Chapter

IMPORTANT VARIABLES WHEN STUDYING THE INFLUENCE OF PARTICULATE MATTER ON HEALTH

João Garcia[1,*], Rita Cerdeira[1], Luís Coelho[1], Prashant Kumar[2,3] and Maria da Graça Carvalho[4]
[1]Escola Superior de Tecnologia de Setúbal,
Instituto Politécnico de Setúbal, Setúbal, Portugal
[2]Department of Civil and Environmental Engineering,
Faculty of Engineering and Physical Science (FEPS),
University of Surrey, Guildford, UK
[3]Environmental Flow (EnFlo) Research Centre, FEPS,
University of Surrey, Guildford, UK
[4]Instituto Superior Técnico, Lisboa, Portugal

ABSTRACT

This chapter intends to make a contribution to the understanding of various aspects related to particulate matter (PM) in the urban environment, in particular, regarding its impact on the human health. A methodology is presented to identify, relate and understand the diverse and multidisciplinary variables that contribute to PM concentration in urban environments and associated health impacts. A particular emphasis has been given to the PM but the approach could be applied to the other air pollutants in urban areas. The main challenges associated with the application of this methodology are also pointed out.

---

[*] Escola Superior de Tecnologia de Setúbal, Instituto Politécnico de Setúbal, Campus do IPS, 1910-761 Setúbal, Portugal. Email: joao.garcia@estsetubal.ips.pt.

INTRODUCTION

Air quality and its relation to health are aspects of growing importance in understanding the issues linked to public health. These issues become more important when demographic movements and the ageing of populations lead to new efforts to develop health policies, urban planning and sustainable development both locally and globally. These aspects are closely connected, given that good air quality is essential for human health and for the balance in the planet's environmental system. On the other hand, air pollution also affects the quality of life of the population both in the social aspects and in terms of public health. According to the World Health Organisation (WHO), around 7 million people died (one-eighth of the total number of deaths) in the year 2012 as a result of exposure to air pollution (WHO, 2014). The International Agency for Research on Cancer (IARC), in late 2013, classified particulate matter (PM) as carcinogenic to humans, thus considering it as an environmental cause of death by cancer (WHO, 2013).

Although air pollution issues are nowadays widely discussed and receive growing attention from the scientific community and public opinion in general, there is still an ample debate about the way of studying and assessing the impact of air quality on health. One of the important aspects debated is adequate planning of cities in the form of their global geometry (buildings, industrial activities, roads, footpaths, bridges, roundabouts, among others) as well as decisions concerning road traffic management, thus decision-making by political decision-makers about municipal master plans is a strategic factor.

This chapter aims to help understand the global and complex relation between air quality, paying special attention to particles (PM) and health, developing a methodology to identify the main variables that were applied to specific pollutants (e.g., PM).

Among atmospheric pollutants, tropospheric ozone (O_3) and fine particles are related through their common precursors (WHO, 2000, 2003, 2004), namely nitrogen oxides (NOx) and volatile non-methane organic compounds (COVNMs). When inhaled, both ozone and fine particles are believed to cause adverse effects to human health. Such effects include worsening respiratory diseases such as asthma (after a short exposition) and respiratory and cardiovascular conditions as well as cancer and premature mortality (after prolonged exposition) (WHO, 2013). According to some studies, their effect is likely to be additive at least in the short-term (Camargo, 2003; Branis, 2004; Ballester et al., 2006). These impacts on health are caused by occasional high concentrations or systematic and persistent concentrations throughout time. One way or another, or through a combination of both forms, air quality is nowadays a primordial aspect of health. In the case of particles, typically the concentration levels remain high throughout the whole year while ozone-related problems are manifested mainly in the summer months. For example, the levels of ozone recorded during the heat wave in Portugal in the summer of 2003 were particularly high. It is also known that some groups are more vulnerable than others to high concentrations of ozone and particles. The most affected groups are generally children, people with asthma, chronic patients and the elderly (Domici, 2004; EEA, 2005; Jimenez et al., 2009).

OBJECTIVE

The objective of this chapter is to present the main variables to study and collect in situations when the goal is to study the relationship between air quality and health in urban environments. This relation is difficult to quantify, given the numerous variables that are inter-linked due to the multidisciplinary aspects involved. Particular attention has been paid to the specific case of PM particles, as they are commonly accepted as one of the most important pollutants for this matter. We aim to identify the main multidisciplinary aspects, namely meteorology, urban geometry, buildings, roads and footpaths, road traffic, industries and health. The other aims include using numerous types of tools, from urban scale numerical simulation to numerical simulation with CFD for a given street, including local measurement of concentrations of particles in the outdoors environment and the indoors environment to assess the possible impact on health.

RELATION BETWEEN AIR POLLUTION AND HEALTH

The assumption that atmospheric pollution might cause deaths in situations of high concentrations of pollutants arose in the mid-20th century, essentially because of an array of disasters that occurred in the United States and Europe (EEA, 2011). Later on, in the early 90s, work on the study of temporal series in different locations showed that even less high levels of pollution, but persistent in time, may lead to increased levels of mortality and morbidity in the population. More recent, nevertheless, are studies that try to associate levels of atmospheric pollution (even if not high) to the arousal of respiratory problems in certain groups that are more susceptible to these problems, such as children, the elderly and chronic patients. All these types of study continue, nevertheless, to try to consistently correlate levels of atmospheric pollution and public health in general. Being a subject of constant development, one should highlight the works listed below in these fields.

Although some works mainly led by physicians were developed in the 60s, 70s and 80s, trying to relate health with levels of pollution, it was in the 90s that said works gained great momentum, namely through the systematisation of methodologies and application of statistical methods. Important in this decade were the works by Timonen and Pekkanen (1997), who studied the association between daily atmospheric pollution during the winter of 1994 and the respiratory health of children aged 7 to 12 in the city of Kuopio, Finland. Seventy-four children with symptoms of asthma and ninety-five children with symptoms of a persistent cough, living in urban or suburban areas, were followed during three months. During the period under study, the daily average concentration of particles with diameters below 10 µm (PM_{10}) was 18 µg/m^3 in the urban area and 13 µg/m3 in the suburban area. The authors conclude that the results suggest that atmospheric pollution due to PM_{10} is associated to levels of respiratory health, especially in children with asthma. The greatest association was recorded with a two-day delay between the peak concentrations of PM_{10} and the peak of problems in children with asthma. Ciccone (Ciccone et al., 1998) also researched the relation between road traffic indicators in the area of residence of children and the occurrence of respiratory chronic episodes in those children. The method used was carrying out surveys in 10 areas in Northern and Central Italy, from autumn 1994 to winter 1995, divided into two age groups (6–7 and 13–14 years).

Information on several respiratory disorders and on the road traffic close to their homes was collected through a questionnaire given to children and their parents. The sample reviewed included 39,275 individuals and regression models were used to treat the data. The results were that, in metropolitan areas, high frequencies of road traffic in the zone of residence were associated with a significant increment of risks to the respiratory system through several symptoms. The strongest correlations were found with Bronchitis, Bronchiolitis and Pneumonia. Nevertheless, the same study found strong correlations between road traffic and respiratory problems in rural or urban areas of smaller size. Hence the authors conclude that exposition to exhaustions due to intense road traffic may have significant adverse effects on the respiratory health of children living in metropolitan areas, thus increasing the occurrence of respiratory infections, causing symptoms of lung diseases at school age. Hajat et al. (1999) also ascertained the association between atmospheric pollution in London and the number of visits due to asthma and the other diseases related to respiratory system. The method they followed was an analysis of the temporal series of visits due to respiratory diseases between the years 1992 and 1994. Data from 295,740 patients from 47 hospital units in London were reviewed. They concluded that there was an association between atmospheric pollution and daily visits due to asthma and other respiratory system diseases. The most significant associations were seen in children and the most important pollutants that potentiated such effects were Nitrogen Dioxide (NO_2), Carbon Monoxide (CO) and Sulphur Dioxide (SO_2). In adults, the sole consistent association found was with PM_{10}.

Particles (PM_{10}) being, in effect, the pollutant whose results are more direct and with consequences for health, some works also suggested the influence of other pollutants on health, namely the works by Segala (Segala et al., 1998), who studied the short-term effects of low levels of pollution in children with asthma in Paris. For that, they developed a follow-up of 84 children with diagnosed asthma, divided into two groups according to the seriousness of the disease. This follow-up was done during 6 months. They verified the existence of a correlation between an increase in the number of asthma cases reported and the level of atmospheric pollution. The greatest correlation with asthma was fond when there was an increase of 50 $\mu g/m^3$ of SO_2 on the same day. Nevertheless, correlations were also found with respiratory problems 3 days after that increase of 50 $\mu g/m^3$ of SO_2. The results found allowed authors to conclude that there was evidence of effects of low levels of atmospheric pollution related with symptoms of respiratory problems in children with asthma.

With the new millennium, the study of the influence of atmospheric pollutants on health had a great development. Among the many works carried out, we would highlight the works produced by the WHO (WHO, 2003, 2004, 2005, 2008, 2012), which tried to systematise the knowledge on the effect of atmospheric pollution from several pollutants, with particular emphasis on particles, ozone and nitrogen dioxide. This report was meant to provide Guidelines to establish regulatory frameworks, decision-making and support to environmental management. It also had the aim of integrating European policies for air quality, namely the Clean Air For Europe (CAFE) programme. This work group proposes using finer particles, with diameters under 2.5 µm ($PM_{2.5}$) as indicators of risks associated with health due to pollution by particles. Also noteworthy are works by Peng et al. (2004), who studied the application of temporal series models, trying to relate changes in levels of air quality with levels of daily mortality. The authors develop semi-parametric Bayesian models to estimate the effects of the temporal variation of pollution on mortality, by applying them to studies, in multiple cities of the United States. This method was applied to the National Morbidity and Mortality

Air Pollution Study Database for the period 1987-2000 and includes data from 100 United States cities. They thus ascertained that in the cities studied in the United States, an increase of 10 µg/m3 in atmospheric PM_{10} is associated with an increase of 0.15%, 0.14%, 0.36% and 0.14% in mortality in winter, spring, summer and autumn, respectively. Sunier (2001) also tried to find consistency in the relation between an increase in levels of urban air pollution and short-term effects on public health, namely mortality and hospital admissions. This study is essentially focused on particles and studied patients suffering from chronic obstructive lung disease. They concluded that more studies must be carried out, enlarging the geographic study base and increasing the trial period, as cross effects and the different variables that influence data hindered drawing conclusions. Clancy published in 2002, in the prestigious Lancet review, a paper comparing concentrations of atmospheric pollution in Dublin during 72 months, with deaths due to respiratory and cardiovascular problems in that same period (Clancy et al., 2002). This study was carried out reviewing figures before and after the prohibition of selling coal in Dublin. They thus verified that average concentration of particles fell from 35 to 6 µg/m3 (70%) after the prohibition of selling coal and that non-traumatic deaths due to respiratory causes fell from 15% to 5%, cardiovascular deaths from 10% to 3%. They thus concluded that the reduction of deaths due to respiratory and cardiovascular diseases in Dublin suggests that controlling the level of particles in the air may substantially reduce the number of daily deaths. Qian et al. (2004) also studied the relation between respiratory health and polluted environments by observing 7048 school-age children, aged between 5 and 16 years and living in four Chinese cities Lanzhou, Chongqing, Wuhan and Guangzhou. The levels of particulate matter pollution ($PM_{2.5}$, PM_{10}), total particles in suspension (TSP), SO_2, and NOx were measured in these cities, from 1993 to 1996. Based on an analysis of the average arithmetic concentrations of $PM_{2.5}$, PM_{10}, TSP, SO_2 and NOx, the authors ranked children in four categories of exposition to atmospheric pollution. They tested the exposition-response relation using linear regression models and ascertained the existence of positive relations between exposition and concentrations of pollutants as far as respiratory problems and cough. They thus concluded that exposition to mixtures of atmospheric pollutants has adverse effects for children who lived in these four Chinese cities. Several similar studies were developed in other countries. Jalaludin et al. (2004) developed a similar study, in which they followed, during 11 months, children from primary schools in Sydney, trying to relate levels of atmospheric pollution with respiratory morbidity. In this work, they obtained daily values of different pollutants (ozone, PM_{10} and NO_2), values of weather variables and values of atmospheric pollen. Figures from 125 children were reviewed, in all, linear regression models having been used to try to find associations between atmospheric pollution and symptoms of respiratory problems, such as asthma, visits to the physician and medication. The analysis of the results allowed concluding that there was no correlation between levels of atmospheric Ozone and respiratory problems, physician visits or the use of medication. They concluded, nevertheless, that there was a correlation between PM_{10} concentrations and problems related to children with asthma and they also ascertained the existence of a correlation between NO_2 concentrations and respiratory problems associated with a persistent cough. Ballester et al. (2006) developed a similar study, in Spain, which they called EMECAM, trying to assess the impact of atmospheric pollution on mortality in this country. They thus studied 14 Spanish cities from 1995 to 1999, trying to relate daily mortality due to two causes, cardiovascular diseases and respiratory diseases, with levels of atmospheric pollution for particles (PM_{10}) and other pollutants (SO_2, NO_2, CO and O_3). They used a Poisson regression model, considering simple analyses of a single pollutant and combined analyses of both pollutants. They ascertained that the increase in 10 µg/m3 in the average concentration of PM_{10} led (with a one-day delay) to a 0.8% increase in total mortality. They those concluded that there was a correlation between mortality and pollution due to high levels of concentration of particles and other pollutants in the atmosphere, in Spain.

Peters et al. (2000) studied the effects of particles on public health in Central Europe. Values of mortality and atmospheric pollution were collected in a much-polluted region of the Czech Republic and of a rural region in Germany. An analysis using Poisson linear regression methods was developed. They saw that the Czech Republic had 3.8% increase in mortality associated with values of 100 $\mu g/m^3$ of TSP with a two-day delay and a 9.5% increase in mortality with a one-day delay. No correlations were found between mortality and the levels of TSP in the rural zone of Germany. The authors conclude that there is an association between concentrations of particles in polluted places of Central Europe and mortality in said places. Koenig et al. (2005) presented a different perspective of the analysis of air quality on public health, given that most studies related concentrations of particles with health using only values of outdoor air concentrations as an indicator for human exposition. Nevertheless, according to these authors and due to the fact that people spend more time indoors, exposed to pollutants such as particles, which are a combination of particles generated indoors with particles infiltrated from outdoors, it is important to research the effects on health differentiating indoors and outdoors and their relation. They thus present a model considering the filtering efficiency in personal exposition. The study is focused on the importance of the indoor air quality component on effects on the health of children with asthma. Garcia et al. (2013a) present a study to correlate the relation between indoor/outdoor PM concentrations in school classrooms.

Schwartz et al. (2002) paid particular attention to the shape of the concentration-response curve for daily concentrations of atmospheric pollution versus daily deaths. In this work, the authors studied such a relationship using a hierarchic model in six cities of the United States, paying particular attention to $PM_{2.5}$. They try to ascertain whether there is a threshold under which deaths due to particles had no expression. They concluded that said threshold did not exist. Nevertheless, they concluded that control of these fine particles might cause a decrease of thousands of deaths each year in these cities of the United States. Slaughter et al. (2004) studied the influence of the different fractions of particle diameters in cardiac and respiratory morbidities and mortality. They studied the short-term correlations between four fractions of particle diameters (PM_1, $PM_{2.5}$, PM_{10} and $PM_{10-2.5}$), CO and hospital admissions due to cardiac and respiratory problems, in the city of Spokane, Washington. They used a generalised log-linear model to compare the daily average PM and CO with daily values of morbidity and mortality in the period from January 1995 to June 2001. They also reviewed the delays of 0 to 3 days between the respective concentration, morbidity and mortality values. They found no consistent correlation between concentrations of particles and mortality or morbidity. On the contrary, they found correlations between CO concentrations and hospital admissions, and with visits due to asthma, with a three-day delay. They also found no correlation between the diameter of particles and hospital admissions due to cardiac problems or mortality.

Aga et al. (2003) paid particular attention to the same type of studies, which tried to find correlations between concentrations of pollutants and effects on health, but in this case, they focused on studying the elderly (>65 years). Daily values of particle concentrations (PM_{10}) were compared with the daily number of deaths of people aged over 65, in 29 European cities. The results obtained show that particles have an effect on mortality, for this population group, above the values obtained when compared with the total population. Ribeiro and Cardoso (2003) present a very interesting work in which they compare air quality values measured by the monitoring network of the city of São Paulo, with data on the respiratory health of children. This study was carried out for the year 1986 and repeated in the year 1998, the results having been compared. Thus the effect was assessed of programmes to reduce atmospheric pollution, implemented throughout these years. The results obtained show that programmes to control pollution were partly neutralised by the increase in the number of cars. They concluded nevertheless that the reduction in the levels of concentration of particles and SO_2, throughout the years, led to a reduction in the incidence of respiratory diseases.

The works by Galán et al. (2003) follow the same line in searching for a correlation between atmospheric pollution and asthmatic morbidity. Nevertheless, in this study, they include, in the analysis, pollen as a possible factor that influences results. They thus analyse concentrations of atmospheric pollutants (SO_2, PM_{10}, NO_2 and O_3) and levels of pollen in the atmosphere and compare it with admissions due to asthma in hospitals, in Madrid, in the period from 1995 to 1998. The data were reviewed using regressive Poisson models. The strongest correlations were found for Ozone with a one-day delay and for particles with a three-day delay. They conclude that the presence of pollen is not significant in influencing the results. Recent work has focused on the human health effects of nanoparticles (e.g., Heal et al., 2012; Kumar et al., 2014a, b) that can penetrate deeply into the lungs and may enter the bloodstream.

IMPACT OF PARTICLES ON HEALTH

In recent years a growing number of scientific studies have tried to correlate the result of possible adverse effects on health with the exposition to levels of particle concentration in atmospheric air. In order to understand this correlation, one must understand what are the particles that exist in the atmospheric air, their constitution, their origin, as well as the mechanisms that govern them. Generically a considerably extended group of pollutants that exist in the air are grouped under the name particles and their origin may lie in sources as diverse as cars, steelworks, heating plants, heating systems, cement factories, volcanos, deserts and oceans. Generally speaking, it is current to consider the definition of NIST (Vincent et al., 2001) for a particle as being "any condensed-phase three-dimensional discontinuity in a dispersed system may generally be considered a particle". Nevertheless, in terms of atmospheric pollution, a particle may be defined as a solid dispersed matter, fluid or solid and fluid, whose individual aggregates are greater than small molecules with a diameter above 0.0002 µm, but under 500 µm.

In terms of epidemiological and toxicological studies, numerous studies have been developed in recent times to try to understand what type of particles and what dimensions lead to the most negative effects on the human being, from the point of view of health. From a chemical point of view, some studies suggest that the toxicity of particles is essentially due to the organic compounds around the particle (Eiguren-Fernandez et al., 2010), others indicating as the main factor of toxicity the coal nucleus of the particle (Soto et al., 2008). As for the dimension, a considerable number of authors correlate the negative effects for health with the mass concentration of particles (Pope, 2000; Loomis, 2000), other authors mention the importance of the concentration of ultra-fine particles in atmospheric air for the consequences for health (Hauser et al., 2001).

Generically, several epidemiological studies mention particles as the atmospheric pollutant with more negative consequence for health, followed by Ozone but with lesser impact. Nevertheless, even for these pollutants, no fully safe level was yet identified. Some studies suggest that even concentrations under the present air quality level guidelines may represent a risk for health (WHO, 2011).

It is believed that the effects of fine particles ($PM_{2.5}$) on health are caused after inhalation thereof and penetration in the lungs. Several studies suggest that both chemical and physical interactions with lung tissues may cause irritation or damages to the lungs. The smaller the particles are, the more they can penetrate the lungs. Annual levels of mortality are clearly associated with levels of $PM_{2.5}$ concentrations, which in Europe represent 40-80% of the mass concentration of PM_{10} in the atmospheric air. Nevertheless, the fraction of particles of greater dimension (2.5 µm to 10 µm) of PM_{10} also have negative impacts on health and affect mortality, although growing evidence suggests that $PM_{2.5}$ have more adverse impacts (WHO, 2011). Chronic exposition to atmospheric particles contributes to the o risk of developing cardiovascular and respiratory diseases, as well as lung cancer. Mortality associated with atmospheric pollution is around 15-20% greater in cities with high levels of pollution when compared with cities that are relatively less polluted. In this atmospheric pollution, numerous studies show that the most critical pollutant are particles. For example, in the European Union, studies suggest that the average life expectancy is 8.6 months lower due to exposition to $PM_{2.5}$ arising from human activities (WHO, 2008).

Pollution by particles (especially fine particles) contains microscopic solids or fluids that, being very small may deeply penetrate the lungs and cause serious health problems. Numerous scientific studies (Timonen and Pekkanen, 1997; Clancy et al., 2002) correlate exposition to particles with a series of health problems, including increased respiratory problems, such as irritation of respiratory ways, cough or difficulty in breathing (Timonen and Pekkanen, 1997), reduction of the lung function (Jalaludin et al., 2004), worsening of asthma cases (Galan et al. 2003), development of chronic bronchitis (Ciccone et al., 1998), development of irregular heartbeat (Balester et al., 2002), occurrence of non-fatal heart attacks (Clancy et al., 2002) and premature death in people with cardiac or pulmonary disease (Peng et al., 2004). It is also evident that people with cardiac or pulmonary diseases, children and the elderly are the groups more susceptible of being affected by exposition to pollution by particles (WHO 2008).

As previously stated, two types of studies have been developed as far as the consequences for the health of exposition to atmospheric pollutants, thus that also applies to the specific case of particles, epidemiological studies and toxicological studies. Epidemiological studies are global studies that try to study the cause-effect relation of a given disease, using, most of the times, the tool of statistical analysis. In the case of particles, these studies try to review the consequences of the exposition of a given population to a given level of concentration or a given type of particles. Within this type of studies two degrees of incidence have been analysed, morbidity, which may be defined as the rate of bearers of a given disease relative to the whole population studied, and mortality.

Alternatively, toxicological studies are studies that try to analyse the negative or adverse effects that a given toxic agent (chemical substance) have on the body. There are two types of toxicological studies, experimental toxicology, which uses animals to try to understand the action mechanism and the consequences for the body, and analytical toxicology, which has the aim of identifying/quantifying toxifying elements in organs such as the liver, kidneys or matrixes such as blood, urine or saliva.

Among the numerous epidemiological studies that have been developed to try to understand what type of particles and what dimensions lead to the most negative effects on the human being, from the health point of view, worthy of note are, from a chemical point of view, those that suggest that the toxicity of particles is essentially due to the organic compounds around the particle (Eiguren-Fernandez et al., 2010) and those that indicate as the main factor of toxicity the coal nucleus of the particle (Soto et al., 2008). As for dimension, a considerable number of authors correlates negative effects for health with mass concentration of particles (Pope, 2000; Loomis, 2000). Other authors mention the importance of the concentration of ultra-fine particles in the atmospheric air (Hauser et al., 2001).

The groups identified as of greater risk in short-term studies are the elderly, children and individuals with chronic cardiac and pulmonary diseases, as they are more susceptible to the adverse effects of particles in the environment, as far as both mortality and morbidity (WHO, 2008). In sample studies one also sees that asthmatic person respond to the effects of particles in the environment proving more susceptible than the non-asthmatic (WHO, 2008). There is also a negative influence of high concentrations of particles in the decreased rate of lung development in children (WHO, 2003). Long-term studies show that socially disfavored populations are strongly correlated with mortality due to exposition to atmospheric particles. No consistent differences were recorded between men and women.

As far as toxicological studies, they are more recent and in shorter numbers. We would highlight works by Ghio et al. (2000), in which a group of 38 healthy volunteers was exposed to environments with concentrations of particles varying from 23 $\mu g/m^3$ to 311 $\mu g/m^3$ (with an average value of 200 $\mu g/m^3$ of $PM_{2.5})$ in a 2-hour exposition. Authors concluded that exposition to these environments may cause an influx of inflammatory cells in the lower respiratory tract as well as an increase in the blood concentration of fibrinogen, given that 18 hours after exposition the analysis of cells and fluids obtained by bronchoalveolar lavage showed a slight increase in the number of neutrophils in both fractions of bronchi and alveolus.

There were also studies human on controlled exposition to the exhaustion of diesel engines (Salvi et al., 2000; Nightingale et al., 2000), with healthy non-smoking volunteers during times of exposition of 2 hours subject to the flux of exhaustion collected from diesel engines and placed in a testing chamber (200 $\mu g/m^3$ of PM_{10}), which showed located and systematic inflammatory effects in the respiratory tract.

Some studies in animals showed the adverse effects for the health of exposition to particles. Clarke et al. (2000) concluded that fine particles, removed from samples of atmospheric air from cities, may cause inflammations and lesions in the lungs of canines exposed during 6 hours, during 3 consecutive days, in testing chambers with atmospheric air removed from urban environments with high concentrations of $PM_{2.5}$ particles. Changes in the cardiac function were also seen in mice exposed to samples of particles collected from samples of urban air (Wellenius et al., 2002), as well as strong evidence of induction of lung cancer in mice, due to chronic inhalation of products from the exhaustion of diesel engines, with deposition of particles in the respiratory system, inducing inflammatory effects and generating high concentration of oxygen radicals and damages to ADN, and they may be mechanisms that induce tumours in the lungs of mice.

PARTICULATE MATTER

General Characterisation

The classification of particles is frequently done on the base of two different criteria. They may be ranked according to their mechanism of formation and in those cases, they are called primary particles or secondary particles or they may be classified by physical dimension. Following the criterion of formation mechanism, primary particles are those that are issued directly as particles, while secondary particles are those formed from precursor gases that existent in the atmosphere, through a mechanism of gas-particle formation. Both types of particles (primary and secondary) are subject to mechanisms of growth and transformation, given that secondary material may also be formed on the nucleus of the initial existing particle.

Alternatively, (and more commonly) particles are ranked by physical dimension. Typical dimensions vary from some nanometres (nm) to tens of micrometres (µm) in diameter. Dimension is a very important characteristic of particles and has implications in the formation, physical and chemical properties, transformation, transport and removal of particles, from the atmosphere. Knowing that particles suspended in the atmosphere vary considerably in dimension, composition and origin, it is important to classify particles according to their aerodynamic properties, as those properties not only govern transport and removal of particles from the air as they govern their deposition in the respiratory system and are also associated with the chemical composition and origin of particles. Hence the size of particles is normally characterised by their aerodynamic diameter, which refers to the diameter of a sphere of uniform density and with the same sedimentation speed as the particle in question.

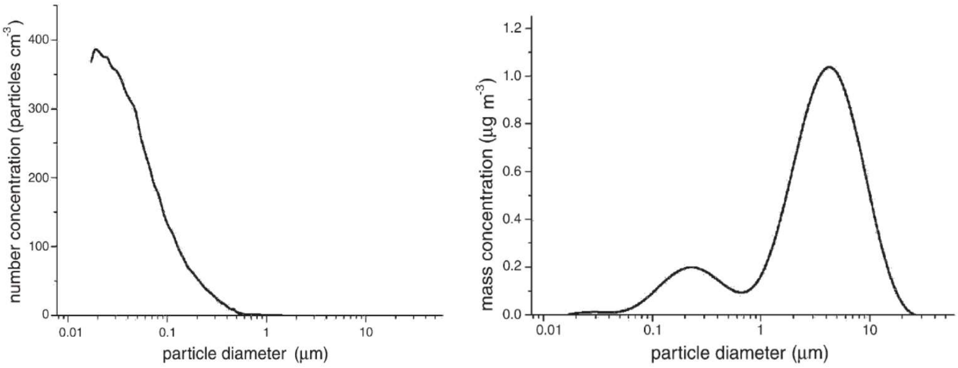

Figure 1. Typical distribution in a sample of urban air of the contribution of the number of particles (right) and mass (left) according to diameter (Morawska, 2002).

The word particle generically refers to a diverse and complex set of organic and inorganic substances. In practical terms, in urban environments, the mass and composition of particles tend to be divided into two main groups: coarse particles (greater dimension) and fine particles (smaller dimension). The frontier between these two classes of particles is generally comprehended between 10µm and 1µm. Nevertheless, this limit between coarse particles and fine particles is generally fixed, by convention, in 2.5 µm of aerodynamic diameter ($PM_{2.5}$). The conventional PM_X notation refers to particles with a diameter under X µm, thus PM_1 refers to particles with a diameter up to 1 µm, $PM_{2.5}$ refers to particles with a diameter under 2.5 µm and PM_{10} refers to particles with a diameter under 10 μm. The phrase “total suspended particles” (TSP) refers to the mass concentration of particles with a diameter under 50 μm and the phrase “ultra-fine particles” refers to particles with a diameter under 100 nm (0.1 μm). Smaller particles (fine particles) include secondary aerosols, formed from gases that exist in the atmosphere, through the mechanism of gas-particle conversion, contain particles resulting from processes of combustion and re-condensed organic and metallic vapours. Particles of a greater diameter (coarse particles) generally contain materials from the earth crust and dust coming from roads and industry. In urban environments, the greater number of particles is found in very small sizes, under 100 nm. Nevertheless, these ultra-fine particles frequently contribute to a small percentage of the total mass of the sample, contributing with more than 90% of the number of particles. This distribution is represented in Figure 1.

Particle Formation Mechanisms

Particles bigger than 2.5 μm (coarse particles) are produced mechanically by the break of solid particles of greater dimension. These particles may include dust from agricultural processes transported by the wind, from open ground, earth roads, or dust from other processes such as mining or quarries. In turn, road traffic also produces dust and turbulence that may raise and agitate dust from the road. Also in coastal locations, the evaporation of seawater may produce particles of this dimension. Also, grains of pollen, mould and plant spores and parts of insects are in this group of greater dimension and size. The amount of energy needed to break the aforementioned elements into particles of smaller dimension increases as size diminishes. This causes a lower limit to be established for the production of these gross particles of approximately 1 μm (WHO, 2003).

Smaller particles (fine particles) are in a large part formed from gases. Smaller particles, of less than 0.1 μm, are formed by nucleation, that is, condensation of substances formed by vaporisation at high temperatures or chemical reactions in the atmosphere. Four main types of sources may form particles through this mechanism: heavy metals (evaporated during combustion processes), elementary carbon (from short carbon molecules arising from combustion processes), organic carbon and sulphates and nitrates. Particles in this range grow by coagulation, that is, a combination of two or more particles to form a bigger particle, or through condensation, that is, a condensation of gas or vapour from molecules on the surface of existing particles. Coagulation is more efficient for great numbers of particles and condensation is more efficient for great areas of the surface. Consequently, the efficiency of both mechanisms, coagulation and condensation, falls with the increase in the size of particles, which in effect produces an upper limit so that particles do not grow, through these processes, beyond 1 μm. Thus this type of particles tends to “accumulate” between 0.1 μm and 1 μm, the zone commonly called “accumulation range”.

Particles under 1 μm may be formed by condensation of metals or organic compounds, which are evaporated in combustion processes, or may also be produced by condensation of gases arising from atmospheric reactions. For example, sulphur dioxide is oxidised in the atmosphere forming sulphuric acid (H_2SO_4), which may be neutralised by ammonium (NH_3) to form ammonium sulphate. Nitrogen dioxide (NO_2) is oxidised into nitric acid (HNO_3), which in turn may react with NH_3 to form ammonium nitrate (NH_4NO_3). Particles produced by these gas reactions in the atmosphere are called secondary particles. Sulphates and nitrate particles are normally the predominant components in these fine particles. So there is a correlation between PM urban concentrations and the concentration of other gaseous pollutants (Garcia et al., 2014). Figure 2 shows a simplified representation of particle formation processes.

Particles in suspension in the environment present, as far as size (diameter), typically a distribution of different size modes, which means that the total mass of particles tends to concentrate around one or more different points. The character of modal distribution in the dimension of the particle arises from the balance of particle formation processes, on the one hand, and, on the other hand, processes of removal of particles from the atmosphere. Hence, this modal distribution of the diameter of particles around one or two characteristic points varies depending on the age of the aerosol and the proximity of sources of emission of particles of different types (Seinfeld and Pandis, 1998). Other very important aspects for the definition of characteristics of particle concentrations in the atmosphere are meteorological variables such as wind speed and direction, atmospheric temperature, precipitation and the height of the planet boundary layer. Higher concentrations of particles are frequently recorded during meteorological conditions of atmospheric stability, especially in situations if thermal inversion, with low-speed wind and also because physical and chemical processes of particle formation are greatly regulated by meteorological variables (Pohjola et al., 2000).

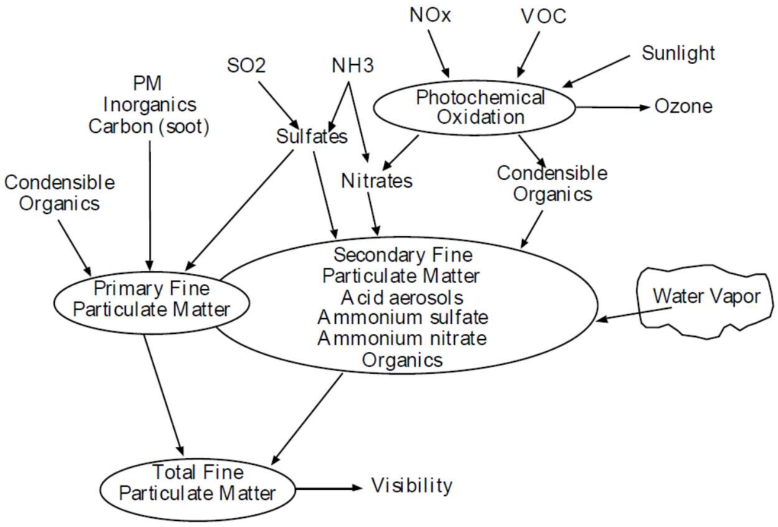

Figure 2. Summarised characterisation of particle formation mechanisms (CCPA, 2001).

Sources of Particles

Exhaustive studies (Putaud et al., 2002) suggest that a great part of particle emissions to the atmosphere is due to natural sources, such as dust from the earth surface, oceans and seas, volcanos, forest fires and gas emissions from natural processes. The natural sources with greater impact on the concentrations of particles in urban environments in Europe include suspension of dust from the earth surface, sea, salt, salt water spray (mainly from coastal areas), burnings and forest fires (Lazaridis et al., 2002). On the other hand, the main sources of anthropogenic particles, that is, originated by human activity, come from combustion processes, heating, burning biomass, industrial and road traffic emissions. These anthropogenic particles that exist in urban environments are, indeed, a complex mixture, because most of the sources issue not only particles proper as precursor gases, previously mentioned, which originate secondary particles. One also sees that most of these anthropogenic particles are originated in relatively limited areas of the urban or industrial type, representing critical points (hot spots) of high concentration of particles and other atmospheric pollutants (Vallius, 2005). Anthropogenic particles, primary and secondary, also affect background regional concentrations, given that these particles may remain in suspension several days and travel up to thousands of kilometres in the atmosphere.

The fact is that samples of particles of atmospheric air, from urban areas the world over, repeatedly present the same main components (Harrison and Yin, 2000), albeit in considerably different proportions according to the place of sampling. Such main components are typically (Vallius, 2005):

i) Sulphate – coming, mainly, from oxidation of sulphur dioxide in the atmosphere, given that SO_2 is oxidised slowly, the spatial variation of sulphate at the scale of ten kilometres is small, that variation being significant only at the scale of one hundred kilometres;
ii) Nitrate – Formed mainly from the oxidation of nitrogen oxides (NO and NO_2) to nitrate. NO_2 oxidises much quickly than SO_2;
iii) Ammonium – Ammonia existing in the atmosphere forms ammonium salts (NH_4) through reactions of neutralisation with sulphuric and nitric acids;
iv) Chloride – the main sources are vaporisation of seawater and also neutralisation of ammonia from hydrogen chloride gas (HCl) from incineration plants and heating plants;
v) Elementary carbon (CE) and organic carbon (OC) – From combustion processes in urban areas (mainly from road traffic) that issue particles of primary carbonaceous materials and semi-volatile precursor gases;
vi) Crust Materials (dust from the ground) – they are very diverse in composition, depending on local geology and earth surface conditions. Its concentration is strongly dependent on climate, because processes that tend to suspend these particles, in the atmosphere, tend to be favoured by dry surfaces and strong winds;
vii) Biological materials – bacteria, spores, pollens, plant waste and fragments, generally bigger. They are frequently seen as part of the organic carbon component, instead of an independent biological component.

There are, indeed, great differences in the relative importance of the different sources of particle emission and their impact on atmospheric air, from one geographic location to another. Several studies (ApSimon et al., 2000; Vallius, 2005) suggest, for example, that most particle emissions in Eastern Europe come from occasional sources of combustion and industrial processes, while in Western Europe emissions are more distributed between the different economic sectors of activity, including emissions from road transport. In the Northern and Central regions of Europe, anthropogenic sources dominate average long-term concentrations of particles, while in Southern European countries re-suspended dust, desert sand and forest fires take greater relative importance.

In 2002, a very exhaustive study, full and comprehensive, developed by the Joint Research Centre on particles in European atmospheric air (Putaud et al., 2002) concluded that organic matter and sulphate are the two main contributors for the average annual mass concentrations of PM_{10} and $PM_{2.5}$, except in locations close to roadsides, where mineral dust in the sidewalk also contributes significantly to PM_{10} concentrations. The same study concludes that, in days when average concentrations of PM_{10} are above 50 µg/m^3, nitrate also becomes one of the main contributors for PM_{10} and of $PM_{2.5}$ concentrations, and it also concludes that black carbon contributes with 5% to 10% for $PM_{2.5}$ concentrations and little less for PM_{10} concentrations in all places, including locations of stations classified as background, while the contribution of black carbon increases to 15% to 20% in some locations close to the roadside.

Road Traffic

Particle emissions from road traffic are the result of a great number of processes, such as, for example, products of combustion of engines running on gasoline, diesel and gas, products from vehicle oil, tyre rubber, brake system, bearings, chassis, road material, and release of dust from the road and ground (Laschober et al., 2004).

Traffic is, indeed, an important source of particles both smaller in dimension (fine particles) as of greater dimension (coarse particles), but it is also a source of emission of condensable organic gases and an important source of nitrogen oxides, which later on form nitrate aerosols (secondary). Particles of carbonaceous condensed material are emitted, mainly, by diesel vehicles, but also by gasoline vehicles with motor with degraded operating conditions (Vallius, 2005). Particles from diesel engines are, mainly, carbonaceous agglomerates under 100 nm in diameter, while particles emitted by vehicles running on gasoline are, mainly, smaller carbonaceous agglomerates, varying from 10 nm to 80 nm (Morawska and Zhang, 2002).

Although it is not possible to generalise conclusions about the association of the different elements present in atmospheric particles, with origin in road traffic, some elements have been frequently associated thereto. Those elements include copper (Cu), zinc (Zn), lead (Pb), bromine (Br), iron (Fe), calcium (Ca) and barium (Ba) (Sternbeck et al. 2002, Kemp, 2002, Morawska and Zhang, 2002). Nevertheless, emissions from many metallic elements from road traffic are not due to exhaustion emissions (non-exhaust emissions) but from other sources in the vehicle, such as tyres, brakes and other vehicle parts (Lough et al. 2005, Adachi and Tainosho, 2004, Laschober et al., 2004).

Re-Suspension

The re-entry, in atmospheric air, of particles previously deposited and their re-dragging to the atmosphere, is called re-suspension. This is a complex process that may be initiated by mechanical disturbances, such as the wind, turbulence induced by road traffic circulation, tensions arising from passing tyres and building activities.

The so-called “road dust” is an agglomeration of particles from several contributions from several anthropogenic and biogenic sources. On the roads, this dust from different sources accumulates on the roadsides, close to the pavement and along the central partitions. Re-suspension, deposition, “washout” inside and outside the road and the emission of new particles is a dynamic mechanism of “source” and “well” of particle emission that characterises road traffic. Roads are among the greatest sources that emit particles in urban environments (Vallius, 2005). Several studies have also shown that re-suspension of this element is a predominant source of particles of greater dimension (coarse particles) in locations with strong road traffic (Ruellan and Cachier 2001, Manoli et al., 2002, Sternbeck et al., 2002) making the impact of re-suspension on the concentration of particles in atmospheric air of utter importance.

Road dust may also act as a repository for the different elements from anthropogenic particle sources and re-suspension may work in certain places as a re-emission, thus contributing to increase the atmospheric concentration of such elements. The plausibility of this theory is supported by studies that have demonstrated that greater particles are more easily re-suspended by the wind and by road traffic and that materials deposited are more susceptible of re-suspending if associated to host particles of greater dimension (Nicholson and Branson, 1990).

But although most re-suspended particles are of greater dimension (coarse particles), there is a reduced portion of particles of smaller dimension (fine particles). The proportion of such fine particles has two important implications with possible important consequences. Firstly, fine particles may remain in suspension much longer than coarse particles and that may cause a greater spatial impact of atmospheric concentrations of particles, and secondly the fine fraction of re-suspended particles is more likely to contain constituents of anthropogenic origin, potentially more toxic, than fine particles of natural origins.

Occasional Sources, Area Sources and Remote Sources

Particles sources not originated by road traffic, frequently called occasional sources, include several types of facilities, such as energy production facilities (heating plants), industrial, incineration of municipal waste, paper production, the burning of fossil fuels and household heating facilities. Many of these sources are often deemed to be occasional sources, such as, for example, heating chimneys of plants and industries, but they may also be deemed to be area sources, such as for example household combustion facilities. The physical and chemical characteristics of particles emitted from these categories of sources depend on the combustion process in itself and the type of fuel burnt (solid, fluid or gas), presenting very diverse physical, chemical and dimensional characteristics, according to the combustion process that originates them. In this area, as an example, works by Halliburton (2006) conclude that particles emitted from processes arising from heating plants strongly depend on the combustion process and the fuel used whereas as Fernandes and Costa (2011) quantified and characterised the emission of particles in the exhaustion of a household boiler for several levels of charge and concluded that particles emitted have, mostly, diameters under 2.5 μm. Morawska and Zhang (2002) present an exhaustive study of combustion processes and the properties of particles emitted from several types of occasional sources.

As for emissions that do not arise from combustion processes, the main industrial processes that may contribute to particle emission to the atmosphere include metal-processing chemicals product processing factories, processing and handling of building materials or industry. Emissions of particles from this type of sources arise frequently from fugitive emissions, uncontrolled and released in a non-homogenous way. The type of particles and their physical and chemical properties also depend on the processes by which they are emitted, and it is not at all possible to generalise their characteristics. Knowledge of the relation of the different dimensions of particles in a given sample of atmospheric air is important to try to characterise the origin of the sources of emission of those very particles. Some recent studies (Van Dingenen et al., 2004) focused on studying that relation, based on samples collected in 31 locations in Europe, and concluded that diameter relations were very similar for all locations. In turn, dust from natural sources transported by the wind may contribute to high concentrations of particles of greater (coarse particles) and smaller dimension (fine particles), and in some cases, they are found in locations hundreds or even thousands of kilometres from their origin. The contribution of wind to transport dust from the desert to places far from the origin has been reported in several studies carried out the world over (Pio et al., 1996, Rodriguez et al., 2004, Owega et al., 2004, Chen et al., 2004). For example, in Southern Mediterranean countries, including Portugal, temporary episodes are often recorded (2-4 days) of transport of dust from the Sahara Desert, every year, leading to levels 25 µg/m^3 and 10-15 µg/m^3 higher than average daily expectable concentrations of PM_{10} and $PM_{2.5}$ (Rodriguez et al., 2004).

PROPOSED METHODOLOGY

Aim

The identified variables in this chapter allow framing, systematising, studying, relating and understanding the different and multidisciplinary aspects that contribute to air quality in urban environments and their influence in health, namely concerning children. This chapter also points the means or methods that can be used and the corresponding disciplinary groups to consider, pointing also some specific studies proposed to be applied in this type of analysis, when the aim is to study the relation between air quality in an urban environment (which may be a city, an urban area or part thereof) and their consequences to health.

Variables

Table 1 presents a summary of the main variables used, the means and methods used to obtain them and the respective disciplinary group that they belong to. Throughout the chapter we explain the way that these variables may be obtained; nevertheless, this methodology, when applied to other cases, must be adapted to that case study because very likely the variables available or that one may obtain might not be exactly the same.

Meteorology

The identification of the main meteorological parameters needed must be done on the base of meteorological elements that characterise the area under study. The data to be taken into account must be based on the climatological data of the region for an adequate period. Table 2 summarises the main meteorological variables needed to be taken into account.

Table 1. Summary of the main multidisciplinary variables

Variable	Means or method	Disciplinary group

Wind speed	Weather stations	Meteorology
Wind direction	Private stations	
Frequency	Meteorological modelling	
Air temperature		
Radiation		
Concentration of PM_{10}	AQ network stations	Outdoor and indoor air quality
Concentration of CO	AQ equipment	
Concentration of NO, NO_x	Monitoring campaigns	
Concentration of SO	Macroscale modelling	
Concentration of O_3	Microscale modelling	
	Relation Indoor/Outdoor	
	Modelling of the relation between pollutants	
Location	Municipal studies	Industry
Emission rates	Industries' records	
Emission temperature	Monitoring campaigns	
Emission speed	Pollutant emission models	
Height of chimneys		
Diameter of chimneys		
Location of lanes	Municipal studies	Road traffic
Type of vehicle	Monitoring campaigns	
Type of fuel	Pollutant emission models	
Speed of vehicles		
Emission rates		
N.º children admitted to ER	Teams of physicians	Health
Symptomatology SDR	Surveys	
Symptomatology asthma	Statistical studies	
Symptomatology cough	Hospital records	
Age distribution	Models of exposition	
	Time lag	

Table 2. Main meteorological variables needed

Annual average temperature (°C)
Total precipitation (mm)
Relative humidity (%)
Nº days per year with precipitation > 10 mm
Fog (days)
Cloudiness (9 hours) (scale 0-10)
Frost (days/year)

Air Quality

This section identifies the variables that characterise air quality in the zone under study and indicators of the levels of atmospheric pollution in the space considered; the two main components are usually industrial sources and traffic. For this characterisation, it is crucial to usually employ the available air quality data, which is frequently achieved using pollutant concentration data from air quality stations from the local, regional or national monitoring networks. These stations usually measure, continuously, several atmospheric pollutants, the most common of which are Nitrogen dioxide, Ozone, Sulphur dioxide, PM_{10} and carbon monoxide. Usually, in these stations, air samples to be analysed by each analyst are collected continuously, through a sampling head and with the help of a pump that guarantees air suction. Air is then taken to the different analysers, where the concentration of pollutants is determined, essentially on the basis of the optical characteristics or physical properties of the different pollutants. Electric signs issued continuously by each analyser, proportional to the concentrations of the pollutant analysed, are then converted to numerical values by a data acquisition system that stores hourly average values. These values are regularly transmitted to a central computer (the management unit) located in the headquarters of the monitoring network. The data collected are usually stored in a database, validated and treated statistically on the base of hourly average concentrations, with the exception of total particles in suspension in which treatment is carried out on the base of daily averages. Table 3 shows the characterisation of pollutants and methods of analysis of measured pollutants.

Industry

For the characterisation of industrial sources, it is necessary to know the pollutant emissions that may influence air quality in that urban space, including local emissions but also more remote emissions that may have an impact in the zone under study. To know these pollutant emissions the existing surveys could be used. The main characteristics to known in emission sources include location, height and diameter of chimneys, emission speed, flow and emission temperature. Table 4 shows an example of occasional sources identification, their name, the pollutant emitted, as well as coordinates of their location in metres, the height of chimney in metres, and an exit temperature of pollutants in °C. It also shows values of average exit speeds of pollutants, as well as the diameter of the chimney, in metres.

Table 3. Characterisation of the main pollutants and methods of analysis of pollutants usually measured in urban air quality stations

NO_2	CO	O_3	SO_2	PM_{10}	C_6H_6
Chemo-luminescence	Infrared non-dispersive absorption	Photometry	Ultraviolet Fluorescence	Beta Absorption	Chromatography in gaseous phase with a photoionization detector (PID)

Table 4. Example of location of occasional sources and emission conditions

Source	Pollutant	Flow (g/s)	UTM (m)		H (m)	Temp (ºC)	Av. speed (m/s)	Diam. (m)
			X	Y				
Source 1	PM	0,21	95388	80975	104	165	12,87	2,5
Source 2	SO2	0,91	95685	80523	73,3	59	2,82	1,5
Source 3	NOx	0,45	94475	80675	16	190	1,20	0,3

Source 4	COV	0,06	95575	81175	12	45	3,84	5,9

Road Traffic

To characterise the sources of atmospheric pollutants from road traffic, one needs to identify the main emission levels in the urban area under study. For that, one must use useful traffic studies, or carry out road traffic count and identification campaigns. The main variables to identify and that characterise this source are: number of vehicles; type of vehicles (light, heavy duty vehicles, heavy passenger vehicles and motorcycles); type of fuel used (diesel or gasoline); type and characteristics of the road (urban or highway, width of the road and height of surrounding buildings) and average circulation speed.

Table 5. Example of road traffic characterisation in number of vehicles per hour for line sources considered

Source	Empty Hours					Rush Hours				
	Light gasoline	Light Diesel	Heavy duty	Heavy Pass.	Motor cycles	Light gasoline	Light Diesel	Heavy duty	Heavy Pass.	Motor cycles
Street 1	361	155	84	24	12	571	245	120	48	36
Street 2	395	169	48	36	12	580	248	96	60	24
Street 3	823	353	120	48	12	907	389	144	60	36

Table 6. Example of estimates of emissions on empty hours and rush hours due to road traffic

Source	Empty hours					Rush Hours				
	CO	CO_2	SO_2	NO_x	PM	CO	CO_2	SO_2	NO_x	PM
Street 1	0.56	9.2	0.008	0.27	0.09	2.61	29.6	0.026	0.60	0.29
Street 2	0.84	11.4	0.010	0.32	0.10	3.24	36.1	0.032	0.74	0.35
Street 3	3.37	52.6	0.045	1.45	0.45	11.3	119.5	0.105	2.28	1.10

In this road traffic counting campaigns, two methods may be used: visual counting with volunteers and automatic counting through an automatic traffic counting system. In the case of counting campaigns, they must be developed in two different periods, rush hours and empty hours. Estimation of road traffic (line sources) emission is carried out by counting the number and type of vehicles that pass in each considered road. Counting must be made (in characterisation studies) for a given time lapse, in two different conditions (empty hours and rush hours). Tables 5 and 6 show examples of typical examples of traffic count, characterisation and estimation of traffic emissions.

Health

The aim being an assessment of the impact of air quality in an urban environment on the health of the population thereof, it is crucial to identify and select correctly what is the relevant target population for the study, namely whether one must consider the population of that urban environment in general, in whole, or only a part or subgroup of the population. In the specific case of particles, as previously stated, the most sensitive subgroups are children, the elderly and people with chronic diseases associated with the respiratory system. In the specific case of children their sensitivity to atmospheric pollution, and specifically particles, is linked to the fact that they are a sensitive population, as they are more vulnerable to the effects of atmospheric pollution than adults, for several reasons, from the time they spend outdoors to the anatomy and physiology of the respiratory system still in development. Besides, children have higher ventilation rates than adults and the low stature of children also increases their exposition to traffic emissions. Besides having ventilation rates higher than those of adults, they breathe preferably through the mouth, which does not have cilia capable of doing initial filtration (as in the nose) favouring the entry of pollutant particles capable of causing irritation. The immaturity of the pulmonary and immune systems favours the exacerbation of respiratory symptoms (APHEIS, 2005, EEA, 2005). All these factors help trigger more frequent episodes of respiratory troubles, even in the presence of lesser concentrations of pollutants.

Table 7. General description of health variables to be collected

Variable	Description of the variable
Date	Date of observation
Total children	Total number of children observed
Children 0-2	Number of children observed between 0 and 2 years of age
Children 3-5	Number of children observed between 3 and 5 years of age
Children 6-10	Number of children observed between 6 and 10 years of age
Children 11-15	Number of children observed between 11 and 15 years of age
Cough	Number of children observed with a symptomatology of cough
SDR	Number of children observed with a symptomatology of respiratory difficulty syndrome
Asthma	Number of children observed with a symptomatology of asthma
intern	Number of children admitted after observation
F	Number of children observed of the female sex
M	Number of children observed of the male sex

For the present methodology, we proposed that teams of paediatrician's record, daily, the number of children, age, sex, address and type of symptoms shown, in the emergency room. Children observed and having respiratory complaints of a non-infectious aetiology must be classified according to age, sex, residence area and type of symptom. As for symptomatology, at least 3 types of symptoms must be taken into account: cough; respiratory difficulty syndrome (SDR) and asthma. Although numerous international studies classify symptomologies according to the International Statistical Classification of Diseases (ICD), this simplified classification limits the subjectivity inherent to the classification in the groups. Table 7 shows a summary of the variables related to health to be considered.

Urban Geometry

In urban environments, local weather conditions, especially wind flow inside s*treet canyons*, are mainly controlled by the micro-local effects of the geometry of urban buildings, instead of mesoscale forces that control the conditions of the planet boundary layer (Hunter et al., 1992). Hence, a clear distinction must be done between the synoptic conditions of wind conditions in zones above the roofs and wind flow inside the s*treet canyon* cavity.

Generically, when wind flow above the higher part of the s*treet canyon* is perpendicular to the s*treet canyon* and the wind speed in that plane is above 2 m/s, flow inside the s*treet canyon* may be described in terms of three regimes, depending on the street dimensions (Oke, 1988): (a) *isolated roughness flow*, (b) *wake interference flow*, and (c) *skimming flow*. For wide type s*treet canyons* (H/W < 0.3) where buildings are well spaced, they act essentially as isolated roughness elements, given that air moves in a sufficient distance downwind in the wind direction after the first building and before finding the following obstacle. As the space between buildings decreases (H/W ≈ 0.5) the disturbance induced by the first building produces a disturbance in the air that does not have enough distance to reposition itself before finding a new disturbance induced by the second building, thus causing an interference in a drainage of the w*ake interference flow* type. In the case of regular s*treet canyons* (H/W ≈ 1), it is characterised by the formation of a vortex inside it (Hunter et al., 1992) called *skimming flow*. Figures 3 and 4 graphically represent the types of flow according to AIR.

As the *aspect ratio* increases (H/W > 2) it is possible to frequently observe the appearance of the second vortex of weak intensity and circulation contrary to the first vortex (Pavageau et al., 1999). For *aspect ratios* of even higher values (H/W > 3) a third vortex may also be formed (Jeong and Andrews, 2002).

Numerical Modelling

There is a need to complement or validate knowledge of the values of pollutant concentrations in the urban environments. In such situations, an important tool is the use of computation methods such as numerical modelling of pollutant dispersion. In these situations, it is crucial to choose the adequate model, which may depend on the aims to be reached but also on the existing data and computational tools available. As for types of numerical simulation models, the classification of models of dispersion and transport of pollutants in the atmosphere may be carried out through several approaches, such as for example the spatial scale used (global, regional-continental, local-regional, local), the time scale used (episodic models, statistical long-term models), the transport equations applied (Eulerian, Lagrangian, etc.) and the dimension of treatment of the phenomena at stake (chemistry, dry and wet deposition, etc.).

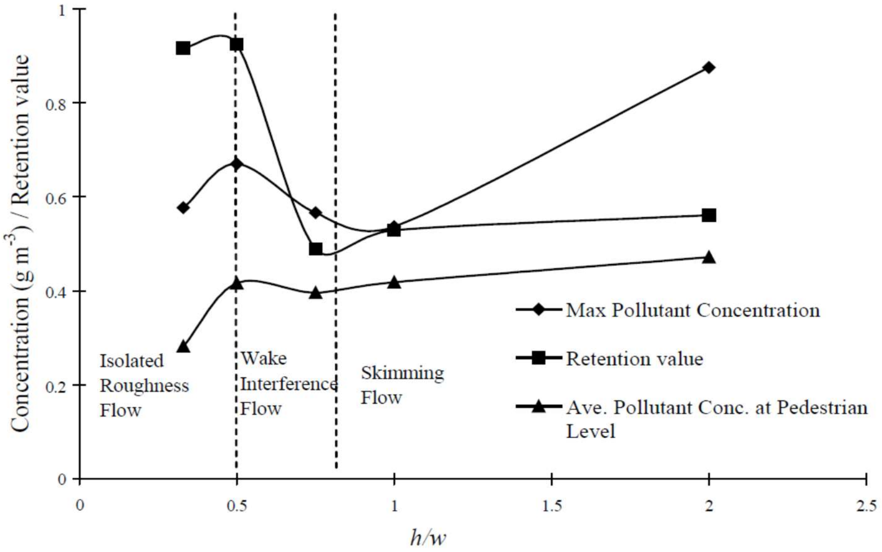

Figure 3. Type of predominant flow inside the *street canyon* according to *aspect ratio* (Chan et al., 2003).

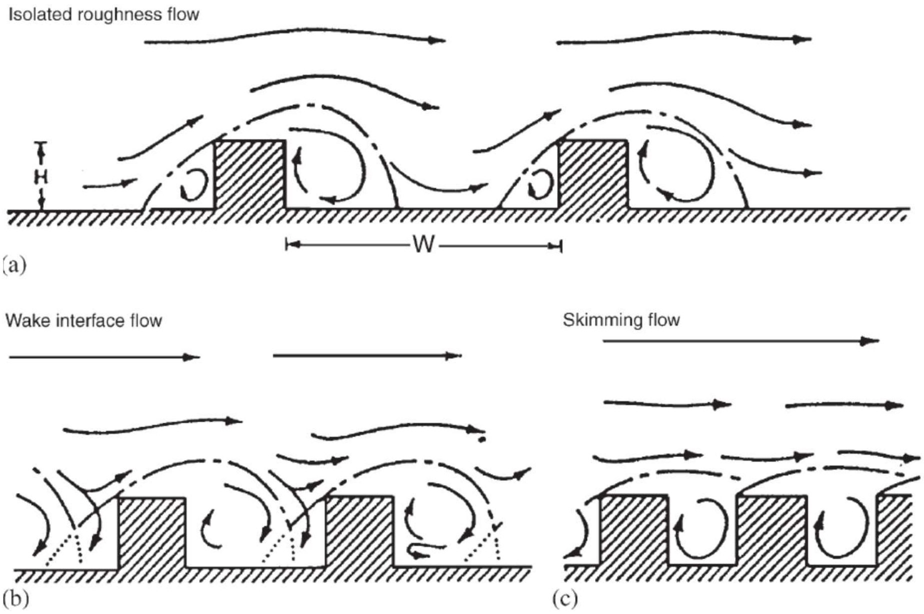

Figure 4. Characterisation of flow regimes perpendicular to the *street canyon* for different *Aspect Ratios* (Oke, 1988).

For purposes of modelling of pollutant dispersion in urban environments, some of the most frequently used models are:

i) Plume super elevation models;
ii) Gaussian models;

iii) Semi-empirical models;
iv) Eulerian models;
v) Lagrangian models;
vi) Chemical models;
vii) Receiver models.

Plume super elevation models compute vertical displacement and general behaviour of the plume in the initial dispersion stage, using both semi-empirical formulations and advanced formulations. In many cases, pollutants emitted to the environment have a higher temperature than surrounding air and many industrial pollutants are emitted through chimneys, thus having an initial vertical moment. Both factors, of thermal impulsion and vertical moment, help increase the average height of the plume above the chimney.

Gaussian models were the most used air pollution models in the past, due to their simplicity. They are based on the assumption that the concentration of pollutants at any distance has independent distributions in both directions, horizontal and vertical. Most models recommended by the U.S. Environmental Protection Agency (EPA) are Gaussian models. These models have been, nevertheless, modified so as to incorporate special cases of dispersion.

Semi-empirical models are formed by several types of models, developed mainly for practical applications. Despite the great conceptual difference among models in this category, all of them are characterised by the simplifications considered and the high level of empirical parameterization employed.

Eulerian models are used when transport of inert pollutant gases may be conveniently simulated through models that numerically solve the equations for conservation of the amount of movement and mass of the pollutant in the atmosphere. These models are normally included in weather forecast models. Advanced Eulerian models include refined submodels for the description of turbulence.

As an alternative to Eulerian models, the Lagrangian approach consists of describing fluid elements that follow the instantaneous flow. Lagrangian models use a certain number of fictitious particles to simulate the dynamic of a defined physical parameter. The movement of particles may be produced both by deterministic velocities and semi-random pseudo-velocities, generated by Monte Carlo processes.

Many air pollution models include modules to compute chemical transformations; they are named chemical models. The complexity of said modules goes from the simplest cases that consider only first order reactions (for example the transformation of sulphur dioxide into sulphates) to the most complicated cases of models that describe complex photochemical reactions. These chemical models may be implemented both in Lagrangian models and in Eulerian models. In Eulerian models, a three-dimensional mesh is built that covers the whole simulation domain, and all chemical reactions are simulated in each cell and in each time iteration. In Lagrangian models, a single cell (or column of cells) is computed according to wind direction.

Contrasting with dispersion models (that compute the contribution of one or several sources taking into account a given rate of emission and a given dispersion coefficient), receiver models take as their initial data measured values of concentrations in one or several points and try to correlate the concentrations values observed with the surrounding sources. This is done on the base of the knowledge of the chemical composition of sources and receiver materials.

Receiver models are based on equations of the balance of mass and are intrinsically statistical, insofar as they do not include a deterministic relation between emissions and concentrations.

Stochastic models are based on statistical or semi-empirical techniques, to analyse trends, periodicities and air quality relations and atmospheric measures and to forecast the evolution of episodes of pollution. Several techniques are used to reach that goal, such as, for example, analyses of distribution in frequency, analyses of time series, spectral analysis, etc. Stochastic models are limited because they do not establish cause-effect relations.

In an urban dimension, there may be a need to carry out two levels of modelling. The mesoscale level and the microscale level. In microscale modelling (typical length of 1 km), the air flow is very complex, depending strongly on the detailed characteristics of the surface (form and orientation of buildings, wind direction, etc.). On the other hand, thermal effects may also help generate these flows. They are mainly determined by aerodynamic effects (flow channels, roughness, etc.), thus they must be conveniently described through an appropriate simulation model. Due to the high level of complexity of these effects, dispersion phenomena at the local scale (normally associated with atmospheric microscale processes) are mainly described through simple models applied to specific situations such as “street canyons” and others.

In the numerical modelling of mesoscale pollutant dispersion (typical length between 1 km and 1000 km) flows depend on both effects previously described: aerodynamic effects (flow channels, roughness, etc.) and energetic balance surface heterogeneities (land characteristics, vegetation, water tables, etc.). Mesoscale atmospheric processes affect mainly the local/regional (local-to-regional) dispersion phenomena, of which urban studies are the most important example.

The minimum data needed for the typical operation of a mesoscale model are, as far as pollutant sources: location in geographic coordinates, emission rates of pollutants, height of occasional source or mesh, exit speed and temperature of emission gases from industrial sources, internal diameter of the chimney of the industrial source, dimension of buildings surrounding traffic sources, width of roads in traffic sources, size and speed of deposition of particles, meteorological data, wind direction and speed and parameters of the boundary layer (height of boundary layer and Monin-Obukhov height). Other meteorological data, concerning pollutant sources and topography, may and must be introduced, so as to optimise the simulation to obtain more real results. Background pollution may also be computed considering the concentration of pollutants not directly produced by sources that exist within the computation domain. The simulation may also take into account the daily or monthly profile of the road traffic flow, so as to consider variations in the number of vehicles throughout the day or month. In most of these models, once the sources are introduced, they may be viewed through a geographic information system. The processing of entry data by the software normally results, namely, in the average concentration of pollutants in a specific time lapse. These models compute the dispersion of pollutants and respective spatial and time concentrations by solving a given number of equations that, for example, in the case of the ADMS-Urban model (CERC, 2010), uses an advanced Gaussian approximation to simulate the elevation of the plume emitted by pollutant sources, also using a model based on two plumes to simulate the effect of buildings and, to compute the effect of complex topography, it uses the linearized Flowstar model.

In the case of ADMS-Urban, the distribution profile of concentrations is assumed as Gaussian plume with reflexions on the ground and on the inversion height, the concentration being given by (CERC, 2003b):

$$C = \frac{Q_S}{2\pi\sigma_y\sigma_z U} e^{-y^2/2\sigma_y^2} \left\{ e^{-(z-z_p)^2/2\sigma_z^2} + e^{-(z+z_p)^2/2\sigma_z^2} + e^{-(z+2h-z_p)^2/2\sigma_z^2} + \right.$$

$$\left. + e^{-(z-2h+z_p)^2/2\sigma_z^2} + e^{-(z-2h-z_p)^2/2\sigma_z^2} \right\} \tag{1}$$

where:

C is concentration (g/m^3)
Q_s is intensity of the source (g/s)
z is height above ground (m)
y is lateral distance at the centre of the plume (m)
Z_p is height of location of the source above ground (m)
U is wind speed at the height of the plume (m/s)
σ_y is horizontal dispersion of the plume (m)
σ_z is vertical dispersion of the plume (m)

In the case of the ADMS-Urban model, the Monin-Obukhov theory (Monin Obukov, 1954) is used to characterise the boundary layer of the atmosphere. The model uses the Monin-Obukhov length (L_{MO}) and the height of the planet boundary layer (h), allowing the variation of turbulence in height, the dispersion of the plume being a function of height (Collet, 1997). This method has the advantage of being based on physical experimental parameters. The Monin-Obukhov similarity theory (Monin Obukov, 1954) describes the statistical turbulent variables of the boundary layer according to a theory applied to the superficial layer, where vertical flows are deemed constant with height. The Monin-Obukhov length (m) represents the height of the boundary layer where the effects of mechanic turbulence are equal to the effects of convective turbulence (Holmes, 2006) and is defined by the following equation (CERC, 2002):

$$L_{MO} = \frac{-u_*^3}{kgF_{\theta_0} / (\rho c_p T_0)} \text{ (m)} \tag{2}$$

In which:

u_* - Speed of friction on the earth surface (m/s)
k - Von Karman Constant (0.4)
g - Gravity acceleration (m/s^2)
F_{θ_0} - Heat flow at the surface (W/m^2)
ρ - Volume mass of air (kg/m^3)
c_p - Specific air heat (J/(kg.K))
T_0 - Temperature at the ground surface (°C)

To study the dispersion of pollutants in some specific lanes, or that are critical for the impact of air quality on health, there may be a need to develop pollutant dispersion studies at the microscale level, namely important roads with a street canyon type geometry. This study becomes more important when those roads include buildings or activities associated with more sensitive groups such as children. In these situations, there is a need to carry out numerical microscale simulations, for purposes of analysis of the dispersion of PM inside the street canyons and their influence on air quality, studying the influence of the geometry of buildings and the configuration of roads, to see what their influence is on air quality.

For the numerical simulation of microscale dispersion, one may use several types of computation tools, an example of which is the commercial code Ansys Fluent 14.0 (Ansys Fluent, 2009). This computer code is a commercial software developed by Ansys Inc. for numerical modelling of fluid flow and heat transfer in complex geometries, widely used in microscale modelling of flows in mesh and urban roads of the street canyon type, as it allows great flexibility in meshes, solving problems in unstructured meshes, ideal to be used in complex geometries. The code is based on the resolution of discretized differential equations of mass balance, quantity of movement and other scales such as energy, turbulence, radiation, by the control volume computation method that is, dividing the domain into control volumes, which integrate the state equations, building algebraic equations for discretised dependent variables, such as speed, pressure, temperature and other scales. Discretised equations are linearized and the solution allows updating the values of dependent variables. Ansys Fluent solves mass conservation and quantity of movement equations and in the case of flows that involve heat transfer, chemical reactions or turbulence, the model also uses energy conservation equations, species conservation equations or additional transport equations, respectively (Ansys, 2009a). Hence, the domain being discretized in a finite number of control volumes, mass conservation, the quantity of movement, energy and species equations are solved in this set of control volumes. Partial differential equations are discretized in a system of algebraic equations and all algebraic equations are solved numerically so as to find the field of solutions (Ansys, 2009b).

$$\underbrace{\frac{\partial}{\partial t}\int_V \rho\phi \mathrm{d}V}_{\text{Não estacionário}} + \underbrace{\oint_A \rho\phi \mathbf{V}\cdot \mathbf{dA}}_{\text{Convecção}} = \underbrace{\oint_A \Gamma_\phi \nabla_\phi \cdot dA}_{\text{Difusão}} + \underbrace{\int_V S_\phi dV}_{\text{Geração}} \qquad (3)$$

Generically, the mass conservation equation is given by:

$$\frac{\partial \rho}{\partial t} + \nabla.(\rho\vec{v}) = S_m \qquad (4)$$

In which,

ρ - Specific mass (kg/m3)

t - Time (s)

$\vec{v}$ - Vector component of fluid speed

S_m - Mass source or well (kg/m3/s)

Likewise and generically the quantity of movement conservation equation may be given by:

$$\frac{\partial}{\partial t}(\rho\vec{v}) + \nabla \cdot (\rho\vec{v}\vec{v}) = -\nabla p + \nabla \cdot \left(\bar{\bar{\tau}}\right) + \rho\vec{g} + \vec{F} \qquad (5)$$

In which:

p - Static pressure (Pa)

$\bar{\bar{\tau}}$ - Viscous tensions tensioner

$\rho\vec{g}$ - Gravitational force

$\vec{F}$ - External force of source

In the study of street canyon dispersion, a basic and fundamental condition to study the dissipation of pollutants is the choice of the turbulence model. Turbulent flows are usually characterised by fluctuations in the field of speed that promote the mixture of the physical characteristics of flow, such as quantity of movement, energy and concentration of species, making them fluctuate too, which makes the simulation process very complex.

There are modified equations that simplify this process. However, in these equations, there are also variables that one must define and it is at this point that turbulence models arise (Reis, 2006, Vardoulakis et al., 2003, Zhiqiang et al., 2007). Although there is no model universally accepted for the simulation of turbulent flows, the choice of the turbulent model depends on the goal that one wishes to reach but also on computer limitations. In the case of wind flow in a street (study of the street canyon effect) one of the turbulence models mostly used is RANS k - ε, proposed by Launder and Spalding in 1972 (Launder and Spalding, 1972, Zanetti, 1993, Kim, 2004, Li et al., 2006).

In Ansys Fluent the k model – ε is available through the Standard model and two changes, the Renormalization-group (RNG) and the Realizable. The three models are similar using transport equations for turbulent kinetic energy (*k*) and for the turbulent dissipation rate (ε), differing as to the computation method for viscous turbulence, in the Prandtl number and the terms of generation and degradation in the equation ε. As common characteristics, we have the generation of turbulence, the cut tension, the effect of compressibility and modelling of heat and mass transfer. The characteristics that are altered in each submodel are transported equations, the computation method of turbulent viscosity and the constants of the model. The RNG and Realizable submodels have shown better performance than the standard model. The simplest submodel is model k – ε standard in which two transport equations are solved, one for k and another for ε. This model allows obtaining rather consistent results, saving time and resources. It is a semi-empirical model, in which equations are based on physical and empirical considerations (Kim, 2004). It is assumed in this submodel that the flow is turbulent and the effect of molecular viscosity is neglectable, making it viable only for totally turbulent flows. The RNG k - ε submodel, albeit similar to the standard sub-model, arose from this submodel using a complex mathematical statistical technique, called renormalization group theory (RNG), including the following items, which make this submodel more realistic and precise. This submodel consequently arises, also, from the instantaneous Navier-Stokes equations. The transport equations for RANS RNG k – ε are:

$$\frac{\partial}{\partial t}(\rho k)+\frac{\partial}{\partial x_i}(\rho k u_i)=\frac{\partial}{\partial x_j}\left(\alpha_k \mu_{eff}\frac{\partial k}{\partial x_j}\right)+G_k+G_b-\rho\varepsilon-Y_M+S_k \tag{6}$$

and

$$\frac{\partial}{\partial t}(\rho\varepsilon)+\frac{\partial}{\partial x_i}(\rho\varepsilon u_i)=\frac{\partial}{\partial x_j}\left(\alpha_\varepsilon \mu_{eff}\frac{\partial \varepsilon}{\partial x_j}\right)+C_{1\varepsilon}\frac{\varepsilon}{k}(G_k+C_{3\varepsilon}G_b)-C_{2\varepsilon}\rho\frac{\varepsilon^2}{k}-R_\varepsilon+S_\varepsilon \tag{7}$$

In which:
G_k – Rate of turbulent kinetic energy generation due to the average gradient of velocities
G_b – Rate of turbulent kinetic energy generation due to impulsion
Y_M - Contribution of dilatation dissipation
α_k - Inverse of the Prandtl number for k
α_ε - Inverse of the Prandtl number for ε
S_k, S_ε - Sources.

For the specific case of the dispersion of particles, it may be convenient or necessary to use a Lagrangian submodel of discrete phase, which not only solves transport equations for the continuous phase but also allows introducing a discrete phase through Lagrangian approximation. This phase consists of spherical particles dispersed in the continuous phase, the trajectories of such discrete-phase entities being computed as well as the heat and/or mass transfers to or from those entities. The coupling between both phases (discrete and continuous) as well as the interaction between both also considered. This Lagrangian approach presents an excellent simulation capacity, with lower computational costs (Zannetti, 1990). In these cases, modelling is done on the basis of the computation of the discrete phase trajectory using a Lagrange formulation that includes discrete phase inertia, aerodynamic resistance the force of gravity for stationary and non-stationary flows, considering the effects of turbulence on the dispersion of particles due to turbulent vortexes present in the continuous phase. This type of computation assumes that the discrete phase is diluted enough for particle-particle interactions and effects of the volume fraction of particles in the gaseous phase to be neglectable. In practice, these issues imply that the discrete phase must be present in a very low volume fraction, generally under 10% to 12%.

In the case of the commercial code Ansys Fluent, the trajectories of a discrete phase are simulated through the integration of force balances in the particle, written in a Lagrangian referential (Ansys, 2009). These force balance equations count inertia and forces acting on the particle, and may be written (for direction x in Cartesian coordinates) as:

$$\frac{du_p}{dt}=F_D\left(u-u_p\right)+\frac{g_x(I?_p-I?)}{I?_p}+F_x \tag{8}$$

In which $F_D\,(u-u_p)$ is the aerodynamic resistance force (Drag) per mass unit of the particle

$$F_D=\frac{18I?}{I?_p d_p^2}\,\frac{C_D\,Re}{24} \tag{9}$$

In which:
u - speed of continuous flow (m/s)
u_p - speed of particle (m/s)
μ - molecular viscosity of fluid (N·s/m^2)
ρ – specific mass of fluid (kg/m^3)
ρ_p – specific mass of the particle (kg/m^3)
d_p - particle diameter (m)
R_e – relative Reynolds number, defined as:

$$R_e = \frac{\rho d_p \mid u_p - u \mid}{\mu} \tag{10}$$

The aerodynamic resistance coefficient C_D is given by:

$$C_D = a_1 + \frac{a_2}{R_e} + \frac{a_3}{{R_e}^2} \tag{11}$$

In which a_1, a_2 and a_3 are constants that characterise the flow (Ansys, 2009b).

Exposition

In understanding the impact and for the study of the influence of PM on health, it is indispensable to know human exposition to that pollutant. Exposition to a given pollutant is a result of the time that the human being remains in a given level of concentration of a given pollutant. Thus a simplified way of computing the personal exposition (Δt) in a time lapse (t) may be estimated using equation (12) given by Brown et al. (1998) and Moschandreas and Saksena (2002):

$$E(\Delta t) = \int_0^t C(t)dt \cong \sum_i^n C_i t_i \tag{12}$$

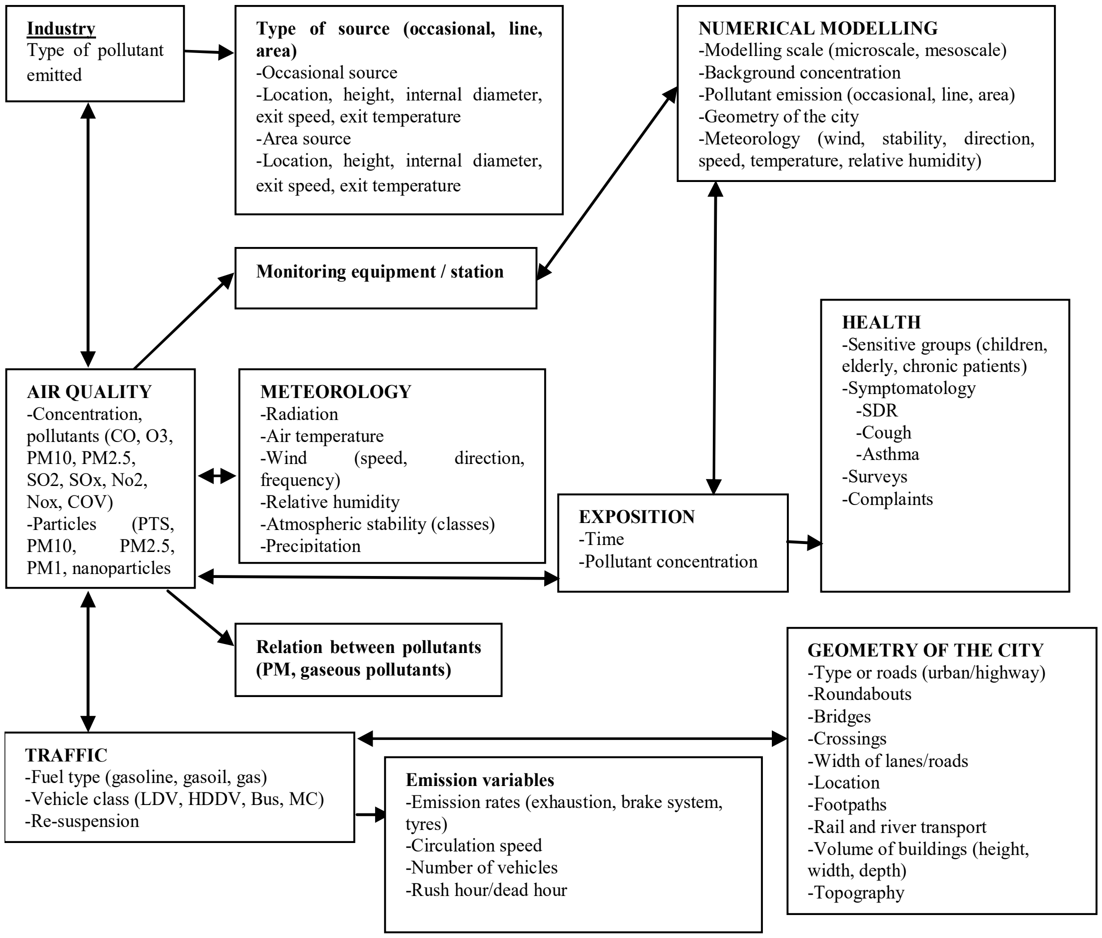

Figure 5. Detailed schema of variables.

In which:

$C(t)$ - concentration of pollutant (µg/m^3) in a time lapse t

C_i - discrete concentration in the cell i (µg/m^3)

t_i - time of exposition in the cell i (s)

n - number of cells of exposition.

To compute the exposition to particles in the urban domain a study must be discretized in a mesh with the adequate number of cells, the exposition of children (E) being computed in the corresponding cells considered.

General Interdisciplinarity

Having identified the important variables to be considered, Figure 5 shows the full scheme of variables presented identifying all interdisciplinary families and the connections between them.

SUMMARY AND CONCLUSION

An exhaustive and detailed description of the main variables to be considered in the study of air quality in urban environments and its impact on health was presented and developed, giving particular emphasis and detail to the specific case of PM.

The identified variables, allow framing, systematising, studying, relating and understanding the different and multidisciplinary aspects that contribute to air quality in urban environments and their influence in health, namely concerning children.

An important air quality characterization is fundamental and that depends on the available pollutant concentration data from air quality stations from the local, regional or national monitoring networks.

Also, to complement the measurement data it is important to produce numerical simulation work. To have enough details it should be used numerical simulations in different spatial scales, from global, regional-continental to local-regional, local and street canyon. This suggest to use different numerical models of dispersion and transport of pollutants in the atmosphere, in the same study. After obtaining a detailed characterisation of the air quality in the domain of the study, it is necessary to have an efficient methodology to evaluate the human exposition to the air pollutants.

This chapter also points the means or methods that can be used and the corresponding disciplinary groups to consider, pointing also some specific studies, proposed to be applied in this type of analysis, when the aim is to study the relation between air quality in an urban environment and their consequences to health.

The methodology presented here, with application to PM, one sees that the same principles with adaptations may apply the other pollutants such as NOx, CO and SO_2.

Also, the case was developed for the specific study of relationship between PM and children, but we can conclude that the same methodology can be applied to other population groups, like e elderly or people with chronic respiratory or cardiac diseases.

REFERENCES

Adachi K., Tainosho, Y. 2004. “Characterization of heavy metal particles embedded in tire dust”. *Environmental International 30*: 1009-1017.

Aga, E., Samoli, E., Touloumi, G., Anderson, H.R., Cadum, E., Forsbergz, B., Goodman, P., Goren, A., Kotesovec, F., Kriz, B., Macarol-Hiti, M., Medina, S., Paldy, A., Schindler, C., Sunyer, J., Tittanen, P., Wojtyniak, B., Zmirouzzz, D., Schwartz, J., Katsouyanni, K. 2003. “Short-term effects of ambient particles on mortality in the elderly: results from 28 cities in the APHEA2 project”. *European Respiratory Journal 21*: Suppl. 40, 28–33.

Alves, C., Scotto, M., Freitas, M. 2010. “Air pollution and emergency admissions for cardiorespiratory diseases in Lisbon (Portugal)”. *Química Nova 2*: 337-344.

Ansys, 2009a. ANSYS Fluent 12.0, Getting Started Guide. Ansys Fluent Guides.

Ansys, 2009b. ANSYS Fluent 12.0, Theory Guide. Ansys Fluent Guides.

ANSYS FLUENT, 2009. Manual, Chapter 4. Turbulence. ANSYS, Inc. January.

APHEIS. 2005. “Air Pollution and Health: a European Information System. Centro Nacional de Microbiologia”, *Boletin Epidemiologico Semanal. 13*, 97-108.

ApSimon, H.M., Gonzalez del Campo, M.T., Adams, H.S., (2000). “Modelling long-range transport of primary particulate material over Europe”. *Atmospheric Environment 35*: 343-352.

Ballester, F., Sáez, M., Pérez-Hoyos, S., Iñíguez, C., Gandarillas, A., Tobias, A., Bellido, J., Biggeri, A., Baccini, M., Bellini, P., Terracini, B. 2006. “Air pollution and cardiovascular admissions association in Spain: results within the EMECAS project”. *Journal of Epidemiological Community Health* 60(4): 328–336.

Borrego, C., Tchepel, O., Costa, A.M., Amorim, J.H., Miranda, A.I. 2003. “Emission and dispersion modelling of Lisbon air quality at local scale”. *Atmospheric Environment 37*, 5197– 5205.

Branis, M., Rezacová, P., Domasová, M. 2004. “The effect of outdoor air and indoor human activity on mass concentrations of PM10, PM2,5, PM1 in a classroom”. *Environmental Research, 99*: 143–149.

Brown, M.J., Muller, C., Bush, B., Stretz, P. 1998. “Exposure estimates using urban plume dispersion and traffic microsimulation models”. Proceedings of 10th Conference on Air Pollution Meteorology, Phoenix, AZ, USA, Jan. 10 - 15.

Camargo, C.A., Schatz, Jr. M. 2003. “The Relationship of Gender to Asthma Prevalence, Healthcare Utilization, and Medications in a Large Managed Care Organization”. *Academic Emergency Medicine, 10*: 508-538.

CCPA. 2001. Ambient Particulate Matter Chacterization Guidelines. Canadian Chemical Producer´s Association.

CERC. 2003, Guia do Utilizador do ADMS-Urban, Versão 2.0. Cambridge Environmental Research Consultants Ltd.

CERC 2002. Flowstar, Modelling Flow Over Complex Terrain. User Guide. Cambridge Environmental Research Consultants Ltd.

CERC 2003a ADMS-Urban User Guide, Version 2.0. Cambridge Environmental Research Consultants Ltd.

CERC 2003b. ADMS-Urban, Urban Air Quality Management System. User Guide. Cambridge Environmental Research Consultants Ltd.

Chan, A.T., William, T.W. A., Ellen, S.P. S. 2003. "Strategic guidelines for street canyon geometry to achieve sustainable street air quality—part II: multiple canopiesand canyons". *Atmospheric Environment 37*: 2761 – 2772.

Chen, Y., Sheen, P., Chen, E., Liu, Y., Wu, T., Yang, C.C. 2004. "Effects of Asian dust storm events on daily mortality in Taipei, Taiwan". *Environmental Research 95*: 151 - 155.

Ciccone, G., Forastiere, F., Agabiti, N., Biggeri, A., Bisanti, L., Chellini, E., Corbo, G., Dell'Orco, V., Dalmasso, P., Volante, T.F., Galassi, C., Piffer, S., Renzoni, E., Rusconi, F., Sestini, P., Viegi, G. 1998. "Road traffic and adverse respiratory effects in children. SIDRIA Collaborative Group". *Occupational Environmental Medicine 55*: 771 - 778.

Clancy, L., Goodman, P., Sinclair, H., Dockery, G.W. 2002. "Effect of air-pollution control on death rates in Dublin, Ireland: an intervention study". *The Lancet 360*, 1210–1214.

Clarke, R. W., Coull, B., Reinisch, U., Catalano, P., Killingsworth, C.R., Koutrakis, P., Kavouras, I., Murthy, G.G., Lawrence, J., Lovett, E., Wolfson, J.M., Verrier, R.L., Godleski, J.J. 2000. "Inhaled concentrated ambient particles are associated with hematologic and bronchoalveolar lavage changes in canines". *Environmental health perspectives 108*: 1179 – 1187.

Dominici, F. 2004. Time-Series Analysis of Air Pollution and Mortality: A Statistical Review. Health Effects Institute, Research Report 123.

E.E.A. 2005. Environment and Health. EEA report, Denmark – Copenhagen, No 10/2005.

E.E.A. 2011. Air Quality in Europe – 2011 report. EEA technical report, Denmark – Copenhagen, No 12/2011.

Eiguren-Fenandes, A., Shinyashiki, M., Schmitz, D.A., Di Stefano, E., Hinds, W., Kumagai, Y., Cho, A.K., Froines, J.R. 2010. "Redox and electrophilic properties of vapour and particle-phase components of ambient aerosols". *Environmental Research 10*: 207-212.

Fernandes, U., Costa, M. 2011. "Particle emissions from a domestic pellets-fired boiler". Fuel Processing Technology, doi:10.1016/j.fuproc. 2011.08.020.

Galán, I., Tobias, A., Banegas, J.R., Aranguez, E. 2003. "Short-term effects of air pollution on daily asthma emergency room admissions". *European Respiratory Journal 22*: 802–808.

Garcia, J.M., Teodoro, F., Cerdeira, R., Coelho, L.M.R., Carvalho, M.G. 2014. "A methodology to estimate PM10 outdoor urban concentrations using GLM". Proceedings of Air Quality 2014 - 9th International Conference on Air Quality - Science and Application, Garmisch-Partenkirchen, 24-28 March 2014.

Garcia, J., Cerdeira, R., Tavares, N., Coelho, L.M.R., Carvalho, M.G. 2013a. "Study of children exposure to Particulate Matter Indoor Air in School Classrooms", VII Mediterranean Congress of Climatization, Proceedings Book, pp 648-655, Istanbul, 3-4 October 2013.

Garcia, J., Cerdeira, R., Tavares, N., Coelho, L.M.R., Kumar, P., Carvalho, M.G. 2013b. "Influence of virtual changes in building configurations of a real street canyon on the dispersion of PM10", *Urban Climate* 5: 68-81.

Ghio, A. J., Kim, C., Devlin, R.B. 2000. "Concentrated ambient air particles induce mild pulmonary inflammation in healthy human volunteers". *American journal of respiratory and critical care medicine 162*: 981–988.

Hajat S., Haines A., Goubet S.A, Atkinson R.W., Anderson H.R. 1999. "Association of air pollution with daily GP respiratory consultations for asthma and other lower conditions in London". *Thorax 54*: 597-605.

Halliburton, B.W., Carras J.N., Nelson P.F. 2006. Fine particle emission from power stations. Techology assessment report 55. Cooperative Research Centre for Coal in Sustainable Development, QCAT Tecnology Transfer Centre.

Harrison, R.M., Yin, J.X. 2000. "Particulate matter in the atmosphere: which particle properties are important for its effects on health?". *Science of Total Environment 249*: 85-101

Hauser, R., Godleski, J.J., Hatch, V., Christiani, D.C. 2001. "Ultrafine particles in human lung macrophages". *Archives of Environmental Health*: 56, 150-156.

Heal, M.R., Kumar, P., Harrison, R.M. 2012. "Particles, Air Quality, Policy and Health". *Chemical Society Reviews 41*: 6606-6630.

Holmes, L. Morawska. 2006. "A review of dispersion modelling and its application to the dispersion of particles: An overview of different dispersion models available". *Atmospheric Environment 40*: 5902-5928.

Hunter, L.J., Johnson, G.T., Watson, I.D. 1992. "An investigation of three-dimensional characteristics of flow regimes within the urban canyon". *Atmospheric Environment 26B (4)*: 425–432.

Jalaludin B.B., O'Toole B.I., Leederd S.R. 2004. "Acute effects of urban ambient air pollution on respiratory symptoms, asthma medication use, and doctor visits for asthma in a cohort of Australian childrens". *Environmental Research 95*: 32–42.

Jeong, S.J., Andrews, M.J. 2002. "Application of the k-e turbulence model to the high Reynolds number skimming flow field of an urban street canyon". *Atmospheric Environment 36*: 1137 – 1145.

Jiménez E., C. Linares, L. Rodríguez, M. Bleda, J. Díaz. 2009. "Short-term impact of particulate matter (PM2,5) on daily mortality among the over-75 age group in Madrid (Spain)". *Science of the Total Environment 407*: 5486–5492.

Kemp K. 2002. "Trends and sources for heavy metals in urban atmosphere. Nuclear Instruments and Methods in Physics, Research Section B". *Beam Interactions with Materials and Atoms 189*: 227-232.

Kim J., Baik, 2004. "A numerical study of the effects of ambient wind direction on flow and dispersion in urban street canyons using the RNG k–ε turbulence model". *Atmospheric Environment 38*: 3039-3048.

Koenig J.Q., Mar T.F., Allen R.W., Jansen K., Lumley T., Sullivan J.H., Trenga C.A, Larson T.V., Liu J.S., 2005. "Pulmonary Effects of Indoor- and Outdoor-Generated Particles in Children with Asthma". *Environmental Health Perspectives 113*, no4 : 449-503.

Kumar, P., Morawska, L., Birmili, W., Paasonen, P., Hu, M., Kulmala, M., Harrison, R.M., Norford, L., Britter, R. 2014a. "Ultrafine particles in cities". *Environment International 66*: 1-10.

Kumar, P. 2014b. "A review of fundamental drivers governing the emissions, dispersion and exposure to vehicle-emitted nanoparticles at signalised traffic intersections". *Atmospheric Environment 97*: 316-331.

Laschober C., Limbeck A, Rendl J, Puxbaum H. 2004. "Particulate emissions from on-road vehicles in the Kaisermuhlen-tunnel (Vienna, Austria)". *Atmospheric Environment, 38*: 2187-2195

Launder B., Spalding, D. 1972. "Lectures in mathematical models of turbulence". Academic press, London, England.

Lazaridis M., Semb A., Larssen S., Hjellbrekke A.G., Hov O., Hanssen J.E., Schaug J., Torseth K. 2002. "Measurements of particulate matter within the framework of the European Monitoring and Evaluation Programme (EMEP) I. First results". *Science of Total Environment 285*: 209-235.

Li, X., C. Liu, D. Leung, K. Lam, 2006. "Recent progress in CFD modeling of wind field and pollutant transport in street canyons". *Atmospheric Environment, 40*: 5640-5668.

Loomis D. 2000. "Sizing up air pollution research". *Epidemiology 11*: 2-4.

Lough G.C., Schauer J.J., Park J.S., Shafer M.M., Deminter J.T., Weinstein J.P. 2005. "Emissions of metals associated with motor vehicle roadways". *Environmental Science Technology 39*: 826-836.

Manoli E., Voutsa D., Samara C. 2002. "Chemical characterization and source identification/apportionment of fine and coarse air particles in Thessaloniki, Greece". *Atmospheric Environment 36*: 949-961.

Martins, A., Cerqueira M., Ferreira F., Borrego C., Amorim J. H. 2009. "Lisbon air quality: evaluating traffic hot-spots". *International Journal Environment and Pollution, V39*, 374: 306-320.

Monin, A. Obukhov. 1954. "Basic laws of turbulent mixing in the ground layer of the atmosphere". Transboundary Geophysics Institute Akad. Nauk, USSR 151:163-187.

Morawska L, Zhang J. 2002. "Combustion sources of particles. 1. Health relevance and source signatures". *Chemosphere 49*: 1045-1058.

Moschandreas, J.,D., Saksena S. 2002. "Modelling exposure to particulate matter". *Chemosphere 49*: 1137–1150.

Nazridoust K. 2007. "Gaseous And Particulate Dispersion In Street Canyons". Department of Mechanical and Aeronautical Engineering, Clarkson University, Potsdam.

Nicholson, K.W., Branson J.R. 1990. "Factors affecting resuspension by road traffic". *Science of Total Environment 93*: 349-358.

Nightinghale, J. A., Maggs, R., Cullinan, P., Donnely, L.E., Rogers, D.F., Kinnersley, R., Chung, K.F., Barnes, P.J. Ashmore, M., Newman-Taylor, A. 2000. "Airway inflammation after controlled exposure to diesel exhaust particulates". *American journal of respiratory and critical care medicine, 162*: 161–166.

Oke, T.R., 1988. "Street design and urban canopy layer climate". *Energy and Buildings 11*: 103–113.

Owega S., Evans G.J., Jervis R.E., Fila M., D'Souza R., Khan B., 2004. “Long-range sources of Toronto particulate matter ($PM_{2.5}$) identified by Aerosol Laser Ablation Mass Spectrometry (LAMS)”. *Atmospheric Environment 38*: 5545-5553.

Peng R.D, Dominici F., Pastor-Barriuso R., Zeger S., Samet J.M. 2004. “Seasonal Analyses of Air Pollution and Mortality in 100 U.S. Cities”. *American Journal of Epidemiologhy 161(6)*: 585-594.

Peters A., Skorkovsky J., Kotesovec F., Brynda J., Spix C., Wichmann E., Heinrich J. 2000. “Associations between Mortality and Air Pollution in Central Europe”. *Environmental Health Perspectives 108*: 347–353.

Pio C.A., Castro L.M., Cerqueira M.A., Santos I.M., Belchior F., Salgueiro M.L. 1996. “Source assessment of particulate air pollutants measured at the southwest European coast”. *Atmospheric Environment 30*: 3309-3320.

Pohjola M, Kousa A, Aarnio P, Koskentalo T, Kukkonen J, Härkönen J, Karppinen A. 2000. “Meteorological Interpretation of Measured Urban PM2,5 and PM10 Concentrations in the Helsinki Metropolitan Area”. Longhurst JWS, Brebbia CA, Power H (eds.), Air Pollution VIII. Wessex Institute of Technology Press.

Pope, C. A., (2000). “What do epidemiologic findings tell us about health effects of environmental aerosols? ”. *Journal of Aerossol Medicine 13*: 335-354.

Putaud, J.P., Dingenen, R.V., Alustey, A., Raes, F., A. (2002). A European Aerosol Phenomenology: physical and chemical characteristics of particulate matter at kerbside, urban, rural and background sites in Europe. http://ies.jrc.cec.eu.int/Download/cc, Joint Research Centre, Ispry. Italy.

Reis, N., (2006). “Fundamentos da dispersão atmosférica”. Departamento de Engenharia Ambiental, Centro Tecnológico, UFES.

Ribeiro H., Cardoso M.R.A., (2003). “Air pollution and children’s health in São Paulo (1986–1998)”. *Social Science & Medicine 57*: 2013–2022.

Riddle A., Carruthers D., Sharpe A., McHugh C., Stocker J., (2003). “Comparisons between FLUENT and ADMS for atmospheric dispersion modelling”. *Atmospheric Environment 38(7)*: 1029-1038.

Rodriguez S., Querol X., Alastuey A., Viana M., Alarcon M., Mantilla E., Ruiz C.R., (2004). “Comparative PM10-PM2,5 source contribution study at rural, urban and industrial sites during PM episodes in Eastern Spain”. *Science of Total Environment 328*: 95-113.

Ruellan S, Cachier H., (2001). “Characterisation of fresh particulate vehicular exhausts near a Paris high flow road”. *Atmospheric Environment 35*: 453-468.

Salvi, S.S., Nordenhall, C., Blomberg, A., Rudell, B., Pourazar, J., Kelly, F.J., Wilson, S., Sandstrom, T., Holgate, S.T., Frew, A.J., (2000). “Acute exposure to diesel exhaust increases IL-8 and GRO-alpha production in healthy human airways”. *American journal of respiratory and critical care medicine 161*: 550–557.

Santiago J.L., Martín F., (2004). “Modelling the air flow in symmetric and asymetric street canyons”. Proceedings of the 9th Int. Conf. on Harmonisation within Atmospheric Dispersion Modelling for Regulatory Purposes. Garmisch-Partenkirchen, 24-28 March 2014.

Schwartz J., Laden F., Zanobetti A., (2002). "The Concentration–Response Relation between PM2,5 and Daily Deaths". *Environmental Health Perspectives 110*: 1025-1029.

Segala C., Fauroux B., Just J., Pascual L., Grimfeld, Neukirch F., (1998). "Short-term effect of winter air pollution on respiratory health of asthmatic children in Paris". *European Respiratory Journal 11*: 677–685.

Seinfeld J.H., Pandis S.N. 1998. "Atmospheric Chemistry and Physics: From Air Pollution to Climate Change". John Wiley & Sons, Inc., New York.

Slaughter J.C., Kim E., Sheppard L., Sullivan J.H., Larson T.V., Clainborn C. 2004. "Association between particulate matter and emergency room visits, hospital admissions and mortality in Spokane, Washington". *Journal of Exposure Analysis and Environmental Epidemiology*, 1–7.

Soto, K.F, Garza, K.M., Shi, Y., Murr, L.E. 2008. "Direct contact cytotoxicity assays for filter-collected, carbonaceous (soot) nanoparticles material and observations of lung cell response". *Atmospheric Environment 42*: 1970-1982.

Sternbeck J., Sjödin A., Andreasson K. 2002. "Metal emissions from road traffic and the influence of resuspension - results from two tunnel studies". *Atmospheric Environment 36*: 4735-4744.

Tang W., Huber A. 2006. "Application of CFD simulations for short-range atmospheric dispersion over open fields and within arrays of buildings". Proceedings of AMS 14th Joint Conference on the Applications of Air Pollution Meteorology with the A&WMA, Atlanta, GA, Jan 30 - Feb 2.

Timonen K.L., Pekkanen J. 1997. "Air Pollution and Respiratory Health among Children with Asthmatic or Cough Symptoms". *American Journal of Respiratory and Critical Care Medicine 156*: 546–552.

Vallius, M. 2005. Characteristics and sources of fine particulate matter in urban air. National Public Health Institute, Department of Environmental Health.

Van Dingenen R, Raes F, Putaud J, Baltensperger U, Charron A, Facchini M-, Decesari S, Fuzzi S, Gehrig R, Hansson H. 2004. "A European aerosol phenomenology 1: physical characteristics of particulate matter at kerbside, urban, rural and background sites in Europe". *Atmospheric Environment 38*: 2561-2577.

Vardoulakis, S., Bernard E.A. Fisher, KoulisPericleous, Norbert Gonzalez-Flesca, 2003. "Modelling air quality in street canyons: a review". *Atmospheric Environment 37*: 155-182.

Vincent A., Hackley, Chiara F., Ferraris, 2001. "The Use of Nomenclature in Dispersion Science and Technology", NIST Recommended Practice Guide, NIST, Special Publication 960-3.

Wellenius, G.A. Saldiva, P.H.N., Batalha, J.R.F., Murty G.G.K., Coull, B.A., Verrier, R.L., Godleski, J.J., 2002. "Exposure to residual oil fly ash (ROFA) particles exacerbates the effects of myocardial infarction in the rat". *Toxicological Science 66*: 327–335.

WHO. 2000. Evaluation and use of epidemiological evidence for environmental health risk assessment. WHO Regional Office for Europe.

WHO. 2003. Health Aspects of Air Pollution with Particulate Matter, Ozone and Nitrogen Dioxide. WHO Regional Office for Europe.

WHO. 2004. Outdoor air pollution: assessing the environmental burden of disease at national and local levels. WHO Regional Office for Europe.

WHO. 2005. Air quality guidelines - global update 2005. WHO Regional Office for Europe.

WHO. 2008. Update of WHO Air quality guidelines 2008. WHO Regional Office for Europe.

WHO. 2012. Health effects on black carbon. WHO Regional Office for Europe.

WHO. 2013. Outdoor air pollution a leading environmental cause of cancer deaths. International Agency for Research on Cancer (IARC), The Lancet Oncology online, http://www.iarc.fr/en/publications/books/sp161/index. php.

WHO. 2014. Burden of disease from Household Air Pollution for 2012. Public Health, Social and Environmental Determinants of Health Department, World Health Organization.

Zannetti, P. 1990. "Air pollution modelling". Van Nostrand Reinhold, New York.

Zhiqiang, Z., W. Zhang, Z. Zhang, C. Qingyan, (2007). "Evaluation of various turbulence models in predicting airflow and turbulence in enclosed environments by CFD: Part 1 summary of prevalent turbulence models". *HVAC & Refrigeration Research* 13: 871-886.

RR