Dissertation

The effects of compact urban development on air pollution

도시압축개발이 대기오염에 미치는 영향에 관한 연구

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Abstract

The influence of the compact city on sustainability is still not sufficiently verified. And especially there remains a room for debate on the relationship between the compact city and air pollution. Researchers, both for and against the compact city are hampered by the absence of cogent reasons to support the effects of changes in density on air pollution because they have not been taking into account ambient air pollution path which pollutants are dispersed or diluted in the air. This study aims to investigate the air pollutant concentration distribution brought about by cumulative of emission sources empirically and to explore the effects of urban compactness on air quality, along with an aspect of dispersion and thus to guide sustainable urban development from the perspective of the atmospheric environment.

One of the weak points of evaluating the effects of urban compactness on air pollution in planning literature is that it is still to approach short-sighted way. When taking into consideration that environmental damage from urban development is long-term and cumulative, air pollution problems should be analyzed as a time-series approach. A model accounting for intra- and inter-regional characteristics is required since changes in urban characteristics make a difference for air pollution and the scope of influence varies by time and spatial variability. Unique and unobservable properties of urban need to be employed as well because the advances in air pollution technologies and policies for air pollution mitigation can potentially influence air pollution in the mid- to long-term. The panel data model allows for optimal modeling results not only by regulating estimate errors that arise from the time-series process and regional unit data but also by giving proper

treatment to omitted unobservable variables that have a significant effect on air pollution difference econometrically.

This study attempted to identify that high-density development causes the spatial concentration of emission sources, which may result in increase of air pollution. The distribution of pollutant concentrations according to the distance from the CBD was conducted at the local level, at the metropolitan level, and at the interurban level. The results showed that the concentration distribution of air pollutants was high or low when getting closer to the CBD. In certain cases there are pollutants that had an even distribution depending on the distance from the CBD. PM10 emissions were concentrated in the CBD at the local level, while the opposite was true with PM10 at the metropolitan level. The distribution of O_3 concentrations was low in the CBD at the local and metropolitan level, while NO_2 and CO concentration values appeared high at the metropolitan level. With regards to the spatial distribution of pollution levels at the interurban level, the distribution of CO concentrations appeared significantly higher closer to the CBD but NO_2 concentrations had a low or an even distribution in the CBD. The pollution level distribution of PM10 was low in the CBD only from 2006 to 2008.

As a result, it cannot be determined that air pollution is aggravated by the spatial concentration of emission sources, suggesting that the pollution levels are influenced by the extent and magnitude of dispersion, which may vary according to urban characteristics and the diverse conditions they exist in. Therefore, there is a need to differentiate whether the emission sources are concentrated at the local or regional level and to establish air pollution control strategies appropriate for such conditions.

The main concern of this study was to investigate the effects of urban compactness on air pollution by controlling for factors which affect air quality.

The definition of urban compactness here encompasses the high-density built form with a proportion of green land within a standard spatial unit. Two meanings involved in this definition were presented as follows. High-density brings the spatial concentration of emission sources, which lead to an increase in pollution, while green land secured from high-density development can encourage dispersion and dilution, resulting in a reduction of air pollution. The relative magnitudes of opposing effects determine air quality. The panel data model showed that NO_2 and CO concentrations significantly increased with a rise in net density, while SO_2 and CO decreased with increase in proportion of green land and more importantly, green land was relatively more effective at decreasing CO compared to SO_2. Although the results are confined to only certain pollutants, urban compactness had two dimensions to air pollution. The dispersion and dilution of pollutants may hold the answer. The results suggest that high-density developments that secure enough green land can enlarge dispersion and contribute to reduced pollution levels. Meanwhile, PM10 and O_3 emission values were irrelevant to urban compactness and PM10 increased with population growth, implying that PM10 has a potential to increase as the urban size increases.

This study may offer a clue to the debate on whether the compact city improves air quality or not. A number of studies have not considered that air pollution concentrations are determined by the dispersion and dilution process varying with regard to time and space. Therefore, urban air pollution problems may not only require an understanding of spatial and temporal differences in urban characteristics but a comprehension of the dispersion mechanism, which undergoes complex diffusion in the atmosphere. It is imperative to develop an

integrated management system, which minimizes local-to citywide emissions and thus regulates total urban emissions. It is essential to set historical emission trends as it can be used to guide appropriate antipollution measures. Preferential controls and optional management strategies need to be followed to respond to changes in the pollution levels, especially the maximum concentration at a certain period.

Key words: *urban compactness, high-density development, green land, air pollution, dispersion, sustainability*

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Chapter 1: Introduction

1.1 Background and Objectives

The development and growth of urban areas is regarded as a significant cause of environmental degradation and resource depletion. Throughout the past few decades, developing countries have experienced rapid urban development while, Korea's urbanization rate has recently exceeded 90 percent. Urban sprawl is unavoidable and using valuable land without damaging sustainability is to be considered. Researchers, planners, and other stakeholders have discussed ways of managing the sprawl, which leads to loss of green spaces and to a rise in traffic and energy consumption. As a result, the compact city concept has put forward as a form of sustainable urban living.

The influence of the compact city on sustainability is still not sufficiently verified. Some studies have demonstrated positive effects by suggesting that high-density may be efficient for reducing energy consumption; however, there is still a room for debate as to whether it improves ambient air quality or not. In seeking to provide empirical data to advance the debate, one of the key problems researchers face is the task of measuring urban compactness. The compact city concept has been described from different perspectives, but it does not have a common definition. There have been differing measures on the compactness and an index of density was selected as a representative element of the compact city. Not only was the compact city unable to demonstrate that it is as sustainable as some of us believed, but previous studies have provoked controversy in terms of the effects of high-density on air pollution. Thought needs to be given to more practical measures that reflect compact-city attributes and the potential impact of compact development across an entire city.

Air pollution exists on all scales, from local to global and its impact continues over the mid- to long-term. Air pollution, which is caused by not only the natural environment limited to individual cities, but also by external properties in the areas surrounding cities, may be influenced by socio-economic activities such as production and consumption, land-use behavior, and urban structural characteristics. Most studies have mainly determined a correlation between urban structural characteristics and air pollution and these studies are bound to have contradictory results. Analyses of spatiotemporal changes in urban characteristics are rare and a certain study (Choi *et al*., 2007) experienced difficulties in identifying consistent factors that influence air pollution with time-series data.

There is a notable claim (Kim *et al*., 2009) that air pollution may be aggravated by the spatial concentration of emission sources and there is a need to verify it. One weak points of evaluating the impact of air pollution from the perspective of urban development is that such an approach is short-sighted. Researchers, both for and against the compact city are hampered by the absence of cogent reasons to support the effects of changes in density on air pollution because they have not been taking into account ambient air pollution path which pollutants are dispersed or diluted in the air.

This study attempts to explore the implications of urban compactness for air quality along with an aspect of atmospheric dispersion. Two principle research questions are addressed. First, does the spatial concentration of emission sources aggravate air pollution? Second, what is the cause of contradictory arguments about the relationship between the compact city and air pollution? The significance of these questions lies in their potential to inform land-use strategies to reduce air pollution. Specifically, this study has three objectives: 1) to reveal the relationship between the spatial concentration of emission sources and air pollution distribution, 2) to investigate the effects of urban compactness on air pollution in consideration of spatiotemporal differences in urban characteristics, 3) and thus to propose strategies that guide sustainable urban development from the perspective of the atmospheric environment.

1.2 Organization

This thesis is organized into five chapters. Chapter 2 reviews literature on the compact city concept which has been defined by many authors and planners, but there are inherent difficulties in finding an accurate index of urban compactness. It also describes the relationship between high-density and air pollution, and the atmospheric dispersion mechanism of pollutants. Chapter 3 presents new evidence in regards to whether the spatial concentration of air pollution sources worsen air quality and examines the concentration distribution of pollutants according to the distance from the Central Business District (CBD) at the local level, at the metropolitan level, and at the interurban level. Chapter 4 provides a definition of urban compactness that has been the subject of argument for years, and investigates the effects of compactness on air pollution through balanced panel data recorded in 17 cities from 1996 to 2009. Chapter 5 outlines implications and recommendations to guide sustainable urban development from the perspective of atmospheric environment (Figure 1.1).

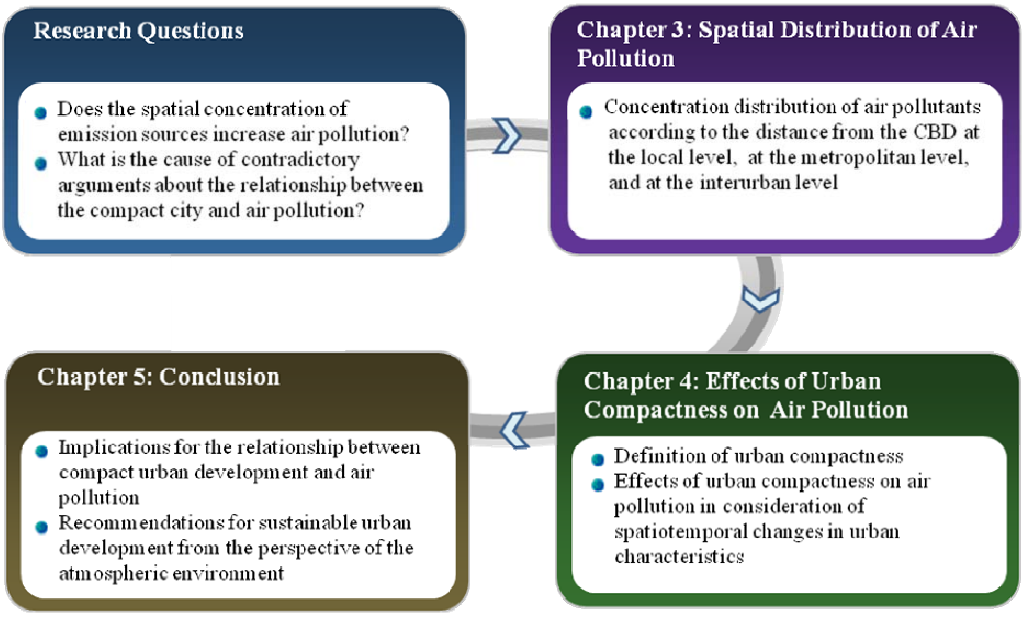

Figure 1.1 Research framework

Chapter 2: Literature Review

2.1 Sustainable Urban Form: the Compact City Debate

2.1.1 Concept of Compact City

Urban planning evolved throughout the twentieth century, leading to a great variety of urban forms that often had little regard for their impacts upon the environment (Ardeshiri and Ardeshiri, 2011). As the rapid growth of world population and its concentration in cities around the globe takes place, sustainable urban development has constituted a crucial affecting the long-term outlook of humanity (Auclair, 1997). Sustainability has been incorporated in urban planning theory through the promotion of a ‘compact city’ model for urban growth rather than ‘dispersed city’. There remains a debate about which urban form encourages a more sustainable urban living and it is difficult to distinguish different degrees of compactness and sprawl.

The compact city theory (Dantzig and Saaty, 1973; Elkin *et al*, 1991; Girardet, 1992) has been developed as a form of sustainable city and the concept was seen as an approach that could end ‘the evil of urban sprawl’ (Beatley, 1995). The compact city is considered to be effective in restraining urban sprawl by intensifying activity density in urban areas and providing diverse services through mixed land use, and by revitalizing old urban areas and preserving rural areas by promoting infill development (Lin and Yang, 2006).

Promotion of the compact city-in terms of higher density development, mixed uses, and reuse of brownfield land-is now enshrined land use planning policy in many countries, including the United Kingdom (DoE, 1994; DETR, 1998a; 1999). Also in Norway, resistance against the dominance of the compact city has been modest (Skjeggedal *et al*., 2003). However, interpretations of the compact city differ according to the specific nature of the arguments either in its favor or against it. The compact city can be defined in an abstract sense: for example, in the case of Thomas and Cousin's 'virtual city' (1996) or Green's 'social city region' (1996). Another abstract in interpretation of the compact city is the idea of the 'autonomous city', as espoused by Scoffham and Vale (1996). Higher densities are seen to be an essential component of the 'walkable city' antidote to the car-dependent, sprawling city in the USA (Calthorpe, 1993; Duany and Plater-Zyberk, 1991).

The compact city was defined as high-density and monocentric development (Gordon and Richardson, 1997) and as some concentration of employment and housing, as well as some mixture of land uses (Ewing, 1997). Anderson *et al*. (1996) defined both monocentric and polycentric forms as being compact. Lock's (1995) definition of the compact city as a process of ensuring "[..] that we make the fullest use of land that is already urbanized, before taking green fields"; Naess' (1993) definition of encouraging development to where 'technical encroachments on nature have already taken place' typify the approach of the compact city advocate. There are claims more than just environmental benefits can be gained from intensifying urban areas; in fact "higher density settlements are argued to be more socially sustainable because local facilities and services can be maintained, due to high population densities, and therefore accessibility to goods and services is more equitably distributed" (Williams, 1999).

Burton (2000; 2002) identified three main aspects of the compact city: the high-density city, the mixed-use city, and the intensified city. The previous two concepts are related to 'product (form of the compact city)' and the intensified city is related to 'process' of making the city more compact.

The high-density city is the most common interpretation (Elkin *et al*., 1991; McLaren, 1992) and density is considered in terms of population density. The reason is as stated by Breheny (2001), "at the core of the whole urban renaissance and compaction debate [...] has been the question of residential density; protagonists see higher residential density as a necessary component of a compaction policy". High population density is arguably critical to support public transport and to provide adequate demand to make local facilities and services viable (Burton, 2002). Population density is also found closely related to social vitality of the city. Moreover, it is claimed to be one of the pathogens for many social-environmental diseases like overcrowding, urban waste generation and noise (Cadman and Payne, 1990).

The mixed-use city is another key component of sustainability (DETR, 1998a; 1998b; DETR and CABE, 2000) and is interpreted from three different perspectives. Firstly, proponents of the compact city envisage a city well served by facilities, with a balance of residential and nonresidential land uses (Burton, 2002). Secondly, the horizontal mix of uses refers to the mix of uses within streets or neighborhoods, where individual developments of different uses sit side by side (DETR and CABE, 2000). It is argued that the local provision of services and facilities reduces the need to travel by car (Elkin *et al*, 1991). Finally, the vertical mix of uses refers to the mix of uses within individual buildings, with different uses often on separate floors. It supports mixed residential and commercial developments (Goodchild, 1994).

The intensified city is a city that has experienced compaction process. Intensification is a generic term for the process of making cities more compact, and may be considered in terms of three main phenomena: an increase in population, an increase in development, and an increase in the mix of uses within the city boundary (Burton, 2002). This aspect is critical because an exclusive and comprehensive theory to measure compactness has not been accomplished yet. Thus, "[..] more compact cities can only be achieved through a process of making existing cities more dense, of encouraging more people to live in urban areas, and of building at higher densities" (Williams *et al*., 1996). The different aspects of intensification together with key components of urban compactness identified through literatures are discussed below (Table 2.1).

The concept of the compact city has been described with different perspectives, however, the concept does not have a common definition, and it is still contentious issue in the urban development literatures. Merely, the compact city concept encompasses the concentration of development.

Table 2.1 Key aspects of urban compactness

Product (Form of the compact city)	Process (how end product can be achieved)
Density	*Intensification*
Gross density (high average density of populations) Net density (high density of built form)	Increase in population (reorganization) : subdivisions and conversions, reuse of empty buildings Increase in development: development on vacant or derelict open land, redevelopment at higher densities, extensions to existing property
Mix of uses	*Increase in the intensity/mix of uses*
Varied and plentiful supply of facilities Balance of residential land uses Horizontal mix of uses: mixed districts and mixed streets, Vertical mix of use: mixed residential and commercial development	Creation of new mixed-use settlements and neighborhoods Inclusion of facilities in new housing developments Strengthening of district centers sitting of commercial / retail development in residential areas Increase in housing in city centers: conversion of empty office space

Summarized from: Burton (2002)

2.1.2 Measurement of Urban Compactness

There still remain many questions surrounding exactly *how compact* the compact city should be, and to what extends beyond a simple population density increase in the urban development. Scoffham and Vale (1996) argued that it is highly important to ask these questions about what the compact city is; whether buildings should be brought closer together; whether the number of people living in buildings should be increased; whether it is dwelling density or activity density that needs to be ‘compacted’; and what role a mix of urban uses has in the compact city debate. According to Pratt and Larkham (1996) "One of the key problems with the compact city hypothesis is that it brings very diverse concepts together under a potentially misleading banner. Moreover, these concepts vary from polemics based on rather utopian ideologies through to minutely detail empirical research."

The compact city suggests a variety of norms including urban density over decentralization, open space protection over completed built up areas, mixed land uses over Euclidian zoning, vital downtowns and central business districts containing high percentage of residential uses over strictly commercial spaces, and high use of public transit over individual transportation (Marcotullio, 2001). Bertaud and Malpezzi (1999) developed a compactness index, rho-the ratio between the average distance from home to central business district (CBD), and its counterpart in a hypothesized cylindrical city with equal distribution of development. Galster *et al.* (2001) described compactness as the degree to which development is clustered and minimizes the amount of the land developed in each square mile.

The so-called compact city concept, in general is employed the high-density city. It was measured as gross density or residential density (the number of people within residential area) that has been associated with travel behavior (Newman and Kenworthy, 1989; Barrett, 1996; Stone, 2008). This fails to reflect the new development or the cumulative effects of development across the town or city as a whole. Gross densities can be misleading, especially where the boundary of the district does not coincide with the boundary of the urban area and reveal little about the density of the built-up parts of a city. Certain arguments relate more to the density of built environment (that is, how built up an area is) that affects the loss of open or rural land (Burton, 2002). Burton (2000) measured that high-density built form with a high proportion of the land surface covered by buildings and other artificial structures and surfaces. The density of the built-up area may not reflect the density at which people actually live: if much of the built-up area is given over to nonresidential land uses than the area may appear to be relatively low density even through residents are living at high densities (Burton, 2002).

A city with dense development within large areas of open space may appear to be low density on the basis of gross measures (Sherlock, 1991). The Department of Environment, Transport and the Regions (DETR, 1998c) found that significant land savings can be made by avoiding development below densities of about 20 dwellings per hectare. The UK government uses on aspect of compactness-the proportion of new housing on brownfield land-as the purpose of achieving sustainability (DETR, 1998b) and good urban design (DETR and CABE, 2000). Three aspects such as residential density, employment density, and building density were considered in China (Lin and Yang, 2006). Net population density, namely non-agricultural population density in built-up area of the city is employed for measuring urban compactness (Chen e*t al*., 2008). Researches on the compact city in Korea described gross density (Lee and Kim, 2002; Kim *et al*., 2009) or urbanized density (people per sq.km) (Choi *et al*., 2007).

Tsai (2005) developed a set of quantitative variables to characterize urban forms at the metropolitan level and in particular, to distinguish compactness from sprawl. There are two variables such as population and population density to measure urban form. Although land area might better characterize urban size, population is more sensible in practical application since it is not affected by land consumption per capita, which is related to the density; that is, in a statistical description, population is theoretically independent from density, but land area is not. Density measures overall activity intensity and is the most commonly used variable in characterizing urban form as well as intensity-based compactness. However, undeveloped sub-areas (such as rivers, mountains) may be excluded in calculating urban form variables because the inconsistency of urban boundaries may bias the variables. Nam *et al*. (2012) referred that indicators such as population size and gross density correspond to urban size and intensity.

Despite various measurements of urban compactness, there is no technical or professional agreement on how best to measure density, and that few planners are comfortable in distinguish between net and gross residential density, or overall town density (Lock, 1995).

2.1.3 Socio-Economic and Environmental Conflicts in the Compact City

Over the past decades, cities have been seen as the sources of environmental degradation and resource depletion (Breheny, 1992; Jenks *et al*., 1996; Williams *et al*., 2000). Urban sprawl in particular is apparent in developed countries and is increasing in core cities of developing countries (Burgess, 2000; Chen *et al.*, 2008), and it leads to loss of natural landscape and to an increased energy consumption (EEA, 2006). In an urban area that undergoes sprawl the overall emissions increase owing to enhanced vehicle kilometers (De Ridder *et al*., 2008). Those problems cause stakeholders to become more concerned than ever about the environmental issues. In the early and mid-1990s, a widespread consensus began to develop that urban compaction is the greatest planning strategy to achieve a sustainable development. The compact city concept became “[..] so dominant that it seems inconceivable that anyone would oppose the current tide of the opinion towards promoting greater sustainable development and the compact city in particular" (Smyth, 1996).

The debate on the compact city concept was heating up when studies have been shown that the benefits expected from the implementation of compact policies did not happen as it was claimed. Empirical experiences in some cities in Britain demonstrated that after ten years since the intensification, no reduction of cars used has been proved, and other problems showed up, like the increase of pollution in the city centers due to the higher density and traffic. "[..] there is an evidence which suggests that these claims are at the very least romantic and dangerous, and do not reflect the hard reality of economic demands, environmental sustainability and social expectations' (Thomas and Cousins, 1996). As a result of the increased uncertainty surrounding the compact city concept, a critique can be developed, focused on the compact city hypothesis's veracity (whether compaction actually delivers the environmental, social, and economic benefits that it is supposed to); feasibility (whether compaction defies the market and can be properly implemented); and acceptability (whether urban compaction will lead to a political backlash from local residents) (Breheny, 1997).

The compact city concept, in favor of high-density appeared to have environmental, social, and fiscal advantages. Many believe that a compact form of cities decreases the need for travel and the frequency of car trips, by provoking shorter journeys (Breheny, 1996; Thomas and Cousins, 1996; Ferguson and Woods, 2010) and better public transport services, the re-use infrastructure and previously developed land (Thomas and Cousins, 1996). High-density development can preserve farmland and green fields in rural areas (Jenks *et al*., 1996; Thomas and Cousins, 1996; Gordon and Richardson, 1997; Williams *et al*., 2000; Burton, 2002). Some studies concluded that the compact city reduces less car dependency, and hence fuel consumption and emissions, and encourages walking and cycling (Breheny, 1992; Hillman, 1996; Thomas and Cousins, 1996; Burton, 2000; Chen *et al.*, 2008). Further, agricultural landowners have enlisted in the compact city policies as a way to preciously guard their resource (Beatley, 2000). However, Garcia and Riera (2003) claimed that “[..] there seems to be no conclusive evidence clearly supporting the view that compact cities better accomplish certain environmental goals”.

There are those who argued against the process of urban compaction on the ground that higher density led to traffic congestion, greater local air pollution, more crime, noise, and overcrowding (Breheny, 2001; Tony, 1996; Rudlin and Falk, 1999) and decrease in the amount of green and open space (Frey, 1999; Burton, 2000; Lin and Yang; 2006). Gordon and Richardson (1997) and Brueckner (2000) argued that shortening the average travel distance in compact cities may not result in decreased automobile usage and vehicle kilometers traveled. They contended that despite the decreased distance under the 'compact city' urban form, the frequency of automobile trips could increase traffic congestion and, thus, energy consumption.

Some suggested that while mixed-use development, a crucial aspect of the compact city, reduces vehicle trip rates, this can be in widely varying degrees – as increased walk-trips in mixed-use neighborhoods often supplement, rather than replace, auto trips (Handy, 1992; Ewing *et al.*, 1994; Frank and Pivo, 1994). Other claimed benefits and problems of compact cities are well documented (Table 2.2).

Table 2.2 Benefits and shortcomings of urban compactness

Socio-economic and environmental benefits	Socio-economic and environmental shortcomings
Protecting the countryside and reduce land occupation by building	Higher urban density implies heavy exploit of urban green or open space for development
Limit travel distance, reduce emission and greenhouse gases	Overcrowding in compact neighborhood may result in habitants escape to suburban area and cause decentralization
Less car dependence, less fuel consumption for traffic, encourage public transport	Heavy traffic volume, increase travel time more fuel consumption, and bad air quality
Increase open space and green space on ground	Noise, poverty, and crime
Compact residential built form help to reduce heating loads in winter because of less exposed wall area and no heat-loss roof or floor	Compact building are normally high-rise blocks, which discourage community life and personal communication
Promote economics of scales, encourage facilities like hospitals, schools, and libraries	High-density building may affect energy demand for domestic services such as lighting, ventilation, and refrigeration

Summarized from: Newman and Kenworthy (1989), Pacione (1989), Katz (1991), ECOTEC (1993), Calthorpe (1993), Hillman (1996), Thomas and Cousins (1996), Breheny (1996), Burton *et al*. (1996), Rudline and Falk (1999), Schiller and Evans (2000), Burton (2000),Travers (2001)
Adapted from: Burton (2002)

2.1.4 Disputes on the Effects of High-density on Air Pollution

Urban air pollution has been recognized as a serious social issue as urbanization and related problems start gaining an increasing attention. Boubel *et al*. (1994) stated that during last few decades people were experiencing a shift in nature of air pollution from spatially localized issue to much wider and ubiquitous phenomenon. Air pollution has taken an increasingly important role in new urban development planning and addressing problems of existing metropolitan area (Marques and Smith, 1999). Despite trends in transition of the air pollution problems, each country, region, and area has different problems attributed by their degree of development and urban characteristics.

Air quality modeling has been performed in most cities (Karppinen *et al.*, 2000; Leksmono *et al.*, 2006; Slini *et al.*, 2006; Mensink *et al.*, 2008) and main emission sources (cars, energy, etc) have been determined. After the framework integrating land usage, traffic, and airshed has been established in the late 1990s (Newton, 1997; Marquez & Smith, 1999), it started to expand researches on evaluating the influence of urban structural characteristics or travel behavior on air quality. Previous studies mostly have been dealt with the relationship between density and transportation, and energy efficiency, but they had difficulties in verifying the effects of change in density on air pollution.

There are disputes on the effects of high-density on air pollution. Supporters of the compact city theory assert that high-density development can result in less car dependency, reduced energy consumption, and low emissions via a decrease in distance traveled and an increase in household density (Thomas and Cousins, 1996; Frank *et al*, 2000; EPA, 2001; Borrego *et al.*, 2006; Stone *et al.*, 2007; Stone, 2008). Specifically, Stone (2008) demonstrated that large metropolitan regions ranking highly on a quantitative index of sprawl experience a greater number of O_3 exceedances than more spatially compact metropolitan regions. The significant association of NO_x and VOCs suggests that urban spatial structure plays a role O_3 formation through its effects on O_3 precursor emissions from transportation, industry, and power generation facilities. Vehicle emissions of CO, NO_x, and VOCs were found to exhibit a significant negative relationship with household and employment density when controlling for household size, income, and vehicle ownership (Frank *et al*., 2000).

Opponents contend that high-density development concentrates many activities in a limited space, usually causing increased air pollution (van der Waals, 2000). Higher density rather led to traffic congestion and greater local air pollution (Tony, 1996; Rudlin and Falk, 1999; Breheny, 2001). Large cities pollute more and generate more environmental damage that medium-sized ones; higher levels of production, linked to increasing physical urban size, are likely to mean a higher pollution density in Italian cities (Capello and Camagni, 2000). There are also claims that compactness has no statistical relation to SO_2 per built-up area (Chen *et al.*, 2008).

Recent studies from the Korea described that increase in population density reduces energy consumption (Ahn, 2000; Lee and Kim, 2002, Nam *et al*., 2008; Kim *et al*., 2009), but it has positive correlation with air pollution (Oh *et al*., 2006, Kim *et al*., 2009**)**. Meanwhile, it was reported that population density has negative correlation with NO_2 and PM10 (Oh and Jeong, 2007). Kim *et al* (2009) stated that increase of development density results in concentrating most of emission sources including vehicles, and then aggravates air pollution. Its impact was shown to be greater than the amount of reduction in pollution level caused by increased density. On the other hand, after simulating the impact of urban sprawl on air quality, the total amount of daily passenger traffic kilometers increased by 16.7 %, while emissions of pollutants (CO, PM10, and nitrogen oxides) increased by approximately 12%. This is less than the increase in total traffic kilometers because other sources than traffic also contributed to the total emission (De Ridder *et al*., 2008).

There is a need to verify a debate on whether concentration or decentralization of emission sources may aggravate air pollution

2.2 Air Pollutants and Atmospheric Dispersion

2.2.1 Major Pollutants and Source Emissions

The air pollutants can be divided into two groups: the classical major air pollutants (e.g., sulfur dioxide gas, nitrogen dioxide, carbon monoxide, ozone, and particulate matter) and the hazardous air pollutants (e.g., benzene, formaldehyde, etc), which are generally present in the atmosphere in much smaller concentrations than the major air pollutants. The major air pollutants will be discussed here only.

Sulfur dioxide gas (SO_2) is the primary air pollutants that emitted directly from sources. The emission is associated with sulphur in fossil fuels and it can be successfully reduced using fuels with low sulphur content (e.g., natural gas or oil) instead of coal (Fenger, 1999). Nitrogen dioxide (NO_2) is formed by oxidation of atmospheric nitrogen during combustion. The emission can be reduced by optimization of the combustion process in power plants and in motor vehicles or by means of catalytic converters in the exhaust. Carbon monoxide (CO) is the result of incomplete combustion with vehicles and industrial facilities. The emission can be reduced by increasing the air/fuel ration, but with the risk of increasing the formation of nitrogen oxide. Most effective reductions are carried out with catalytic converters (Fenger, 1999). Ozone (O_3) is a pervasive and relatively long-lived pollutant, and then winds can transport O_3 for hundreds of miles. It is not usually emitted directly into the air, but at ground level is created by photochemical reaction of the primary pollutants such as oxides of nitrogen (NO_x) and volatile organic compounds (VOC_S), so it is called a secondary pollutant. The main emission source has not been known, but O_3 can only be regulated via the primary pollutants. PM10, or Particulate Matter, is a mixture of microscopic solids and liquid droplets suspended in air. PM10 is characterized by size: particles less than 10 micrometers in diameter (PM10) and particles less than 2.5 micrometers in diameter (PM 2.5) are referred to as fine particles. PM10 is a secondary pollutant that is formed through chemical reactions of the primary pollutants and may also from gases that have been previously emitted (Vallero, 2008). They have two-type sources: the natural sources and the anthropogenic sources. Emissions in the air from the largest natural sources are from wind-blown dust, volcanoes, and forest fires, debris from live and decaying plants, and so on. It may be emitted directly to the air from the burning of fossil fuels in vehicles, power plants, factories, and wind-blown dust from construction sites. The amount of smaller particles has increased (Tuch *et al*., 1997), but the particles of anthropogenic origin can be reduced by use of cleaner fuels, better combustion techniques and a series of filtration (Fenger, 1999).

Emission of air pollutants is mainly caused by different anthropogenic processes which can be categorized into the source groups such as motor traffic, industry, power plants, trade, and domestic fuel (Mayer, 1999). Table 2.3 indicates the typical relative importance of emission source categories for the pollutants excluding O_3.

Table 2.3 Main emission sources and pollutants in commercial non industrial cities

Source category			Pollutant			
			SO_2	NO_2	CO	TSP
Power generation (Fossil fuel)			xx	x	x	
Space heating	-	Coal	xx	x	xx	xx
	-	Oil	xx	x		
	-	Wood				xx
Traffic	-	Gasoline		xx	xxx	
	-	Diesel	x	xx		xx
Industry			x		x	x

Note: 1. relative importance of emission sources. x: 5-25%, xx: 25-50%, xxx: More than 50%

2. TSP is referred as total suspended particulates

Source from: Stanner and Bourdeau (1995)

2.2.2 Ambient Air Pollution Path and Characteristics of Dispersion

Emitted air pollutants dispersed and diluted in the atmosphere (Lyons and Scott, 1990) and moved freely by the flow of air (Figure 2.1). There is also chemical reaction, depending on ambient weather condition because they are influenced by shortwave radiation, air temperature, and air humidity. Dispersion and dilution of air pollutants are strongly influenced by meteorological condition, especially wind direction, wind speed, turbulence, and atmospheric stability. Topographical siting and urban structures have a great effect on these meteorological parameters (Mayer, 1999).

The importance of pollutant dispersion was recognized already with the invention of chimneys (Brimblecombe, 1987), and the dispersion mechanisms have received special interest with the increasing urban traffic in built-up areas (Fenger, 1999). Dispersion and dilution process result in ambient air pollution which shows concentrations of different substances varying with regard to time and space (Mayer, 1999). The temporal variability of air pollutants can be generally characterized by time courses and by trends. The spatial variability of air pollutants is pronounced if they are emitted or produced near the ground level, i.e., especially for emissions from motor traffic (Mayer and Haustein, 1994).

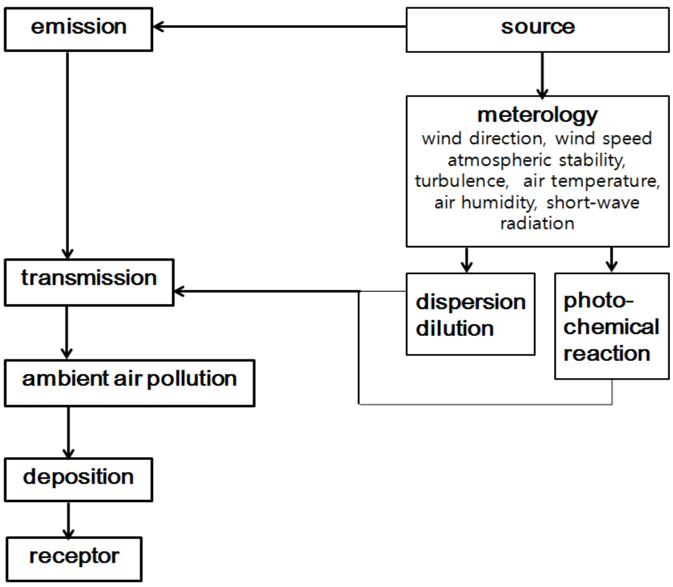

Figure 2.1 Schematic illustration of the ambient air pollution path
Adapted from: Mayer (1999)

The characteristics of dispersion are classified by the size of the urban (Britter and Hanna, 2003). At the neighborhood scale (up to 1 – 2 km) the increased turbulence levels within the urban canopy (over those occurring in the absence of obstacles) (Figure 2.2) produce larger dispersion coefficients that tend to reduce concentrations. However, the accompanying reduction in the advection velocity within the canopy tends to increase concentrations. The relative magnitudes of these opposing effects determine whether the obstacles lead to increased or decreased concentrations as the roughness is increased (Davidson *et al*., 1995; Macdonald *et al*., 1997, 1998). The Kit Fox field experiments (Hanna and Chang, 2001) showed clear evidence of substantial reductions in ground-level concentrations from a ground-level source for conditions in which the plume centroid was comparable to or smaller than the obstacle heights.

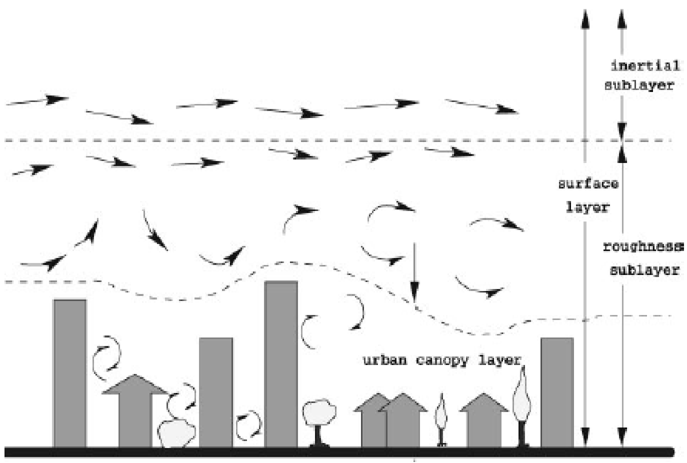

Figure 2.2 Schematic illustration of the air flow through and over an area
Adapted from: Grimmond and Oke (2002), *Sources from*: Britter and Hanna (2003)

At the urban scale (up to 10 -20 km) the variations in flow and dispersion around individual buildings or groups of similar buildings have been mostly averaged out. Most of the mass of any pollutant cloud traveling over this distance will be above the height of the buildings (Britter and Hanna, 2003). Larger surface roughness produces a significant increase in turbulence levels, and these lead to greater dilution of a plume and reduced concentrations downwind (Hanna *et al*., 1982; Robert *et al*., 1994).

The regional scale (up to 100 – 200 km) is affected by the urban area and the urban plume is observed to extend downwind of urban areas. A complex mix of pollutants is present, and there are likely to be chemical reactions and gas-to-particle conversions. The sides of the urban plume generally grow at a rate of approximately 0.5 m/s, and the maximum vertical extent of the plume is the daytime mixing depth, usually at a height of 500-1000 m. In the urban plume at night, the near-surface layer may be relatively pollutant free and stable over downwind rural surfaces, whereas the air aloft (heights of 100 m or more) may be well mixed and polluted (Britter and Hanna, 2003). Observations by satellites, aircraft, and surface monitors have shown that the urban plume can sometimes be detected several hundred kilometers downwind of the urban area and may have a width of 100 or 200 km (White *et al*., 1983).

2.2.3 Evidence on the Dispersion and Dilution of Air Pollutants

The transport and dispersion of pollutants over the urban area is altered as a result of increased mechanical turbulence caused by the relatively large obstacles (building and other structures) over which the pollutants must travel. The urban heat island causes boundary layer over an urban area to become more unstable as thermal turbulence increases (Britter and Hanna, 2003). Both of these effects enhance dispersion. Clarke *et al* (1978) reported that during the night the turbulence over the residential and commercial surfaces is approximately twice that over the rural surface. During the day the difference is less, approximately 20% or 30%. These diurnal differences are expected because at night the roughness obstacles not only generate more turbulence, but also force the atmosphere to be less stable. In addition, at night human activities add heat to the atmosphere (Britter and Hanna, 2003).

A number of studies have revealed that pollution level is affected by emission sources as well as dispersion and dilution process. Considering dispersion of emitted pollutants from district heating facilities, it showed that the pollutant concentration was lower at the location closest to the heat source than farthest from the source. It demonstrated that correlation between pollutant concentration and source is slight. Pollutant concentration near the heating facilities was almost the same as average concentration at the automatic air monitoring site (Yeon and Kim, 2003). Ambient particle concentration near the ground level exhibited maximum concentration at approximately 2.2 km from the source (Yoon and Lee, 1996). It was estimated pollutant transmission and dispersion process near Gunsan and maximum concentration was shown between 50 and 100 km from the source according to geostrophic wind speed (Yoon, 1991). Moreover, urban areas with a complex landscape may be significantly affected by sources located hundreds of kilometers away (Kallos, 1998). As mentioned earlier, urban air pollution is characterized by spatial variability of pollutants with rapid decay form the source (Briggs *et al*., 1997, 2000). For example, NO_2 has been shown to have two- to threefold differences within 50 m or less (Hewitt, 1991), sulfur concentrations have been demonstrated to decrease by one-half between 50 and 150 m from a highway (Reponen *et al*., 2003). Ultrafine particles have been shown to be elevated above background concentrations to approximately 300 m from high ways (Zhu *et al*., 2002)

It has been reported that dispersion and dilution of air pollutants is related to open space. Vegetation directly absorbs pollutants on its foliage, thus reducing air pollution levels (Hill, 1971). Open spaces planted with trees, shrubs, and grasses alter local climate, increasing wind speeds and reducing temperatures, thereby encouraging air circulation and thus increasing dispersion of pollutants. In more open spaces (parks, squares, and residential areas) the pollution levels take the form of an urban background, with increasing impact of more distant sources (Fenger, 1999). Very small areas of open space in an urban area can reduce particulate pollution levels (Wood, 1990). Consequently, there is no doubt that the average concentration of pollutant (particularly particulates) declines with increasing proportions of planted open space (Chandler, 1976).

2.3 Summary

The compact city concept emerged from skepticism about urban sprawl and has put forward as a form of sustainable urban living. There have been disputes between the supporting and opposing sides of compact city, which is not converging into a coherent view in regards to the traffic environment, energy usage, and especially air pollution problems. For example, there are claims that because compact cities have a low dependency on vehicles, they can reduce energy consumption, and eventually decrease emissions, while there are opposing arguments that they could actually induce more traffic congestion, increase more energy consumption, and aggravate air quality.

Such arguments are different in how they have interpreted the density representing the compact city. Various interpretations about the compact city have been made, but the literature about the topic has not found a general consensus yet. What is most important is answering the question of how to appropriately define and measure urban compactness. The so-called compact city concept, in general is employed the high-density city. Some studies focused on gross density or residential density, while certain arguments relate more high-density of built environment.

Most of previous studies on urban structural characteristics have been dealt with the relationship between density and transportation, and energy efficiency; however, there remains a debate on whether the compact city improves the air quality or not. One reason is that the impact of spatiotemporal changes in urban characteristics on air pollution was not considered. The other reason is lack of understanding pollutants' formation and dispersion mechanism.

Air pollutants are largely divided into gas phase and particle. For gas phase pollutants, there are primary pollutants (e.g., SO_2, NO_2, and CO) that come out directly from emission sources and a secondary pollutant (e.g., O_3) that is formed through photochemical reaction of the primary pollutants such as NO_x and VOCs. Particle pollutants can be categorized into several types depending on the diameter, the most representative type is a substance of 10㎛ diameter (PM10). The main emission sources of each pollutant are generally the burning of fossil fuels in vehicle, power plants, factories, and buildings.

Urban air pollution is influenced by the pollutants' spatial variability and dispersion process. Atmosphere dispersion differs by size of urban but ultimately, it is determined by the surface roughness. Concentration is highest at a certain distance from the emission source and decreases close to the emission source or beyond the highest concentration point, and this proves that it originates from the atmosphere dispersion effect. One thing that cannot be left out, with respect to air pollution reduction, is green land or planted open space. It has been found that even very small open space in an urban area can contribute to the dispersion of pollutants and reduce pollution.

This study is interested in disputes on the effects of compact urban development on air pollution. It is to reveal the relationship between the spatial concentration of emission sources and air pollution concentration distribution and to investigate the effects of urban compactness on air pollution, along with an aspect of atmospheric dispersion.

Chapter 3: The Spatial Concentration of Emission Sources and Distribution of Air Pollutants

3.1 The Spatial Distribution of Air Pollutant Concentrations in the Seoul Metropolitan Area

3.1.1 Research Scope

Among various discussions on the influence of air pollution resulting from compact urban development, Kim *et al* (2009) claimed that the spatial concentration of emission sources may aggravate air quality. The distribution of air pollutant concentrations according to the distance from the CBD was observed to verify that air quality worsens when emission sources are concentrated in the CBD.

The scope of the research covered the Seoul Metropolitan Area (SMA) with 85 neighborhoods that have an ambient air quality monitoring station, based on data from 2009. Yangju city[1] and five counties were excluded because these areas are less urbanized (Table 3.1).

[1] The air quality monitoring station of Yangju city is located in Gwangjuk-myeon

Table 3.1 Study areas that are located in the Seoul Metropolitan Area, Korea

Location	Unit: neighborhood area (n=85)
Seoul	- 25 neighborhoods
Incheon	- 12 neighborhoods
Gyeonggi province	- 48 neighborhoods, 25 cities Gimpo (1), Goyang (2), Uijeongbu (1), Guri (2), Hanam (1), Gwacheon (2), Bucheon (4), Seongnam (5), Gwangmyeong (2), Yongin (3), Suwon (4), Anyang (2), Ansan (2), Pyeongtaek (1), Uiwang (2), Gwangju (1), Gunpo (2), Siheung (2), Namyangju (1), Osan (1), Hwaseong (1), Dongducheon (1), Anseong (1), Icheon (1), Paju (1), Pocheon (1)

Note : 1. Excluded areas are Ongjin and Ganghwa-county in Incheon and Yeoju, Gapyeong, Yeoncheon-county, and Yangju city in Gyeonggi province

2. The figure in parentheses indicates the number of neighborhoods which have an air quality monitoring station in each city

3. n: Number of samples

3.1.2 Data Acquisition and Analysis

Air quality data for five main pollutants (e.g., SO_2, NO_2, CO, O_3, and PM10) was obtained from the Annual Report on Ambient Air Quality in Korea (MoE, 2010). The direct measurement of pollutants, which undergo complex diffusion in the air to reach the receptor, requires significant time and incurs expenses. Hence, automatic monitoring sites are installed and operated. An urban air quality monitoring network measures the average concentration in an urban residential area. There are 220 monitoring networks throughout the nation. The network in principle is installed at a site that is not obstructed by a nearby building or tree and measures and collects data pollution levels for the area (MoE, 2010b). In general, gas-phase pollutants are measured every 5 minutes and particulate matter is measured every hour (five minutes in some equipment) (Environmental White Paper, 2007).

The following two methods were used to calculate the value of the distance from the CBD to air quality monitoring stations in the SMA: At the local level, the CBDs of 27 cities were selected from Seoul, Incheon, and Gyeonggi province (including 25 cities), and the distance to an air quality monitoring station was defined as starting from an individual CBD. At the metropolitan level, assuming the SMA is a single region, the distances from Seoul City Hall (CBD) to air quality monitoring stations of each neighborhood were computed. The distances from air quality monitoring stations to CBDs and to Seoul City Hall were measured using GIS (ArcGIS 10.0).

3.1.3 Air Quality Conditions in the Seoul Metropolitan Area

Before reviewing the distribution of pollution concentrations according to the distance from the CBD, an analysis of descriptive statistics for air pollution was conducted and it was based on data from the SMA, 2009. The results are presented in Table 3.2. The average concentration of NO_2 in 85 neighborhoods was about 0.032 (±6.68E-04, SD) ppm/yr and the maximum value was 0.045 ppm/yr. These results are slightly above the Environmental Air Quality Standards (EAQS) of 0.03 ppm/yr. At twenty-three out of twenty-five monitoring stations in Seoul[2], NO_2 concentration values were above the EAQS. NO_2 concentrations in Incheon also exceeded standards at nine stations excluding four neighborhoods[3] and more than half

[2] Bulgwang and Bangi-neighborhood in Seoul are below the EAQS

[3] Gojan, Gyesan, Yeonhee-neighborhood, and Geomdan

of the stations[4] in Gyeonggi province exceeded standards. There is no doubt that intensive management of NO_2 emission sources is required.

The maximum concentration of PM10 was 79 $\mu g/m^3$/yr and somewhat higher than the EAQS of 70 $\mu g/m^3$/yr. PM10 values in Seoul and Incheon were below the EAQS, however, on the other hand five stations[5] in Gyeonggi province were above standards. It is necessary to designate an emission control area to reduce PM10 concentrations in Gyeonggi province.

The average concentration of SO_2 was 0.006 (±1.69E-04, SD) ppm/yr, which was below the EAQS of 0.02 ppm/yr. CO and O_3 concentration values are given as average annual concentrations, which are not suitable for comparison with the EAQS (9 ppm/8 hrs[6] and 0.06 ppm/8 hrs[7] respectively). Together with SO_2, CO and O_3 levels were similar for each neighborhood, however, it does not indicate that those pollutants have been mostly managed or controlled.

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4 Bucheon, Seongnam, Gwangmyeon, Guri, Yongin, Suwon, Ansan, Uiwang, Gwangju, and Siheung

5 Simgok-neighborhood in Bucheon, Bugok-neighborhood in Uiwang, Dongducheon, Icheon, and Pocheon

6 The carbon monoxide standard based on 8-hrs averaged concentrations is 9 ppm

7 The ozone standard based on 8-hrs averaged concentrations is 0.06 ppm

Table 3.2 Comparison between average annual concentrations and Environmental Air Quality Standards (EAQS) in the Seoul Metropolitan Area, 2009

	Min	Max	Mean	Std.Dev	EAQS
SO_2	0.003	0.010	0.006	1.69E-04	0.02 ppm/yr
NO_2	0.014	0.045	0.032	6.68E-04	0.03 ppm/yr
CO	0.400	0.800	0.604	1.10E-02	9 ppm/8 hrs
O_3	0.015	0.036	0.021	3.37E-04	0.06 ppm/8 hrs
PM10	46.000	79.000	58.835	0.733	70 $\mu g/m^3$/yr

Number of samples, n=85

3.1.4 Concentration Distribution of Air Pollutants according to the Distance from the CBD at the Local Level

The air pollutant concentration distribution according to the distance from the CBD was examined at the local level (Table 3.3, Figure 3.1). PM10 concentrations were significantly higher when getting closer to the CBD of each city ($p < 0.01$). PM10 is a mixture of microscopic solids and liquid droplets suspended in air (Vallero, 2008), signifying that the dispersion and dilution of PM10 are less than gas-phase pollutants. It may be inferred that controls on the PM10 emission are more effective at the local level.

The distribution of O_3 concentrations appeared low when getting closer to the CBD ($p < 0.01$). O_3 is a pervasive pollutant and is not usually emitted directly into the air. The emission of O_3 can be regulated by the primary pollutants such as NO_x and VOCs, and then wind can transport O_3 for hundreds of miles (Vallero, 2008).

Although it turned out to be insignificant, the distribution of SO_2 and NO_2 concentrations showed no difference whether in the CBD or not and CO concentrations were only slightly higher near the CBD.

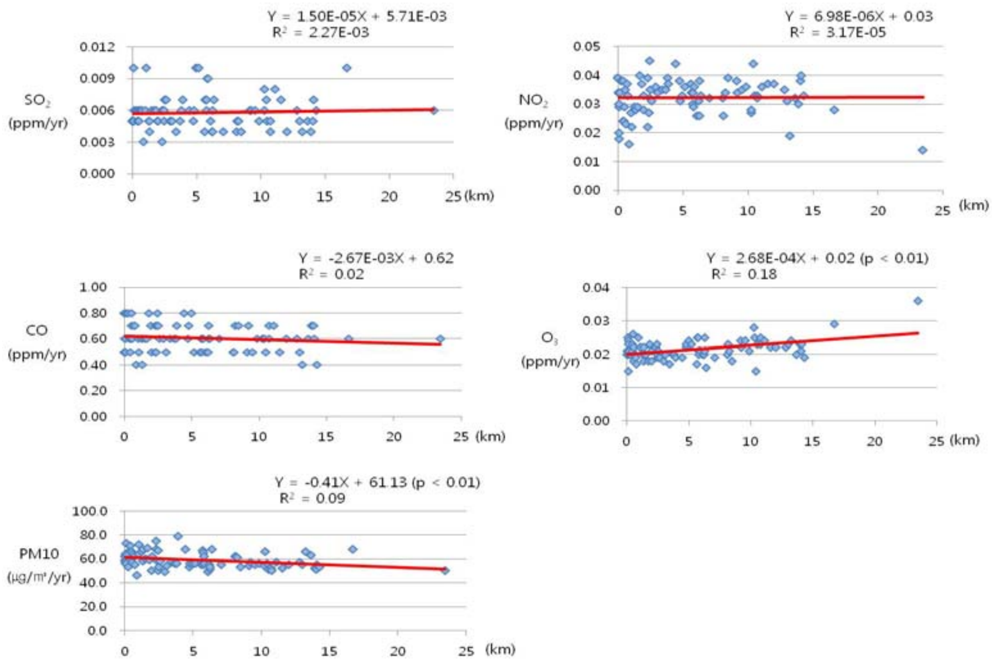

Figure 3.1 Linear models explaining the concentration distribution according to the distance from the CBD at the local level

Table 3.3 Linear-regression model estimates for air pollutants and the distance from the CBD to air quality monitoring stations at the local level

	Model	unstandardized coefficient		standardized coefficient	t-value	F-value	Sig.	R^2
		B	Std.Err	B				
SO_2	CBD to St.(km)	1.50E-05	3.44E-05	0.05	0.43	0.19	0.66	2.27E-03
	Intercept	5.71E-03	2.56E-04		22.30			
NO_2	CBD to St.(km)	6.98E-06	1.36E-04	0.01	0.05	2.63E-03	0.96	3.17E-05
	Intercept	0.03	1.01E-03		31.80			
CO	CBD to St.(km)	-2.67E-03	2.23E-03	-0.13	-1.20	1.44	0.23	0.02
	Intercept	0.62	0.02		37.32			
O_3	CBD to St.(km)	2.68E-04	6.20E-05	0.43	4.33**	18.74	0.00	0.18
	Intercept	0.02	4.61E-04		43.32			
PM10	CBD to St.(km)	-0.41	0.14	-0.30	-2.91**	8.45	0.00	0.09
	Intercept	61.13	1.06		57.77			

Number of samples, n=85 ** $p < 0.01$, * $p < 0.05$

3.1.5 Concentration Distribution of Air Pollutants according to the Distance from the CBD at the Metropolitan Level

The distribution of pollution concentrations at the metropolitan level is as follows (Table 3.4, Figure 3.2). NO_2 and CO concentrations were slightly higher when getting closer to the CBD ($p < 0.01$, $p < 0.05$), while the concentration distribution of O_3 and PM10 appeared higher as the distance from the CBD increased ($p < 0.01$, $p < 0.01$). Although insignificant, SO_2 concentration values indicated that its emission source was not concentrated in the CBD.

The emissions of NO_2 and CO are mainly formed as a result of the combustion process of vehicles and buildings and higher density development brings traffic congestion and increased activity into the CBD and nearby areas. According to total traffic volume data[8] of the SMA (2009), Seoul accounted for 44.8 percent and Incheon and Gyeonggi province covered 14.0 percent and 41.2 percent respectively. In other words, average traffic was 0.47 veh/d/m^2 (3.69 veh/d/m^2) in Seoul, 0.13 veh/d/m^2 (0.94 veh/d/m^2) in Incheon, and 0.15 veh/d/m^2 (1.57 veh/d/m^2) in Geoynggi province on the basis of the administrative district area (road area).

The pollution levels of PM10 and O_3 decreased closer to the CBD, but the distribution of PM10 was the opposite at the local level. This indicates that emitted pollutants are transported or dispersed in the atmosphere as the size of the urban area increases. However, it is necessary to monitor sources as much as possible because they are secondary pollutants that are produced

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[8] Traffic volume was calculated with an equilibrium assignment using EMME 3 (Multimodal Equilibrium) and data of metropolitan trip O / D (Origin / Destination) and network (MTA, 2010) which were gathered from the existing 1522 traffic analysis zones from Korea Transport Institute

not only by chemical reactions of primary pollutants but also by existing gas pollutants.

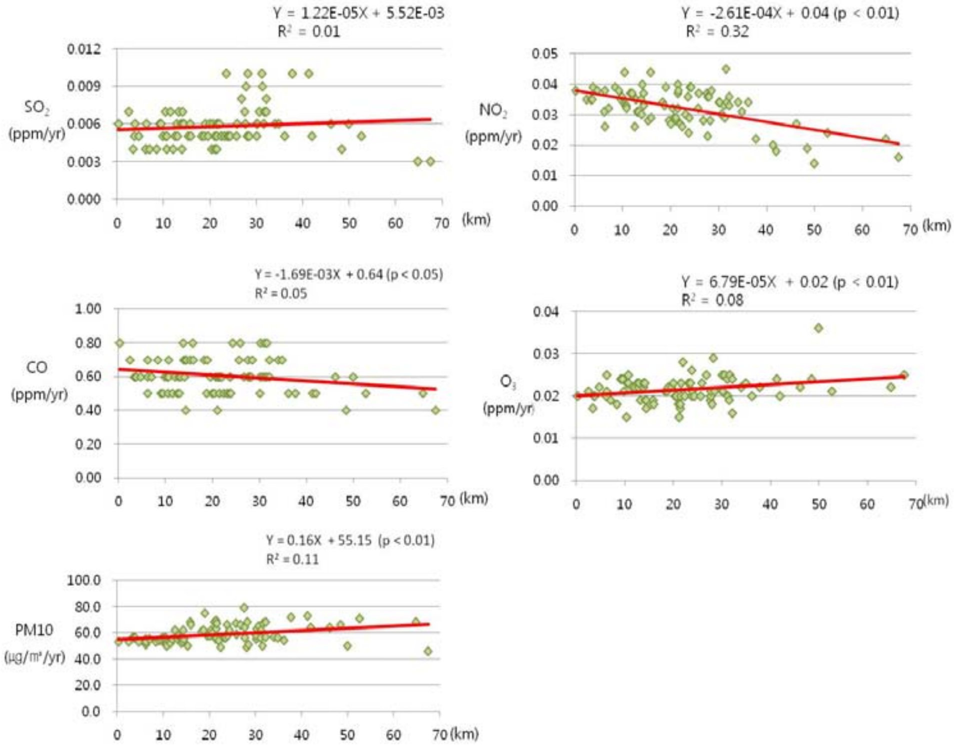

Figure 3.2 Linear models explaining the concentration distribution according to the distance from the CBD at the metropolitan level

Table 3.4 Linear-regression model estimates for air pollutants and the distance from the CBD to air quality monitoring stations at the metropolitan level

	Model	unstandardized coefficient		standardized coefficient	t-value	F-value	Sig.	R^2
		B	Std.Err	B				
SO_2	CBD to St.(km)	1.22E-05	1.28E-05	0.10	0.95	0.91	0.34	0.01
	Intercept	5.52E-03	3.31E-04		16.66			
NO_2	CBD to St.(km)	-2.61E-04	4.18E-05	-0.57	-6.25**	39.09	0.00	0.32
	Intercept	0.04	1.08E-03		35.09			
CO	CBD to St.(km)	-1.69E-03	8.16E-04	-0.22	-2.07*	4.30	0.04	0.05
	Intercept	0.64	0.02		30.28			
O_3	CBD to St.(km)	6.79E-05	2.45E-05	0.29	2.77**	7.69	0.01	0.08
	Intercept	0.02	6.35E-04		31.44			
PM10	CBD to St.(km)	0.16	0.05	0.33	3.14**	9.89	0.00	0.11
	Intercept	55.15	1.36		40.41			

Number of samples, n=85 ** $p < 0.01$, * $p < 0.05$

3.2 The Spatial Distribution of Air Pollutant Concentrations at the Interurban Level

3.2.1 Research Scope

There was an attempt to identify the distribution of pollution levels according to the distance from the CBD at the interurban level. Gas-phase pollutant data was obtained from 17 selected cities (Figure 3.3) with populations in excess of 200,000 people from 1996 to 2009, considering the availability and consistency of measured data. Whereas PM10 was based on data which targeted nine cities (i.e., Seoul, Busan, Incheon, Daegu, Gwangju, Ulsan, Daejeon, Suwon, and Bucheon) during the same years, depending on the availability of their respective time series data.

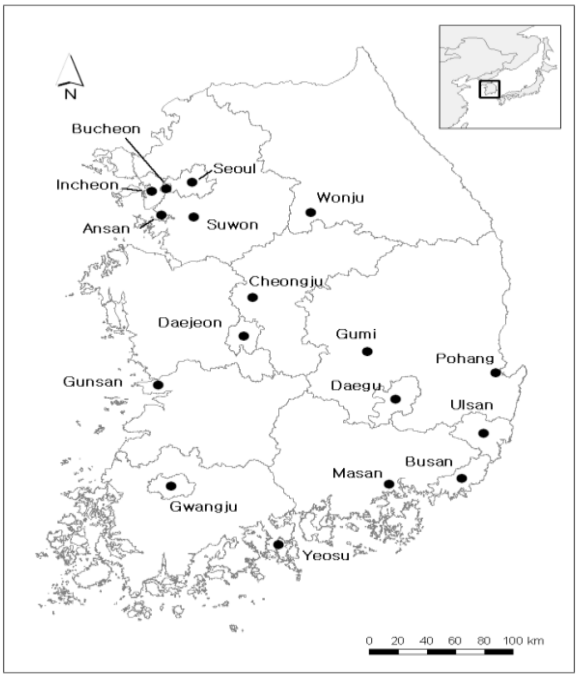

Figure 3.3 17 study areas in Korea

3.2.2 Data Acquisition and Analysis

Air quality data was obtained from the Annual Report on Ambient Air Quality in Korea (MoE, 2010a). The CBDs of 17 individual cities were selected and the distance from the CBD to air quality monitoring stations was calculated through GIS (ArcGIS 10.0). The distribution of pollution concentrations was measured with two methods: concentration distribution based on pooled data and concentration distribution in each year from 1996 to 2009.

3.2.3 Variations in Interurban Air pollution

The concentration of SO_2 in the 17 cities averaged 0.016 (±0.0048, SD) ppm in 1996 and then decreased gradually each year to a level below the EAQS of 0.02 ppm/yr (Figure 3.4a). With the exception of 2007, emission concentrations from 2002 to 2009 remained constant at 0.006 (±0.0019, SD) ppm, which indicates that the technical and policy management of SO_2 emissions such as directives on the sulphur content (1981), prohibition of solid-fuel use (1985), and expansion of clean fuel usage (1988) has been being reliably enforced. It has been reported that SO_2 emissions has been significantly reduced in heating facilities such as households (KEPA, 1999).

In the case of NO_2, yearly emissions fluctuated with a peak of 0.027 (±0.005, SD) ppm in 2001. The average concentrations in general were below the EAQS of 0.03 ppm/yr (Figure 3.4b), but the pollution level in three cities (i.e., Seoul, Bucheon, and Suwon) exceeded the EAQS sporadically for the past 14 years.

Annual average CO concentration is not suitable for comparison with EAQS (9 ppm/8 hrs), but it steadily decreased year to year similar with SO_2, indicating that emission control is effective (Figure 3.4c). The O_3 standard based on 8 hour averaged concentrations is 0.06 ppm and the yearly average of O_3 concentrations increased gradually with some fluctuation (Figure 3.4d).

Meanwhile, concentrations of PM10 were the highest in 1996, and then decreased with some fluctuation although an increase was observed in 2001 and 2002 (Figure 3.4e).

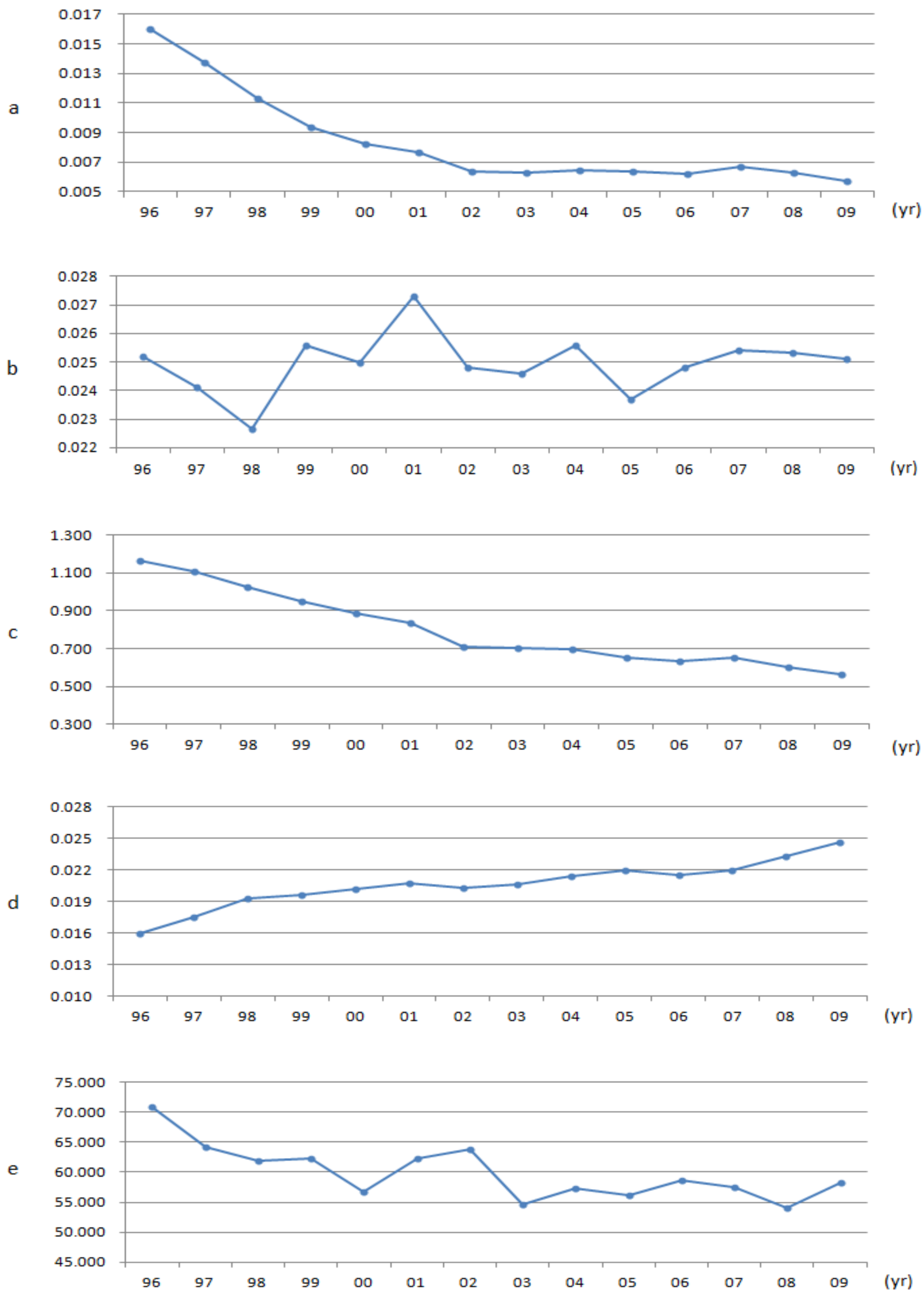

Figure 3.4 Variations in annual average concentrations from 1996 to 2009: a (SO_2), b (NO_2), c (CO), d (O_3), and e (PM10)

3.2.4 Concentration Distribution of Air Pollutants according to the Distance from the CBD at the Interurban Level

With regards to the distribution of pollution concentrations represented in the pooled data, emissions of SO_2 and PM10 were evenly distributed depending on the distance from the CBD ($p < 0.05$, $p < 0.01$). While higher CO levels were reached in the CBD ($p <0 .01$), NO_2 concentration values decreased closer to the CBD ($p < 0.01$). O_3 appeared to be distributed evenly (Table 3.5, Figure 3.5).

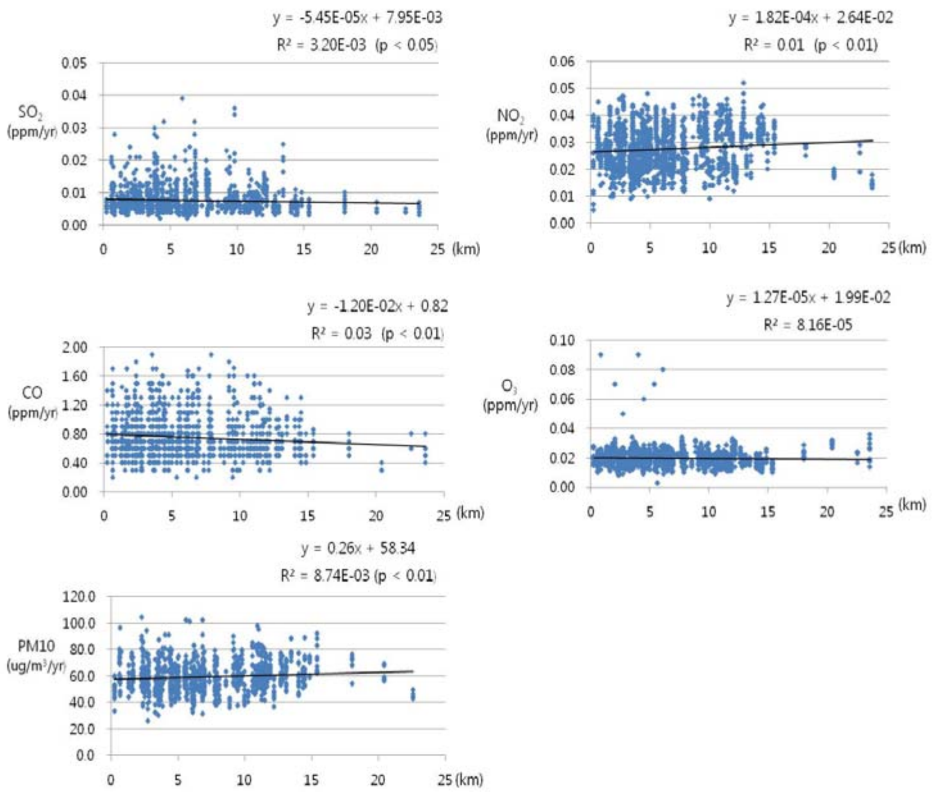

Figure 3.5 Linear models explaining the concentration distribution according to the distance from the CBD at the interurban level based on pooled data

Note: 1. Number of air quality monitoring stations for gas-phase pollutants, n = 1446

2. Number of air quality monitoring stations for particulate matter, n= 1004

Table 3.5 Linear-regression model estimates for air pollutants and the distance from the CBD to air quality monitoring stations at the interurban level based on pooled data

	Model	unstandardized coefficient		standardized coefficient	t-value	F-value	Sig.	R^2
		B	Std.Err	B				
SO_2 (n=1446)	CBD to St.(km)	-5.45E-05	2.53E-05	-0.06	-2.15*	4.64	0.03	3.20E-03
	Intercept	7.95E-03	1.94E-04		41.10			
NO_2 (n=1446)	CBD to St.(km)	1.82E-04	4.84E-05	0.10	3.76**	14.10	0.00	0.01
	Intercept	2.64E-02	3.70E-04		71.18			
CO (n=1446)	CBD to St.(km)	-1.20E-02	1.70E-03	-0.18	-7.06**	49.87	0.00	0.03
	Intercept	8.23E-01	1.30E-02		63.47			
O_3 (n=1446)	CBD to St.(km)	1.27E-05	3.69E-05	0.01	0.34	0.12	0.73	8.16E-05
	Intercept	1.99E-02	2.83E-04		70.57			
PM10 (n=1004)	CBD to St.(km)	0.26	0.09	0.09	2.97**	8.84	0.00	8.74E-03
	Intercept	57.34	0.72		80.02			

n: Number of samples ** $p < 0.01$, * $p < 0.05$

An analysis of concentration distribution according to the distance from the CBD in each year from 1996 to 2009 was conducted (Appendix A, B, C, D, E). As the CBD approaches, the distribution of CO concentrations appeared to increase significantly since 2002 (Table 3.6, Figure 3.6), indicating that the incomplete combustion of CO was relatively larger than dispersion at the interurban level. The pollution level distribution of NO_2 decreased only four times between 1996 and 2002 (Table 3.7, Figure 3.7) and PM10 showed a low distribution from 2006 to 2008 (Table 3.8, Figure 3.8). Although it turned out to be insignificant, SO_2 and O_3 concentrations showed no difference whether in the CBD or not (Table 3.9, 3.10, Figure 3.9, 3.10).

In short, the distribution of air pollutant concentrations was higher or lower when getting closer to the CBD. In certain cases there are pollutants that had an even distribution depending on the distance from the CBD. This study partially supports Kim *et al*. (2009)'s findings, which referred to the increase of air pollution brought about by cumulative emission sources. However, they did not consider the atmospheric dispersion of pollutants. A number of studies have revealed that air pollution is affected by emission sources as well as the process of dispersion (Hewitt, 1991; Briggs *et al*., 1997; Zhu *et al*., 2002; Yeon and Kim, 2003). As a result, it cannot be determined whether air pollution is aggravated by the spatial concentration of sources because air pollution levels are influenced by the extent and magnitude of dispersion, which may vary according to urban characteristics and diverse conditions they exist in.

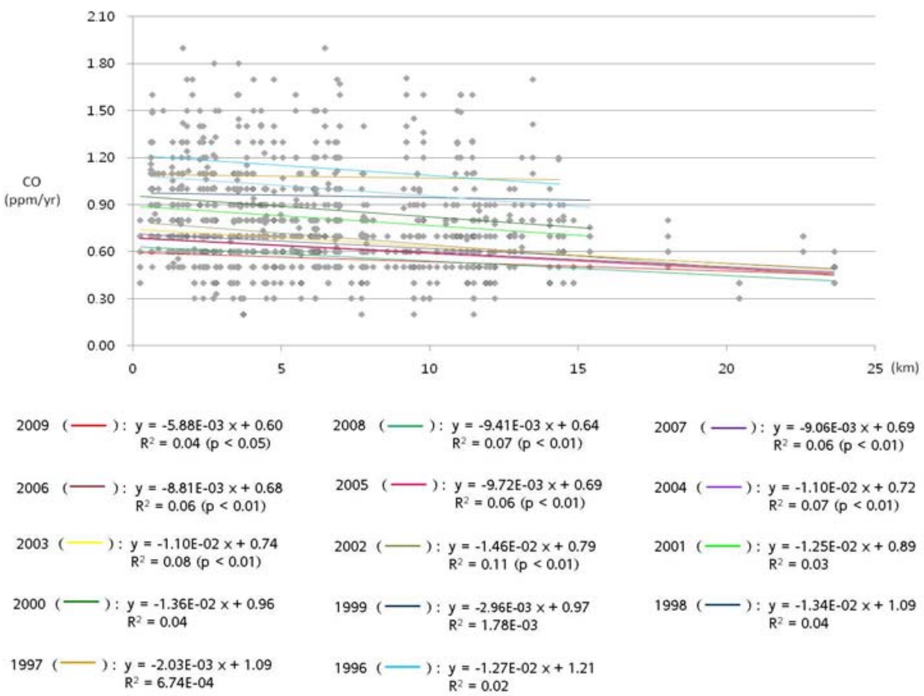

Figure 3.6 Linear models explaining the distribution of the yearly average concentrations of CO according to the distance from the CBD at the interurban level (1996 - 2009)

Table 3.6 Linear-regression model estimates for CO and the distance from the CBD to air quality monitoring stations at the interurban level (1996 - 2009)

CO	Model	unstandardized coefficient		standardized coefficient	t-value	F-value	Sig.	R^2
		B	Std.Err	B				
1996 (n=71)	CBD to St.	-1.27E-02	1.10E-02	-0.14	-1.18	1.38	0.24	0.02
	Intercept	1.21	7.30E-02		16.62			
1997 (n=78)	CBD to St.	-2.03E-03	8.97E-03	-0.03	-0.23	0.05	0.82	6.74E-04
	Intercept	1.09	6.20E-02		17.48			
1998 (n=87)	CBD to St.	-1.34E-02	7.32E-03	-0.20	-1.83	3.35	0.07	0.04
	Intercept	1.09	5.40E-02		20.16			
1999 (n=90)	CBD to St.	-2.96E-03	7.47E-03	-0.04	-0.40	0.16	0.69	1.78E-03
	Intercept	0.97	5.40E-02		17.87			
2000 (n=93)	CBD to St.	-1.36E-02	7.17E-03	-0.20	-1.90	3.60	0.06	0.04
	Intercept	0.96	5.20E-02		18.39			
2001 (n=95)	CBD to St.	-1.25E-02	6.82E-03	-0.19	-1.84	3.38	0.07	0.03
	Intercept	0.89	4.90E-02		18.18			
2002 (n=100)	CBD to St.	-1.46E-02	4.11E-03	-0.34	-3.55**	12.61	0.00	0.11
	Intercept	0.79	3.10E-02		25.36			
2003 (n=106)	CBD to St.	-1.10E-02	3.59E-03	-0.29	-3.05**	9.31	0.00	0.08
	Intercept	0.74	2.80E-02		26.08			
2004 (n=117)	CBD to St.	-1.00E-02	3.40E-03	-0.27	-2.95**	8.71	0.00	0.07
	Intercept	0.72	2.70E-02		26.36			
2005 (n=119)	CBD to St.	-9.72E-03	3.46E-03	-0.25	-2.81**	7.89	0.00	0.06
	Intercept	0.69	2.80E-02		24.47			
2006 (n=122)	CBD to St.	-8.81E-03	3.19E-03	-0.25	-2.76**	7.63	0.00	0.06
	Intercept	0.68	2.60E-02		26.33			
2007 (n=122)	CBD to St.	-9.06E-03	4.03E-05	-0.24	-2.67**	7.14	0.00	0.06
	Intercept	0.69	2.60E-02		25.93			
2008 (n=124)	CBD to St.	-9.41E-03	8.18E-03	-0.26	-2.96**	8.75	0.00	0.07
	Intercept	0.64	2.50E-02		25.65			
2009 (n=124)	CBD to St.	-5.88E-03	2.55E-03	-0.21	-2.31*	5.34	0.02	0.04
	Intercept	0.60	1.98E-02		30.05			

n: Number of samples ** $p < 0.01$, * $p < 0.05$

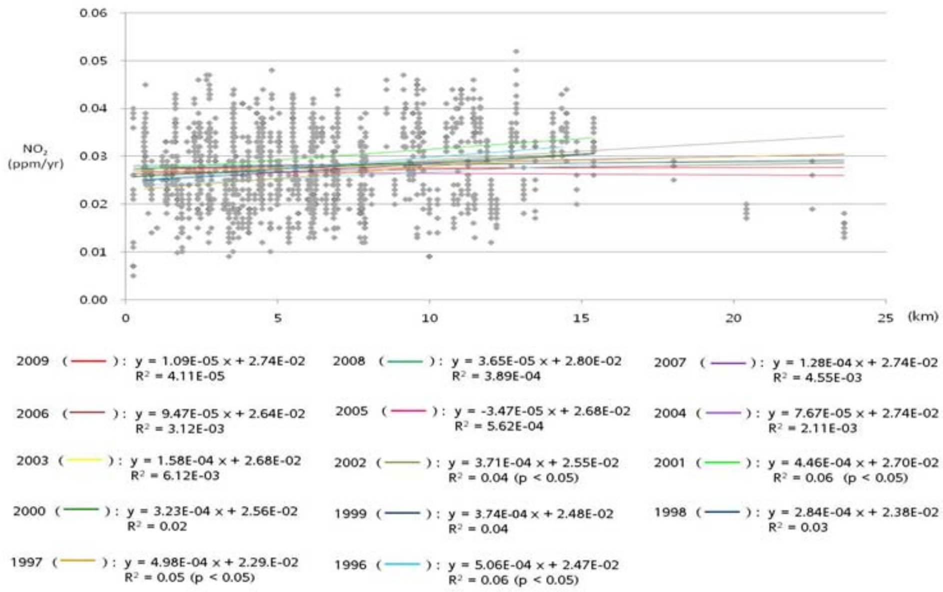

Figure 3.7 Linear models explaining the distribution of the yearly average concentrations of NO_2 according to the distance from the CBD at the interurban level (1996 - 2009)

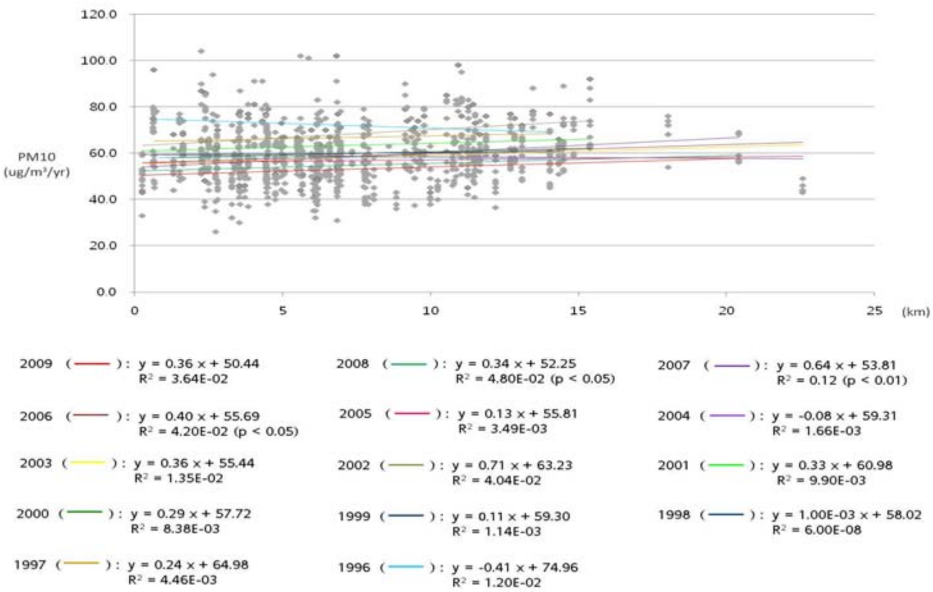

Figure 3.8 Linear models explaining the distribution of the yearly average concentrations of PM10 according to the distance from the CBD at the interurban level (1996 - 2009)

Table 3.7 Linear-regression model estimates for NO_2 and the distance from the CBD to air quality monitoring stations at the interurban level (1996 - 2009)

NO_2	Model	unstandardized coefficient		standardized coefficient	t-value	F-value	Sig.	R^2
		B	Std.Err	B				
1996 (n=70)	CBD to St.	5.06E-04	2.44E-04	0.24	2.07*	4.29	0.04	0.06
	Intercept	2.47E-02	1.66E-03		14.91			
1997 (n=78)	CBD to St.	4.98E-04	2.43E-04	0.23	2.05*	4.21	0.04	0.05
	Intercept	2.29E-02	1.69E-03		13.57			
1998 (n=87)	CBD to St.	2.84E-04	1.96E-04	0.16	1.45	2.09	0.15	0.03
	Intercept	2.38E-02	1.45E-03		16.45			
1999 (n=90)	CBD to St.	3.74E-04	1.99E-04	0.20	1.87	3.51	0.06	0.04
	Intercept	2.48E-02	1.45E-03		17.05			
2000 (n=93)	CBD to St.	3.23E-04	2.14E-04	0.16	1.51	2.28	0.13	0.02
	Intercept	2.56E-02	1.56E-03		16.48			
2001 (n=95)	CBD to St.	4.46E-04	1.90E-04	0.24	2.34*	5.49	0.02	0.06
	Intercept	2.70E-02	1.37E-03		19.67			
2002 (n=101)	CBD to St.	3.71E-04	1.90E-04	0.19	1.95*	3.80	0.05	0.04
	Intercept	2.55E-02	1.43E-03		17.81			
2003 (n=106)	CBD to St.	1.58E-04	1.98E-04	0.08	0.80	0.64	0.43	6.12E-03
	Intercept	2.68E-02	1.57E-03		17.06			
2004 (n=117)	CBD to St.	7.67E-05	1.56E-04	0.05	0.49	0.24	0.62	2.11E-03
	Intercept	2.74E-02	1.27E-03		21.67			
2005 (n=119)	CBD to St.	-3.47E-05	1.35E-04	-0.02	-0.26	0.07	0.80	5.62E-04
	Intercept	2.68E-02	1.10E-03		24.41			
2006 (n=120)	CBD to St.	9.47E-05	1.56E-04	0.06	0.61	0.37	0.55	3.12E-03
	Intercept	2.64E-02	1.27E-03		20.73			
2007 (n=122)	CBD to St.	1.28E-04	1.72E-04	0.07	0.74	0.55	0.46	4.55E-03
	Intercept	2.74E-02	1.35E-03		20.35			
2008 (n=124)	CBD to St.	3.65E-05	1.68E-04	0.02	0.22	0.05	0.83	3.89E-04
	Intercept	2.80E-02	1.30E-03		21.49			
2009 (n=124)	CBD to St.	1.09E-05	1.54E-04	6.00E-03	0.07	5.00E-03	0.94	4.11E-05
	Intercept	2.74E-02	1.20E-03		22.95			

n: Number of samples ** $p < 0.01$, * $p < 0.05$

Table 3.8 Linear-regression model estimates for PM10 and the distance from the CBD to air quality monitoring stations at the interurban level (1996 - 2009)

PM10	Model	unstandardized coefficient		standardized coefficient	t-value	F-value	Sig.	R^2
		B	Std.Err	B				
1996 (n=23)	CBD to St.	-0.41	0.81	-0.11	-0.51	0.26	0.62	1.20E-02
	Intercept	74.96	6.19		12.11			
1997 (n=28)	CBD to St.	0.24	0.70	0.07	0.34	0.12	0.74	4.46E-03
	Intercept	64.98	5.64		11.53			
1998 (n=37)	CBD to St.	1.00E-03	0.48	0.00	1.00E-03	0.00	0.99	6.00E-08
	Intercept	58.02	4.19		13.85			
1999 (n=60)	CBD to St.	0.11	0.42	0.03	0.26	3.51	0.06	1.14E-03
	Intercept	59.30	3.29		18.04			
2000 (n=66)	CBD to St.	0.29	0.39	0.09	0.74	0.54	0.47	8.38E-03
	Intercept	57.72	3.14		18.38			
2001 (n=71)	CBD to St.	0.33	0.40	0.10	0.83	0.69	0.41	9.90E-03
	Intercept	60.98	3.14		19.43			
2002 (n=77)	CBD to St.	0.71	0.40	0.20	1.78	3.16	0.08	4.04E-02
	Intercept	63.23	3.11		20.36			
2003 (n=80)	CBD to St.	0.36	0.35	0.12	1.03	0.64	0.43	1.35E-02
	Intercept	55.44	2.93		18.94			
2004 (n=88)	CBD to St.	-0.08	0.22	-0.04	-0.38	0.14	0.71	1.66E-03
	Intercept	59.31	1.90		31.15			
2005 (n=90)	CBD to St.	0.13	0.24	0.06	0.56	0.31	0.58	3.49E-03
	Intercept	55.81	2.03		27.44			
2006 (n=95)	CBD to St.	0.40	0.20	0.20	2.02*	0.37	0.05	4.20E-02
	Intercept	55.69	1.70		37.72			
2007 (n=95)	CBD to St.	0.64	0.18	0.35	3.57**	12.74	0.00	0.12
	Intercept	53.81	1.47		36.68			
2008 (n=97)	CBD to St.	0.34	0.16	0.22	2.19*	4.79	0.03	4.80E-02
	Intercept	52.25	1.27		41.16			
2009 (n=97)	CBD to St.	0.36	0.19	0.19	1.90	3.59	0.06	3.64E-02
	Intercept	50.44	1.54		32.73			

n: Number of samples ** $p < 0.01$, * $p < 0.05$

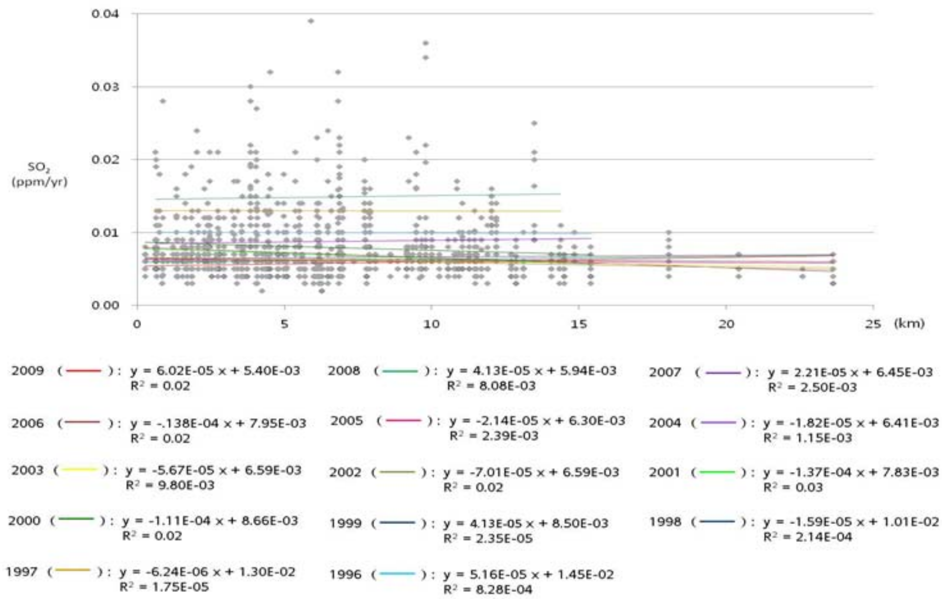

Figure 3.9 Linear models explaining the distribution of yearly average concentrations of SO_2 according to the distance from the CBD at the interurban level (1996 - 2009)

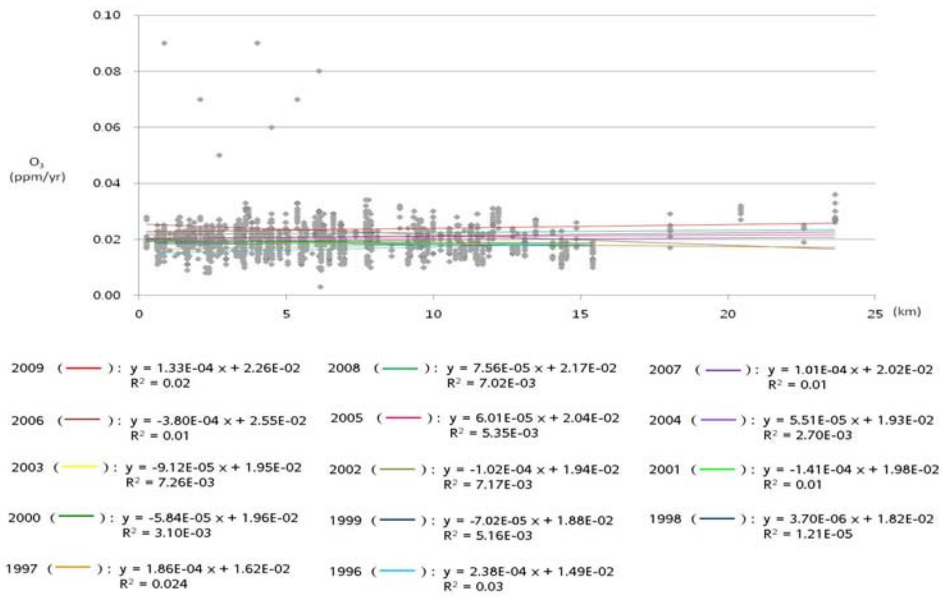

Figure 3.10 Linear models explaining the distribution of yearly average concentrations of O_3 according to the distance from CBD at the interurban level (1996 - 2009)

Table 3.9 Linear-regression model estimates for SO_2 and the distance from the CBD to air quality monitoring stations at the interurban level (1996 - 2009)

SO_2	Model	unstandardized coefficient		standardized coefficient	t-value	F-value	Sig.	R^2
		B	Std.Err	B				
1996 (n=70)	CBD to St.	5.16E-05	2.17E-04	0.03	0.24	0.06	0.81	8.28E-04
	Intercept	1.45E-02	1.48E-03		9.85			
1997 (n=78)	CBD to St.	-6.24E-06	1.71E-04	-4.00E-03	-0.04	1.00E-03	0.97	1.75E-05
	Intercept	1.30E-02	1.19E-03		10.96			
1998 (n=87)	CBD to St.	-1.59E-05	1.18E-04	-0.02	-0.14	0.02	0.89	2.14E-04
	Intercept	1.01E-02	8.71E-04		11.59			
1999 (n=90)	CBD to St.	4.13E-05	9.09E-05	0.05	0.46	0.21	0.65	2.35E-05
	Intercept	8.50E-03	6.62E-04		12.83			
2000 (n=93)	CBD to St.	-1.11E-04	7.95E-05	-0.15	-1.40	1.96	0.17	0.02
	Intercept	8.66E-03	5.78E-04		14.98			
2001 (n=95)	CBD to St.	-1.37E-04	8.03E-05	-0.17	-1.70	2.90	0.09	0.03
	Intercept	7.83E-03	5.79E-04		13.52			
2002 (n=101)	CBD to St.	-7.01E-05	5.60E-05	-0.14	-1.25	1.57	0.21	0.02
	Intercept	6.59E-03	4.22E-04		15.62			
2003 (n=106)	CBD to St.	-5.67E-05	5.59E-05	-0.10	-1.02	1.03	0.31	9.80E-03
	Intercept	6.59E-03	4.43E-04		14.87			
2004 (n=117)	CBD to St.	-1.82E-05	4.99E-05	-0.03	-0.36	0.13	0.72	1.15E-03
	Intercept	6.41E-03	4.04E-04		15.88			
2005 (n=119)	CBD to St.	-2.14E-05	4.04E-05	-0.05	-0.53	0.28	0.60	2.39E-03
	Intercept	6.30E-03	3.28E-04		19.22			
2006 (n=120)	CBD to St.	-1.38E-04	9.10E-05	-0.14	-1.51	2.29	0.13	0.02
	Intercept	7.95E-03	7.43E-04		10.71			
2007 (n=122)	CBD to St.	2.21E-05	4.03E-05	0.05	0.55	0.30	0.59	2.50E-03
	Intercept	6.45E-03	3.15E-04		20.48			
2008 (n=124)	CBD to St.	4.13E-05	4.14E-05	0.09	1.00	0.99	0.32	8.08E-03
	Intercept	5.94E-03	3.22E-04		18.44			
2009 (n=124)	CBD to St.	6.02E-05	3.78E-05	0.14	1.59	2.54	0.11	0.02
	Intercept	5.40E-03	2.94E-04		18.36			

n = Number of samples ** $p < 0.01$, * $p < 0.05$

Table 3.10 Linear-regression model estimates for O_3 and the distance from the CBD to air quality monitoring stations at the interurban level (1996 - 2009)

O_3	Model	unstandardized coefficient B	unstandardized coefficient Std.Err	standardized coefficient B	t-value	F-value	Sig.	R^2
1996 (n=71)	CBD to St.	2.38E-04	1.59E-04	0.18	1.50	2.24	0.14	0.03
	Intercept	1.49E-02	1.07E-03		13.85			
1997 (n=78)	CBD to St.	1.86E-04	1.35E-04	0.16	1.37	1.00E-03	0.97	0.02
	Intercept	1.62E-04	1.35E-04		17.25			
1998 (n=87)	CBD to St.	3.70E-06	1.16E-04	3.00E-03	0.03	1.00E-03	0.97	1.21E-05
	Intercept	1.82E-02	8.58E-04		21.26			
1999 (n=90)	CBD to St.	-7.02E-05	1.04E-04	-0.07	-0.67	0.45	0.50	5.16E-03
	Intercept	1.88E-02	7.62E-04		24.65			
2000 (n=93)	CBD to St.	-5.84E-05	1.10E-04	-0.06	-0.53	0.28	0.60	3.10E-03
	Intercept	1.96E-02	8.03E-04		24.45			
2001 (n=95)	CBD to St.	-1.41E-04	1.24E-04	-0.12	-1.14	1.30	0.26	0.01
	Intercept	1.98E-02	9.92E-04		22.23			
2002 (n=101)	CBD to St.	-1.02E-04	1.21E-04	-0.09	-0.85	0.72	0.40	7.17E-03
	Intercept	1.94E-02	9.10E-04		21.33			
2003 (n=106)	CBD to St.	-9.12E-05	1.05E-04	-0.09	-0.87	0.76	0.39	7.26E-03
	Intercept	1.95E-02	8.29E-04		23.47			
2004 (n=116)	CBD to St.	5.51E-05	9.91E-05	0.05	0.56	0.31	0.58	2.70E-03
	Intercept	1.93E-02	8.02E-04		24.11			
2005 (n=119)	CBD to St.	6.01E-05	7.58E-05	0.07	0.79	0.63	0.43	5.35E-03
	Intercept	2.04E-02	6.15E-04		33.09			
2006 (n=120)	CBD to St.	-3.80E-04	2.65E-04	-0.13	-1.44	2.06	0.15	0.01
	Intercept	2.55E-02	2.16E-03		11.80			
2007 (n=122)	CBD to St.	1.01E-04	7.91E-05	0.12	1.28	1.64	0.20	0.01
	Intercept	2.02E-02	6.17E-04		32.76			
2008 (n=124)	CBD to St.	7.56E-05	8.14E-05	0.08	0.93	0.86	0.36	7.02E-03
	Intercept	2.17E-02	6.33E-04		34.30			
2009 (n=124)	CBD to St.	1.33E-04	7.47E-05	0.16	1.78	3.17	0.08	0.02
	Intercept	2.26E-02	5.81E-04		38.96			

n = Number of samples ** $p < 0.01$, * $p < 0.05$

3.3 Summary

Looking at the relationship between the spatial concentration of emission sources and the distribution of air pollutant concentrations, the pollution levels was high or low when getting closer to CBD (Table 3.11). The results partially support Kim *et al*. (1009)'s findings, which referred to the increase of air pollution brought about by cumulative emission sources, however, it also involves that the air pollution levels vary according to the dispersion or dilution process of pollutants. The extent and magnitude of dispersion may be influenced by urban characteristics and the diverse conditions they exist in.

The distribution of pollutant concentrations differed depending upon the method used to compute the distance from the CBD to air quality monitoring stations. PM10 emissions were concentrated in the CBDs at the local level, while PM10 at the metropolitan level showed a low distribution when getting closer to the CBD. At the interurban level PM10 concentrations appeared a low distribution only from 2006 to 2008. PM10 is in the form of microscopic solids or liquid droplets, and then its dispersion is relatively less than gas-phase pollutants at the local level. It suggests that regulations on the local level can be part of a countermeasure against PM10.

The distribution of O_3 concentrations appeared low when getting closer to the CBD at the local and metropolitan level. O_3 concentrations based on pooled data were evenly distributed depending on the distance from the CBD at the interurban level. It is related that O_3 is a pervasive pollutant and is transported to long distances by wind. Like PM10, it is necessary to monitor any sources because they are secondary pollutants that are produced not only by existing gas pollutants but also by chemical reactions of primary pollutants.

The distribution of NO_2 and CO concentrations at the metropolitan level was significantly higher when getting closer to the CBD. The emissions of NO_2 and CO are mainly formed by the combustion process of vehicles and buildings, implying that higher density development brings traffic congestion and activity density into the CBD and nearby areas. At the interurban level NO_2 concentration values showed a low or an even distribution while, CO had a little high distribution when getting closer to CBD. With regards to the distribution of pollution concentrations in each year from 1996 to 2009, as the CBD approaches, the distribution of CO concentrations appeared to increase significantly since 2002, indicating that the regulations of CO emissions from the local level must be reinforced in terms of individual cities.

Table 3.11 Summary of the spatial distribution of air pollutant concentrations according to the distance from the CBD at the local level, at the metropolitan level, and at the interurban level

Pollutant	Seoul Metropolitan Area (2009)		17 cites, 1996 - 2009	
	Local level	Metropolitan level	Interurban level	
			Pooled data	Distribution in years
SO_2			-	
NO_2		↑	↓	↓ (1996 and 1997, 2001 and 2002)
CO		↑	↑	↑ (2002 to 2009)
O3	↓	↓	-	
PM10	↑	↓	-	↓ (2006 to 2008)

Note : 1. An Arrow indicates high (↑) or low (↓) concentration values when getting closer to the CBD

2. A bar (−) indicates that pollutant concentrations have no difference whether in the CBD or not

Chapter 4: Effects of Urban Compactness on Air Pollution

4.1 Definition of Urban Compactness

The relationship between the compact city and air pollution is controversial for some reason. Not only did the compact city prove to be less sustainable than some of us believed, but compact urban development would likely have both positive and negative benefits on air quality. Especially, a lack of tools for measuring urban compactness leads to difficulties in distinguishing different degrees of compactness and creates confusion about the effects of compact development on air pollution.

Urban compactness may contain three definitions: monocentric and polycentric (i.e., the spatial structure-based concept), mixed-use (i.e., land-use-based concept), and high-density (i.e., the intensity-based concept). The most commonly used measures of the compact city are related to population density. The reason is stated by Breheny (2001), "at the core of the whole urban renaissance and compaction debate [...] has been the question of residential density; protagonists see higher residential density as a necessary component of a compaction policy". High population density is arguably critical to support public transport and to provide adequate demand to make local facilities and services viable (Burton, 2002). Population density has also been found to be closely related to the social vitality of the city. It is also claimed to be one of the pathogens for many social-environmental diseases such as overcrowding, urban waste generation and noise pollution (Cadman and Payne, 1990).

However, gross density and residential density reveal little about the activity density of the built-up area of a city and new development. Net density may not show the density at which people actually live in case much of the built-up area is used for non-residential land-use (Burton, 2002). These overall measures insufficiently reflect the whole range of compact-city attributes as well as potential and cumulative effects of high-density development across the entire city.

There are criticisms with respect to negative and positive aspects of the relationship between high-density, transportation, and air pollution. There are two different sides for this debate: high-density development can reduce energy consumption and promote low emissions through a decrease in distance traveled. On the other hand, it can also lead to traffic congestion and greater air pollution. This suggests that activity densities within limited spaces cause a concentration of emission sources, but may increase or decrease air pollution in terms of energy efficiency. Their arguments have never taken into account that securing enough green land resulting from high-density development can encourage dispersion of pollutants and reduce pollution concentrations.

Korea is mostly heavily populated in built-up areas, and besides, new developments and redevelopments which affect the loss of planted open space have been undertaken. Therefore, thought needs to be given to more practical measures to interpret the concept of urban compactness. The definition of urban compactness here encompasses the high-density built form with a proportion of the green land within a standard spatial unit. The measurement of compactness is subjected to the number of people within a built-up area (net density) and the ratio of green land area to an administrative district area (proportion of green land) (Figure 4.1).

Net density involves the spatial concentration of emission sources and can be a proxy variable for the density of housing, employment, and the overall commercial mix. Densely populated district may reflect the lives of actual residential and concentration of employment and commercial facilities in the place. The built-up area is for private land-use excluding public facilities and includes building areas and factory sites according to land-use classifications in Korea. The proportion of green land represents the dispersion effect of air pollutants; green-land category is limited to forests, parks, and recreational areas. It can be inferred that urban compactness has two meanings: the spatial concentration of emission sources by high-density and the dispersion of pollutants by green land. The relative magnitudes of opposing effects determine air quality.

Meanwhile, urban size might need to be controlled to evaluate the effects of compactness depending on the different sizes of urban areas (Figure 4.2). Tsai (2005) developed a set of quantitative variables to characterize urban compactness from sprawl and population, as a dimension of urban size was used. The land area of an urban area was proposed as an index of sprawl, based on the idea that sprawl cause the consumption of more land than compact development (Hess *et al*., 2001). Although land area might better characterize urban size, which may be problematic since overall land consumption is highly associated with population. Population is more sensible in practical application because it is not affected by land consumption per capita, which is related to the dimension of density. Population is theoretically independent from density, but land area is not (Tsai, 2005).

$$\frac{\text{population}}{\text{administrative district area}} = \frac{\text{built}-\text{up area}}{\text{administrative district area}} \times \underbrace{\boxed{\frac{\text{populaiton}}{\text{built}-\text{up area}}}}_{\textit{Concentration of sources}}$$

$$\text{here, } \frac{\text{built}-\text{up area}}{\text{administrative district area}} = 1 - \underbrace{\boxed{\frac{\text{green land}}{\text{administrative district area}}}}_{\textit{Dispersion of pollutants}} - \frac{\text{other land uses}}{\text{administrative district area}}$$

Figure 4.1 Definition of urban compactness

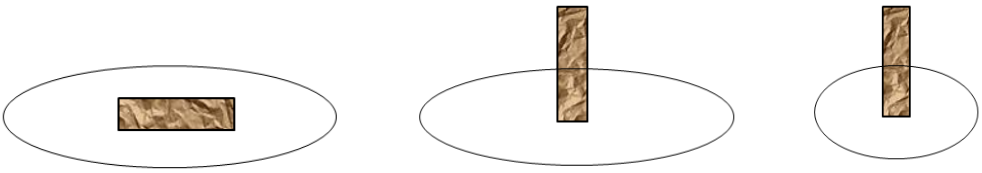

Figure 4.2 Low-density versus high-density dimensions with different urban size

4.2 Panel Data Model for Investigating the Relationship between Spatiotemporal Changes in Urban Characteristics and Interurban Air Pollution

4.2.1 Research scope and Data acquisition

To investigate the effects of urban compactness on air pollution, it is necessary to consider that spatiotemporal changes in urban characteristics affect pollution concentration which resulted in the process of dispersion and dilution. As mentioned in Chapter 3, in case of the gas-phase pollutants, the scope of the research was based on data which targeted 17 cities from 1996 to 2009, while PM10 was limited to nine cities between 1996 to 2009 (Figure 3.5).

Five elements of urban characteristics are presented in Table 4.1. Net density represents urban compactness together with the proportion of green land. The following three variables are used as control parameters to examine the effects of urban compactness on air quality. A variable of manufacturing is defined as the number of workers engaged in manufacturing industry which hires five or more employees. Vehicle dependency means both vehicle ownership and infra availability: vehicle ownership is calculated per capita according to the number of registered motor vehicles and infra availability can express the sum of road area and parking lot for each administrative district area. Urban size is controlled by population according to Tsai (2005).

The data set was obtained from the Statistical Yearbook (1996 - 2010) and Report of the Census on Establishments (1996 - 2010), which are published from government agencies in different cities.

Table 4.1 Variables for urban characteristics and air pollution

Variables		Description (unit)
Air pollution	Sulfur dioxide gas (SO_2), Nitrogen dioxide (NO_2), Carbon monoxide (CO), Ozone (O_3)	Annual average concentration (ppm/yr)
	Particulate matter (PM10)	Annual average concentration ($\mu g/m^3/yr$)
Urban character-ristics	Proportion of green land	Ratio of green land to administrative district area
	Net density	Population per built-up area (no. of persons/$10^3 m^2$)
	Manufacturing	Manufacturing workers per built-up area (no. of workers/ $10^3 m^2$)
	Vehicle dependency	$\frac{\text{registered motor vehicles}}{\text{population}} \times \frac{\Sigma(\text{road} + \text{parking lot})}{\text{administrative distric area}}$ (vehicle ownership) (infra availability)
	Population	Population (no. of persons)

4.2.2 Analysis and modeling

Environmental damage from urbanization is cumulative[9] over long periods of time as a result of various processes. In other words, if various development projects are continuously undertaken on a broad scale, their effects will be accumulated spatially and temporally, and have a serious impact on the urban environment (Oh *et al*., 2006). Changes in urban characteristics make a difference for air pollution and the scope of influence varies by time and spatial variability. In this regard, the effect of time-dependent urbanization can be obtained from time-series data, and a cross-sectional analysis is required for determining factors that influence air pollution.

A panel data model (Baltagi, 2008) was used to analyze the impact of spatiotemporal changes in urban characteristics on air pollution. The model is a quantitative analytical method that can be used when time-series and cross-section data are both available. It handles variables that are important to the model, but are not included as explanatory variables. Another advantage of the panel data model is that it can also regulate estimate errors that arise from time-series processes and regional unit data. It is an ideal analysis method for this study, considering that it can account for an unobservable omitted variable that has a significant effect on interurban air pollutant concentration differences.

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[9] Cumulative effects are changes to the environment that are caused by an action in combination with other past, present and future human actions [Sources from: US NEPA (National Environment Policy Act); Cumulative Effects Assessment Practitioners' Guide, Canadian Environmental Assessment Agency]

To regulate omitted variables, error terms are categorized as variables such as individual (regional)-variant but time-invariant (or time-constant), or time-variant but individual-invariant. It also includes remainder a stochastic disturbance term that is both dependent on individual and time.

The estimation equation for the panel data model is given below (Ashenfelter *et al.*, 2003).

$Y_{it} = \alpha + X_{it}\beta + \varepsilon_{it}$

where $\varepsilon_{i,t} = \mu_i + \lambda_t + \nu_{i,t}$, i(region) = 1, 2, ..., N, t(year) = 1, 2, ..., T

μ_i = unobservable individual effect

λ_t = unobservable time effect

$\nu_{i,t}$ = remainder stochastic disturbance term.

The model is divided into either a fixed effects model (FEM) or a random effects model (REM) depending on the form of the error term. In the FEM, it is assumed that each subject has its own specific characteristics due to inherent individual characteristic effects in the error term, thereby allowing differences to be intercepted between subjects. Fixed effects are due to the fact that, although the intercept may differ across subjects, each entity's intercept does not vary over time, that is, it is time-invariant (Gujarati and Porter, 2009). The REM assumes that individual characteristic effect changes stochastically, and then differences in subjects are not fixed in time and independent between subjects. Individual differences vary over cross-sections (i.e., subject) as well as time (Gujarati and Porter, 2009).

It is essential to determine which model (FEM or REM), is more suitable for this study. The choice of model is affected by the characteristics of the data itself, but the practical selection of an analytical model is determined by applying the Hausman specification test (Greene, 1997).

The estimation equation for the Hausman specification test is given below.

$$H = (\widehat{\beta_{RE}} - \widehat{\beta_{FE}})'(\widehat{\Sigma_{RE}} - \widehat{\Sigma_{FE}})^{-1}(\widehat{\beta_{RE}} - \widehat{\beta_{FE}})$$

Where

$\widehat{\beta_{RE}}$ = Matrix of parameter values estimated by random effects model

$\widehat{\beta_{FE}}$ = Matrix of parameter values estimated by fixed effects model

$\widehat{\Sigma_{RE}}$ = Covariance matrix for random effects model

$\widehat{\Sigma_{FE}}$ = Covariance matrix for fixed effects model.

The null hypothesis underlying the Hausman specification test is that the FEM and REM estimators do not differ substantially. The test statistic developed by Hausman (1978) has an asymptotic χ^2 distribution. If the null hypothesis is rejected, the conclusion is that the REM is not appropriate because the random effects are probably correlated with one or more regressors (Gujarati and Porter, 2009). The FEM was selected for this study because the estimated χ^2 value is highly significant.

The FEM is divided into a one-way fixed effects model (one-way FEM) and a two-way fixed effects model (two-way FEM), depending on the hypothesis of the error term. The one-way FEM assumes that the individual effect of the observation unit is invariant over time. The two-way FEM assumes that both the individual effect and the time effect have a constant influence over all observation units.

Individual effects are defined as unique, unobservable properties of the 17 cities in this study. Time effects, which target measurement data from 1996 to 2009, are defined as unique properties of each time series. The production of air pollutants may be caused by unique and unobservable traits of individual cities. Moreover, air pollution control technologies and policies can potentially influence air quality in the mid- to long-term, and may improve or worsen. It was considered that individual effects and time effects must be regulated in order to clearly understand the influence of each explanatory variable, and the two-way FEM was used for TSCSREG (Time Series Cross Section Regression) in SAS software (ver. 9.2).

4.3 The Relationship between Urban Compactness and Air Pollution

The panel data model on the relationship between urban characteristics and air pollution indicates that urban compactness partly contributes to improvements in air quality. In order to better understand the effects of urban compactness on air pollution, factors which affect air quality were controlled. SO_2 concentrations decreased by 0.15 ppb/yr[10] as the proportion of green land increased ($p < 0.05$) (Table 4.2), empirically showing that green land serves an important function in air pollution mitigation.

The same comparison for NO_2 is presented in Table 4.3, which shows that, a rise in net density led to an increase of 0.19 ppb/yr ($p < 0.1$). It is relevant that NO_2 is emitted from sources caused by high-density and local emission control measures, which can be part of the pollution solution.

The effects of urban compactness on CO concentration values had both dimensions: dispersion of CO by green land versus spatial concentration of CO emissions by high-density. It showed that CO concentrations decreased by 13.7 ppb/yr with increase in the proportion of green land ($p < 0.05$), while net density was the cause of rising CO ($p < 0.05$) (Table 4.4). Green land has relatively larger effect on CO reduction compared to SO_2.

PM10 concentrations significantly increased by 2.20E-05 $\mu g/m^3$/yr with a growing number of people ($p < 0.05$) (Table 4.5), indicating that larger the size of an urban area, higher the PM10 concentrations. Meanwhile, PM10 was irrelevant to urban compactness like O_3 (Table 4.6). PM10 and O_3 are not usually emitted directly into the air and are created by chemical reactions of primary pollutants or previously emitted gases. It is difficult to identify

[10] ppb = parts per billion, 1ppb = 1ug/L

emission sources and to regulate the total emissions because there are likely to be gas-to-particle conversions. Therefore it is preferable to monitor primary pollutants and sources overall.

Some claim compact growth reduces automobile exhaust gas, while others report that it actually exacerbates air pollution. Vehicle dependency was predicted to be related to NO_2 and CO, which is mainly produced by automobile exhaust gas, but the relationship was not significant in this study.

The panel data model shows two dimensions of urban compactness for air quality. This indicates that high-density development causes the spatial concentration of emission sources, which lead to an increase in pollution, while green land secured from high-density development can encourage dispersion and dilution, resulting in air pollution reduction. Although this result is confined to only certain pollutants, it supports the argument that the compact city allows for preservation of green lands (Jenks *et al*., 1996; Williams *et al.*, 2000) and shows low levels of pollutant emissions (Fenger *et al*., 1998; Marques and Smith, 1999; EPA, 2001; Borrego *et al*., 2006; Stone *et al*., 2007).

Table 4.2 Panel data model estimates for urban characteristics and SO_2

SO_2 (n=238)	Estimate	Std. Err	t-value	Pr > |t|
Proportion of green land	-1.50E-04	6.90E-05	-2.17 **	0.03
Net density	7.60E-06	7.55E-06	1.01	0.32
Manufacturing	4.98E-04	4.31E-04	1.15	0.25
Vehicle dependency	-3.15E-02	2.48E-02	-1.27	0.20
Population	4.93E-09	0.00E+00	.	.
Intercept	6.32E-03	1.76E-03	3.58	0.00
R-square	0.828			

n: Number of samples *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

Table 4.3 Panel data model estimates for urban characteristics and NO_2

NO_2 (n=238)	Estimate	Std. Err	t-value	Pr > |t|
Proportion of green land	4.65E-06	1.20E-05	0.39	0.80
Net density	1.90E-04	1.09E-04	1.74*	0.08
Manufacturing	9.82E-04	6.81E-04	1.44	0.15
Vehicle dependency	-3.55E-02	3.91E-02	-0.91	0.37
Population	7.74E-09	0.00E+00	.	.
Intercept	1.45E-02	2.78E-03	5.230	0.00
R-square	0.810			

n: Number of samples *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

Table 4.4 Panel data model estimates for urban characteristics and CO

CO (n=238)	Estimate	Std. Err	t-value	Pr > |t|
Proportion of green land	-1.37E-02	5.31E-03	-2.58**	0.01
Net density	1.30E-03	5.80E-04	2.25**	0.03
Manufacturing	7.14E-03	3.31E-02	0.22	0.83
Vehicle dependency	-3.48E+00	1.90E+00	-1.83	0.17
Population	-2.79E-08	0.00E+00	.	.
Intercept	8.00E-01	1.35E-01	5.91	0.00
R-square	0.767			

n: Number of samples *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

Table 4.5 Panel data model estimates for urban characteristics and PM10

PM10 (n=126)	Estimate	Std. Err	t-value	Pr > |t|
Proportion of green land	-4.34E+01	2.99E+01	-1.45	0.15
Net density	2.28E-01	7.25E-01	0.31	0.75
Manufacturing	2.26E-01	2.56E-01	0.88	0.38
Vehicle dependency	-7.28E+02	4.32E+02	-1.68	0.11
Population	2.20E-05	1.10E-05	2.05**	0.04
Intercept	7.56E+01	2.29E+01	3.30	0.00
R-square	0.698			

n: Number of samples *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

Table 4.6 Panel data model estimates for urban characteristics and O_3

O_3 (n=238)	Estimate	Std. Err	t-value	Pr > |t|
Proportion of green land	9.10E-06	8.13E-06	1.12	0.26
Net density	-4.00E-05	7.40E-05	-0.59	0.55
Manufacturing	9.20E-05	4.64E-04	0.20	0.84
Vehicle dependency	-2.61E-02	2.67E-02	-0.98	0.33
Population	4.01E-09	0.00E+00	.	.
Intercept	277E-02	1.90E-03	14.59	0.00
R-square	0.606			

n: Number of samples *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

4.4 Summary

The panel data model analysis was performed to evaluate the effects of urban compactness on air pollution by controlling for factors which affect air quality. Urban compactness was defined as the high-density built form with a proportion of the green land within a standard spatial unit. That is, the measurement of compactness is limited to the number of people within a built-up area (net density) and the ratio of green land area to an administrative district area (proportion of green land). According to the current compactness definition, there are two meanings: the spatial concentration of emission sources by high-density versus the dispersion of pollutants by green land. The relative magnitudes of opposing effects determine air quality.

Emission concentrations of NO_2 and CO significantly increased with a rise in net density (Table 4.7). It is concluded that high-density may cause concentration of sources and get worse urban air quality and it is therefore required to local emission controls. It showed that the higher ratio of green land to an administrative district area, the lower concentrations of SO_2 and CO (Table 4.7). It revealed that green land was relatively more effective to decrease CO compared to SO_2, suggesting that the dispersion according to green land decrease pollution level. In other words, activity densities within the limited space result in concentrating emission sources, but contribute to mitigate air pollution owing to secured green land. As a result, there are two dimensions to the relationship between urban compactness and air pollution problems.

PM10 and O_3 were irrelevant to urban compactness but PM10 increased with a growing number of people (Table 4.8), indicating that larger the size of an urban area, the higher PM10 concentrations. PM10 and O_3 are produced by chemical reactions of primary pollutants or previously emitted gases and so the total emissions regulation is effective way to reduce pollution.

Table 4.7 Summary of pollutants' characteristics, sources, dispersion, and effects of urban compactness on air pollution (SO_2 and NO_2)

pollutant	Characteristics	Emission sources	Effects of compactness on air pollution	Atmospheric dispersion
SO_2	○ primary pollutants ○ Both gas phase and liquid phase oxidation of SO_2 occurs in the troposphere. The SO_3 reacts with water vapor, which is in sulfates (fine particulates)	○ combustion of fossil fuels (especially from coal and oil) ○ heating	○ proportion of green land ↑ ⇒ SO_2 ↓	○ Dispersion of air pollutants in the atmosphere differs depending on meteorological condition that is influenced by topographical siting and urban structure. ○ Dispersion of pollutants is related to planted open space.
NO_2	○ primary pollutants ○ NO_2 reacts with other constituents, forming nitrates, which is also in fine particulate form	○ auto mobiles ○ combustion processes of factories or power plants ○ heating	○ net density ↑ ⇒ NO_2 ↑	

Table 4.8 Summary of pollutants' characteristics, sources, dispersion, and effects of urban compactness on air pollution (CO, O_3, and PM10)

<table>
<tr><th>pollutant</th><th>Characteristics</th><th>Emission source</th><th>Effects of compactness on air pollution</th><th>Atmospheric dispersion</th></tr>
<tr><td>CO</td><td>○ primary pollutants

○ relatively nonreactive pollutants like PM10</td><td>○ motor vehicles

○ power plants or industrial sources, and buildings</td><td>○ proportion of green land ⇒ CO ↓

○ net density ↑ ⇒ CO ↑</td><td>○ The characteristics of dispersion are classified by the size of urban.</td></tr>
<tr><td>O_3</td><td>○ secondary pollutants

○ photochemical reactions of oxides of nitrogen and various species of hydrocarbons</td><td>○ solvent facilities

○ motor vehicles</td><td></td><td rowspan="2">○ At the neighborhood to city scale, increased turbulence levels caused by the relatively large obstacles produce larger dispersion.

○ At the regional scale, the urban area influence on the dispersion and can sometimes be detected several hundred kilometers.</td></tr>
<tr><td>PM10</td><td>○ secondary pollutants

○ chemical reactions of primary pollutants

○ It may also from gases that have been previously emitted, such as when gases released from burning fuels react with sunlight and water vapor</td><td>○ anthropogenic sources: combustion processes of factories, power plants, and vehicles; dusts from construction site; heating

○ natural sources: debris from live and decaying plant and animal life; wind-blown dust, desert, soil; particles from volcanic and forest fires</td><td>○ No. of population ↑ ⇒ PM10 ↑</td></tr>
</table>

Chapter 5: Conclusion

5.1 Summary of Major Findings

Research on the compact city, which is still debated in contemporary planning literature, has mainly been conducted with concern for the correlation between urban structural characteristics and air pollution. There are few studies which investigate how much influence urban compactness has on air quality. When taking into consideration that environmental damage from urban development is long-term and cumulative, air pollution problems should be analyzed as a time-series approach. A model accounting for intra- and inter-regional characteristics is required since changes in urban characteristics make a difference for air pollution and the scope of influence varies by time and spatial variability. Unique and unobservable traits of urban need to be employed as well because the advances in technology and policies for air pollution mitigation can potentially influence air pollution in the mid- to long-term.

The panel data model allows for optimal modeling results not only by regulating estimate errors that arise from the time-series process and regional unit data but also by giving proper treatment to omitted unobservable variables that have a significant effect on air pollution difference econometrically. Therefore, it is considered that the two-way fixed effects model helps to understand the impact of spatiotemporal changes in urban characteristics on air pollution.

This study attempted to identify that high-density development causes the spatial concentration of emission sources, which may result in increase of air pollution. The distribution of pollutant concentrations according to the distance from the CBD showed high or low when getting closer to the CBD. PM10 emissions were concentrated in the CBD at the local level, while the opposite was true with PM10 at the metropolitan level. The distribution of O_3 concentrations was low in the CBD at the local and metropolitan level, while NO_2 and CO concentration values appeared high at the metropolitan level. With regards to the spatial distribution of pollution levels at the interurban level, the distribution of CO concentrations appeared significantly high closer to the CBD but NO_2 concentrations had a low or an even distribution in the CBD. The pollution level distribution of PM10 was low in the CBD only from 2006 to 2008. Therefore, it cannot be determined that air pollution is aggravated by the spatial concentration of emission sources, suggesting that air quality may be varied according to the dispersion and dilution of pollutants which are influenced by urban characteristics and the diverse conditions they exist in.

The main concern of this study was to reveal the effects of urban compactness on air pollution by controlling for factors which affect air quality. Urban compactness was defined as the high-density built form with a proportion of green land within a standard spatial unit. Two meanings involved in the current compactness definition were presented as follows. High-density brings the spatial concentration of emission sources, which lead to an increase in pollution, while green land secured from high-density development can encourage dispersion and dilution, resulting in a reduction of air pollution. The relative magnitudes of opposing effects determine air quality. Although the results are confined to only certain pollutants, urban compactness had two dimensions to air pollution. NO_2 and CO concentrations significantly increased with a rise in net density, while SO_2 and CO decreased with increase in proportion of green land and more importantly, green land was relatively more effective at decreasing CO compared to SO_2. Meanwhile, PM10 and O_3 emission values were irrelevant to urban compactness and PM10 increased with population growth, implying that PM10 has a potential to increase as the urban size increases**.**

5.2 Implications

This study may offer a clue to the debate on whether the compact city improves the air quality or not. There have been arguments for and against the effects of compact development on air pollution, and a number of studies have overlooked the air pollution path which pollutants are dispersed or diluted in the air. The variability of air pollution is influenced by the dispersion and dilution process which determines concentrations of air pollutants to vary with regard to time and space. Therefore, urban air pollution problems may require not only an understanding of spatial and temporal differences in urban characteristics but a comprehension of the dispersion mechanism, which undergoes complex diffusion in the atmosphere.

As seen in the results of pollutant concentration distribution according to the distance from the CBD, air pollution may or not be aggravated by the spatial concentration of sources and the pollution levels vary in terms of the respective dispersion and formation of pollutants. There is a need to differentiate whether the emission sources are concentrated at the local or regional level and to establish air pollution control strategies appropriate for such conditions.

Many studies have been reported about the relationship between the compact city and air pollution, but no studies have figured out why the effects of urban compactness on air pollution are inconsistent. Although the results of this study are confined to only certain pollutants, urban compactness has two dimensions to air pollution. The dispersion and dilution of pollutants may hold the answer. As a result, this suggests that high-density developments that secure enough green land can enlarge dispersion and contribute to reduced pollution levels.

Air pollution assessment is desirable to determine average concentration levels of an entire city rather than on a local scale. The transport and distribution of pollutants in the ambient air is influenced by emission sources and the dispersion process. The extent and magnitude of dispersion may vary in different pollutants and may depend upon urban characteristics and the diverse conditions they exist in. It is necessary to comprehend in detail the physical and chemical processes that govern the formation and dispersion of pollutants, and their impact. More importantly, understanding historical emission trends is essential as this knowledge can be used to guide appropriate antipollution measures. It is also imperative to develop an integrated management system, which minimizes local-to citywide emissions and thus regulate total urban emissions. Preferential controls and optional management strategies need to be followed to respond to changes in the pollution levels, especially the maximum concentration at a certain period.

5.3 Limitations and Recommendations

This study investigated the effects of urban compactness on air pollution but it did not quantitatively distinguish different degrees of compactness. It has been suggested that encouraging decentralized concentration or polycentric urban forms lowers emissions. Questions remain surrounding exactly how compact the compact city should be, and to what extends beyond a simple population density increase and even a sufficient provision of green land secured by high-density in urban developments. The dispersion of pollutants may differ from the physical characteristics of individual cities besides meteorological conditions and it is necessary to figure out the intensification of development and availability of green land more accurately.

Urban air pollution can be reduced by constructive city planning. Although this study did not find that the spatial configuration of green land affects on air quality, it can be a key factor that contributes to air pollution mitigation along with the total amount of greenery. According to the definition of urban compactness, the category of green land was subjected to forests, parks, and recreational areas but forests make up most of the green land in Korea. There is a concern that this study may overstate the importance of the mass of greenery and instigate indiscriminate infill developments within brown fields. It has been demonstrated that even very small open spaces in an urban area can contribute to the dispersion of pollutants and reduce pollution, and this especially suggests that the value of open spaces within built-up areas must be taken into account. In order to allocate significant planted open spaces in new developments and redevelopments, it is important to evaluate the degree of centralization or decentralization that is required at the urban development stage. It is necessary to understand the current availability of planted open spaces and the spatial distribution of sources depending on differences in urban forms when designing development strategies.

Environmental planning is given more weight in urban planning, but it has failed to work in line with atmospheric environmental policy. This study provides an opportunity to evaluate policy outcomes for the improvement of atmospheric environmental aspects in relation to sustainable land use. Measures taken against pollution should be supplemented concerning spatiotemporal changes in urban characteristics and the government needs to come up with more effective countermeasures to respond to the distribution of emissions.

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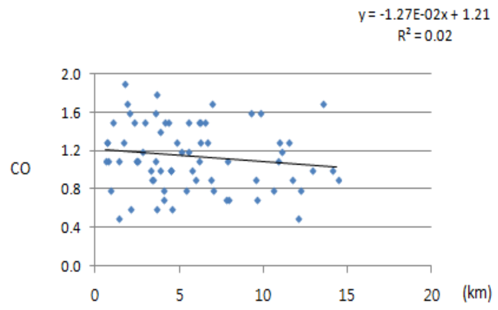
Appendix A. Linear model explaining the CO concentration distribution by the distance from CBD by annual



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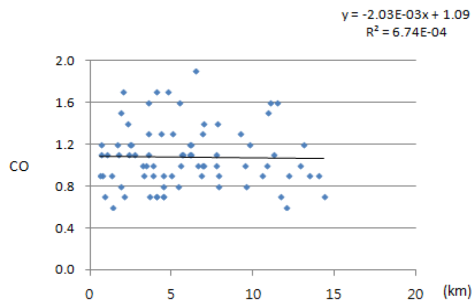

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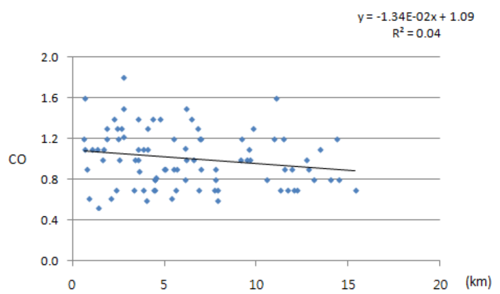

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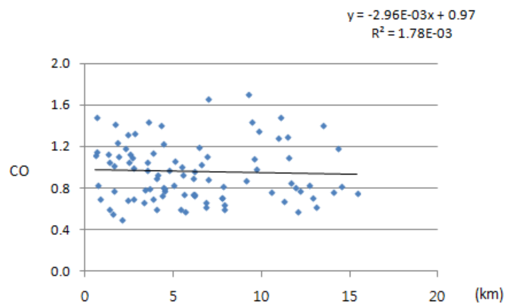

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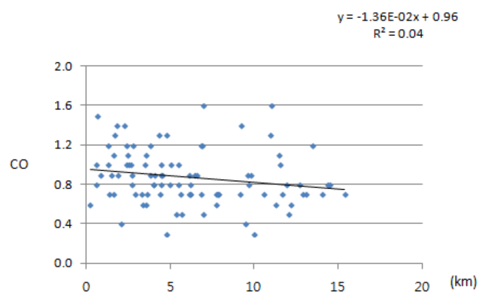

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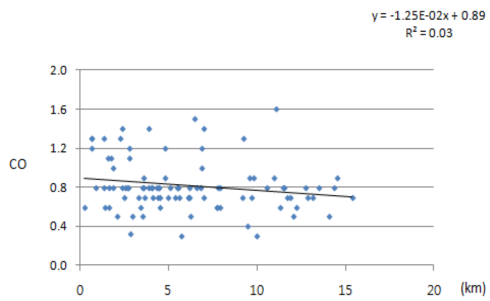
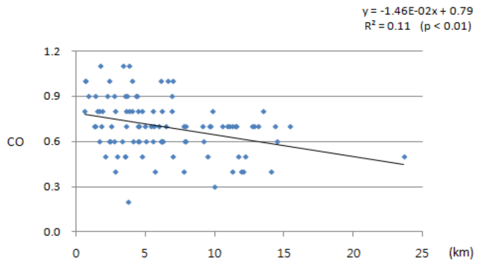


2001yr (n=95)

* n: Number of air quality monitoring stations in 17 cities, 1996 to 2009



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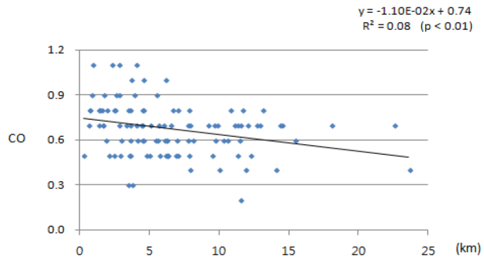

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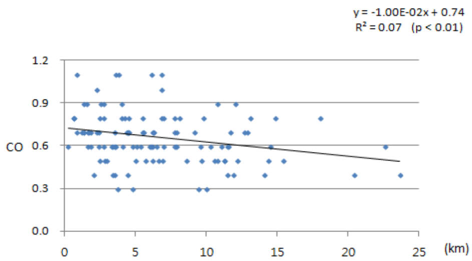

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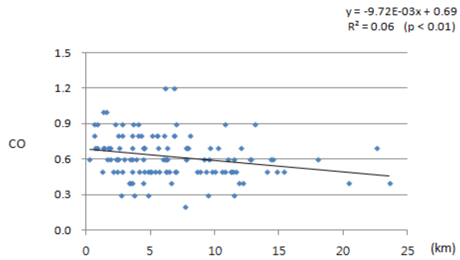

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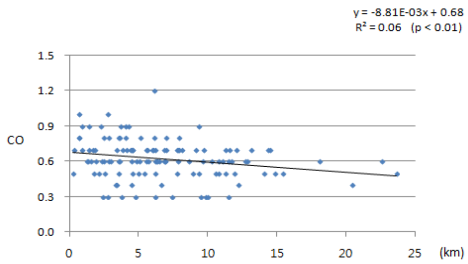

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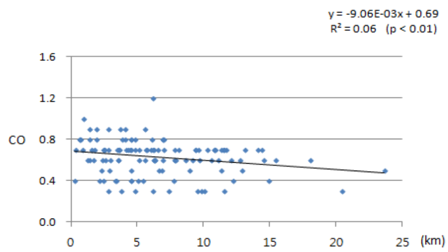

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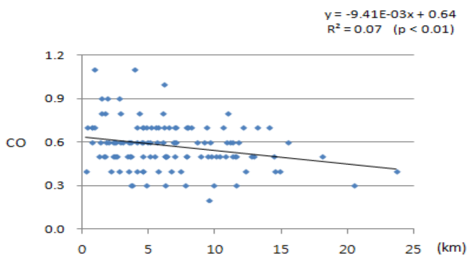

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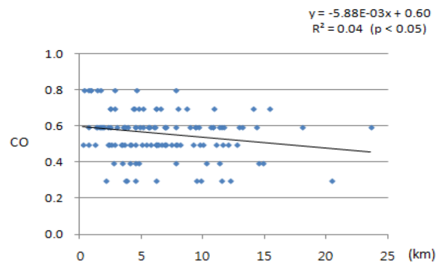
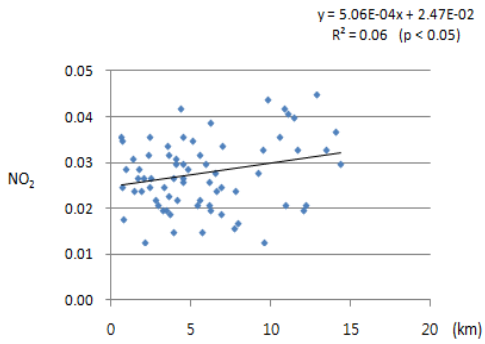


2009yr (n=124)

* n: Number of air quality monitoring stations in 17 cities, 1996 to 2009

Appendix B. Linear model explaining the NO_2 concentration distribution by the distance from CBD by annual



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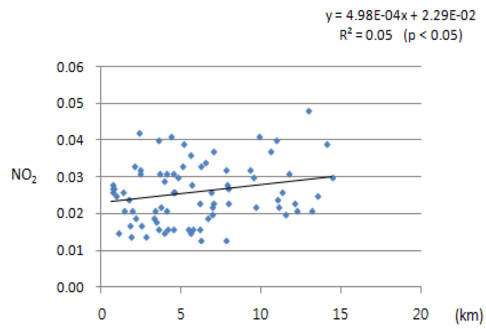

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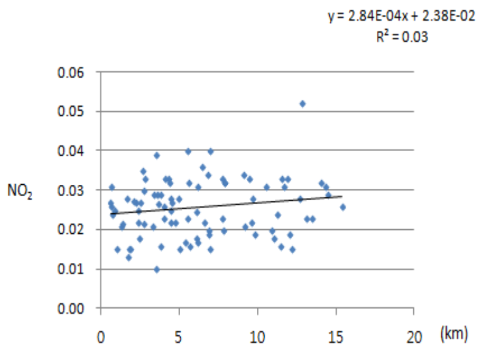

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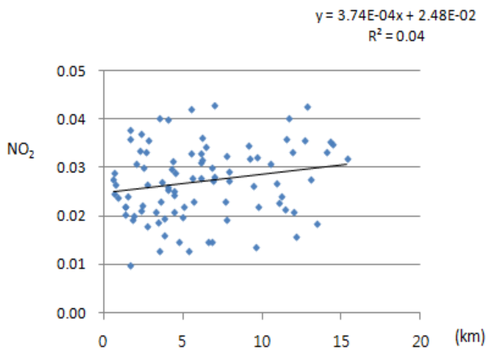

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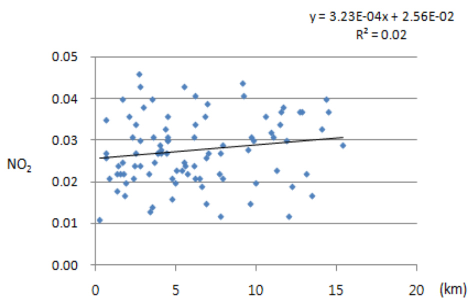
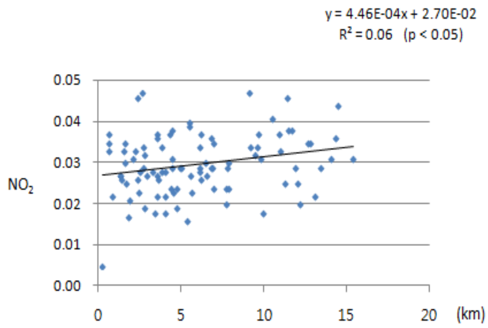
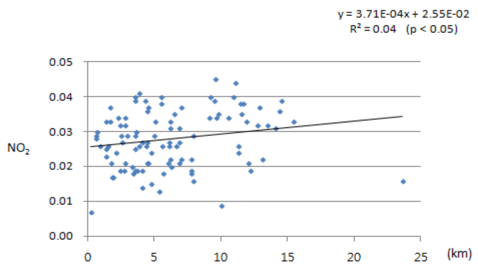


2000yr (n=93)

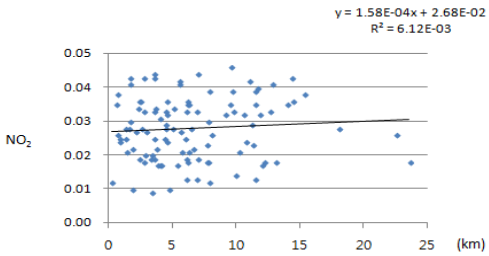


2001yr (n=95)

* n: Number of air quality monitoring stations in 17 cities, 1996 to 2009



2002yr (n=101)



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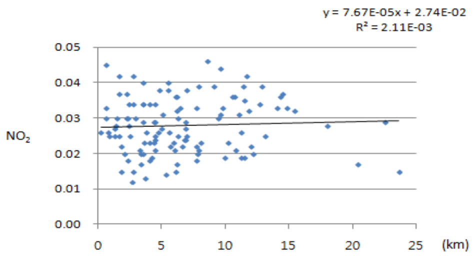
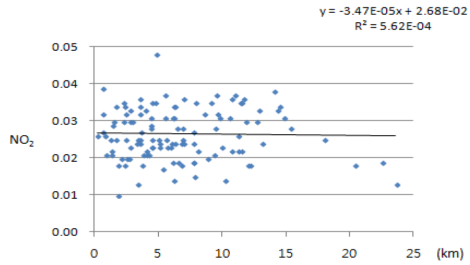
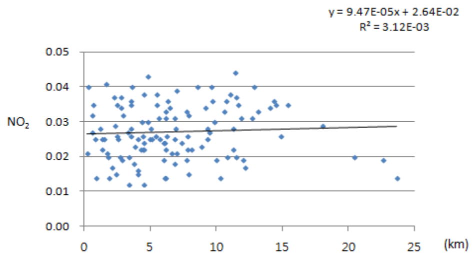


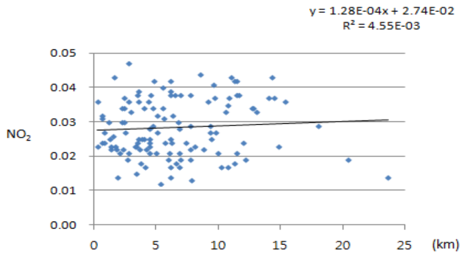
2004yr (n=117)



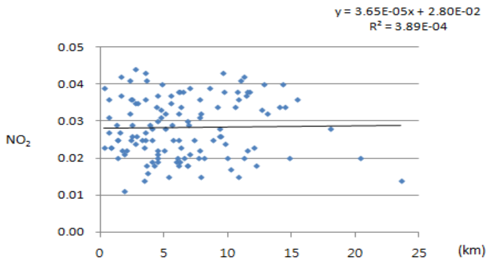
2005yr (n=119)



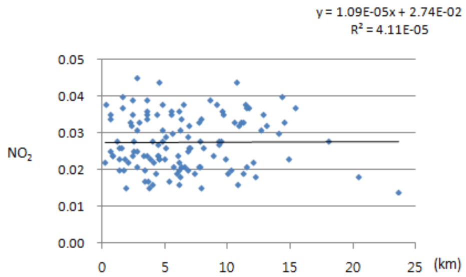
2006yr (n=120)



2007yr (n=122)



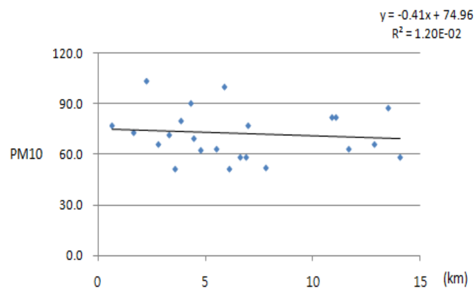
2008yr (n=124)



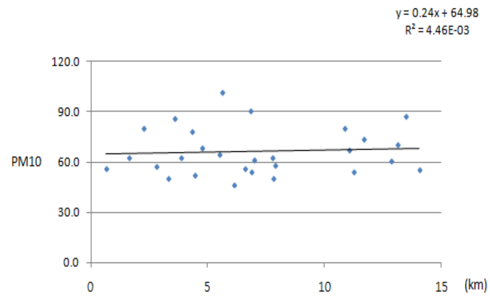
2009yr (n=124)

* n: Number of air quality monitoring stations in 17 cities, 1996 to 2009

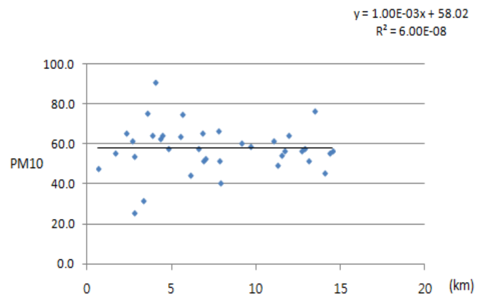
Appendix C. Linear model explaining the PM10 concentration distribution by the distance from CBD by annual



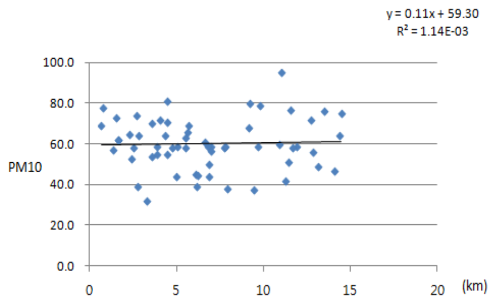
1996yr(n=23)



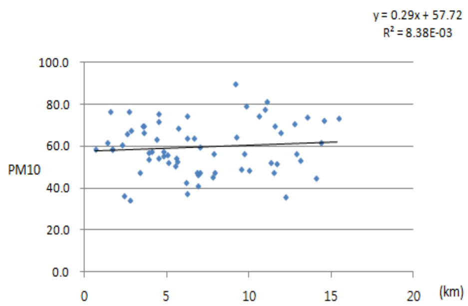
1997yr (n=28)



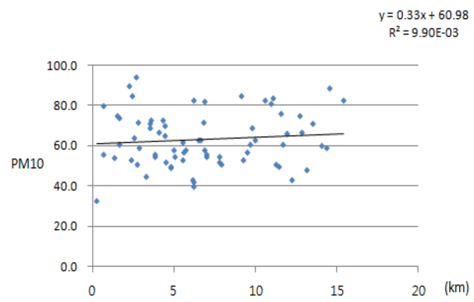
1998yr (n=37)



1999yr (n=60)

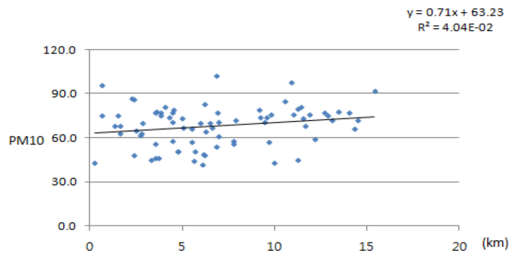


2000yr (n=66)

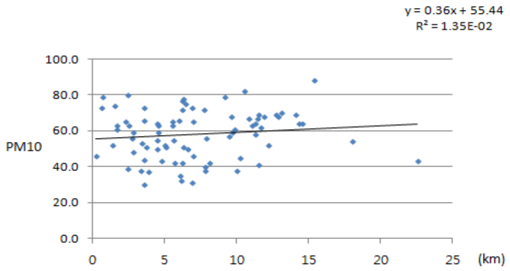


2001yr (n=71)

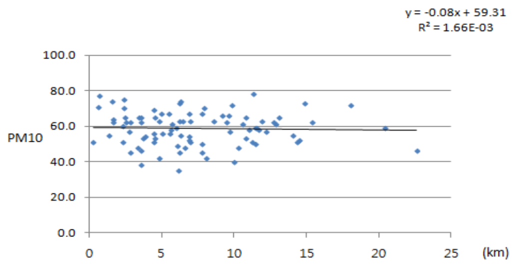
* n: Number of air quality monitoring stations in 17 cities, 1996 to 2009



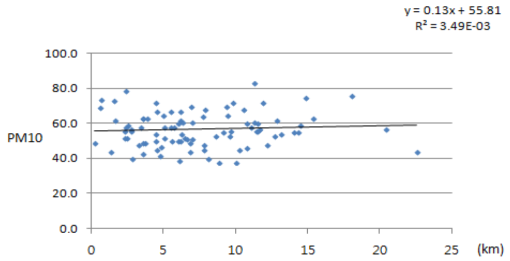
2002yr (n=77)



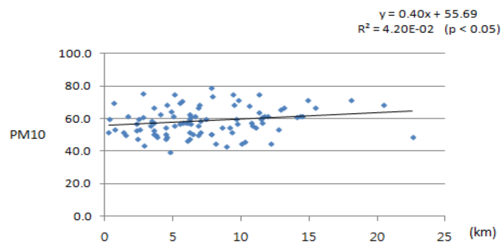
2003yr (n=80)



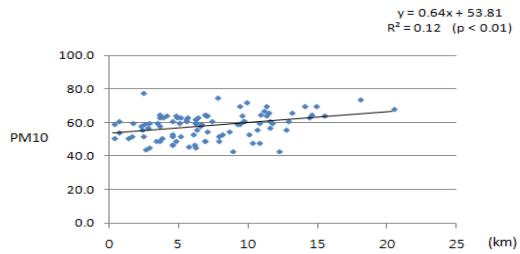
2004yr (n=88)



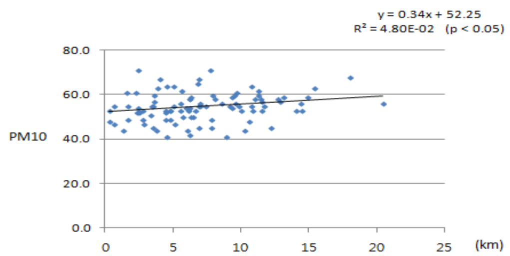
2005yr (n=90)



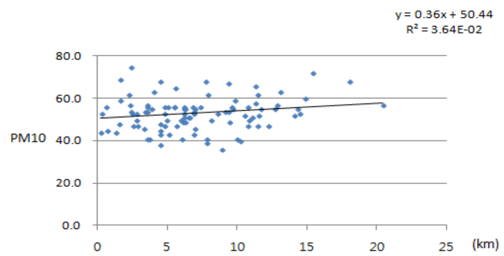
2006yr (n=95)



2007yr (n=95)



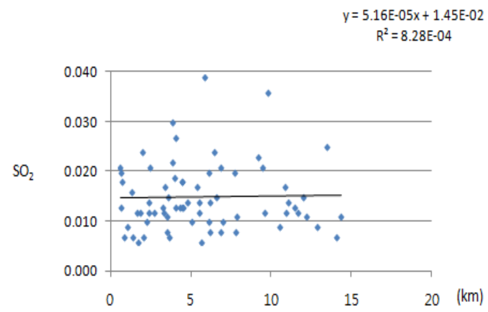
2008yr (n=97)



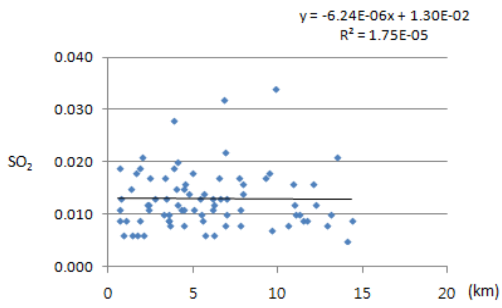
2009yr (n=97)

* n: Number of air quality monitoring stations in 17 cities, 1996 to 2009

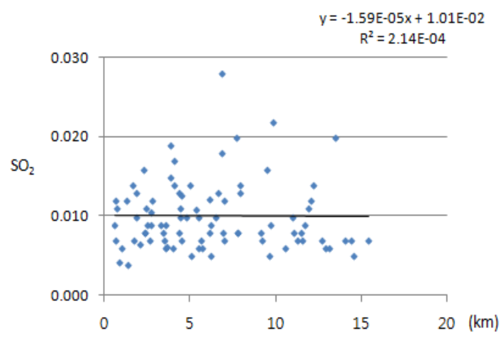
Appendix D. Linear model explaining the SO_2 concentration distribution by the distance from CBD by annual



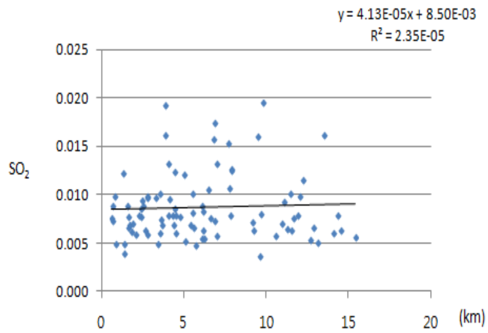
1996yr (n=70)



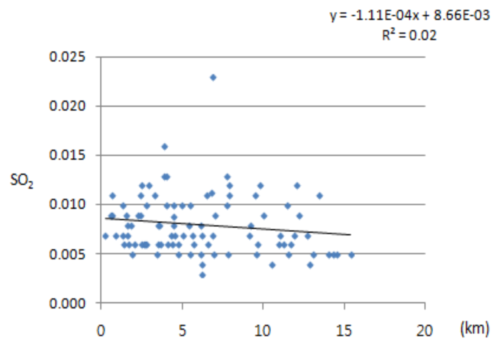
1997yr (n=78)



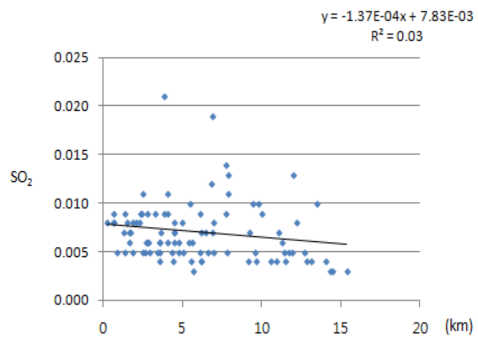
1998yr (n=87)



1999yr (n=90)

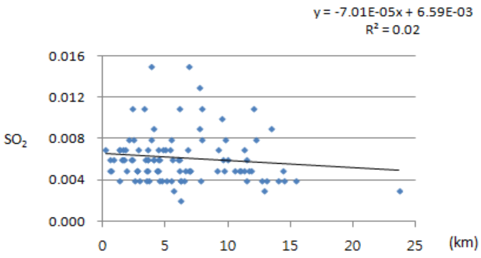


2000yr (n=93)

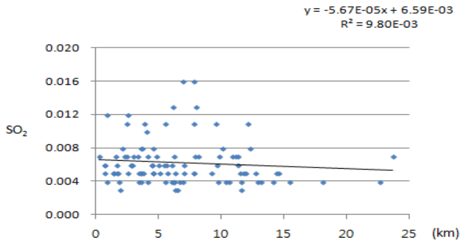


2001yr (n=95)

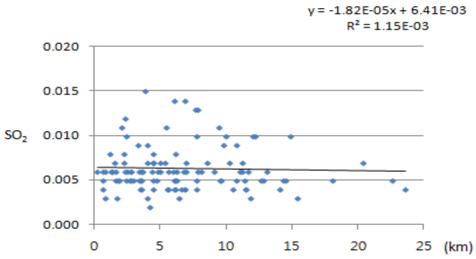
* n: Number of air quality monitoring stations in 17 cities, 1996 to 2009



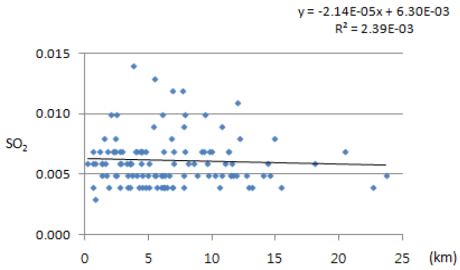
2002yr (n=101)



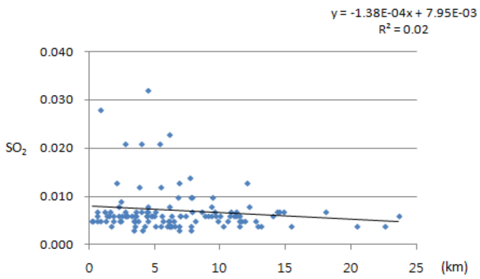
2003yr (n=106)



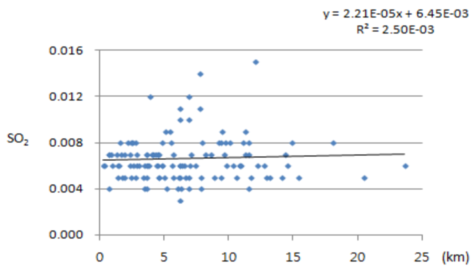
2004yr (n=117)



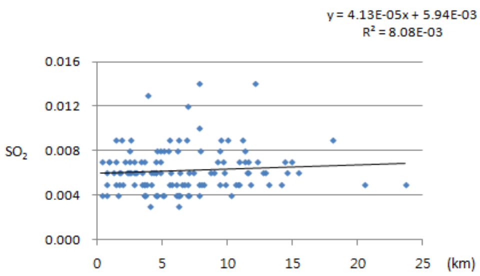
2005yr (n=119)



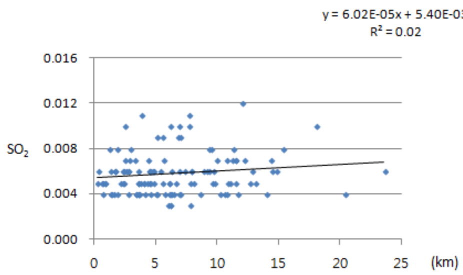
2006yr (n=120)



2007yr (n=122)



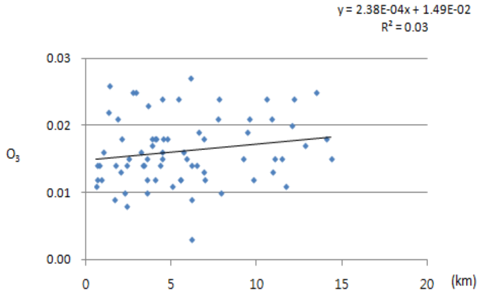
2008yr (n=124)



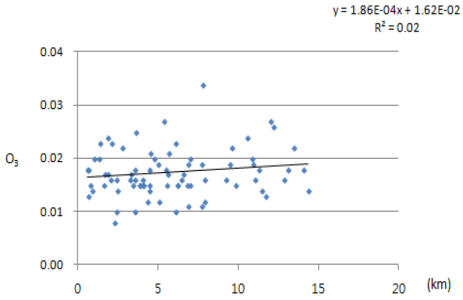
2009yr (n=124)

* n: Number of air quality monitoring stations in 17 cities, 1996 to 2009

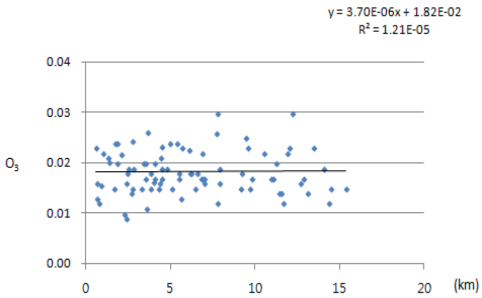
Appendix E. Linear model explaining the O_3 concentration distribution by the distance from CBD by annual



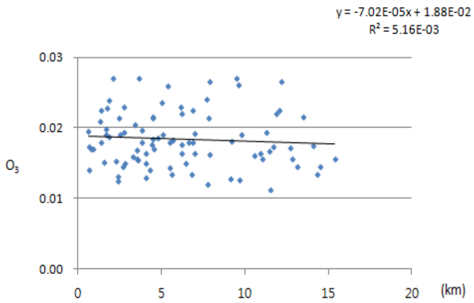
1996yr (n=71)



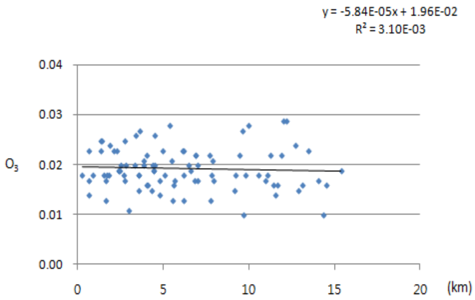
1997yr (n=78)



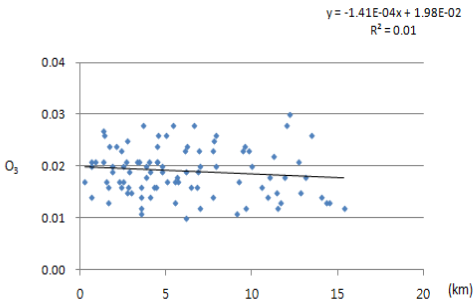
1998yr (n=87)



1999yr (n=90)

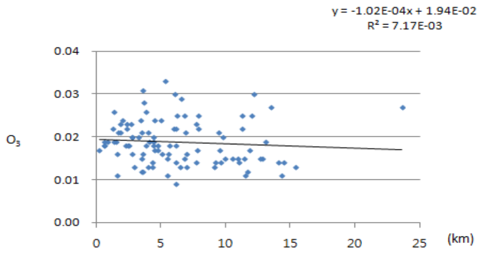


2000yr (n=93)

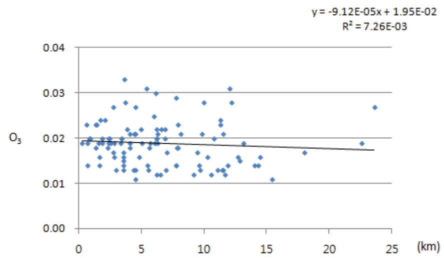


2001yr (n=95)

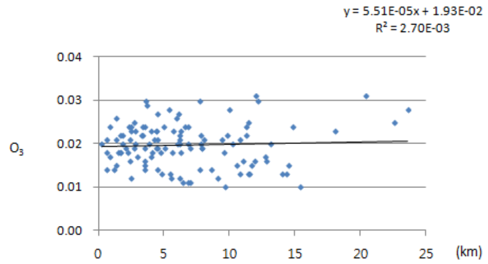
* n: Number of air quality monitoring stations in 17 cities, 1996 to 2009



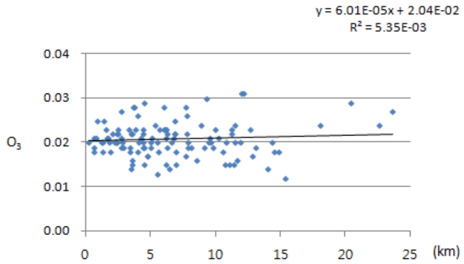
2002yr (n=101)



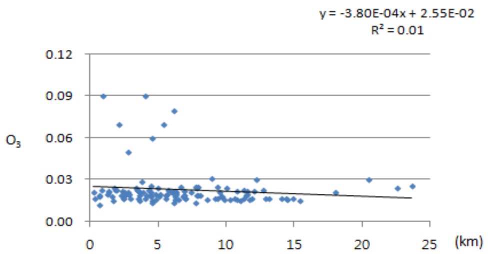
2003yr (n=106)



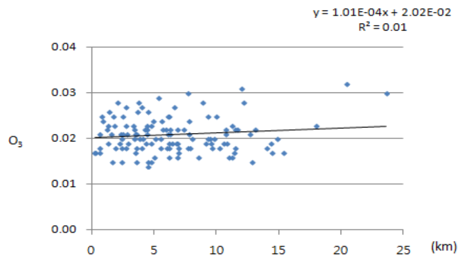
2004yr (n=116)



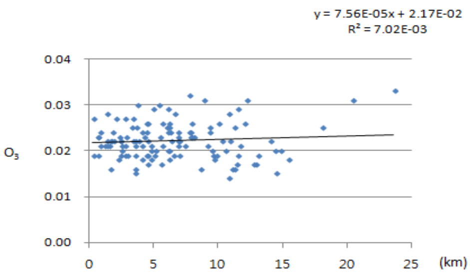
2005yr (n=119)



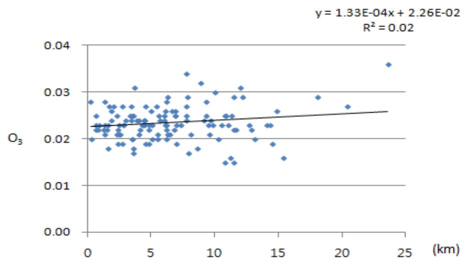
2006yr (n=120)



2007yr (n=122)



2008yr (n=124)



2009yr (n=124)

* n: Number of air quality monitoring stations in 17 cities, 1996 to 2009

국문초록

압축도시의 지속가능성은 아직 충분히 입증되지 않았으며, 특히 압축도시와 대기오염간의 관계에 대해서는 논란의 여지가 있다. 압축도시에 대해 찬반 입장을 갖는 연구자들은 개발밀도의 변화가 대기오염에 미치는 영향을 일반화 시키는데 한계를 가지는데 대기오염물질의 분산이 이루어지는 대기오염 경로에 대한 고려가 없었기 때문이다. 이에 본 연구는 대기분산 메커니즘을 적용하여 대기오염 배출원의 공간적 집중에 따른 오염농도 변화를 살펴보고 도시 압축도가 대기질에 미치는 영향을 평가하여 대기환경관점에서 지속가능한 도시개발을 유도하는 것을 목적으로 한다.

도시계획에서 대기오염 영향에 관한 평가는 여전히 근시안적인 접근으로 이루어지고 있다. 도시개발에 따른 환경적 폐해가 장기적이고 누적적인 것을 감안해 볼 때 대기오염문제는 시계열 방식의 접근이 요구된다. 지역내 그리고 지역간 특성에 대한 고려도 함께 이루어져야 하는데, 도시 특성의 변화가 대기오염의 차이를 가져올 뿐만 아니라 대기오염에 미치는 영향의 크기도 시공간적 차이에 따라 달라질 수 있기 때문이다. 대기오염저감을 위한 기술 진보나 정책은 중장기적으로 대기오염에 영향을 미칠 수 있으므로 도시의 고유하고 비가시적인 특성들에 대한 고려도 필요하다. 이러한 측면에서 볼 때 패널데이터 모형이 분석에 적합한데, 이 모형은 시계열 데이터 처리와 지역 단위의 데이터에서 발생할 수 있는 추정 오차를 조정할 뿐만 아니라 대기오염에 중요한 영향을 줄 수 있으나 누락될 수 있는 변수들을 효율적으로 적절히 처리해 줌으로써 적합한 모형 결과를 도출할 수 있는 것이 특징이다.

본 연구에서는 고밀개발이 배출원을 집중시켜 결국 대기오염을 증가시킨다는 주장에 대해 실증적으로 검증해 보았다. CBD로부터의 거리에 따른 오염

물질의 농도분포를 국지적 규모 수준, 수도권 규모 수준 및 도시간 규모 수준으로 구분하여 분석한 결과, 오염농도는CBD에 가까울수록 높거나 혹은 낮은 것으로 나타났다. 그리고 어떤 경우엔 CBD로부터의 거리에 따라 고른 분포를 보이는 오염물질도 있었다. 미세먼지는 국지적 규모 수준에서 CBD에 가까울수록 오염농도가 높았으나 수도권 규모 수준에서는 반대의 결과를 보였다. CBD에 가까울수록 오존 농도는 국지적 그리고 수도권 규모 수준에서 낮은 분포를 보인 반면, 이산화질소와 일산화탄소는 수도권 규모 수준에서 약간 높은 농도 분포를 보였다. 도시간 규모 수준에서는 CBD에 가까울수록 일산화탄소는 대체로 오염농도가 높게 나타난 반면 이산화질소는 낮은 농도 분포를 보였다. 미세먼지 농도는 2006년부터 2008년까지 단지 세 차례만 CBD에서 낮게 나타났다. 결과적으로 대기오염은 배출원의 공간적 집중으로만 해석할 수 없는 것으로 밝혀졌는데, 이는 오염농도가 대기분산의 범위나 정도에 따라서도 달라질 수 있음을 시사한다. 따라서 배출원이 국지적 혹은 광역적 수준에서 집중되어 있는지 구별할 필요가 있으며 이들 상황에 맞추어 대기오염통제 전략을 마련해야 한다.

본 연구의 주된 관심은 대기질에 영향을 주는 요인들을 통제하면서 도시 압축도가 대기오염에 미치는 효과를 파악하는 것이다. 이 연구에서 도시 압축도는 일정한 공간내에서 시가화지역의 개발 밀도를 높이는 동시에 녹지 비율을 얼마나 확보하는가로 정의된다. 이는 두 가지 의미를 내포한다. 한정된 공간내에서의 집중된 활동은 배출원의 집중을 초래하여 오염을 증가시키는 반면, 녹지는 오염물질의 분산을 증가시켜 오염을 감소시킨다. 결과적으로 고밀과 녹지가 갖는 상반된 효과가 대기질을 좌우하게 된다. 패널데이터 모형의 결과를 살펴보면, 이산화질소와 일산화탄소 농도는 순인구 밀도가 증가할수록 높아지는 반면, 아황산가스와 일산화탄소는 녹지비율이 증가함에 따라 감소하는 것으로 나타났다. 그리고 녹지는 아황산가스에 비해 일산화탄소 저감에 상대적으로 효과적인 것으로 나타났다. 결국 압축도는 대기오

염에 대해 양면성을 가지는데, 오염물질의 분산에서 그 해답을 찾을 수 있다. 비록 특정 오염물질에 국한된 결과이나 녹지를 충분히 확보한 고밀개발이 대기오염 저감에 기여할 수 있음을 보여준다. 한편, 미세먼지 배출은 인구 규모가 커질수록 많아지는데, 도시 규모가 커짐에 따라 미세먼지 농도가 증가할 수 있음을 의미한다.

본 연구는 압축도시의 대기질 개선 유무에 대한 실마리를 제공한다는 점에서 의의를 가진다. 기존의 연구들은 대기오염 농도가 시공간적으로 달라질 수 있는 대기오염 분산에 의해 결정된다는것을 고려하지 못했는데, 대기오염문제에 대한 접근은 도시 특성의 시공간적 차이와 대기분산 메커니즘에 대한 이해를 요구한다. 오염물질의 분산 특성에 따라 분산이 대기질에 미치는 영향은 국지적 혹은 광역적으로 나타날 수 있으므로 대기오염총량을 규제하기 위해서는 통합관리가 필요하다. 그리고 대기오염배출 동향에 관한 정보를 마련하여 오염농도의 변화, 특히 특정 시기의 최대농도에 대해 대응할 수 있도록 우선적 통제와 선택적 관리가 병행되어야 한다.

주요어: 도시압축도, 고밀개발, 녹지, 대기오염, 대기분산, 지속가능성

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