4	2.4	34.2	31.8
Private residential building	42	101.5	30.7	87.7	44.6	171.4	126.8
Public building	40	4.8	1.6	5.0	2.4	11.0	8.6
Transport	258	5.2	3.1	5.9	1.5	22.7	21.3
Work	172	1.9	0.2	2.0	1.3	2.5	1.2
Car	258	5.2	3.1	5.9	1.5	22.7	21.3
Indoor	3,962	7.2	13.0	3.9	1.3	185.8	184.5
Outdoor rural	150	2.5	0.8	2.3	1.5	5.9	4.4
Outdoor urban	229	9.3	5.5	7.5	5.4	34.2	28.7

Table C 8 Summary statistics for profile P1-08 split by microenvironments, transport modes and classes. n= number of data points, all values in µg/m^3.

	n	mean	sd	median	min	max	range
P1-08.PM2.5	1,500	2.8	1.6	2.0	0.9	12.2	11.3
Home	862	2.7	1.0	2.8	1.4	5.8	4.4
Public building	75	1.3	0.2	1.3	0.9	1.7	0.8
Transport	166	5.8	2.7	6.8	1.4	12.2	10.7
Work	397	1.8	0.2	1.8	1.4	4.3	2.9
Car	166	5.8	2.7	6.8	1.4	12.2	10.7
Indoor	1,334	2.4	0.9	2.0	0.9	5.8	5.0
Outdoor rural	49	2.0	0.4	1.9	1.4	2.9	1.5
Outdoor urban	117	7.4	1.1	7.3	5.6	12.2	6.6

Table C 9 Summary statistics for profile P1-09 split by microenvironments, transport modes and classes. n= number of data points, all values in µg/m^3.

	n	mean	sd	median	min	max	range
P1-09.PM2.5	1,221	4.6	6.4	2.4	1.4	51.1	49.7
Outdoor other	410	2.5	2.3	1.6	1.4	9.4	8.0
Public building	52	30.7	10.7	32.1	1.6	51.1	49.5
Transport	759	3.9	2.2	3.3	1.4	14.6	13.2
Car	245	3.6	2.4	2.3	1.4	11.1	9.6
Ferry	514	4.1	2.2	3.8	1.6	14.6	13.1
Indoor	52	30.7	10.7	32.1	1.6	51.1	49.5
Outdoor rural	1,005	2.7	1.4	2.1	1.4	8.4	7.0
Outdoor urban	164	8.1	1.6	7.9	6.0	14.6	8.6

Table C 10 Summary statistics for profile P1-10 split by microenvironments, transport modes and classes. n= number of data points, all values in µg/m^3.

	n	mean	sd	median	min	max	range
P1-10.PM2.5	4,030	4.5	5.1	3.4	1.3	72.0	70.7
Outdoor other	23	3.8	3.0	2.1	1.7	10.2	8.5
Private residential building	846	8.0	10.1	4.1	1.7	72.0	70.3
Public building	2,690	3.6	1.1	3.3	1.8	7.0	5.2
Transport	446	3.5	2.4	2.2	1.5	13.0	11.5
Work	25	2.1	1.2	1.3	1.3	4.2	2.9
Car	446	3.5	2.4	2.2	1.5	13.0	11.5
Indoor	3,561	4.6	5.3	3.5	1.3	72.0	70.7
Outdoor rural	343	2.1	0.5	2.0	1.5	4.8	3.3
Outdoor urban	126	7.3	1.3	7.2	5.3	13.0	7.7

Table C 11 Summary statistics for profile P1-11 split by microenvironments, transport modes and classes. n= number of data points, all values in µg/m^3.

	n	mean	sd	median	min	max	range
P1-11.PM2.5	475	5.0	17.3	1.6	0.9	237.3	236.3
Public building	118	11.5	33.6	1.4	0.9	237.3	236.3
Transport	174	4.5	3.7	3.6	1.4	17.9	16.5
Work	183	1.2	0.2	1.1	1.0	2.3	1.3
Car	174	4.5	3.7	3.6	1.4	17.9	16.5
Indoor	301	5.3	21.6	1.2	0.9	237.3	236.3
Outdoor rural	129	2.8	1.0	2.6	1.4	4.7	3.3
Outdoor urban	45	9.4	4.2	7.0	5.1	17.9	12.8

Table C 12 Summary statistics for profile P1-12 split by microenvironments, transport modes and classes. n= number of data points, all values in µg/m^3.

	n	mean	sd	median	min	max	range
P1-12.PM2.5	2,801	6.2	9.2	3.2	0.9	89.4	88.5
Home	1,768	6.3	10.8	2.9	1.2	89.4	88.3
Public building	472	7.5	7.1	4.1	2.5	49.3	46.8
Transport	164	7.1	2.5	7.3	1.4	11.5	10.0
Work	397	3.6	2.3	3.0	0.9	10.4	9.5
Bicycle	164	7.1	2.5	7.3	1.4	11.5	10.0
Indoor	2,637	6.1	9.4	3.0	0.9	89.4	88.5
Outdoor rural	25	2.1	0.3	2.0	1.4	3.0	1.6
Outdoor urban	139	8.0	1.5	7.8	5.4	11.5	6.1

Table C 13 Summary statistics for profile P1-13 split by microenvironments, transport modes and classes. n= number of data points, all values in µg/m^3.

	n	mean	sd	median	min	max	range
P1-13.PM2.5	1,424	2.4	2.7	1.9	1.0	25.3	24.3
Home	714	2.8	3.6	2.1	1.1	25.3	24.1
Public building	35	3.4	0.2	3.4	2.8	3.5	0.8
Transport	43	5.7	1.8	6.0	1.6	8.1	6.5
Work	632	1.6	0.4	1.5	1.0	2.7	1.8
Car	43	5.7	1.8	6.0	1.6	8.1	6.5
Indoor	1,381	2.3	2.7	1.9	1.0	25.3	24.3
Outdoor rural	6	1.7	0.1	1.7	1.6	1.7	0.2
Outdoor urban	37	6.4	0.8	6.5	5.2	8.1	2.8

Table C 14 Summary statistics for profile P1-14 split by microenvironments, transport modes and classes. n= number of data points, all values in µg/m^3.

	n	mean	sd	median	min	max	range
P1-14.PM2.5	5,079	5.0	5.2	3.1	1.0	66.4	65.4
Home	2,762	3.9	4.8	2.2	1.1	41.7	40.6
Outdoor other	166	10.0	5.4	9.1	6.4	46.1	39.7
Private residential building	164	9.1	4.6	9.4	2.4	18.8	16.4
Public building	783	6.9	6.6	4.5	2.0	66.4	64.4
Transport	735	7.1	3.9	7.1	1.4	29.2	27.8
Work	469	2.2	0.7	2.1	1.0	3.9	2.9
Bus	264	8.9	3.1	8.6	2.2	23.4	21.1
Car	71	7.3	3.4	7.3	1.4	11.4	10.0
Train	293	5.0	3.2	3.3	1.7	12.7	11.0
Walk	107	8.6	4.7	6.9	5.5	29.2	23.6
Indoor	4,178	4.5	5.2	2.7	1.0	66.4	65.4
Outdoor rural	223	2.8	1.1	2.6	1.4	8.3	6.9
Outdoor urban	678	9.2	3.8	8.6	5.4	46.1	40.7

Table C 15 Summary statistics for profile P1-15 split by microenvironments, transport modes and classes. n= number of data points, all values in µg/m^3.

	n	mean	sd	median	min	max	range
P1-15.PM2.5	2,387	10.2	11.0	4.4	1.4	55.8	54.5
Home	1,776	12.6	11.7	6.7	1.8	55.8	54.0
Outdoor other	54	2.1	0.4	2.2	1.5	2.6	1.1
Public building	4	18.0	4.5	18.2	12.6	23.3	10.7
Transport	159	5.8	3.5	6.5	1.5	15.6	14.1
Work	394	2.0	0.9	1.7	1.4	8.3	6.9
Bus	102	5.6	3.1	6.6	1.6	11.8	10.2
Walk	57	6.2	4.1	6.2	1.5	15.6	14.1
Indoor	2,174	10.7	11.4	4.4	1.4	55.8	54.5
Outdoor rural	113	2.1	0.5	2.0	1.5	3.9	2.5
Outdoor urban	100	8.0	2.4	7.0	5.5	15.6	10.0

Table C 16 Summary statistics for profile P1-16 split by microenvironments, transport modes and classes. n= number of data points, all values in µg/m^3.

	n	mean	sd	median	min	max	range
P1-16.PM2.5	3,686	8.0	9.0	4.4	1.1	67.0	65.9
Home	2,110	8.1	10.7	3.9	1.1	67.0	65.9
Outdoor other	280	2.2	0.7	2.1	1.9	10.4	8.5
Private residential building	1,015	9.3	5.4	7.8	2.9	19.7	16.8
Public building	12	3.4	0.5	3.2	2.9	4.7	1.8
Transport	262	7.7	7.2	6.7	1.5	44.0	42.5
Work	7	2.2	0.7	2.7	1.2	3.0	1.8
Bus	110	12.1	9.0	8.3	2.5	44.0	41.5
Car	108	4.1	2.5	2.3	1.7	9.9	8.2
Walk	44	5.7	2.8	5.8	1.5	12.6	11.1
Indoor	3,144	8.5	9.3	4.8	1.1	67.0	65.9
Outdoor rural	372	2.4	1.7	2.1	1.5	16.7	15.2
Outdoor urban	170	10.3	7.5	7.6	5.3	44.0	38.7

Table C 17 Summary statistics for profile P1-17 split by microenvironments, transport modes and classes. n= number of data points, all values in µg/m^3.

	n	mean	sd	median	min	max	range
P1-17.PM2.5	1,680	3.3	2.8	2.1	1.0	34.1	33.2
Home	862	3.1	2.0	2.3	1.3	18.1	16.8
Outdoor other	62	8.9	3.1	7.8	6.1	21.1	15.0
Public building	68	7.2	4.7	5.8	5.0	34.1	29.2
Transport	150	6.7	3.2	6.6	1.5	13.2	11.7
Work	538	1.5	0.6	1.4	1.0	5.6	4.7
Bicycle	22	4.7	2.3	6.3	1.8	7.3	5.5
Car	82	8.8	2.3	9.6	2.0	13.2	11.2
Walk	46	3.9	2.0	4.1	1.5	6.9	5.4
Indoor	1,468	2.7	2.2	1.9	1.0	34.1	33.2
Outdoor rural	37	2.0	0.4	2.0	1.5	3.5	2.0
Outdoor urban	175	8.4	2.5	7.8	5.3	21.1	15.8

Table C 18 Summary statistics for profile P1-18 split by microenvironments, transport modes and classes. n= number of data points, all values in µg/m^3.

	n	mean	sd	median	min	max	range
P1-18.PM2.5	3,377	6.9	9.0	4.4	1.1	97.3	96.2
Home	2,558	7.7	10.1	4.6	1.1	97.3	96.2
Public building	20	3.8	2.6	2.7	1.3	10.2	9.0
Transport	64	6.3	3.6	7.1	1.8	16.2	14.4
Work	735	4.5	2.3	3.9	1.8	10.5	8.6
Car	35	7.0	3.9	8.6	1.8	15.1	13.4
Walk	29	5.6	3.2	5.6	2.5	16.2	13.7
Indoor	3,313	6.9	9.1	4.4	1.1	97.3	96.2
Outdoor rural	27	2.6	0.4	2.7	1.8	3.3	1.5
Outdoor urban	37	9.1	2.2	9.3	5.5	16.2	10.7

Table C 19 Summary statistics for profile P1-19 split by microenvironments, transport modes and classes. n= number of data points, all values in µg/m^3.

	n	mean	sd	median	min	max	range
P1-19.PM2.5	3,933	6.8	8.4	3.5	0.9	93.9	93.0
Home	3,187	6.7	8.1	3.5	1.1	93.9	92.9
Outdoor other	284	6.0	6.3	6.4	1.9	87.2	85.4
Public building	71	21.3	19.6	8.7	1.9	58.4	56.5
Transport	169	9.9	6.6	7.8	1.8	29.4	27.7
Work	222	1.1	0.1	1.1	0.9	1.3	0.3
Bicycle	26	7.3	0.8	6.9	6.3	9.3	3.0
Bus	79	12.4	8.6	8.0	2.7	29.4	26.8
Walk	64	7.9	3.0	8.0	1.8	14.5	12.7
Indoor	3,480	6.7	8.6	3.2	0.9	93.9	93.0
Outdoor rural	147	2.9	2.1	2.2	1.8	11.6	9.8
Outdoor urban	306	9.6	7.1	7.7	5.9	87.2	81.4

Summary Statistics Individual Profiles (Phase 2)

Table D 1 Summary statistics for profile P2-01 split by microenvironments, transport modes and classes. n= number of data points, all values in µg/m^3.

	n	mean	sd	median	min	max	range
P2-01.PM2.5	6,254	13.8	10.1	12.1	1.4	74.2	72.9
Home	5,891	14.1	10.2	12.8	1.4	74.2	72.9
Public building	110	10.2	3.9	10.1	3.8	22.5	18.7
Transport	180	7.7	2.5	7.6	1.8	15.7	14.0
Work	73	2.7	0.4	2.5	2.3	3.6	1.3
Bus	73	7.9	2.7	8.2	2.0	13.8	11.9
Walk	107	7.6	2.4	6.9	1.8	15.7	14.0
Indoor	6,074	13.9	10.2	12.6	1.4	74.2	72.9
Outdoor rural	16	2.1	0.3	0.3	1.8	2.6	0.9
Outdoor urban	164	8.3	1.9	7.8	5.1	15.7	10.6

Table D 2 Summary statistics for profile P2-02 split by microenvironments, transport modes and classes. n= number of data points, all values in µg/m^3.

	n	mean	sd	median	min	max	range
P2-02.PM2.5	2,814	29.6	55.5	4.5	1.6	265.0	263.4
Home	1,700	46.8	66.0	7.4	1.6	265.0	263.4
Private residential building	3	18.7	13.5	24.8	3.2	28.0	24.8
Transport	121	8.3	3.2	7.1	5.7	19.3	13.6
Work	990	2.5	0.6	2.5	1.6	4.6	3.0
Car	26	12.5	4.2	11.3	7.1	19.3	12.2
Walk	95	7.1	1.4	6.6	5.7	16.1	10.4
Indoor	2,693	30.5	56.6	4.1	1.6	265.0	263.4
Outdoor urban	121	8.3	3.2	7.1	5.7	19.3	13.6

Table D 3 Summary statistics for profile P2-03 split by microenvironments, transport modes and classes. n= number of data points, all values in µg/m^3.

	n	mean	sd	median	min	max	range
P2-03.PM2.5	3,591	8.0	7.9	4.9	1.0	60.9	59.8
Home	3,192	8.2	8.3	4.5	1.0	60.9	59.8
Outdoor other	10	9.7	2.6	8.1	7.6	13.8	6.2
Private residential building	45	5.1	0.8	4.8	4.1	7.2	3.2
Public building	83	7.3	2.9	7.4	1.6	14.1	12.5
Transport	261	6.6	3.7	5.9	1.5	39.5	37.9
Bus	79	7.3	2.8	7.8	1.5	13.0	11.5
Car	90	6.1	5.3	5.6	1.6	39.5	37.9
Walk	92	6.4	2.1	6.6	1.6	11.8	10.2
Indoor	3,320	8.2	8.1	4.6	1.0	60.9	59.8
Outdoor rural	30	2.0	0.6	1.8	1.5	3.4	1.9
Outdoor urban	241	7.3	3.5	6.3	5.0	39.5	34.5

Table D 4 Summary statistics for profile P2-04 split by microenvironments, transport modes and classes. n= number of data points, all values in µg/m^3.

	n	mean	sd	median	min	max	range
P2-04.PM2.5	1,463	5.2	2.2	4.4	1.9	26.4	24.4
Home	720	4.9	2.1	4.2	3.1	26.4	23.2
Outdoor other	*35*	7.8	0.3	7.7	7.4	8.6	1.2
Public building	16	15.1	6.3	18.6	5.1	20.4	15.2
Transport	61	5.2	2.5	5.6	1.9	9.3	7.4
Work	631	5.1	1.3	4.9	2.8	7.8	5.0
Car	57	5.4	2.5	5.6	2.0	9.3	7.4
Walk	4	2.6	0.5	2.8	1.9	2.9	1.0
Indoor	1,367	5.1	2.2	4.4	2.8	26.4	23.5
Outdoor rural	41	3.8	1.6	2.9	1.9	6.5	4.6
Outdoor urban	55	7.9	0.5	7.8	6.9	9.3	2.4

Table D 5 Summary statistics for profile P2-05 split by microenvironments, transport modes and classes. n= number of data points, all values in µg/m^3.

	n	mean	sd	median	min	max	range
P2-05.PM2.5	1,422	18.1	40.5	3.0	1.5	211.1	209.5
Home	738	32.2	52.4	6.2	2.2	211.1	208.9
Outdoor other	31	4.4	8.4	1.7	1.5	45.4	43.8
Public building	58	4.5	3.4	3.7	2.2	24.5	22.2
Transport	80	5.2	3.9	6.0	1.6	31.2	29.6
Work	515	2.3	0.6	2.1	1.6	5.1	3.5
Car	77	5.3	3.9	6.1	1.6	31.2	29.6
Walk	3	1.9	0.0	1.9	1.9	1.9	0.0
Indoor	1,311	19.2	42.0	3.0	1.6	211.1	209.5
Outdoor rural	58	1.8	0.2	1.7	1.5	2.6	1.0
Outdoor urban	53	8.4	6.3	6.9	5.6	45.4	39.7

Table D 6 Summary statistics for profile P2-06 split by microenvironments, transport modes and classes. n= number of data points, all values in µg/m^3.

	n	mean	sd	median	min	max	range
P2-06.PM2.5	4,292	5.8	11.6	2.7	1.2	103.7	102.4
Home	3,754	6.1	12.4	2.7	1.2	103.7	102.4
Public building	10	2.4	0.3	2.3	2.1	3.0	0.9
Transport	209	5.9	1.8	6.2	1.6	11.1	9.5
Work	319	2.5	0.2	2.5	2.0	4.5	2.5
Car	193	5.9	1.9	6.3	1.6	11.1	9.5
Walk	16	5.4	0.9	5.5	2.0	6.5	4.5
Indoor	4,083	5.8	11.9	2.6	1.2	103.7	102.4
Outdoor rural	33	2.1	0.3	2.2	1.6	2.6	1.0
Outdoor urban	176	6.6	0.8	6.4	5.3	11.1	5.8

Table D 7 Summary statistics for profile P2-07 split by microenvironments, transport modes and classes. n= number of data points, all values in µg/m^3.

	n	mean	sd	median	min	max	range
P2-07.PM2.5	2,271	6.6	6.0	4.6	2.2	56.7	54.5
Home	1,237	7.9	7.4	5.4	3.6	56.7	53.1
Public building	120	4.4	0.3	4.4	3.7	6.0	2.2
Transport	154	10.0	5.6	8.7	2.2	25.5	23.4
Work	760	4.1	1.0	4.0	2.3	8.4	6.1
Bicycle	154	10.0	5.6	8.7	2.2	25.5	23.4
Indoor	2,117	6.4	6.0	4.6	2.3	56.7	54.3
Outdoor rural	23	2.8	0.6	2.7	2.2	4.3	2.2
Outdoor urban	131	11.3	5.1	9.1	7.0	25.5	18.5

Table D 8 Summary statistics for profile P2-08 split by microenvironments, transport modes and classes. n= number of data points, all values in µg/m^3.

	n	mean	sd	median	min	max	range
P2-08.PM2.5	4,243	4.8	5.4	3.4	1.0	59.4	58.4
Home	2,668	4.5	6.0	3.0	1.0	59.4	58.4
Outdoor other	31	7.0	1.3	6.0	5.5	9.0	3.4
Private residential building	20	5.3	2.3	4.4	3.8	12.1	8.3
Public building	326	7.1	3.1	6.6	2.7	25.0	22.3
Transport	165	8.9	8.6	6.8	1.5	51.4	49.9
Work	1,033	3.9	2.7	3.4	1.3	25.0	23.6
Car	110	8.9	10.2	6.7	1.6	51.4	49.9
Walk	55	9.1	4.3	8.0	1.5	20.6	19.1
Indoor	4,047	4.6	5.2	3.4	1.0	59.4	58.4
Outdoor rural	38	3.5	4.0	2.1	1.5	19.6	18.1
Outdoor urban	158	9.9	8.2	7.0	4.8	51.4	46.7

Table D 9 Summary statistics for profile P2-01 split by microenvironments, transport modes and classes. n= number of data points, all values in µg/m^3.

	n	mean	sd	median	min	max	range
P2-09.PM2.5	4,187	2.5	2.5	2.1	0.7	24.0	23.3
Home	3,482	2.2	2.1	2.0	0.7	24.0	23.3
Outdoor other	32	6.2	1.7	6.2	1.6	9.6	7.9
Private residential building	102	3.8	2.1	4.3	1.2	18.2	17.0
Public building	242	2.3	1.9	2.1	0.8	19.3	18.4
Transport	179	7.9	4.2	7.1	1.3	21.2	19.9
Work	150	2.0	1.6	1.8	1.1	19.4	18.3
Bus	82	10.4	4.4	8.8	2.4	21.2	18.8
Car	29	4.3	2.6	2.6	1.5	8.0	6.5
Walk	68	6.4	2.0	5.8	1.3	13.1	11.8
Indoor	3,976	2.2	2.1	2.0	0.7	24.0	23.3
Outdoor rural	23	1.9	0.4	1.8	1.3	2.6	1.3
Outdoor urban	188	8.3	3.6	7.2	4.8	21.2	16.4

Table D 10 Summary statistics for profile P2-10 split by microenvironments, transport modes and classes. n= number of data points, all values in µg/m^3.

	n	mean	sd	median	min	max	range
P2-10.PM2.5	3,784	4.2	3.2	3.6	0.9	29.0	28.1
Home	1,788	3.5	1.2	3.6	1.8	10.2	8.4
Outdoor other	5	7.0	0.5	6.8	6.7	7.7	1.0
Public building	1,089	4.0	4.6	2.3	0.9	29.0	28.1
Transport	457	8.2	2.8	7.4	2.1	20.4	18.3
Work	445	3.4	1.3	3.3	1.2	11.3	10.1
Bus	11	7.3	0.3	7.3	6.8	7.7	0.8
Car	82	6.7	1.6	6.9	2.1	9.1	7.0
Train	291	8.6	3.2	7.5	5.1	20.4	15.3
Walk	73	8.0	2.0	8.1	2.2	14.5	12.3
Indoor	3,322	3.7	2.8	3.3	0.9	29.0	28.1
Outdoor rural	8	2.3	0.1	2.2	2.1	2.6	0.5
Outdoor urban	454	8.3	2.7	7.4	5.1	20.4	15.3

Table D 11 Summary statistics for profile P2-11 split by microenvironments, transport modes and classes. n= number of data points, all values in µg/m^3.

	n	mean	sd	median	min	max	range
P2-11.PM2.5	1,475	7.8	10.0	4.3	1.5	76.1	74.6
Home	1,250	4.7	2.3	4.0	1.5	18.1	16.7
Public building	184	27.9	17.4	26.5	7.1	76.1	69.0
Transport	41	10.7	2.8	9.9	8.8	20.3	11.5
Walk	41	10.7	2.8	9.9	8.8	20.3	11.5
Indoor	1,434	7.7	10.2	4.2	1.5	76.1	74.6
Outdoor urban	41	10.7	2.8	9.9	8.8	20.3	11.5

Table D 12 Summary statistics for profile P2-12 split by microenvironment (ME), transport mode (TPM) and class. n= number of data points, all values in µg/m^3.

	n	mean	sd	median	min	max	range
P2-12.PM2.5	1,441	6.7	4.3	5.9	2.0	24.2	22.2
Home	839	8.1	3.4	6.5	3.9	22.1	18.2
Outdoor other	44	6.0	5.1	3.9	2.0	20.7	18.7
Transport	90	13.1	6.4	13.3	2.7	24.2	21.5
Work	468	2.9	0.5	2.8	2.1	6.1	4.0
Bus	64	13.3	6.1	12.4	3.9	24.2	20.4
Walk	26	12.6	7.0	16.1	2.7	20.8	18.0
Indoor	1,307	6.3	3.7	5.8	2.1	22.1	20.0
Outdoor rural	59	3.9	0.6	3.9	2.0	5.3	3.3
Outdoor urban	75	16.2	4.0	16.1	11.0	24.2	13.3

Table D 13 Summary statistics for profile P2-13 split by microenvironments, transport modes and classes. n= number of data points, all values in µg/m^3.

	n	mean	sd	median	min	max	range
P2-13.PM2.5	1,466	4.9	3.1	3.6	1.3	17.3	16.1
Home	739	3.2	0.7	3.3	1.3	4.8	3.5
Outdoor other	53	3.5	1.8	2.4	1.8	6.9	5.1
Public building	124	8.4	1.1	8.8	5.0	9.8	4.8
Transport	153	7.9	3.9	6.4	1.9	17.3	15.4
Work	397	6.0	3.6	7.8	1.6	12.6	11.1
Bus	73	9.2	4.6	8.3	2.0	17.3	15.4
Walk	80	6.7	2.6	6.0	1.9	15.1	13.2
Indoor	1,260	4.6	2.8	3.5	1.3	12.6	11.3
Outdoor rural	65	2.9	1.0	2.4	1.8	5.0	3.2
Outdoor urban	141	8.5	3.5	6.9	5.0	17.3	12.4

Table D 14 Summary statistics for profile P2-14 split by microenvironments, transport modes and classes. n= number of data points, all values in µg/m^3.

	n	mean	sd	median	min	max	range
P2-14.PM2.5	1,707	4.7	1.7	4.6	1.6	10.9	9.2
Home	857	4.8	1.0	4.7	3.1	10.9	7.8
Public building	12	8.4	1.6	9.0	5.8	10.5	4.7
Transport	61	6.5	2.9	8.1	2.1	9.5	7.4
Work	777	4.4	1.9	3.6	1.6	9.6	8.0
Car	16	5.5	3.2	3.0	2.2	9.3	7.1
Walk	45	6.8	2.8	8.2	2.1	9.5	7.4
Indoor	1,646	4.6	1.6	4.6	1.6	10.9	9.2
Outdoor rural	21	2.5	0.3	2.5	2.1	3.0	0.9
Outdoor urban	40	8.5	0.4	8.5	7.9	9.5	1.6

Table D 15 Summary statistics for profile P2-15 split by microenvironments, transport modes and classes. n= number of data points, all values in µg/m^3.

	n	mean	sd	median	min	max	range
P2-15.PM2.5	1457	5.4	3.8	5.5	1.6	30.5	29.0
Home	779	7.4	3.0	6.4	3.4	30.5	27.2
Transport	93	9.0	7.0	6.4	1.6	22.9	21.3
Work	585	2.3	0.4	2.2	1.6	3.3	1.7
Bicycle	43	5.3	2.1	6.0	1.6	9.5	7.8
Bus	35	15.8	7.0	19.4	2.2	22.9	20.7
Walk	15	3.6	2.4	1.9	1.8	7.5	5.7
Indoor	1364	5.2	3.4	5.0	1.6	30.5	29.0
Outdoor rural	31	3.3	2.5	1.9	1.6	7.9	6.2
Outdoor urban	62	11.8	6.9	7.1	5.8	22.9	17.1

Table D 16 Summary statistics for profile P2-16 split by microenvironments, transport modes and classes. n= number of data points, all values in µg/m^3.

	n	mean	sd	median	min	max	range
P2-16.PM2.5	1,464	17.8	8.7	15.7	6.2	73.0	66.8
Home	885	17.8	4.8	16.6	9.5	28.2	18.7
Outdoor other	161	23.8	2.7	23.6	19.7	38.5	18.7
Public building	6	21.9	1.0	22.1	20.4	23.0	2.6
Transport	83	36.1	20.9	23.5	6.8	73.0	66.2
Work	329	10.3	2.4	10.7	6.2	15.1	8.9
Bicycle	38	21.7	2.7	22.6	12.9	24.9	12.0
Bus	35	56.7	16.3	63.1	20.0	73.0	53.0
Walk	10	18.4	9.1	19.1	6.8	34.3	27.5
Indoor	1,220	15.8	5.5	13.7	6.2	28.2	22.0
Outdoor rural	10	16.6	6.0	20.3	6.8	22.5	15.6
Outdoor urban	234	28.4	13.7	23.6	12.9	73.0	60.1

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