

Traffic-related Air Pollution, PM<sub>2.5</sub>: The Case of Shanghai

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**Abstract**

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Vehicle emissions are the most contributory source of urban air pollution in the major metropolitan areas in Europe and the US, so much recent research has focused on transportation-related air pollution (TRAP). However, air pollution in Shanghai is now becoming much more serious than in most of the US, the result of both motorization and industrialization. Fine particulate matter (PM<sub>2.5</sub>) is to be blamed for the worst pollution in recent years. The record shows that the density of PM<sub>2.5</sub> is hovering around 400 micrograms per cubic meter, an almost unthinkable level. These days, the elderly and children are required to stay indoors and some air flights are cancelled. The economic success of Shanghai is counterbalanced by health concerns and the negative economic impacts associated with air pollution. This study focuses on TRAP-PM<sub>2.5</sub> and aims to explain how air quality differs within the region and where the vulnerable populations (adults over 65 and children under 14) live.

This study uses two methodologies to assess the changes and dispersion of PM<sub>2.5</sub> produced by the growing traffic volume between 2003 and 2009. Methodology 1 (TRAP by Year) aims to examine the shifting total amount of PM<sub>2.5</sub> emissions produced by the transportation sector over time. It is calculated with annual vehicle kilometers traveled (VKT) and related fuel consumption by vehicle types. Methodology 2 (TRAP by Location) focuses on the daily transportation-related PM<sub>2.5</sub> emissions across subareas in Shanghai. It is calculated via traffic density. Census, traffic and air pollution data, GIS Geostatistical tools, the Gaussian Dispersion Model and the Kriging

Interpolation Tool are used to analyze  $PM_{2.5}$  dispersion in the Inner City and the suburbs of Shanghai. The Shanghai TRAP-Spatial Health Hazard Priority Area (TRAP-SHHPA) scoring method is then developed to highlight the more polluted subarea locations where the vulnerable populations are concentrated.

The findings show that policies to restrict motorcycles and heavy trucks outside the central districts and the imposition of cleaner emission standards help to reduce the concentrations of  $PM_{2.5}$  in the city center. However, the study also shows that  $PM_{2.5}$  concentrations in suburban areas, primarily residential areas, are increasing.

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# Chapter 1 Introduction

## 1.1. BACKGROUND

### 1.1.1. INTRODUCTION OF RESEARCH SUBJECT

Shanghai, situated on the east coast of China and the estuary of Yangtze River, has been China's busiest transport hub and a major trade city since the 1840s. For the last 30 years, Shanghai has experienced dramatic growth in both population and economy.



(a) City structure of Shanghai



(b) Land use structure of the Shanghai Central City area

Source: Shanghai Comprehensive Plan 1999–2020

*Figure 1* Shanghai’s comprehensive plan and land use map, through 2020.

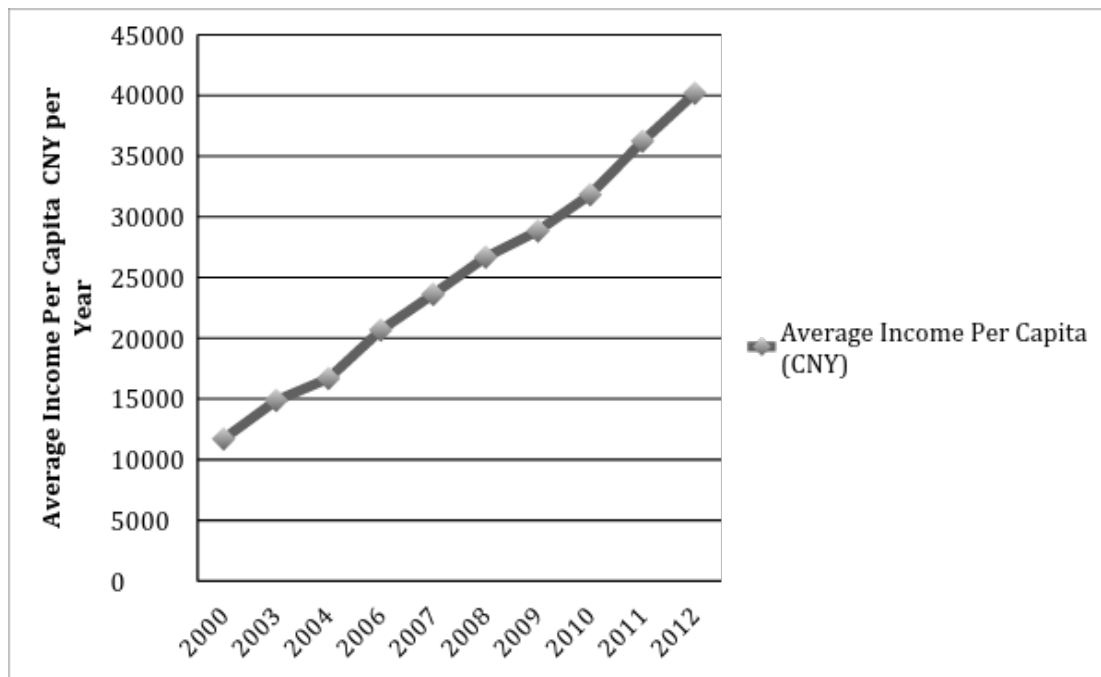
As with other big cities in the world, the city center of Shanghai became an aggregation of commercial and business enterprises surrounded by residential areas. Industrial zones are mostly located in the outer suburban areas.

Centuries ago, Shanghai was a small town located on the boundary of the current “Central City” shown in the picture above (Figure 1). As the Central City developed away from being a traditional trade city with low-speed, human-powered transportation such as rickshaws and bicycles, this area became characterized by its grid street pattern and narrower street spaces.

The outer suburban areas of the city became modernized in the last 20 years. As with other large cities in the world, the outer suburban areas of the city have larger block sizes and cul-de-sac-style streets.

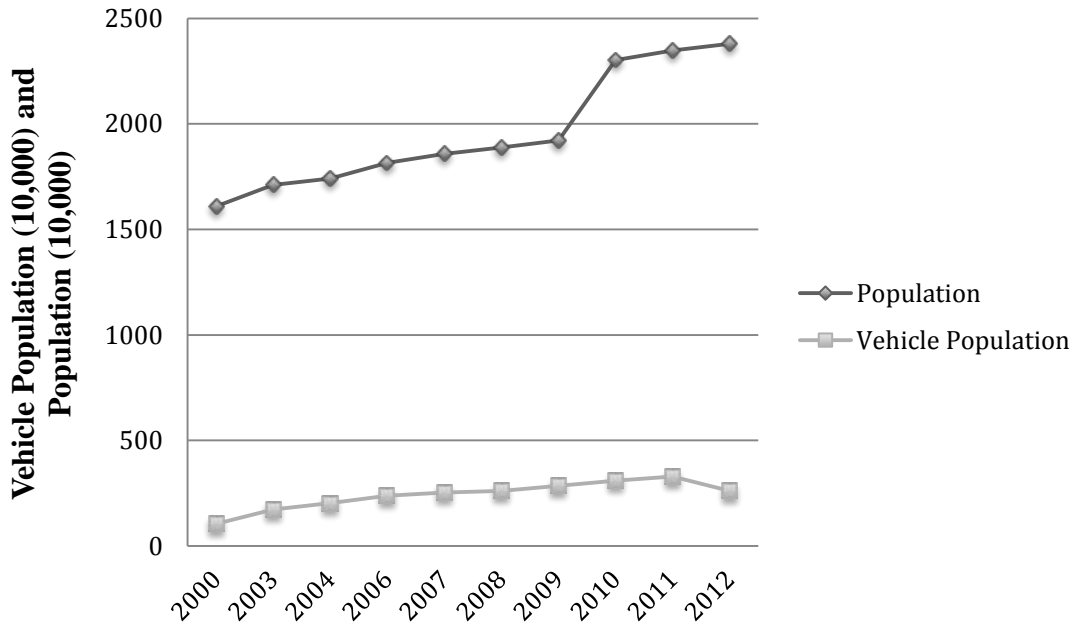
## 1.2. PROBLEM FACED

The total population of the city increased dramatically with development from 16.08 million in 2000 to 23.80 million in 2012. Furthermore, automobile ownership rose from 1.04 million in 2000 to 2.609 million in 2012 (see Figures 2 and 3). The population grew 1.5 times, but the vehicle population grew more than 2.5 times during the same period. Moreover, the average income per capita soared more than three times in 12 years. Coterminously, a tangle of health, quality of life, and efficiency concerns have pushed the city to pursue clean air, since it is now being plagued by air pollution problems.



Source: Shanghai Statistical Yearbook 2005, 2008, 2010, 2013

Figure 2. Average income per capita in Shanghai (2000–2012).



Source: Shanghai Statistical Yearbook 2005, 2008, 2010, 2013

*Figure 3.* Population and motor vehicle population (2000–2012).

It is known that smog hit Shanghai during the last two winters. It was reported that Shanghai’s concentration of PM<sub>2.5</sub> particles reached 602.5 µg per cubic meter on the afternoon of December 6, 2013 (Hoshiko & Tang, 2013). The atmospheric visibility decreased (see Figure 4), and people reported that they were “living in clouds of smog,” “having a headache,” and “beginning to cough” (Hoshiko & Tang, 2013). Furthermore, more children were reported to have asthma during smoggy weather (Wang, 2013). These events triggered discussions among people about air quality: What are the reasons for the smog and the deteriorating air quality of the city?



Source: ChinaFotoPress via Getty Images

*Figure 4. Smoggy days in Shanghai.*

### **1.2.1. DETERIORATING AIR QUALITY DUE TO INDUSTRIALIZATION?**

Shanghai's industrial development began decades before 1949 but was restricted to unpowered and manually operated processes. The progress of Shanghai's modern industrialization can be summarized into three stages. The first stage occurred between 1949 and 1979, before the foundation of the People's Republic of China. Some of the industries founded during this stage, such as cigarette factories and cotton mills, were maintained in the city center.

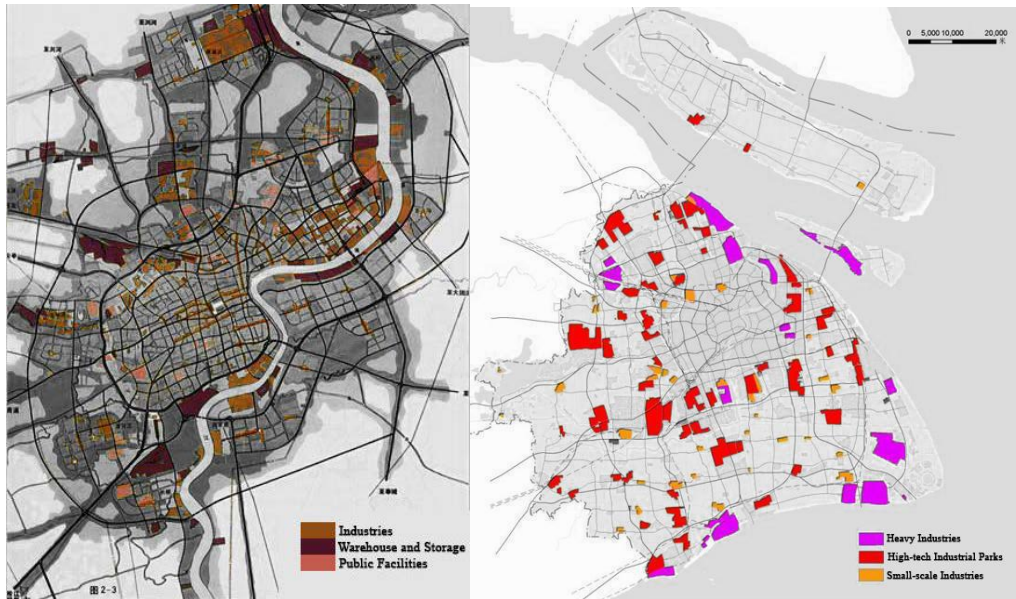
The second stage began in 1979, the year in which the Chinese Economic Reform (改革开放) began. In this stage, some heavy industries began to relocate to suburbs. The idea of industrial parks was put forward by the government as the dispersion of small-scale industries increased transportation distances and fragmented urban elements. The Three Centralization Policy (Yang & Xia, 2001) encouraged upstream–downstream industries to concentrate in industrial parks, which are separate zones planned for exclusive industrial use. During the following 20 years, Shanghai's GDP grew at an annual pace from 3% (in 1989) to 14.9% (in 1993) (Yuan & Yang, 2002)

Studies show that the severest air pollution emerged around 1986. In this period, Sulfur Dioxide (SO<sub>2</sub>) was the dominant air pollutant, and its concentrations in the ambient

atmosphere declined from 1986 to 1997 due to the decline in energy consumption in the industrial sector. During this period, Shanghai's GDP grew at its fastest pace, as did Nitrogen Oxides (NO<sub>x</sub>) emissions (Yuan & Yang, 2002). The time from 1990 through 1997 was well known for Shanghai's decision to construct a "Green Lung"—a large green space—in its city center (Yuan & Yang, 2002). The construction of the Green Lung can also be regarded as one reason for the declining air pollution levels in the following years.

The third stage of Shanghai's industrialization began in 1998. Studies show that the agglomeration of old industrial plants continued, and new technologies were applied to increase the pollution removal efficiency of the plants. During this period, pollution emissions have decreased significantly. By the time this period ends, labor intensive industry will be located within the city center, technology-intensive industry will be in suburbs close to the city, and capital-intensive pillar industries, which include heavy industries and chemical industries, will be in outer suburban areas (Zeng, 2001).

Most of the old industrial plants were displaced out of the city center.

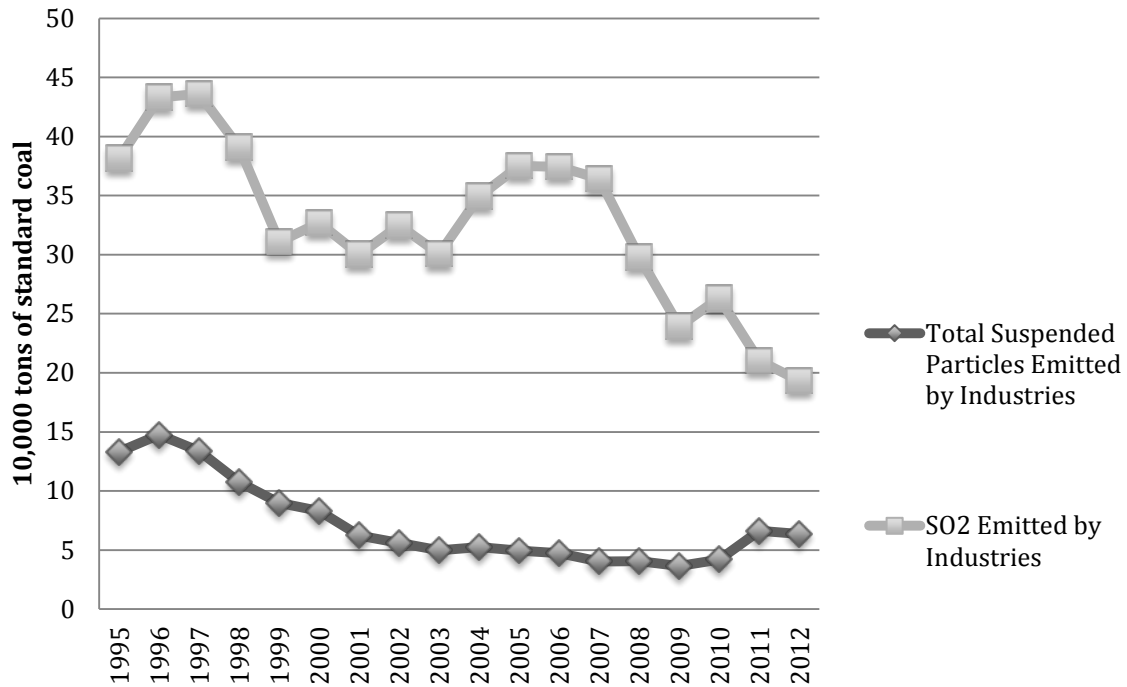


Source: Shanghai Urban Planning and Design Research Institute

*Figure 5.* Distribution pattern of industries in 1959 (left) and 2008 (right).

Current industrial areas are located mainly outside the second ring road (see Figure 3). Polluting industries are all located far from the city center and on both sides of the annual prevailing wind.

The replacement and clustering of industrial areas helped decrease the transportation distances between upstream and downstream factories, thereby decreasing the total emissions from freight transport (see Figure 6). Furthermore, the removal of polluting industries from central Shanghai also helped lower industrial impacts on the air quality of the central area.



Source: Shanghai Statistical Yearbook 2013

Figure 6. Trends of industrial emissions (TSP and SO<sub>2</sub>), 1995–2012.

Many studies have been conducted about the relationship between historical GDP growth and the environment of Shanghai. They have discovered an “inverted U-curve,” also known as an environmental Kuznets curve (Chang & Li, 2010; Yuan & Yang, 2002). In other words, Shanghai’s environment began to deteriorate starting in 1979, while its industrial scale increased. In the years around 1986, Shanghai saw a peak of SO<sub>2</sub> emissions and issued Industrial Wastewater, Waste Gas Emission and Waste Residue Discharge Standards. The Industrial Wastewater, Waste Gas Emission and Waste Residue Discharge Standards (GBJ4-73, 工业“三废”排放试行标准) were published in 1973, and the supplementary standards—for example, the Shanghai Industrial Wastewater Discharge Standard (上海市工业废水排放补充标准) and Shanghai Industrial Waste Gas Emission Discharge Standard (上海市工业废气排放补充标准)—were both issued in 1989. After that, the environmental

recovery began because of the agglomeration of industrial lands and the increase of pollution-control technologies.

## **1.2.2. DETERIORATING AIR QUALITY DUE TO MOTORIZATION?**

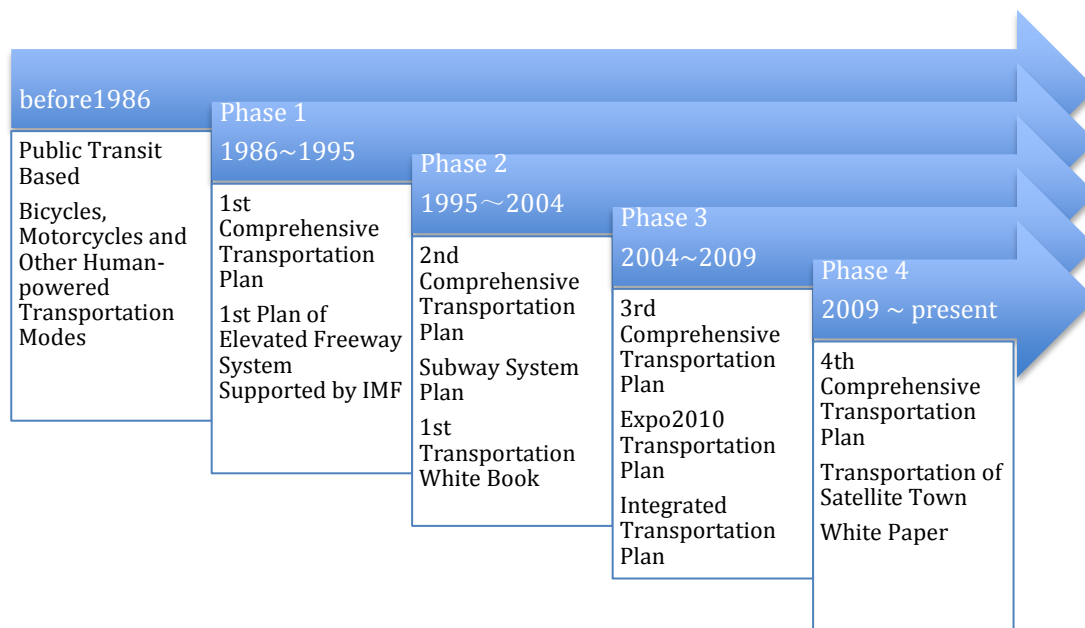
### **1.2.2.1. FOUR TRANSPORTATION INVESTIGATION AND TRANSPORTATION DEVELOPMENT PROCESSES IN SHANGHAI**

Industrialization is one of the most important issues facing the city. Shanghai developed from a public-transit-based city—based on buses and trolley buses—to one with a multimodal transportation system.

Shanghai adopted its first Comprehensive Transportation Plan (Shanghai Synthesis Transportation Strategy Plan 1990–2020) in 1986. In the plan, Shanghai planned to develop an elevated freeway system in the city. In 1995, Shanghai entered its second stage of transportation development (Shanghai Synthesis Transportation Strategy Plan 2000–2020) and started planning to build a subway system .

The third stage, initiated in in 2004, put forward the idea of creating a multimodal system (Shanghai Synthesis Transportation Strategy Plan 2006–2020) linking the elevated freeway system, the subway network, and the public transit systems in different administrative districts. Combined with the Expo 2010 Comprehensive Plan, Shanghai strengthened the linkages among different regions and communities and the park-and-ride systems between different transportation modes.

The fourth and current stage began after Expo 2010 and is intended to lead to a system that matches the new trend of suburbanization (Lu & Gu, 2009).



Source: Lu and Gu, 2009

*Figure 7.* Four stages of multimodal transportation system development in Shanghai.

### (1) **Phase Before 1986: Public Transit Period**

The first phase of the development of Shanghai’s transportation system is also known as the “public transit period.” At the beginning of 1980s, the public transit network in Shanghai, which comprised 250 bus lines, undertook 60% of the total passenger trips and the majority of activities happening in the city (Lu & Gu, 2009). The western part of Shanghai, the west of the Huangpu River, was recognized as the “Central City” of Shanghai.

The existing street network in the 1980s consisted of surface streets in a grid pattern with wider intervals than at present. In Shanghai, sidewalks were available on both sides of the street, but there is not enough road space for motorization (see Figure 8). On-road vehicles were mostly lower-speed diesel buses, motorcycles, and bicycles. Between West and East Shanghai—West Shanghai refers to the area to the west of the Huangpu River and East Shanghai refers to the area to the east of the Huangpu River—connections and communications relied mainly on ferry services.



Photo credit: qnpic.com

*Figure 8.* Typical narrow streets of Shanghai

### (2) **Phase 1: Beginning of Elevated Freeway**

The second phase began in 1986. The incomplete transportation infrastructure before 1986 slowed the pace of urban development and the capability of residents to pursue better living standards. In 1986, the city launched its first synthesized transportation strategy plan and determined its goals for future development. The main achievement of this plan was the decision made to develop a freeway system for the city to increase its transportation efficiency. The first ring road emerged during this period, linking the west and east sections of Shanghai with two cable bridges across the Huangpu River. After the development of the freeway system, the total population of the city reached to 15 million and the total developed area amounted to 400 square kilometers at the end of this phase, while the vehicle population kept increasing at a pace of 50,000–60,000 per year. At the same time, the percentage of trips using public transit decreased slightly (Lu & Gu, 2009).

### (3) **Phase 2: Beginning of the Subway System**

Phase 2 launched the establishment of the subway system in Shanghai. Additionally, during this period the city began construction on the second ring road, and the total length of

the elevated freeway system increased to 308 kilometers (Lu & Gu, 2009). The newly built subway line could only serve the Central City area. At the end of this period, the city was confronted with congestion problems brought about by the construction of the freeway system.

**(4) Phase 3: Beginning of Multimodal Transportation System**

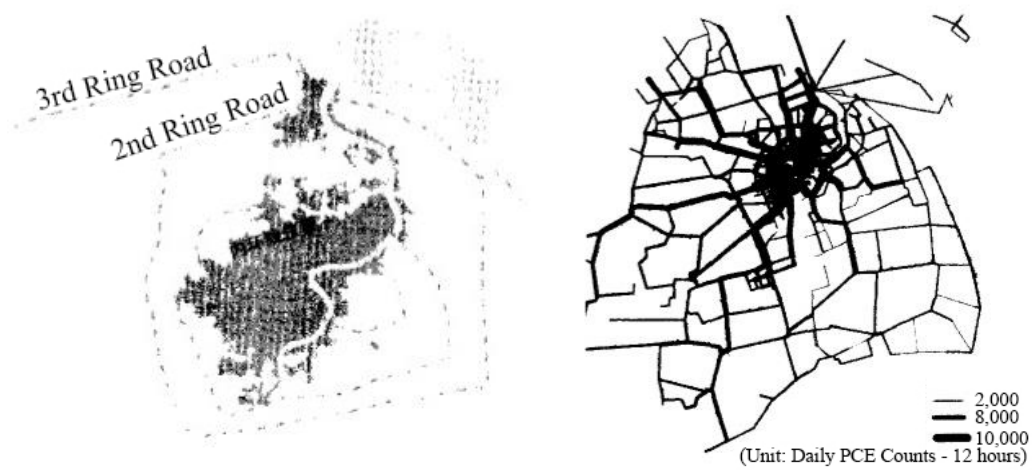
Phase 3 was the beginning of the implementation of the large-scale multimodal transportation system in Shanghai. To satisfy the expected traffic demands of 2010 Expo, all projects, including the rest of the planned subway lines, were accomplished during this period.

By 2007, the total population of the city of Shanghai hit 18.58 million and the total vehicle population reached 2.27 million. Eight subway lines covered almost the entire city with 234 kilometers of line length. In addition to these subway lines, the city also offered to 17,000 buses and 48,000 taxis (Lu & Gu, 2009) to the public.

**(5) Phase 4: Polycentric Development and Connection Between City Center, Harbor, and Satellite Towns**

The future development of Shanghai's transportation system will be based on the newest comprehensive plan, which focuses mainly on optimizing land use and the organization of the urban space. Future development of Shanghai's transportation system will focus on strengthening the connections between the central city and the airports, harbors, and satellite towns located in the outer suburban areas (Lu & Gu, 2009). The future development of Shanghai's transportation system will also focus on the completion and expansion of the freeway and subway systems begun during Phase 1 and Phase 2, respectively.

Phases 1, 2, 3, and 4 overlapped in time, and the end of all of these phases is supposed to be in 2020. The spatial development of both the developed areas and the growth of the street network of Shanghai from 1980 to 2007 was to take place as in Figures 9–12 below:



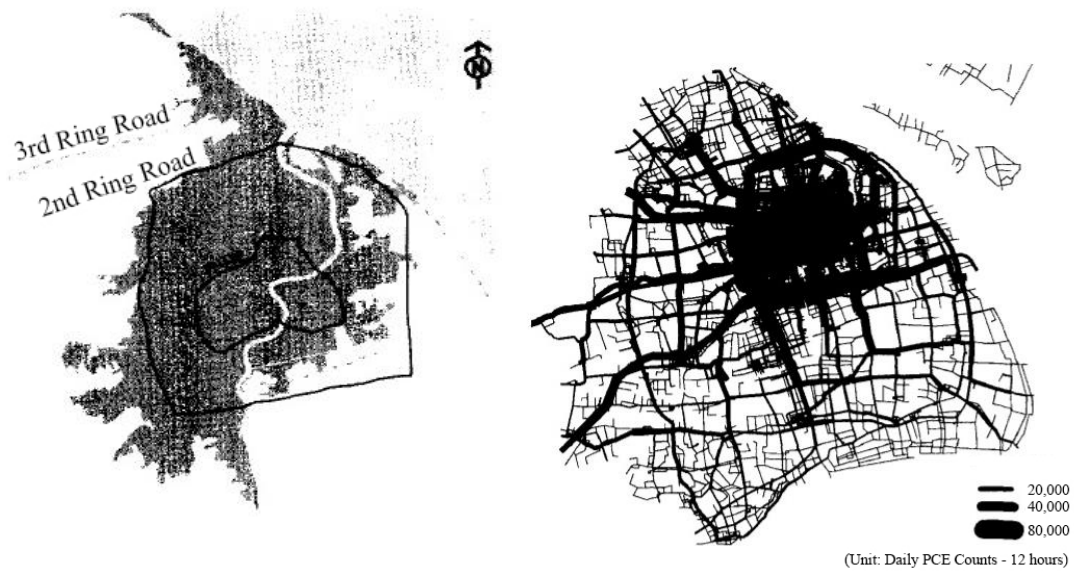
Source: Lu and Gu, 2009

Figure 9. Phase 1: Distribution pattern of urban areas (left) traffic flow (right).



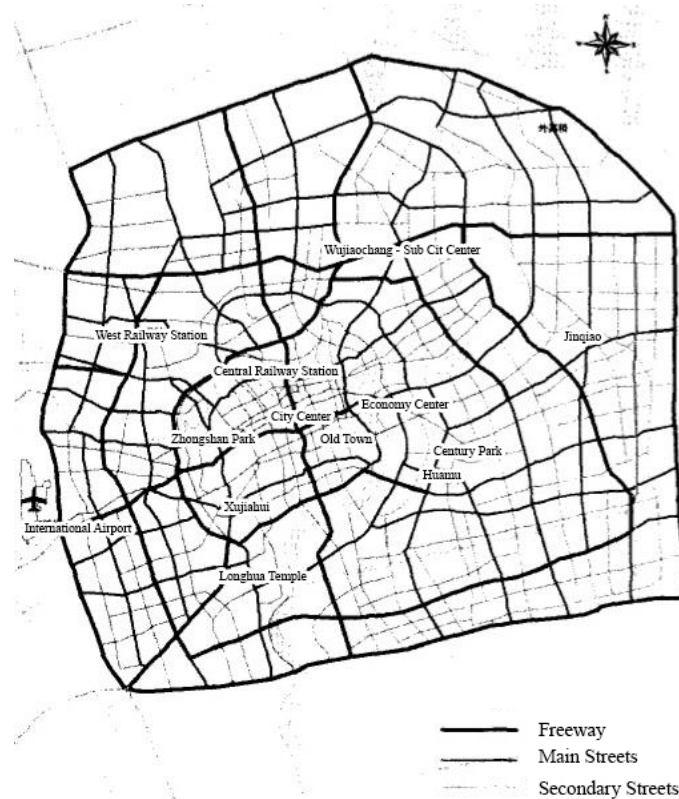
Source: Lu and Gu, 2009

Figure 10. Phase 2: Distribution pattern of urban area (left) and traffic flow (right).



Source: Lu and Gu, 2009

Figure 11. Phase 3: 2007 distribution pattern of urban area (left) and traffic flow (right).



Source: Lu and Gu, 2009

Figure 12. Phase 4: Expectation of future complete road network of Shanghai.

### **1.3. CURRENT TRANSPORTATION SYSTEM IN SHANGHAI AND ITS ENVIRONMENTAL IMPACTS**

#### **(1) Monocentric City and Street Network**

Shanghai is currently a monocentric city with a clearly identifiable city center surrounded by ring and radial arterials (see Figure 1). Currently, the city center contains most of the workplaces—mostly for business, commercial, and financial services—and the suburban areas are mostly used as residential areas. The ring and radial street network pattern supports quick connections between the city center and suburban areas, and ensures convenient commuting between homes and workplaces.








Surrounding the central city are three ring roads that have already been developed into three major ring roads. Inside the second ring road is the area called the Central City or central districts (see Figure 13).

From Figure 14(a), we can see that from 1995 to 2003, the outer districts—that is, the districts outside the second ring road—experienced faster growth in the total length of the motor roads than the central districts—that is, the districts located inside the second ring road. Both the central and outer districts experienced significant growth in the number of branch roads. In other words, the growth of the transportation infrastructure in the city of Shanghai during this period was focused on increasing the street network density, defined as the total length of the streets divided by the area covered by these streets, in lieu of strengthening long-distance connections between different districts.

Figure 14(b) shows that in spite of efforts to increase the total length of the streets in all the regions of Shanghai, the current street network density in a majority of the urban areas in outer districts is still lower than in the central districts.

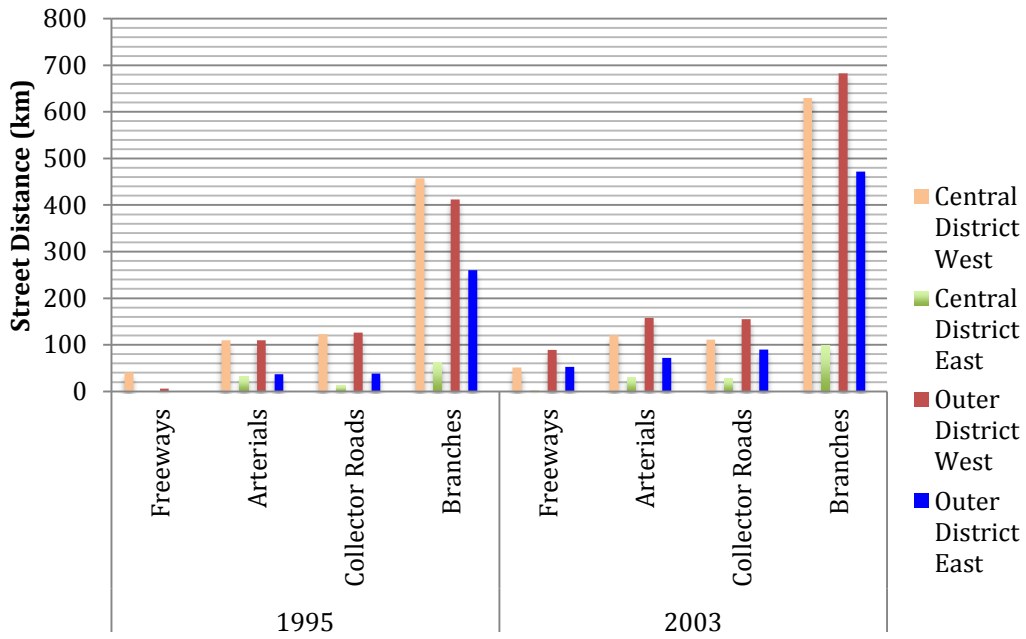


### Legend

	Freeway
	Primary Road
	Residential Road
	Secondary Road
	Tertiary
	Trunk Road
	Waterway

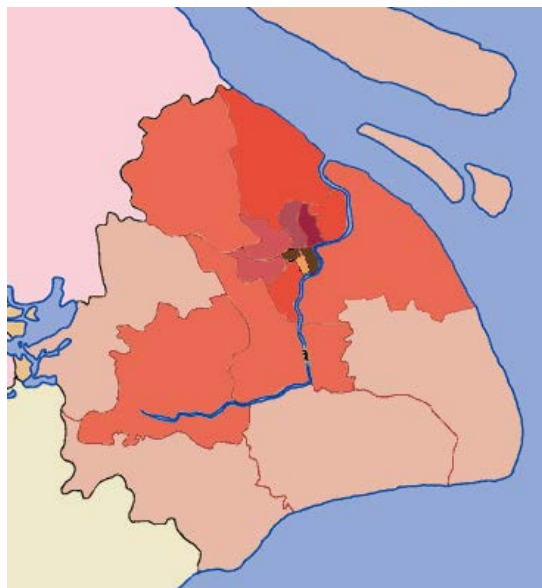
Source: Shanghai Comprehensive Plan 1999–2020

*Figure 13.* Current street network in Shanghai.



Source: Report of the Third Comprehensive Traffic Survey in Shanghai, 2004

Figure 14(a). Increase in total road lengths in kilometers (km) in central and outer districts.



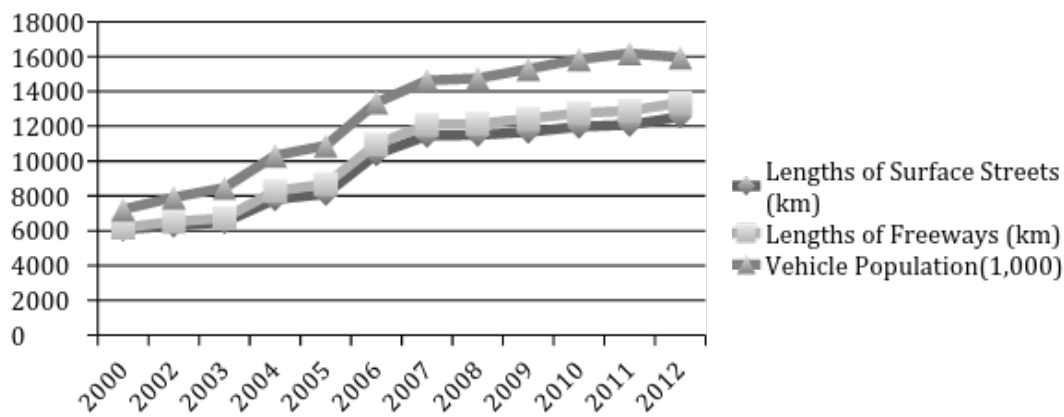
\*Darker red means higher street network density, and lighter red means lower street network density.

Source: Xuan and Wang, 2013

Figure 14(b). Increase of total road lengths in kilometers (km) in central and outer districts, and current street network density in kilometers per square kilometer ( $\text{km}/\text{km}^2$ ) by administrative districts.

## (2) Vehicle Population Growth

Though microeconomic theories state that supply is somewhat determined by demand, they also state that supply can induce demand. Comparing the statistics showing the growth of vehicle population in Shanghai with the growth of total street length from 2000 through 2012, it is possible to see a correlation between the vehicle population and the street infrastructure (see Figure 15). In other words, a causal relationship may exist between the degree of motorization and the degree of infrastructure development suitable for motor vehicles.



Source: Shanghai Statistical Yearbook 2005, 2008, 2010, 2013

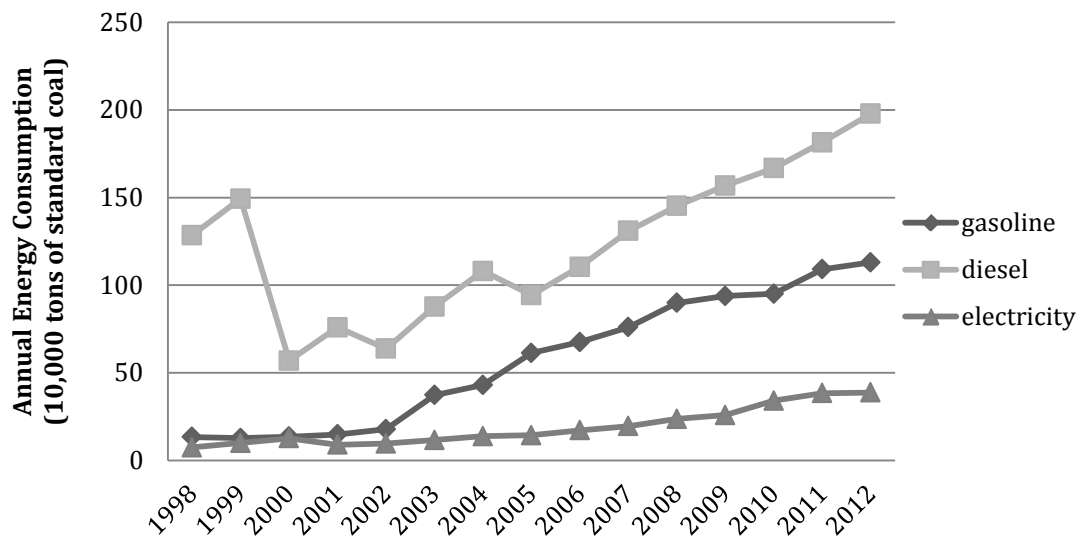
Figure 15. Growth of street lengths in Shanghai, compared with growth of vehicle population.

Rapid growth in vehicle population brought about the overuse of street infrastructure and traffic congestion. In 1986 Shanghai adopted a bidding mechanism (with a reservation price) for allocating licenses to automobile owners (Feng & Li, 2013) to control the number of private cars and at the same time improved the public transit system by expanding bus lines and metro lines in the city region. The subway system is now replacing bus lines gradually to become the most important transportation mode in Shanghai. Its ridership reached more than 9 million per day in April 2014. (Lan, 2014)

It is clear that Shanghai’s automobile license auction was much more effective in controlling the growth of car ownership than Beijing’s auto-license lottery system g. Although these two cities began with almost the same number of rates of registries of automobile ownership per 10,000 people in 1993, the rates of car registration per 10,000 people in 2011 was 200 for Shanghai and 450, or more than double that, for Beijing, for every 10,000 people (Feng & Li, 2013). Because the auction only controls the number of registries for private cars, however, it is fair to say that the number of vehicles on the road does not equal the number of registries for car ownership.

### (3) Transportation Energy Consumption Growth

Along with the vehicle population and the transportation infrastructure growth, the transportation sector of Shanghai also experienced a rapid growth in energy consumption.



Source: Shanghai Statistical Yearbook on Industry, Energy and Transport

Figure 16. Trends in energy consumption in transportation, warehousing, the post and the telecommunications industry by year (1998–2012)

From Figure 16, we can see that diesel consumption was much higher than the consumptions of gasoline and electricity before 2000. In 2000, to mitigate the negative

environmental impact, the city restricted the use of diesel vehicles in the city, and as a result, in 2000, diesel consumption dramatically dropped to one third of the level of 1999.

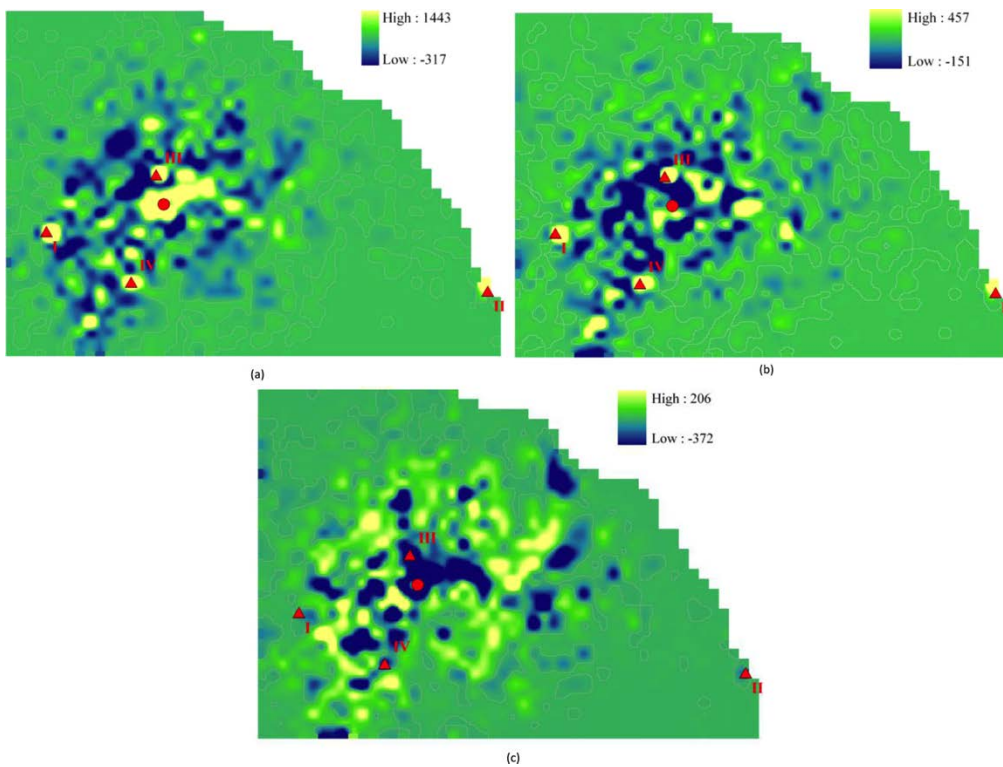
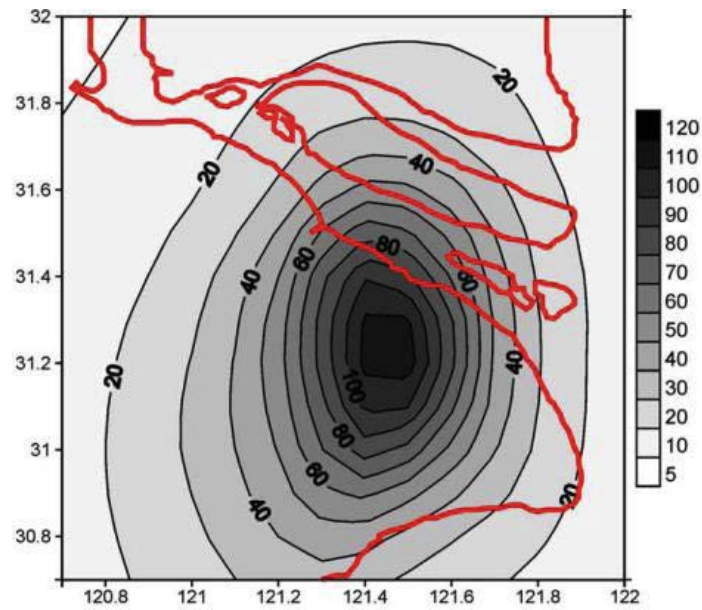
Since 2000, however, all of the transportation-related energy consumption has increased steadily at approximately the same pace as the vehicle population growth. Diesel is no longer overwhelmingly dominant, but it remains the largest type of energy consumed.

#### **(4) Environmental Impacts of Growing Transportation Demand**

Studies show that the central districts always saw the highest frequency of motor vehicle usage and the highest  $PM_{10}$  concentration levels in the whole city region.

At the beginning of the twenty-first century, researchers had already paid attention to the environmental impact of the rapid growth of Shanghai. Figure 17 shows a documentation of coarse particulate matter ( $PM_{10}$ ; Particles less than 10 micrometer in diameter) concentration patterns in Shanghai in 1995 (Li et al., 2004) based on the  $PM_{10}$  concentration data collected at different locations of the city. The map shows an equal level of  $PM_{10}$  concentration along the circular contour line ( $PM_{10}$  concentration levels are indicated with numerals). In Shanghai, the central area's  $PM_{10}$  concentration level is six times higher ( $> 120$ ) than it is at the periphery ( $< 20$ ). The levels of the  $PM_{10}$  concentration decrease further away from the center.

This pattern is somewhat consistent with the distribution of observed frequencies of taxi pickups and dropoffs (Liu et al., 2012), showing there is a possible relationship between transportation and the  $PM_{10}$  concentration distribution pattern. Neither of the two articles (Liu et al., 2012; Li et al., 2004) shows the share of  $PM_{10}$  emitted by transportation sources.



Sources: Li et al., 2004 (left); Liu et al., 2012 (right)

Figure 17. Isocontour map of  $PM_{10}$  concentrations in Shanghai detected in 1995 (up, unit:  $\mu g/m^3$ ) and distribution pattern of taxi pickups and drop-offs at orning, noon, and night (down, unit: number of occurrences) (yellow means drop-offs, dark blue means pickups).

#### 1.4. RESEARCH FOCUS

As mentioned, this study will focus on improving our knowledge of the dispersion pattern of PM particles and extrapolating the PM emissions produced by on-road traffic in Shanghai. This study will focus on answering the questions below:

- To what degree do the current on-road motor vehicles affect Shanghai's air quality?
- What are the negative impacts of transportation-related air pollution (TRAP)?
- What strategies might planners and other stakeholders employ to avoid negative air pollution impacts?

Recent TRAP studies reported that the six common air pollutants—PM<sub>10</sub>, PM<sub>2.5</sub>, NO<sub>x</sub>, SO<sub>2</sub>, CO, and O<sub>3</sub>—PM<sub>2.5</sub> is the most dangerous to human health and the most likely to be related to emissions from automobiles. Furthermore, many researchers find that much smaller particles, called ultrafine particulate matter (PM<sub>0.1</sub>; particle size less than 10 nanometers in diameter), are more dangerous to human health because their small size can enter almost every part of the human body (Beelen et al., 2008; Health Effects Institute, 2010). However, these ultrafine particles are beyond the scope of this thesis. Therefore, this study will focus only on PM<sub>2.5</sub> particles to reveal how the motorization of Shanghai and the increase in on-road motor vehicles has affected the city's air quality.

## **Chapter 2 Air Quality History and Related Urbanization/Suburbanization**

### **2.1. WHAT IS PM<sub>2.5</sub>?**

According to the definition given by the US Environmental Protection Agency (EPA) (EPA website, “What is PM<sub>2.5</sub>?“):

*Particulate matter, or PM, is the term for particles found in the air, including dust, dirt, soot, smoke, and liquid droplets. Such particles can be suspended in the air for long periods of time. Some particles are large or dark enough to be seen as soot or smoke. Others are so small that individually they can only be detected with an electron microscope.*

*Many manmade and natural sources emit PM directly or emit other pollutants that react in the atmosphere to form PM. These solid and liquid particles come in a wide range of sizes.*

*Particles less than 2.5 micrometers in diameter (PM<sub>2.5</sub>) are referred to as “fine” particles and are believed to pose the greatest health risks. Because of their small size (approximately 1/30th the average width of a human hair), fine particles can lodge deeply into the lungs.*

### **2.2. HISTORY OF PARTICULATE MATTER RESEARCH AND DATA COLLECTION IN SHANGHAI**

### **2.3. HEALTH IMPACT OF PM<sub>2.5</sub>**

A high concentration of fine particulate matters (PM<sub>2.5</sub>) puts people at risk due to the harm it does to people’s respiratory systems. The particle size is 2.5 micrometers in diameter and is commonly described as one tenth of the diameter of a human hair. Because of the

particles' small size, they enter the deep pockets of lungs and cause health problems such as myocardial infarction, cardiovascular diseases, lung cancer, and other respiratory diseases.

Bae's research team collected the studies of many other researchers and concluded that exposure to fine particles results in aggravation of asthma, depressed lung function among school children, bronchitis, and increased risks of lung cancer. It may also lead to acute respiratory symptoms, wheezy bronchitis among infants, and a decreased rate of lung growth among children (Bae et al., 2007). In addition, the research defined the vulnerable population: the young (those under 16 years old) and the old (those over 65 years old) who live close to freeways. By using a geographic information system (GIS) and the US Census population data in the Seattle metropolitan area, they demonstrated that there is an overconcentration of the vulnerable population in some areas such as downtown Seattle, where I-5 and I-90 intersect.

### **2.3.1. MOVEMENT OF PARTICULATE MATTERS IN AMBIENT AIR**

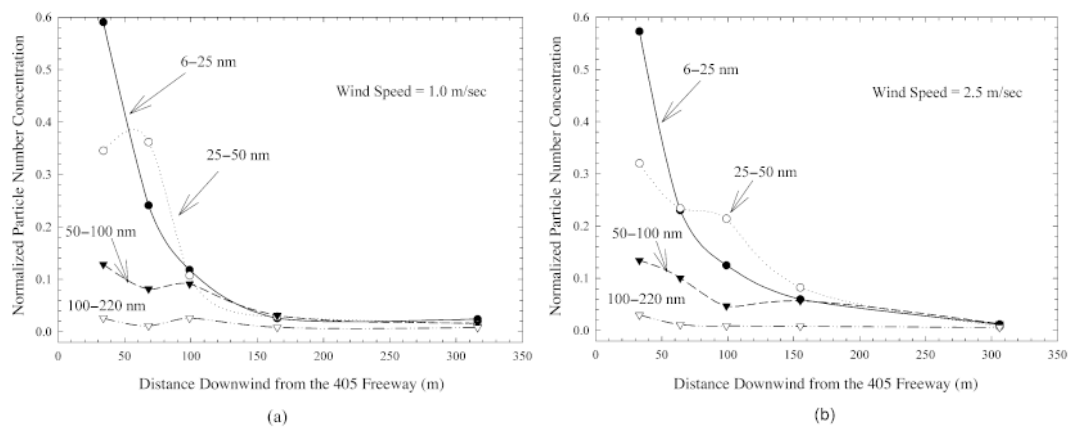
PM<sub>2.5</sub> particles move instead of standing still in the air. As a result, investigating the movement of the particles helps us understand the distribution of PM<sub>2.5</sub> after it is emitted from vehicles. A study conducted in Tianjin shows that PM<sub>2.5</sub> concentrations are different at elevations of 40 meters, 120 meters and 220 meters above ground (Sun et al., 2008). During the morning, the PM<sub>2.5</sub> concentration at the elevation 120 meters above the ground is higher than at lower elevations, while during the evening, the PM<sub>2.5</sub> concentration at 40 meters is higher than at other elevations. This study shows that the dispersion of PM<sub>2.5</sub> particles in the ambient air is related to vertical convection.

Other studies focus on horizontal proximity to the PM<sub>2.5</sub> sources—for example, the vehicles on the streets. A Dutch team measured outdoor levels of PM<sub>10</sub>, PM<sub>2.5</sub>, benzene, and NO<sub>2</sub> at different distances from the roadway. They concluded that although there were significant differences in levels of NO<sub>2</sub> and benzene between the places near and far from the

roadway, the levels of PM<sub>10</sub> and PM<sub>2.5</sub> did not vary much (Roorda-Knape et al., 1998). However, another research team at the University of California, Los Angeles, measured the ultrafine particle and PM concentrations near the 405 freeway. They show that:

*Wind speed and direction are important in determining the characteristics of ultrafine particles near freeways. The stronger the wind, the lower the total particle concentration. Total particle concentration is related directly to traffic density and decreases significantly during a traffic slowdown. (Zhu et al., 2002)*

This study also shows that the smaller the particle size is, the more rapidly the concentration of this particle will decline with increasing distance from the roadway (see Figure 18).



Source: Zhu et al., 2002

*Figure 18.* Concentration of particles of different sizes under different wind speeds along the 405 freeway by distance.

The same conclusion has been reached by other studies focused on the concentration of PM<sub>10</sub>, PM<sub>2.5</sub>, and ultrafine particles near interstate highways or main arterials. At the same time, by studying the movement of PM<sub>10</sub> and PM<sub>2.5</sub> particles in different layers of near-surface atmosphere, a team from the Chinese Academy of Meteorological Sciences has

shown us that the spread of particles with diameters around 2.5  $\mu\text{m}$  relies more on vertical air convection than on horizontal wind speed (Yang et al., 2005).

Urban form, according to relevant studies, is another key factor that determines the  $\text{PM}_{2.5}$  dispersion in urban areas. Studies show that the “street canyons” created by high rises and elevated freeways are the reason that the horizontal dispersion of  $\text{PM}_{2.5}$  is weak and vertical air convection becomes the primary spreading model for  $\text{PM}_{2.5}$  (Li et al., 2007).

The study mentioned above (Li et al., 2007) shows a vertical dispersion pattern of  $\text{PM}_{2.5}$  in urban areas with building heights of more than 20 meters, such as Shanghai, New York City, and Hong Kong. It shows that the larger the particle size is, the more probable that it will concentrate at the height of 20 meters. Because of the size of the  $\text{PM}_{2.5}$  particle, which is less than 2.5  $\mu\text{m}$  in diameter, these particles are more likely to rest and concentrate in the street canyon areas along the streets within a horizontal distance of 50 meters from the streets (Zhu et al., 2002; Li et al., 2007). As a result, the  $\text{PM}_{2.5}$  concentrations along the streets will be much higher than in other areas of the city, and the PM concentrations along the streets will be highly related to the traffic density (Bae et al., 2007), rather than other factors such as wind direction or wind speed.

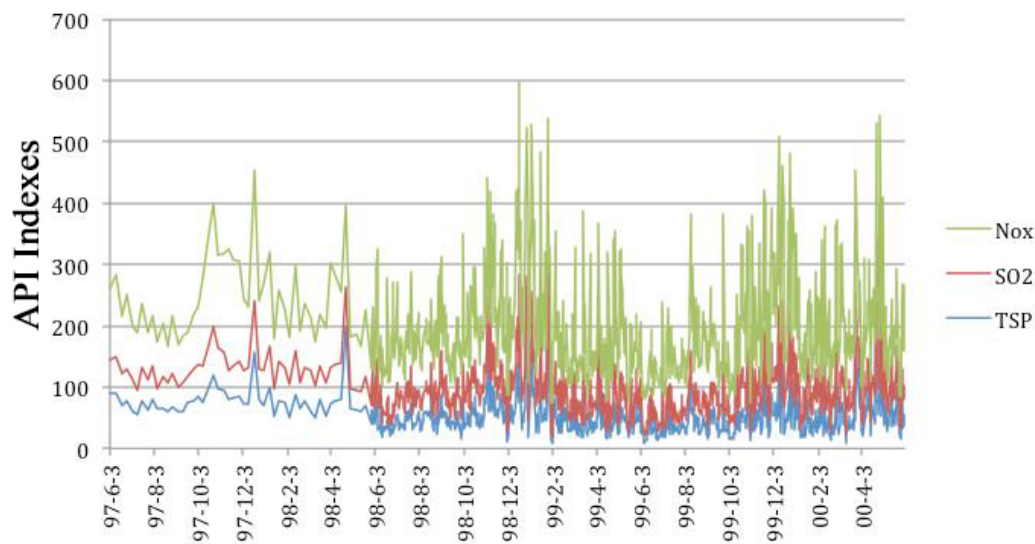
### **2.3.2. DATA COLLECTION HISTORY IN SHANGHAI**

#### **2.3.2.1. HISTORICAL SUSPENDED PARTICLE DATA AND CORRESPONDING TRANSPORTATION DEVELOPMENT PERIODS**

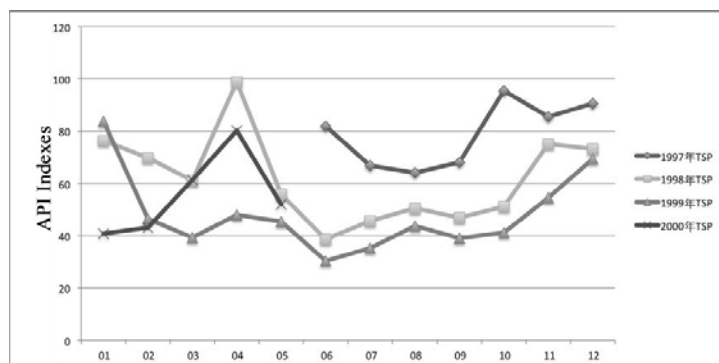
##### **(1) TSP Data Before 2000**

$\text{PM}_{2.5}$  data collection and publication began very recently. It dates back to 2011, and the data collection from all of the  $\text{PM}_{2.5}$  air quality monitoring stations began 1 year later. Before that, most of the literature focused on studying gaseous pollutants such as CO, HC, and  $\text{NO}_x$ .

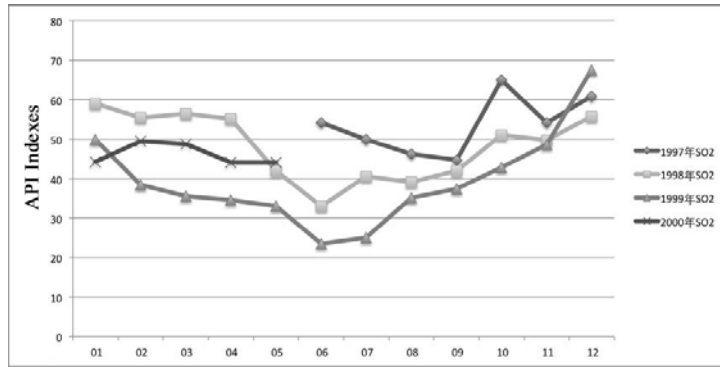
Documents show that before June 1, 2000, sub-indexes of total suspended particles (TSP), SO<sub>2</sub>, and CO were collected in Shanghai according to the Ambient Air Quality Standard of 1996, which came into effect on October 1, 1996. All of the sub-indexes are Air Pollution Indexes (API), a simple way of describing air pollution levels by converting air pollution data from three types of pollutants—SO<sub>2</sub>, NO<sub>x</sub> (or NO<sub>2</sub>), and TSP (or PM<sub>10</sub>)—into a value ranging from 0 to 500 (What Is the API and How Is It Calculated, 2008). APIs have been used elsewhere in mainland China and Hong Kong to show air pollution levels.



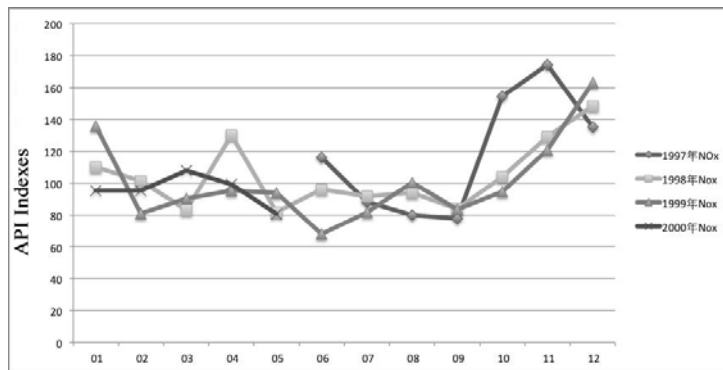
(a) Oscillation chart of API of No<sub>x</sub>, SO<sub>2</sub>, and TSP, 1997–2000



(b) Annual change in TSP API between 1997, and 2000



(c) Annual change in SO<sub>2</sub> API between 1997 and 2000



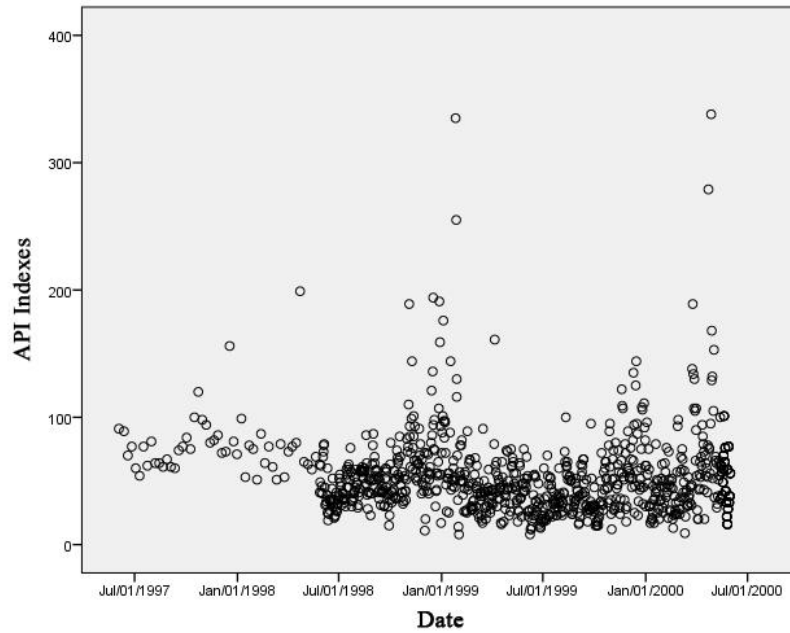
(d) Annual change in NO<sub>x</sub> API between 1997 and 2000 –

Source: Shanghai Air Quality Daily Report

Figure 19. API indexes of NO<sub>x</sub>, SO<sub>2</sub>, and TSP in Shanghai (1997–2000).

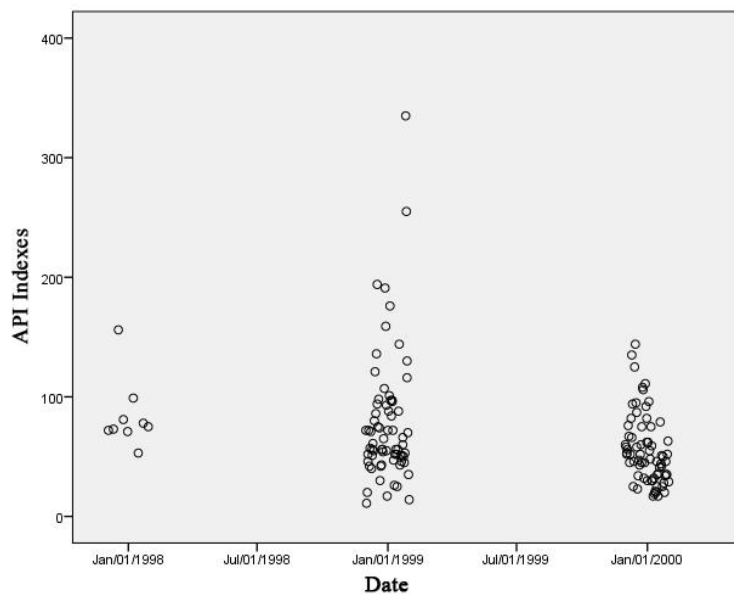
Above are the API indexes of all of the three pollutants of the third day of the month taken every two months between 1997 and 2000. From the graph above, we can see that the NO<sub>x</sub> concentrations experienced a peak in winter and a trough in summer, and the difference between winter and summer looks obvious. Both of the other pollutants also followed that pattern, experiencing a peak in the winter and a trough in the summer. However, the difference in the quantity SO<sub>2</sub> between winter and summer was insignificant. The winter–summer difference for TSP was undetectable.

Focusing on the TSP data, using Statistical Package for the Social Sciences (SPSS) we can clearly see the scatter pattern of TSP indexes between 1997 and 2000.



Source: Shanghai Air Quality Daily Report

Figure 20. Scatter pattern of TSP indexes (1997–2000).

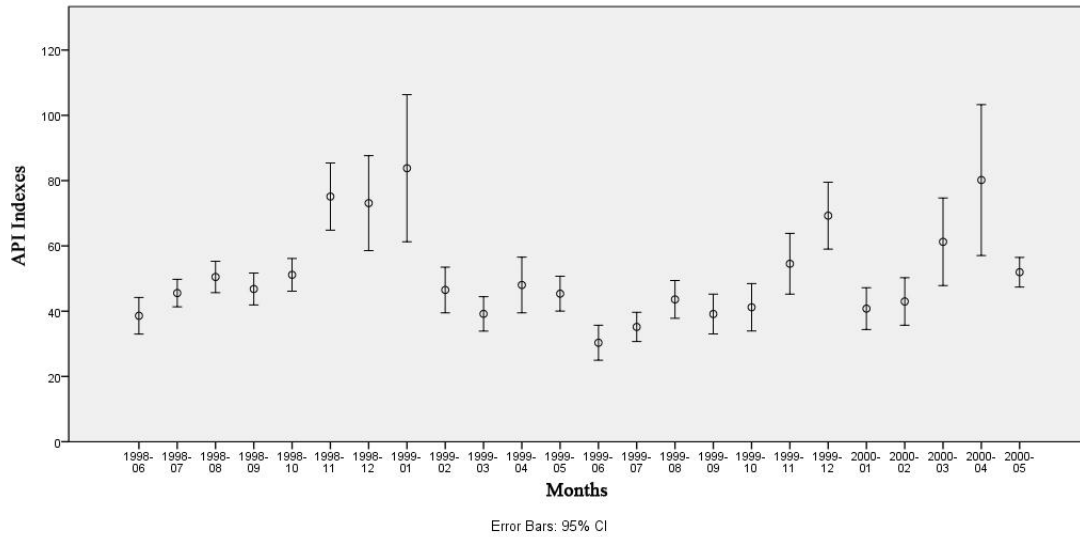


Source: Shanghai Air Quality Daily Report

Figure 21. Scatter pattern of winter TSP indexes (1997–2000).

If we remove some of the data and keep only the data for the same period each year—in this study, December and January for the four years (1997, 1998, 1999 and 2000)—the scatter pattern (see Figure 21) shows that the variation of the TSP indexes at the end of 1999 was much higher than in the other two years. However, SPSS regression analyses also show

that only 6.9% of the TSP indexes (API) varied over time. In other words, although the population, vehicle population, street lengths, and energy consumption (see Figures 15 and 16) have kept rising since 1995, the TSP indexes did not see any immediate change or correlation with the development in the transportation sector.

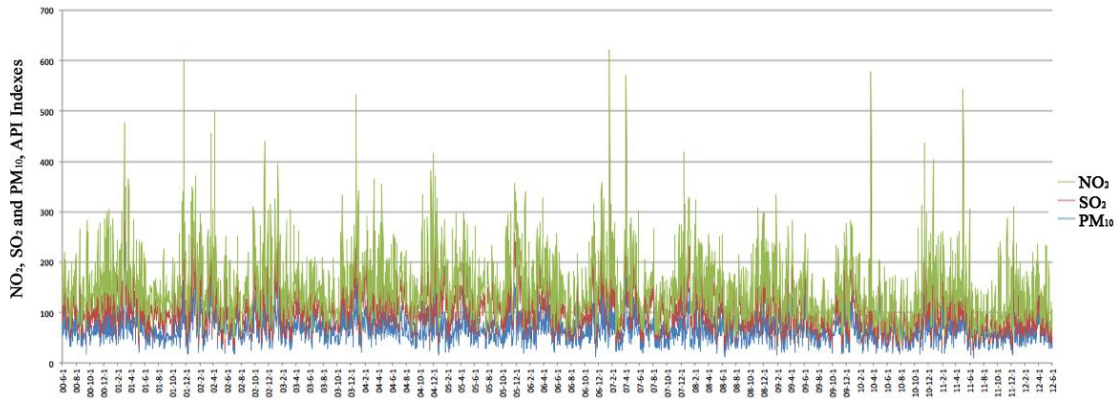


Source: Shanghai Air Quality Daily Report

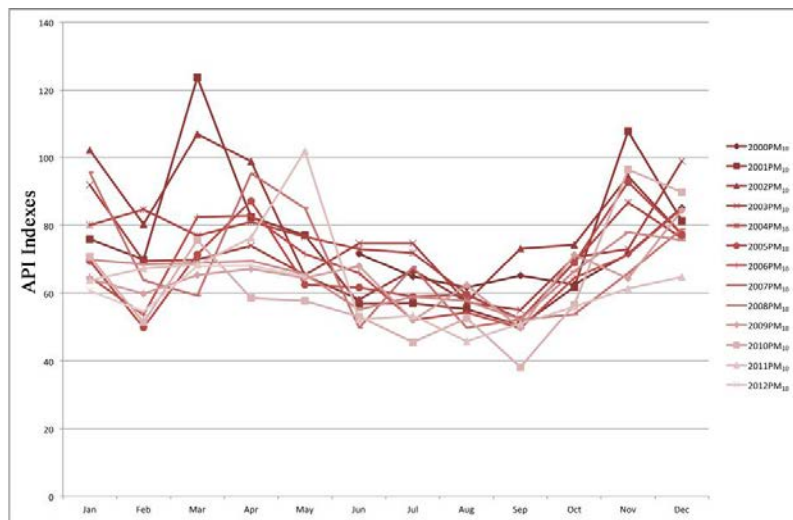
Figure 22. Average monthly TSP variations (1998–2000).

Figure 22 shows the variation of the average monthly TSP indexes from June 1998 through May 2000. Outside of the seasonal difference, the alteration pattern shows a lower variation when the average TSP indexes are lower and a higher variation when the average TSP indexes are higher.

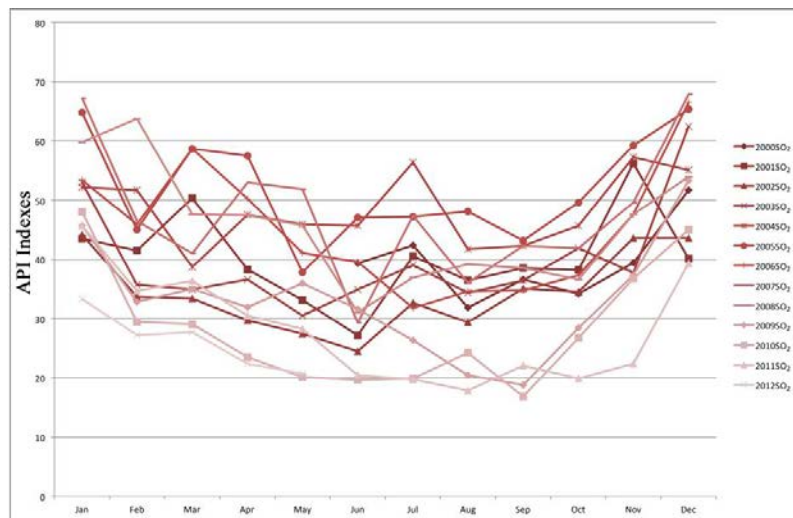
(2) **PM10 Data 2000–2012**



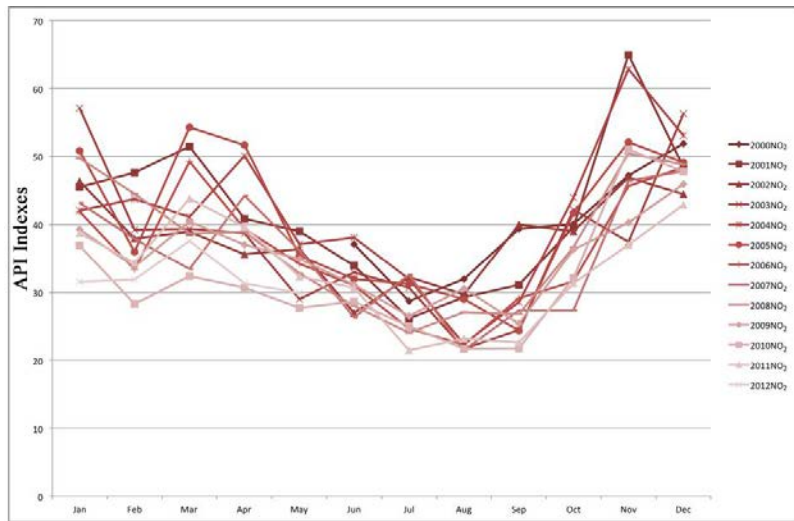
(a) Oscillation chart of API of NO<sub>2</sub>, SO<sub>2</sub>, and PM<sub>10</sub>, 2000–2012



(b) Annual change of monthly PM<sub>10</sub> API



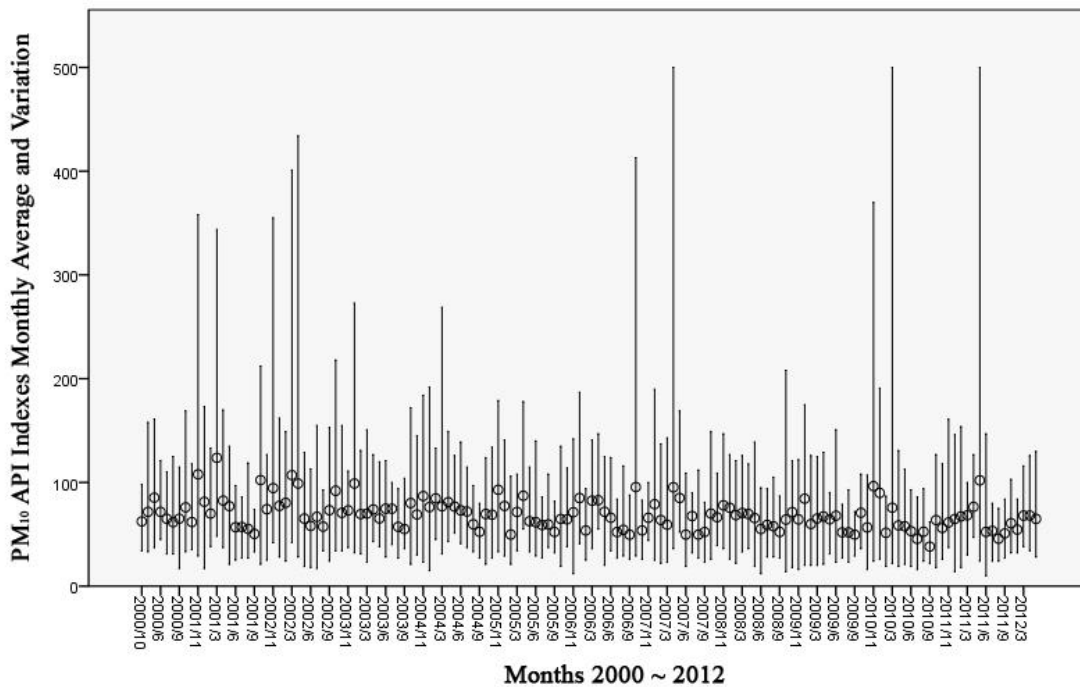
(c) Annual change of monthly SO<sub>2</sub> API



(d) Annual change of monthly NO2 API

Source: Shanghai Air Quality Daily Report

Figure 23. API indexes of NO<sub>2</sub>, SO<sub>2</sub>, and PM<sub>10</sub> in Shanghai (2000–2012).



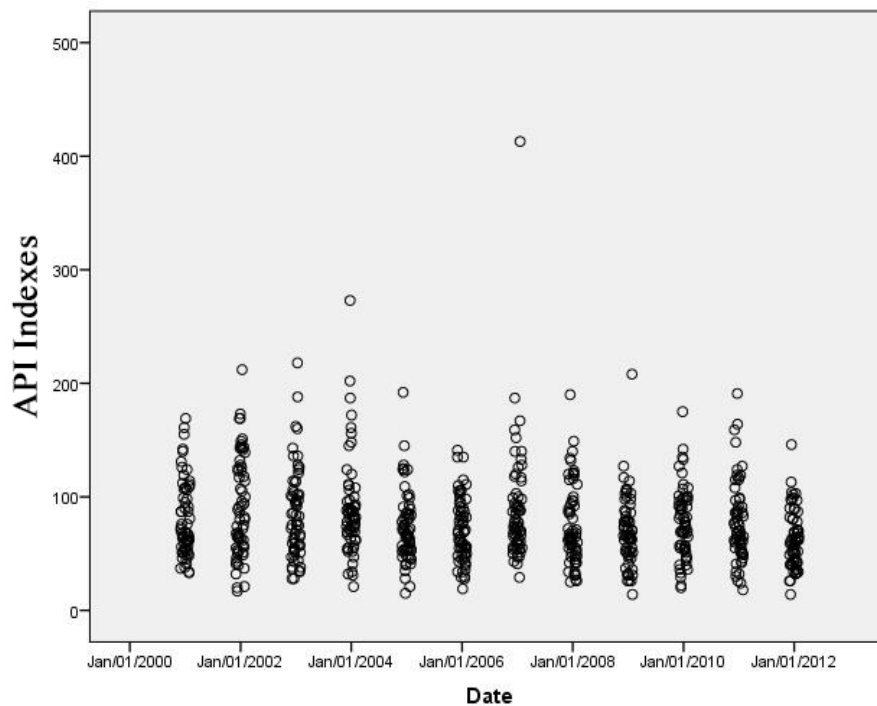
Source: Shanghai Air Quality Daily Report

Figure 24. PM<sub>10</sub> Monthly Variations (2000–2012).

In 2000 the Ambient Air Quality Standard, 1996 Amendment canceled the collection of NO<sub>x</sub> concentration data and began to collect the concentration data for NO<sub>2</sub>. At the same

time, the city of Shanghai started recording PM<sub>10</sub> concentrations. PM<sub>10</sub> indexes from 2000 through 2012 showed larger seasonal variations compared with TSP indexes from 1996 through 2000. Additionally, months with higher average PM<sub>10</sub> indexes did not see the larger variations featured on TSP indexes recorded before 2000.

The year-to-year comparison of the PM<sub>10</sub> indexes collected in winters between 2000 and 2012 and the SPSS regression analyses based on these data show that only 2.2 percent of PM<sub>10</sub> indexes (API) varied over time. In addition, because we found the coefficient with date to be an independent variable and PM<sub>10</sub> daily indexes to be dependent variable has a negative value ( $-5.085E-008$ ), it is appropriate to say that the PM<sub>10</sub> concentrations in the whole city region have decreased slightly since 2000 (see Figure 25).



Source: Shanghai Air Quality Daily Report

Figure 25. PM<sub>10</sub> scatter pattern in winters (2000–2012).

The decrease of TSP from 1997 through 2000 and PM<sub>10</sub> from 2000 through 2012 in the ambient atmosphere of Shanghai was ascribed to the ongoing environmental remediation policies, such as the adoption of National Emission Standards I, II, III, and IV, which are

technically equivalent to Euro 1, 2, 3, and 4, respectively. In addition, the city also planned to displace all of the existing industries out of the central city per the City of Shanghai Comprehensive Plan 1999–2020 and improve the emission treatment technologies of the industries that were already located in suburban areas according to the requirements of the National Emission Standards. Also, 2000 was the first time that the city adopted methods to limit the emissions from the transportation sector.

### (3) $PM_{2.5}$ Data Before 2012



Source: Feng et al., 2009; Ye et al., 2003

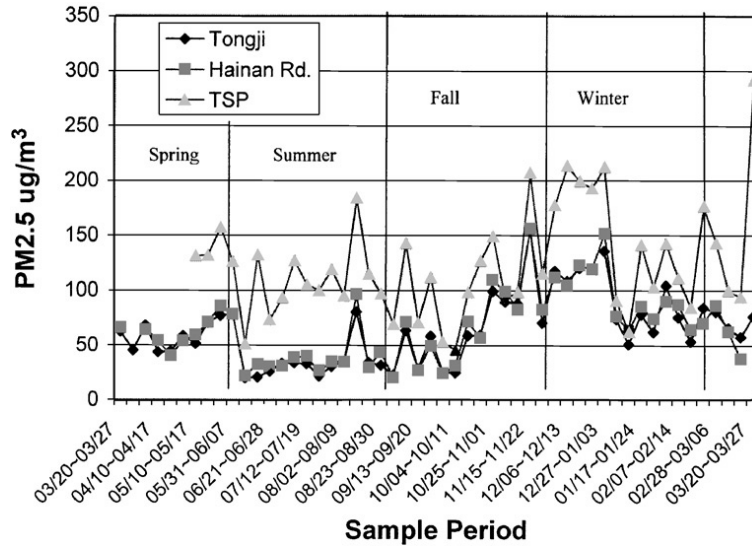
*Figure 26.* Locations of Tongji University Hainan Road, “ZB” site and “JD” site.

$PM_{2.5}$  concentration data have only become available since 2012, but researchers began to collect these data in 2003. In this year, a professor collected  $PM_{2.5}$  concentration data at Tongji University and Hainan Road (see Figure 26).

The seasonal average concentrations and weekly mass concentrations are as follows:

Species	Hainan Rd., $\mu\text{g}/\text{m}^3$			Tongji Univ., $\mu\text{g}/\text{m}^3$			
	Summer	Fall	Winter	Spring	Summer	Fall	Winter
PM <sub>2.5</sub>	35.85	67.78	93.91	61.66	36.80	64.77	88.57

(a)



(b)

Source: Ye et al., 2003

Figure 27. (a) Seasonal and (b) weekly average PM<sub>2.5</sub> concentrations.

Another study was conducted from 2005 to 2006, and data were collected at two other sites: one in the Zhabei District (the ZB site) and the other in the Jiading District (the JD site) (see Figure 28). The average concentrations of PM<sub>2.5</sub> are shown below:

Sampling site	Season	PM <sub>2.5</sub> ( $\mu\text{g}/\text{m}^3$ )
ZB	Annual	90.3 ± 54.9
	Fall, 2005	106.4 ± 63.2
	Winter, 2005	93.4 ± 44.1
	Spring, 2006	113.5 ± 65.5
	Summer, 2006	50.2 ± 23.0
JD	Annual	95.5 ± 41.8
	Fall, 2005	113.3 ± 48.7
	Winter, 2005	88.0 ± 41.8
	Spring, 2006	113.1 ± 36.2
	Summer, 2006	66.9 ± 24.6

Source: Feng et al., 2009

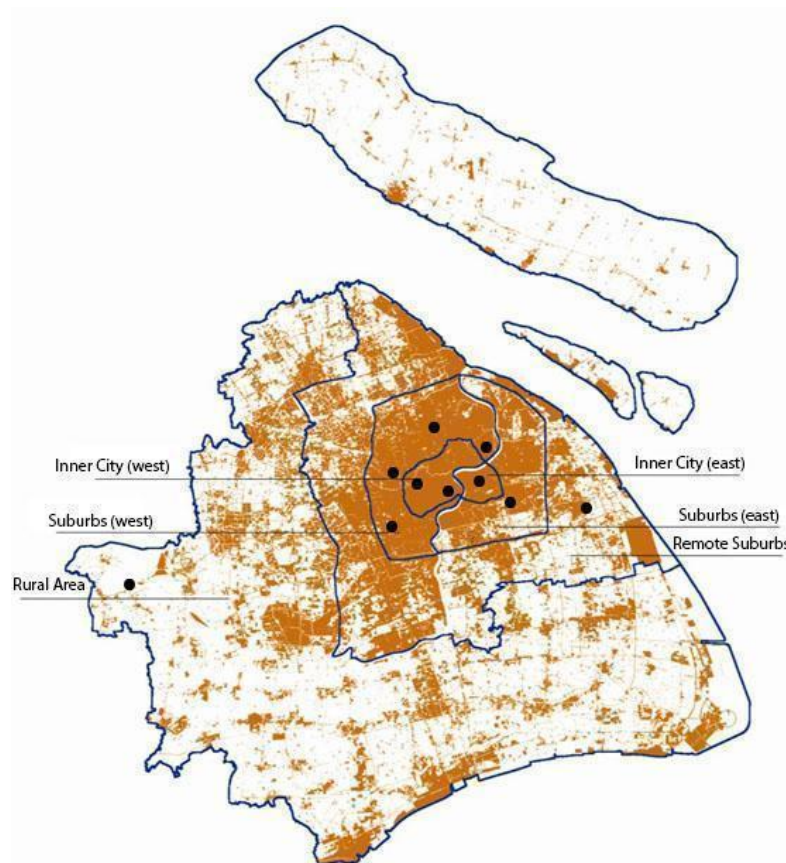
Figure 28. PM<sub>2.5</sub> average concentrations detected at ZB and JD sites.

These two studies differ in the dates used to define winter, spring, summer, and fall, but both draw the conclusion that the highest PM<sub>2.5</sub> concentration appear in the late fall and

the early winter. The average PM<sub>2.5</sub> concentrations of the 2005–2006 study are much higher than in the study conducted in 2003, but the reasons for such differences are impossible to determine because of the limited information we have.

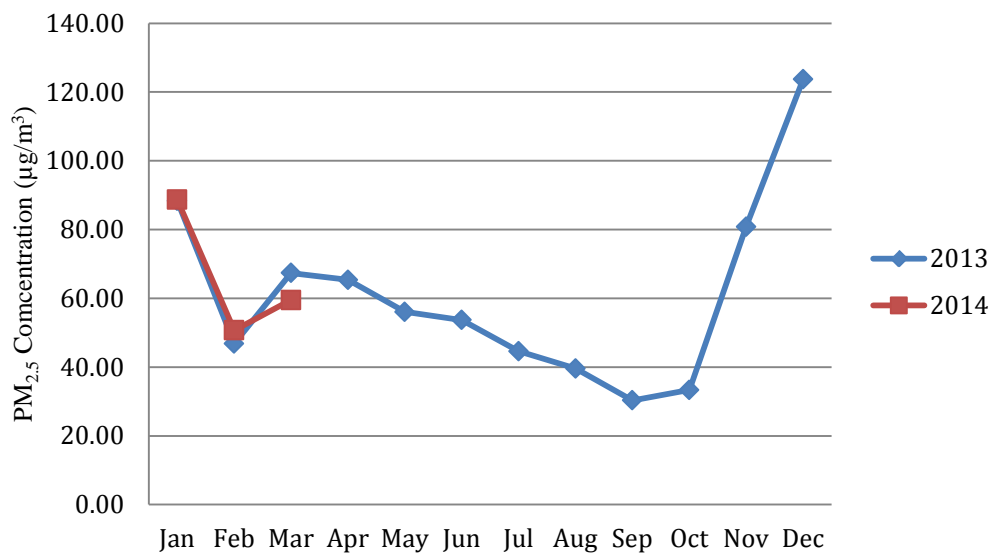
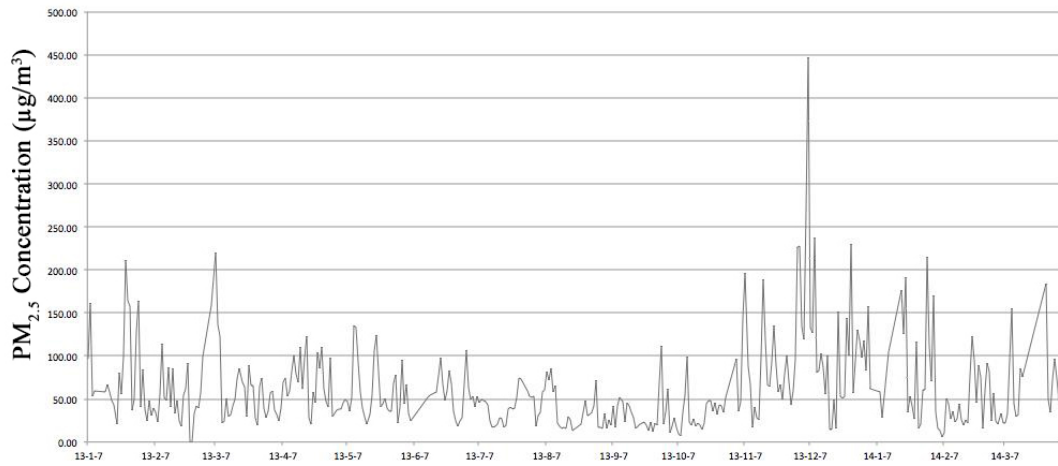
### 2.3.2.2. PM<sub>2.5</sub> DATA COLLECTION AFTER JUNE 2012

Complete PM<sub>2.5</sub> data collected from all 10 air quality monitoring stations throughout the city have been available since June 12, 2012. We collected the data about the PM<sub>2.5</sub> concentrations from all of the monitoring stations between Jan 7, 2012, and April 1, 2014 (see Figure 29).



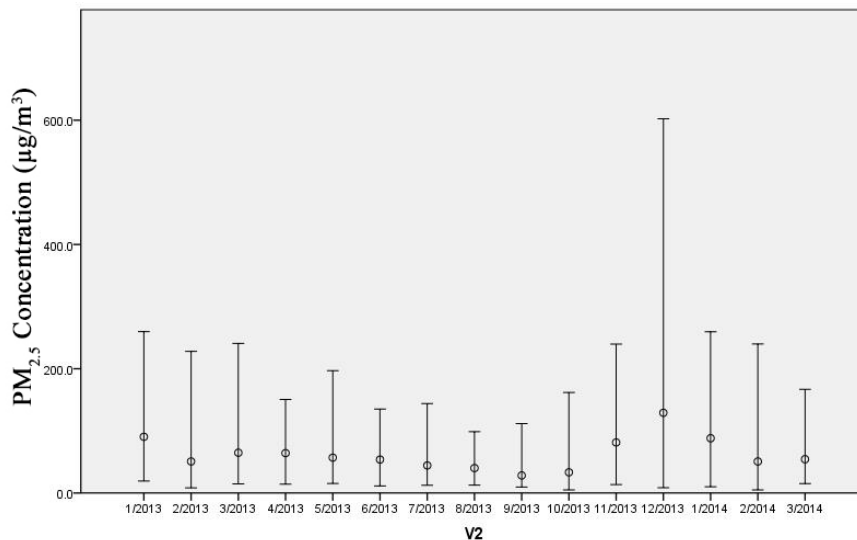
Source: Report of the Fourth Comprehensive Traffic Survey in Shanghai, 2010

Figure 29. Study zones of the survey (Report of the Fourth Comprehensive Traffic Survey in Shanghai, 2010) and locations of the 10 air quality monitoring stations.



Source: Shanghai Environmental Center, 2004

Figure 30. Average daily and monthly citywide PM<sub>2.5</sub> concentrations 2013–2014.



Source: Shanghai Environmental Center, 2004

*Figure 31. Average monthly citywide PM<sub>2.5</sub> concentrations, 2013–2014.*

The above graph shows the PM<sub>2.5</sub> concentration variations from the beginning of 2013 to March 2014 collected at all 10 of the air quality monitoring stations. From this chart, we can see a trend similar to that of the TSP data collected before 2000 and the PM<sub>10</sub> data published after 2000, which show higher concentrations in winter and lower concentrations in summer. Moreover, this data collection also shows that the higher the average PM<sub>2.5</sub> values are, the larger the variations are.

While the PM<sub>10</sub> concentrations in Shanghai show a slight decrease up to the present, the PM<sub>2.5</sub> concentrations in Shanghai show an increase.

The historical data also show that during the past years, although the vehicle population increased dramatically, TSP and coarse particles (PM<sub>10</sub>) showed the opposite trends, with small decreases, while PM<sub>2.5</sub> data showed trends with slight increases. The city began to pay attention to the PM<sub>2.5</sub> from 2012 because of its harmful effects on human health.

## 2.4. CORRELATION BETWEEN HISTORICAL AIR QUALITY DATA AND CORRESPONDING URBAN DEVELOPMENT



Source: Section 1.2.2.1

*Figure 32.* Urban land expansion of Shanghai, 1980, 1990, and 2007.

In 1986 SO<sub>2</sub> emissions hit their peak. Since then, SO<sub>2</sub> concentration levels have decreased as well as the concentration levels of other air pollutants, such as NO<sub>2</sub> and PM<sub>10</sub>, have decreased slightly (see Figures 19 and 24).

From Figure 32 above, it is evident that the total urban area of Shanghai has tripled. Construction sites should have contributed significantly to the amount of suspended particles in the atmosphere, but it is not obvious that the increasing construction sites elevated the total number of PM particles in the ambient atmosphere.

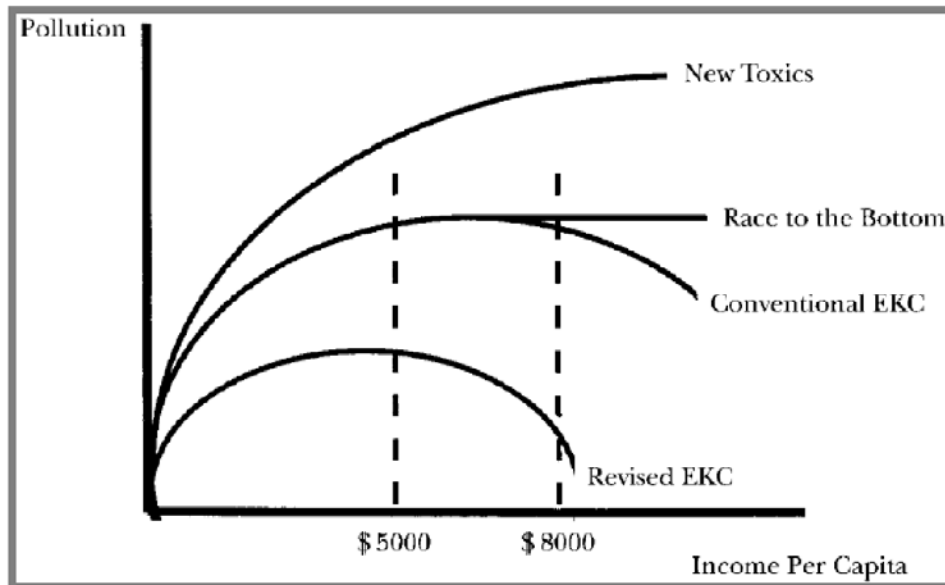
The pollution data collected in the past few years merely show a pattern that in the summer, the concentrations (or indexes) of all types of pollutants are lower. In winter, however, the concentrations (or indexes) are higher, which indicates, as shown in many other studies, the result of the seasonal variation of the near-surface temperature inversion layer in Shanghai, which is thicker in winter and thinner in the summer. In other words, in winter, most of the pollutants are often trapped in the temperature inversion layer and are not able to escape (Zheng, 2005). Therefore, the data collected in winter are more likely to correspond to the exact amount of transportation-related air pollution emissions.

Zheng (2005)) showed that NO<sub>2</sub> is the primary emission monitored in the central city. In SPSS, with PM<sub>10</sub> API indexes collected from 2000 through 2012 as dependent variables and NO<sub>2</sub> indexes as independent variables, the correlation analysis reveals that the correlation between these two air pollutants is 0.636, suggesting that they are highly correlated with each other. Nevertheless, it is not predictable whether the PM<sub>10</sub> and NO<sub>2</sub> concentrations were on the same level in the city center.

The exact relation between PM emissions and urban development requires further study. Due to the lack of detailed historical data of air quality by locations, it is difficult to answer the question of how PM particle concentrations in the atmosphere are changed by urban development.

At the beginning of 2014, the *Shanghai Daily News* reported that Shanghai's annual average PM<sub>2.5</sub> concentration levels were 60.7 µg/m<sup>3</sup> in 2013 (Shanghai Daily, 2014). Although this pollution level is not the worst among the Chinese cities, it is much higher than Chinese national standard (30 µg/m<sup>3</sup>), six times higher than the annual average of the WHO standard (10 µg/m<sup>3</sup>) (WHO, 2014). It is also more than five times higher than the newly revised annual PM<sub>2.5</sub> standard in 2012 (12 µg/m<sup>3</sup>) by the US EPA, (EHS Journal, 2013). It is surprising to observe this high level of PM<sub>2.5</sub> concentration in Shanghai, because since 1986 the city has adopted a lot of policies to improve the environment, including air quality. As we can see, the API of total suspended particles and PM<sub>10</sub> in the ambient atmosphere began to decrease. Dasgupta et. al. (2002) identified an Environmental Kuznets Curve (EKC) showing inverted-U relationships between environmental pollution and economic development. It is clear that the city of Shanghai and all of its air pollutants are now experiencing a turning point at the vertex of the EKC and are beginning to show slight changes, shifting their direction from increasing to decreasing. The turning points of the EKC's pollution reduction zone, which were empirically identified, are usually somewhere from \$5,000 to \$8,000 per

capita. China has entered this EKC zone: The Chinese personal income level reached \$5,447 in 2011 (World Bank). One can expect that the air pollution level will decrease in the future as the economic performance continues to increase in Shanghai.



Source: Dasgupta et al., 2002, Figure 1, p. 148

*Figure 33.* Environmental Kuznets curve and different scenarios.

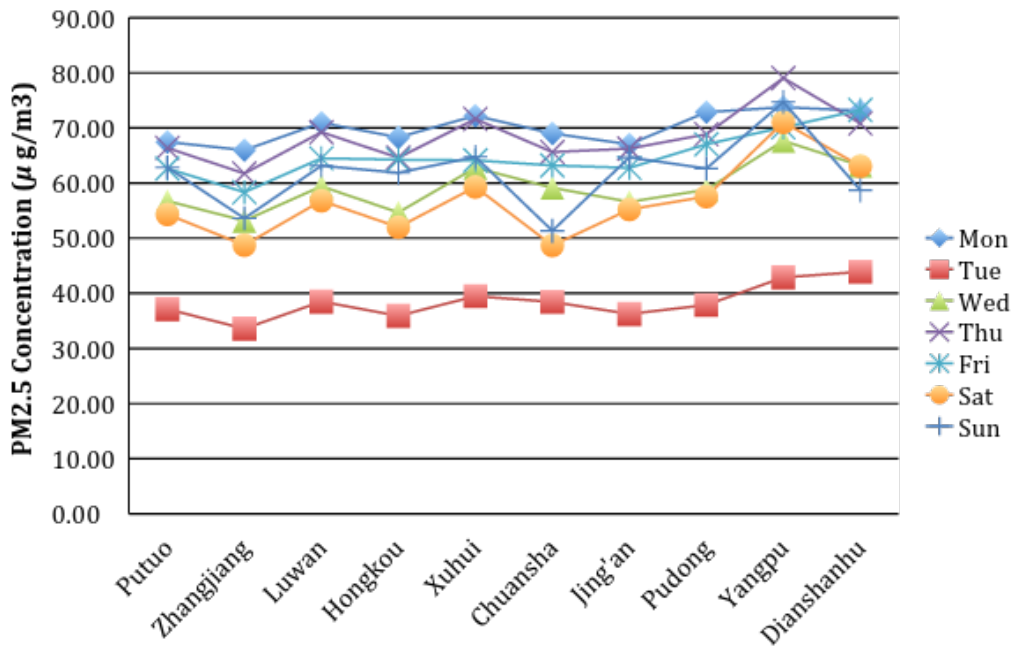
Most existing studies have not dealt with the topic of intra-regional disparities in air quality. In this thesis, we launch questions and discussions about whether there exists an imbalance between different regions of the city. To examine what we call “intra-regional air quality,” it will be necessary to analyze the PM<sub>2.5</sub> data obtained from the 10 monitoring stations in the city of Shanghai. Access to the database was not readily available, but we were able to access several online databases that allowed us to collect the 24-hour, real-time PM<sub>2.5</sub> concentration data from January 2014 to April 2014. The following websites were used for the data collection:

- Shanghai Environmental Monitoring Center  
<http://www.semc.gov.cn/aqi/home/Station.aspx>
- Countrywide PM<sub>2.5</sub> Monitoring Network

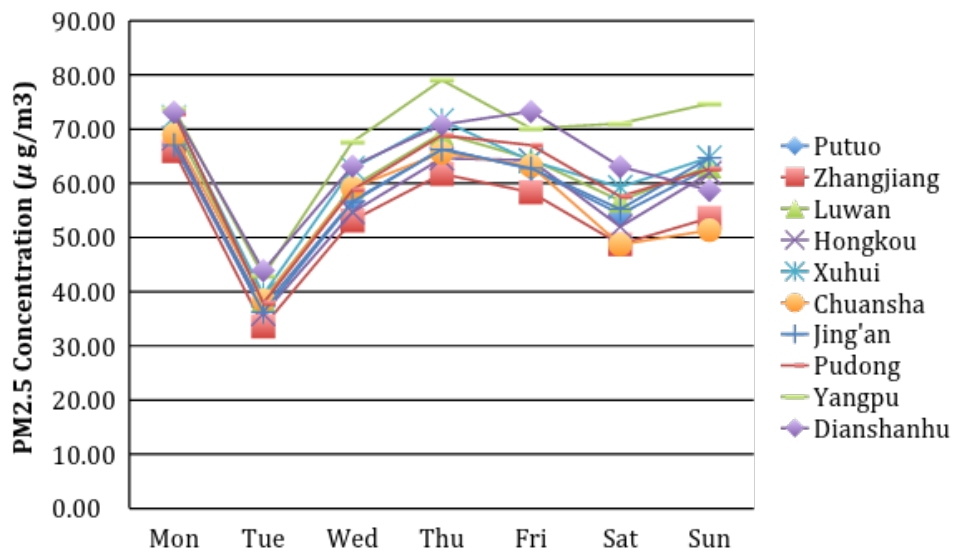
<http://www.cnpm25.cn/city/shanghai.html>

- Shanghai Air Quality PM<sub>2.5</sub> (Blog)

<http://www.weibo.com/airquality?topnav=1&wvr=5&topsug=1>



(a) By location



(b) By Weekdays vs. weekends

Source: Shanghai Environmental Monitoring Center

Figure 34. Average PM<sub>2.5</sub> concentrations of 10 air quality monitoring stations in Shanghai.

To examine the intra-regional geographic distribution pattern of PM<sub>2.5</sub> concentrations, we examined all of the available data and grouped different data into weekday groups. From Figure 34(a) above, we can see that the air pollution levels at different locations of the city across the 10 air quality monitoring stations do not show significant differences in average PM<sub>2.5</sub> concentration levels. Nevertheless, the PM<sub>2.5</sub> concentration levels of the different weekdays vary significantly (see Figure 34(b)). The Monday data showed the highest concentration of PM<sub>2.5</sub>, but it falls to the lowest concentration on Tuesdays for all 10 monitoring station areas. The Tuesday levels (35–45) are a little more than half of the Monday concentration levels (65–75). The second highest day in terms of the PM<sub>2.5</sub> concentration monitored is Thursday (60–70 except in Yangpu District). Unfortunately, we cannot offer any explanation for these striking differences. With regard to the weekends, PM<sub>2.5</sub> levels on Sundays are higher than those on Saturdays in all areas except the Dianshianhu Station, which is different from other stations because it is located in a natural, rural area. Because the patterns of the average PM<sub>2.5</sub> concentrations collected at the 10 air quality monitoring stations for each weekday are similar (see Figure 34(a)), but the PM<sub>2.5</sub> concentrations collected on different weekdays varied dramatically (see Figure 34(b)), we can say that the weekday variation on which we collect data plays a more important role than at which stations we collect these data in terms of determining the amount of PM<sub>2.5</sub> concentrations. Further investigation of the pattern of daily PM<sub>2.5</sub> concentrations may be warranted to manage the air quality in Shanghai.

Several studies have focused on what was called “weekend effect,” meaning that weekend days were supposed to be different from weekdays. For example, the traffic volume and the related NO<sub>2</sub>, NO, and CO emissions on weekend days (Saturday and Sunday) are much less than the emissions on weekdays (Li, 2008; Tang et al., 2008).

It is obvious, as analyzed above, that the  $PM_{2.5}$  concentrations in the whole city region varied between weekdays and the weekends. Tuesdays show the lowest  $PM_{2.5}$  concentrations, and Saturdays and Sundays had the second lowest  $PM_{2.5}$  concentrations. Still, it remains unclear whether such differences in  $PM_{2.5}$  concentration between weekend days and weekdays are due to differences in on-road traffic volume. Had we had the weekday vs. weekend day traffic volume data, we could have tested this relationship.

## 2.5. SUMMARY

In this section, we discussed the following points:

- $PM_{2.5}$  particles emitted by vehicles are supposed to rest along the streets instead of spreading to other places in the city, and  $PM_{2.5}$  creates the vertical air convection.
- All of TSP,  $PM_{10}$ , and  $PM_{2.5}$  levels see a seasonal variation in concentrations in the atmosphere because of the different thicknesses of the near-surface temperature inversion layers in winter and summer.
- Air quality monitoring in Shanghai began in 1997, but the official  $PM_{2.5}$  monitoring started in 2012. The  $SO_2$  API indexes in 1986 saw a peak because of the fastest-growing GDP and underdeveloped environmental protection techniques, and then the air quality got improved—just as the Environmental Kuznets Curve predicts—slowly.
- After 2000, the concentrations of  $SO_2$  and  $PM_{10}$  decreased, while the  $NO_2$  and  $PM_{2.5}$  concentrations in the ambient air did not see an apparent decline, which suggests that the increasing automobile usage could be a contributing factor.
- Almost all of the air quality monitoring stations are located inside the central city (inside the second ring road), so it is hard to tell how the air quality varies in the suburban area.

## **Chapter 3 Methodologies of Transportation-Related Air Pollution (PM<sub>2.5</sub>)**

### **3.1. CURRENT TRANSPORTATION-RELATED AIR POLLUTION IN SHANGHAI**

It is not clear what percentage of air pollution, and PM<sub>2.5</sub> in particular, is related to the transportation sector in China. In general, 26% of all air pollution in Shanghai is related to transportation (Bloomberg, Dec. 25,, 2013).

Examining the differences in the data collected at 10 different monitoring stations is just one methodology of studying intra-regional air quality problems.

In terms of other methodologies of studying regional air quality issues, previous studies give us two options. One assesses the amount of emissions based on energy use, relying on the total amount of yearly vehicle kilometers or miles traveled. The other examines daily traffic density along the streets. These two methodologies are related, since the higher the traffic density is, the more vehicle miles (or kilometers) are operated and the more energy is consumed.

### **3.2. METHODOLOGY 1: TRAP BY YEAR – CALCULATED WITH VEHICLE POPULATION AND VEHICLE KILOMETERS TRAVELED (VKT)**

The amount of transportation emissions can be calculated using the calculation methodology and emission coefficients adopted by the IPCC (2006 IPCC Guidelines for National Greenhouse Gas Inventories). Zhao used this methodology in his study to calculate carbon emissions based on energy consumption in Shanghai from 1994 to 2006 (Zaho, 2009).

Zhao's study is focused on calculating carbon emissions of stationary resources. For mobile resources, according to calculation models such as MOBILE, EMIT, COPERT, IVE, and MOVES (Xu, 2009), emissions should be calculated based on the vehicle population by

vehicle type and relevant vehicle kilometers traveled (VKT). Therefore, although the amount of energy consumption in the transportation sector can be obtained from *Shanghai Statistics Yearbook*, PM<sub>2.5</sub> emissions cannot be calculated based only on the amount of gasoline, diesel, or electricity consumption in the transportation sector.

In their article, Zhai and his team offer the average annual vehicle kilometers traveled (KVT) by all types of vehicles mentioned in the Shanghai Statistics Yearbooks as (a) small passenger cars:  $3.1 \times 10^4$  km; (b) large passenger cars:  $4.0 \times 10^4$  km; (c) heavy freight trucks:  $4.4 \times 10^4$  km; (d) light freight trucks:  $3.2 \times 10^4$  km; and (e) motorcycles:  $1.1 \times 10^4$  km (Zhai et al., 2012).

According to the latest transportation and traffic survey of Shanghai (Report of the Fourth Comprehensive Traffic Survey in Shanghai, 2010), the total percentage of diesel buses (categorized in Shanghai Statistical Yearbooks as large passenger cars) out of the total number of buses in the city is 83.3%, and the percentage of heavy freight trucks among all freight trucks is 67%. In addition, motorcycles and diesel trucks are restricted (Shanghai Public Security Bureau, 2011) in the area of West and East Inner City. Inside the first ring road, we can assume that almost all of the small passenger cars and light freight trucks consume gasoline instead of diesel, and all of the motorcycles consume lower-quality gasoline. Shanghai began to implement National Emission Standard I (National I) in 1999, National II in 2002, National III in 2008, and National IV in 2014. Different emission standards have different restrictions on PM<sub>2.5</sub> emission:

Table 1 *Emission Factors of Mobile Sources (g/km · vehicle)*

	Small Passenger Vehicle	Large Passenger Vehicle	Light Freight Truck	Heavy Freight Vehicle	Motorcycle
	Gasoline	Diesel	Gasoline	Diesel	Gasoline
National I	0.03	0.4	0.05	0.7	0.1
National II	0.03	0.2	0.05	0.7	0.03
National III	0.03	0.2	0.02	0.7	0.01

Source: Zhai et al., 2012

Emissions in a specific period can be calculated with the following equation:

$$E = \sum A \cdot EF \cdot (1 - \eta).$$

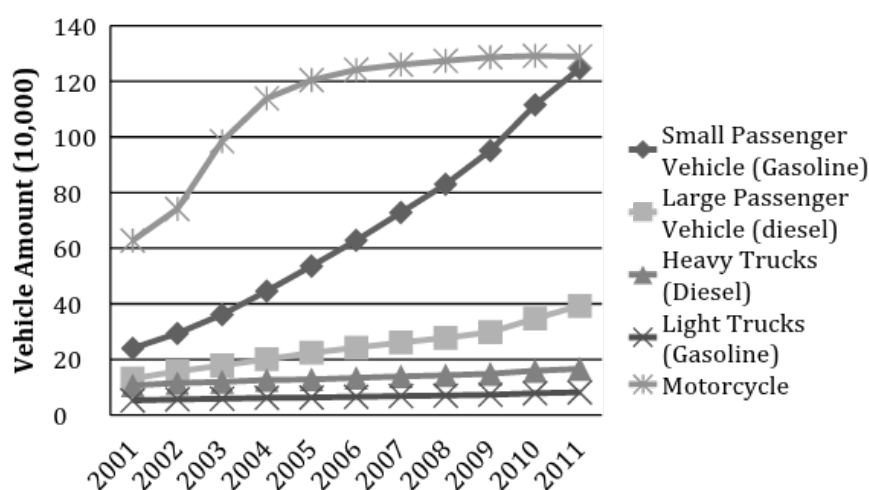
*Equation 1.* Calculation equation of vehicle PM<sub>2.5</sub> emissions.

In this equation, E equals the amount of emissions during a specific period; A is called activity level and is equal to the kilometers traveled by each vehicle type; EF is the emission factor; and  $\eta$  is the contaminant removal efficiency of this vehicle type (Zhai et al., 2012), as shown below:

Table 2 *Removal Efficiencies of Different Types of Vehicles*

Fuel Types	Vehicle Types	(%)
Gasoline	Light Truck	97
	Small Passenger Car	97
	Taxi (equal to small passenger car)	97
	Motorcycle	N/A
Diesel	Heavy Truck	95
	Large Passenger Vehicle (buses)	95

Source: Ministry of Housing and Urban-Rural Development of P.R.C.



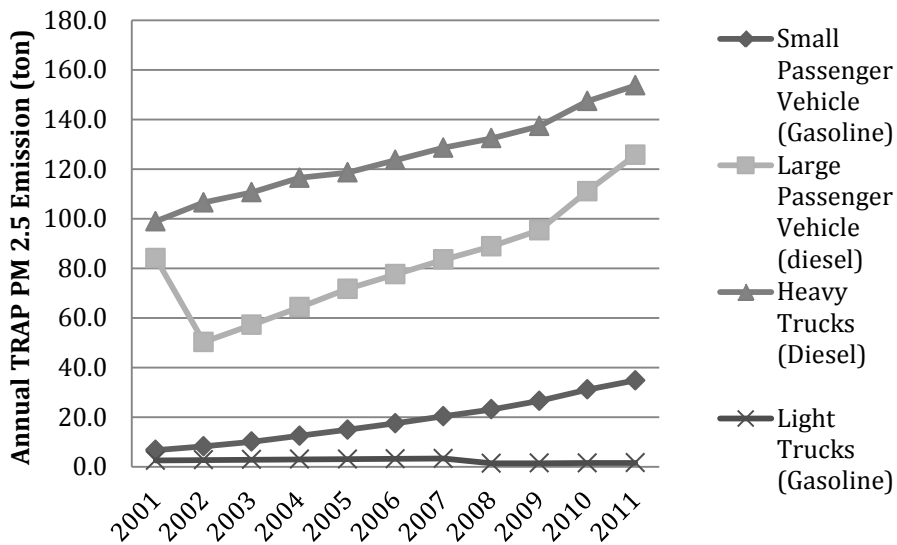
Source: Shanghai Statistical Yearbook 2002–2012

Figure 35. Vehicle population (unit: 10,000) by vehicle type, 2001–2011.

Relying on the vehicle population of different types of vehicles in Shanghai from 2000 to 2012 (see Figure 35), the total amount of the PM<sub>2.5</sub> emissions from 2000 to 2012 for all vehicles of a given type is shown below, using the removal efficiencies of small passenger vehicles, light and heavy trucks as 97%, and large passenger vehicles as 96%:

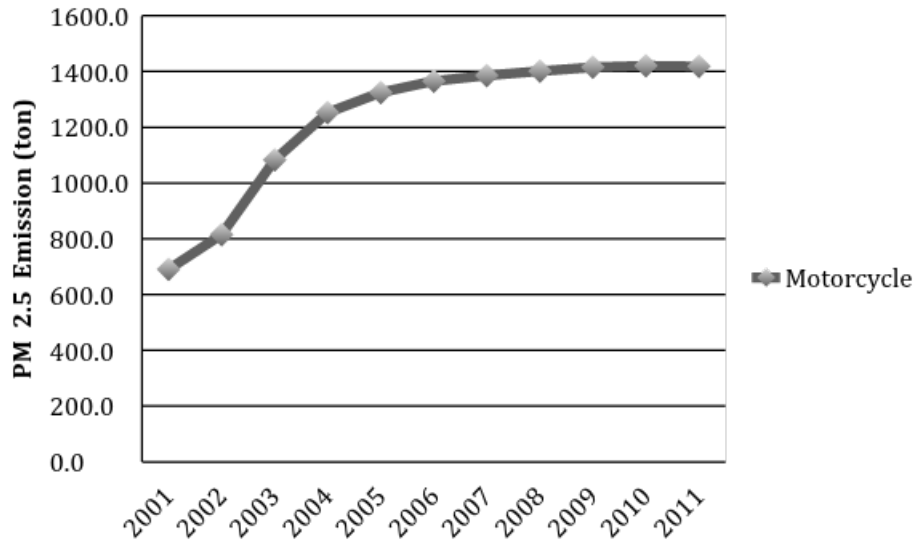
Table 3 Annual PM<sub>2.5</sub> Emissions by Year (Unit: Tons)

	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
Small Passenger Vehicle (Gasoline)	6.7	8.2	10.1	12.4	15.0	17.5	20.3	23.1	26.5	31.1	34.8
Large Passenger Vehicle (diesel)	84.1	50.3	57.2	64.3	71.7	77.6	83.6	88.9	95.4	111.1	125.7
Heavy Trucks (Diesel)	98.9	106.5	110.6	116.5	118.6	123.7	128.6	132.4	137.4	147.4	153.7
Light Trucks (Gasoline)	2.5	2.7	2.8	3.0	3.0	3.2	3.3	1.4	1.4	1.5	1.6
Motorcycle	690.3	815.0	1083.1	1252.4	1324.6	1365.7	1385.7	1401.1	1415.0	1420.3	1417.8



\*Calculated, based on vehicle population by type and annual vehicle kilometers traveled by type.

Figure 36. Annual PM<sub>2.5.5</sub> emissions by vehicle type from 2001 to 2011 (unit: tons).



\*Calculated, based on motorcycle population and annual vehicle kilometers traveled by motorcycles.

Figure 37. Annual PM<sub>2.5</sub> emissions by motorcycles (Unit: tons).

From the above analysis, it is quite evident that when regarding Shanghai City as a whole, motorcycles are probably responsible for most of the PM<sub>2.5</sub> emissions in the ambient atmosphere. One reason is that total motorcycle ownership doubled during the 11 years analyzed. Another reason is that although the newest emission standards decreased the emission factors of motorcycles less than 0.03 g/km in 2002 and less than 0.01 g/km in 2008, motorcycles are incapable of removing contaminants. Motorcycles do not have a valid contaminant removal efficiency, meaning that technologies are not advanced enough to remove PM<sub>2.5</sub> contaminants brought about by fuel combustion. As such, the total amount of PM<sub>2.5</sub> emissions of motorcycles remained at a level of 1,400 tons per year, which is almost 10 times higher than the annual emissions of large trucks.

At the same time, heavy trucks and large passenger vehicles—buses—are the other two major PM<sub>2.5</sub> contributors in Shanghai during the past few years, generating 120 to 160 tons of PM<sub>2.5</sub> particles in 2011. It is clear that the growth of PM<sub>2.5</sub> particles generated by large passenger vehicles during the past years was due to the population growth of this vehicle type.

In spite of the rapid growth of small passenger cars, the PM<sub>2.5</sub> emissions generated by small passenger cars were relatively small due to the numerically low emission factors of this type of vehicle. On the other hand, both of the large passenger vehicles—buses and heavy trucks—have numerically higher emission factors; as a result, they were two of the three main contributors to the transportation-related PM<sub>2.5</sub> emissions during the past few years.

### **3.3. METHODOLOGY 2: TRAP BY LOCATION – CALCULATED WITH TRAFFIC DENSITY**

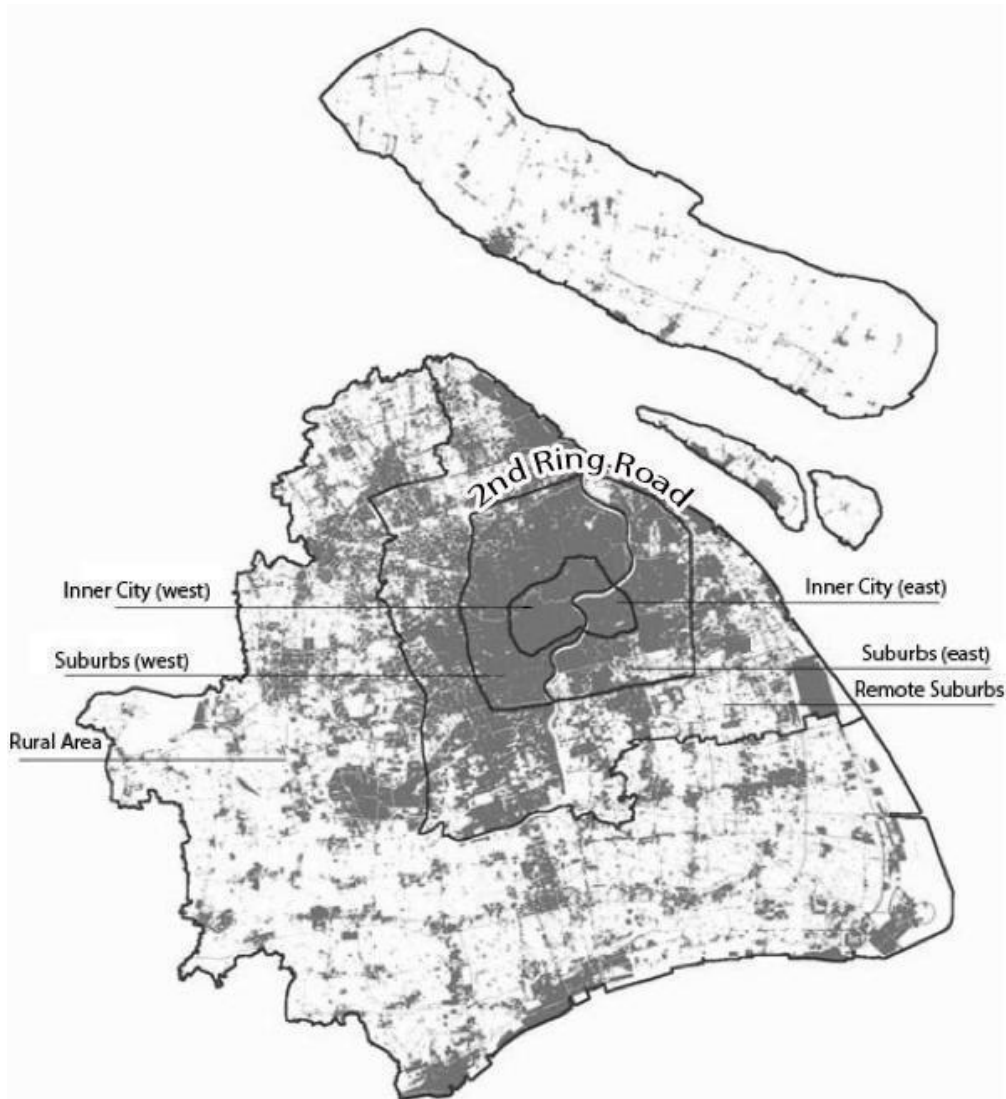
Another common methodology used to estimate transportation-related PM<sub>2.5</sub> pollution uses annual vehicle population and vehicle kilometers traveled (VKT). It should be helpful to see a rough dispersion pattern of PM<sub>2.5</sub> particles based on average daily traffic density, since such a dispersion pattern can help evaluate the regional differences in exposure risks to PM<sub>2.5</sub>.

As analyzed above, a majority of the PM<sub>2.5</sub> particles in the ambient atmosphere should be concentrated along the streets and along the routes of diesel buses and heavy trucks, and concentrated in the areas that motorcycles are able to access.

#### **3.3.1. BOUNDARIES OF STUDY AREA**

##### **3.3.1.1. CITYWIDE REGION**

The boundaries of the study area are based mainly on the availability of the traffic volume data. Both the available traffic speed data and the percentages of different on-road vehicle types can only be found inside the second ring road (see Figure 38), where eight of the 10 air quality monitoring stations of Shanghai are located. As a result, we determine the area inside the second ring road as our study area.



Source: Report of the Third Comprehensive Traffic Survey in Shanghai, 2004

*Figure 38.* Four regions of Shanghai.

The study area can also be divided into four regions—the East and West Inner City regions and the East and West Suburbs.

### **3.3.1.2. MICRO REGION**

The real-time traffic speed data determined by “traffic zones” and freeway segments are available from the government’s official website, Shanghai Real-Time Urban Traffic Information (上海交通出行网), sponsored by the Shanghai Municipal Urban and Rural Construction and Transportation Commission. There are 68 traffic zones and 42 freeway

segments in the study area, which can be regarded as stationary point sources and line sources of pollutants. In addition, we need to use census data for the population analysis. The boundaries of census data are in accordance with the street districts (街道), which are known as the boundaries of Shanghai’s smallest administrative districts. Shanghai’s census data can give us information about “vulnerable groups,” which will be explained in further detail below. Therefore, these two types of boundaries—the boundaries of the traffic zones and of the street districts—are the micro regions in this study.



Source: Shanghai Real-Time Urban Traffic Information 上海交通出行网

Figure 39. Micro regions: (a) Ground-level transportation zones and (b) Elevated freeway segments.

### 3.3.2. DATA COLLECTION

#### 3.3.2.1. TRAFFIC DENSITY AND PASSENGER CAR EQUIVALENT DATA

Data collection will focus on collecting the traffic volume data that can represent the average daily automobile usage along the streets of the city. The intensity of automobile usage can be measured with traffic density. Researchers studying the association between childhood asthma and proximity to roadways (Lin et al., 2002) offer a methodology of

measuring traffic density by multiplying the traffic volume data of one specific segment of roadway by the length of the segment, which leads to the vehicle kilometers traveled (VKT).

As in most of the cities of China, the traffic flows in Shanghai are mixed, with vehicles of different types and quality, and occupy the different path spaces (Wang, 2006). To simplify the traffic volume calculation process and let traffic volume data represent the exact transportation status on the streets, the concept of passenger car equivalent (PCE) was introduced, and all vehicle types were converted to passenger cars with specific conversion coefficients (see Table 3). The PCE trips of all of the city’s streets can be obtained from the Shanghai City Comprehensive Transportation Planning Institute (SCTPI) Annual Report (2003).

The following PCE conversion coefficients for different vehicle types are from the Code for Transport Rules and Regulations on Urban Road (城市道路交通规划设计规范) (Ministry of Housing and Urban-Rural Development of P.R.C., 1995):

Table 4 *PCE Conversion Coefficients by Vehicle Type (95, GB50220)*

Vehicle Types	Conversion Efficient
Light truck	1.0
Small passenger car	1.0
Taxi (equal to small passenger car)	1.0
Motorcycle	0.4
Heavy truck	3.0
Large passenger vehicle (buses)	2.0

Source: Ministry of Housing and Urban-Rural Development of P.R.C., 1995

Therefore, when calculating the number of different types of vehicles on the streets of Shanghai, it is necessary to take into account the above conversion coefficients. For example, if on one street the daily traffic volume can be represented by algebra symbol X (vehicle trips), and if among these vehicles, 6.4% are buses (large passenger vehicles), 19.8% are taxis, 66.3% are small passenger cars, and 7.5% are motorcycles, then we can create an equation as follows:

$$6.4\% \cdot X \cdot 2 + 19.8\% \cdot X \cdot 1 + 66.3\% \cdot X \cdot 1 + 7.5\% \cdot X \cdot 0.4 = \text{Total PCE traffic volume}$$

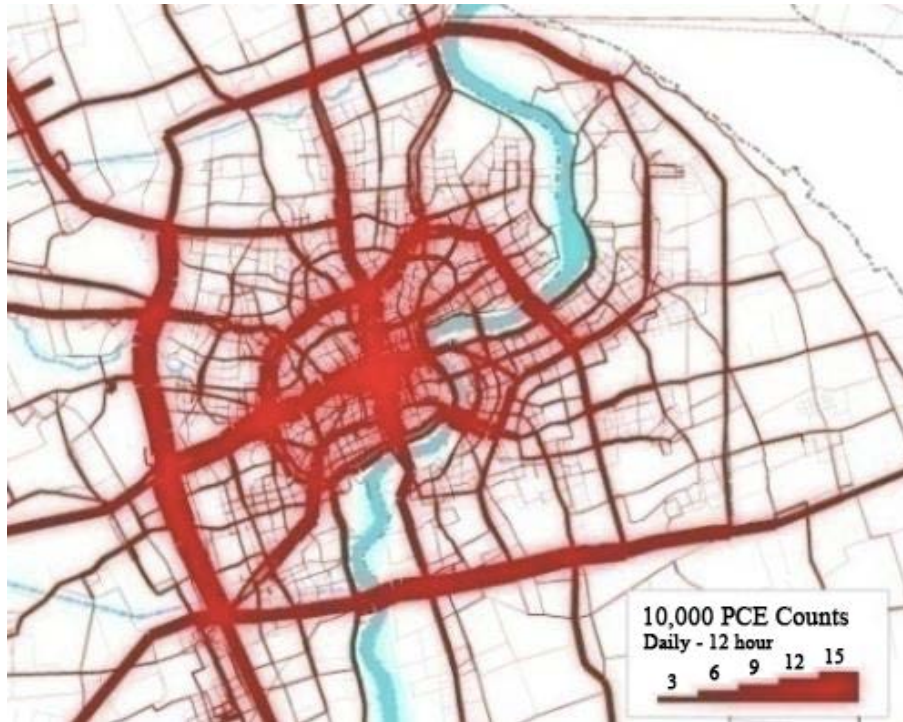
If we know the exact total PCE traffic volume of one street of Shanghai and know the approximate percentage of different types of vehicles, it is possible to obtain the exact traffic volume of different vehicle types from the two transportation surveys (*Report of the Third Comprehensive Traffic Survey in Shanghai, 2003* [上海市第三次综合交通调查总报告], and *Report of the Fourth Comprehensive Traffic Survey in Shanghai, 2009* [上海市第四次综合交通调查总报告]).

The total traffic volume distribution of the city region is from the Third Transportation Survey of Shanghai and a related official report, the SCTPI Annual Report (2003). The Third Transportation Survey of Shanghai was conducted in 2003, but the report (*Report of the Third Comprehensive Traffic Survey in Shanghai, 2004* [上海市第三次综合交通调查总报告]) was published a year later, in 2004. According to the traffic survey report, the total traffic density (traffic volume multiplied by distance of road segments) in the West and East Inner City within the first ring road were  $1,587 \times 10^4$  vehicle · km per day and  $304 \times 10^4$  vehicle · km per day respectively, and in the West and East Suburbs were  $1,973 \times 10^4$  vehicle · km per day and  $949 \times 10^4$  vehicle · km per day respectively.

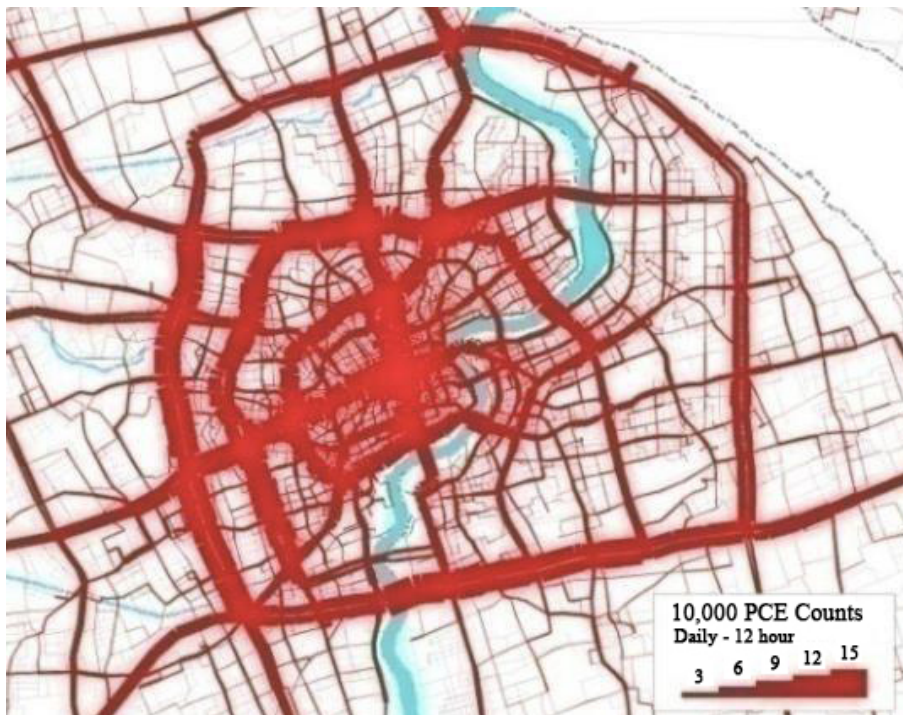
In the fourth transportation survey of Shanghai, conducted in 2009 (*Report of the Fourth Comprehensive Traffic Survey in Shanghai, 2010* [上海市第四次综合交通调查总报

告]), the researchers found that the traffic volume in all of the four study areas (the West and East Inner City and the West and East Suburbs) increased. The traffic volume grew by 15%, 61%, 35% and 54%, respectively (*Report of the Fourth Comprehensive Traffic Survey in Shanghai, 2010*[上海市第四次综合交通调查总报告]) (see Figure 40).

Our study will be based on the traffic volume data of 2003, which is available, and assume that the traffic volume increased between 2003 and 2009 equally in all of the streets in the four study regions (the West and East Inner City and West and East Suburbs).



(a)



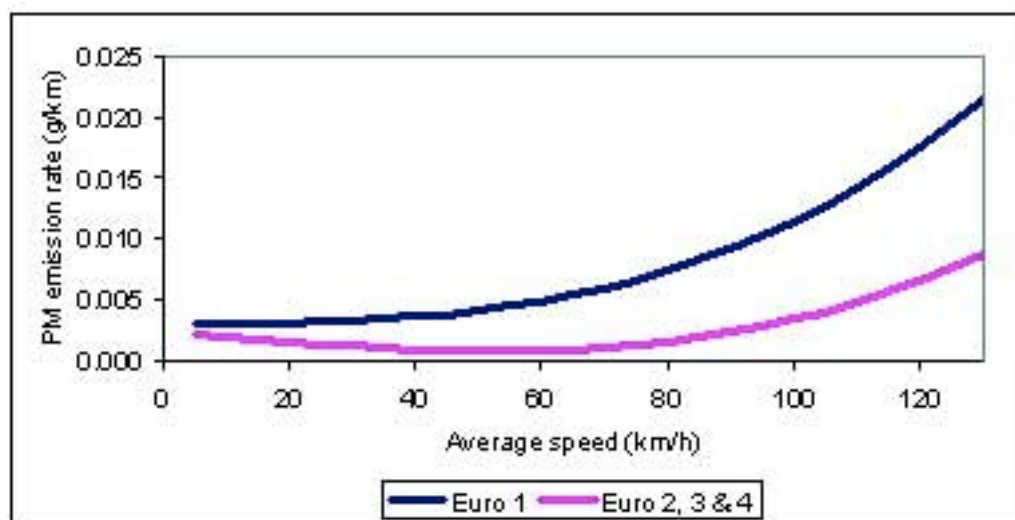
(b)

Source: Report of the Fourth Comprehensive Traffic Survey in Shanghai, 2009

Figure 40. Traffic volume distribution, 2003 (a) and 2009 (b).

### 3.3.2.2. TRAVEL SPEED DATA

Traffic speed is another determinative factor that contributes to the TRAP. This factor is responsible for incomplete combustion and additional on-road emissions, and PM emission levels vary according to vehicle travel speeds. According to the UK Department of Transport, PM emission rates tend to be lowest when the average vehicle speed is around 50 km/h (45 mi/h) and are higher when the average speed is less than 40 km/h (36 mi/h) or higher than 60 km/h (54 mi/h), especially for Euro 2, 3, and 4 (see Figure 41). We can apply these PM emission rates to National I, II, III, and IV in China because the national models are the same as Euro 1, 2, 3, and 4.



Source: The National Archives, UK Government Web Archive, Department of Transport.

*Figure 41.* Average light-duty vehicle speed and PM emission rates for Euro 1, 2, 3, and 4.

The data for real-time traffic speed and the average traffic speed for a specific moment of a day are both available at the Shanghai Transportation Web site 上海交通出行网 (see <http://www.jtcx.sh.cn/index.html> for details), which divides the transportation system

of Shanghai into two systems: the elevated road system and the ground-level road system (see Figure 39).

As stated previously, since the whole ground-level street network can be divided into 68 traffic zones and average real-time and historical hourly speeds for each traffic zone are available, we can calculate the average daily speed in the 68 traffic zones. This calculation will enable us to assess potential risks in all of these traffic zones in terms of potential impacts of traffic speed.

### **3.3.2.3. VEHICLE TYPE DISTRIBUTION DATA**

Vehicle types along the streets of different regions can be obtained from Shanghai's latest transportation survey, which divides the total area of the city into four parts—the West Inner City, the East Inner City, the West Suburbs, and the East Suburbs (see Figure 38).

The two transportation surveys of Shanghai conducted in 2003 and 2009 (*Report of the Third and Fourth Comprehensive Traffic Survey in Shanghai, 2003 and 2009*) give us the different percentages of different vehicle types in our study area (see Table 5) in both years.

Table 5. *Percentages of Different Types of Vehicles on Streets in Study Area (Inside the Second Ring Road) in 2003 and 2009*

Vehicle Type	Traffic Volume (Annual Average Daily 10,000 PCE Kilometers) 2003	Volume (%) in 2003	Traffic Volume (Annual Average Daily 10,000 PCE Kilometers) 2009	Volume (%) in 2009
Bus (Large Passenger Vehicle)	550	10.11%	356	5.99%
Taxi	1210	22.47%	1380	23.21%
Private Cars (Medium, Small, and Midget)	2243	41.57%	3377	56.79%
Motorcycle	104	2.25%	297	4.99%
Freight Vehicles (Heavy Trucks)	1278	23.60%	537	9.02%
Total	5385	100%	5974	100%

Source: Report of the Fourth Comprehensive Traffic Survey in Shanghai 2003 (published in 2004) and 2009 (published in 2010)

Since detailed information about percentages of different types of vehicles on each segment of the road is unavailable at this moment, we calculate the PM<sub>2.5</sub> emissions based on the vehicle type percentage data shown above.

#### **3.3.2.4. EMISSION FACTORS ACCORDING TO THE NEWEST PM<sub>2.5</sub> EMISSION INVENTORY**

After the smoggy days of 2012 (see Chapter 1), the Department of Science and Technology and Standards (DSTS, 技术标准司) of China began to take PM<sub>2.5</sub> emissions seriously and launched a study of PM<sub>2.5</sub> emission inventory. At the end of 2013, a new PM<sub>2.5</sub> emission inventory was completed, and the Ministry of Environmental Protection of the People's Republic of China (中华人民共和国环境保护部) published the Third PM<sub>2.5</sub>

Emission Inventory Draft in China (大气细颗粒物(PM<sub>2.5</sub>)源排放清单编制技术指南(试行)) in 2014.

This inventory (DSTS, 技术标准司) offers the PM<sub>2.5</sub> emission factors for every type of on-road vehicle, which is similar to the EU 4 and refers to the latest MOBILE emission model. In China, vehicles are categorized as small passenger vehicles using gasoline, large passenger vehicles (buses) using diesel, heavy trucks using diesel, light trucks using gasoline, and motorcycles using gasoline, as discussed earlier. All of these categories are related to specific vehicle weight, size, fuel type, fuel consumption per hundred kilometers (Liu et al., 2013), and emission factors (see Table 6).

Table 6 *National Emission Standard IV*

Fuel Types	Vehicle Types	Size	Emission Factor PM <sub>2.5</sub> (g/kg, 2003)	Emission Factor PM <sub>2.5</sub> (g/kg, 2009)	Fuel Consumption per 100 km (liters/100 km) (Liu et al., 2013)
Gasoline	Small Passenger Car	Length ≤ 6m, Seat Number < 20	0.15	0.02	9.2
	Taxi (equal to small passenger car)		0.15	0.02	33.4
	Motorcycle		4.59	4.65	2.0
Diesel	Heavy Truck	Length ≥ 6m, Mass ≥ 12000kg	3.47	1.35	31.8
	Large Passenger Vehicle (buses)	Length ≥ 6m, Seat Number ≥ 20	3.64	1.46	8.3

Source: Liu et al. (2013); The Third PM<sub>2.5</sub> Emission Inventory Draft (2014)

### 3.3.3. CALCULATION FORMULA

The amount of daily PM<sub>2.5</sub> emissions based on daily traffic density along streets can be derived from the calculation steps shown via the equation of on-road vehicle PM<sub>2.5</sub> emissions:

$$E = \sum A \cdot EF \cdot (1 - \eta)$$

(see Equation 1),

where A indicates the activity level of the vehicles, defined as VKT multiplied by fuel consumption per hundred kilometers; EF is the emission factors according to different types of vehicles; and  $\eta$  is the contaminant removal efficiency of different types of vehicles.

Values for the contaminant removal efficiency of different types of vehicles can be obtained from the National IV Emission Standards (see Table 7).

Table 7. *Removal Efficiencies of Different Types of Vehicles*

Fuel Types	Vehicle Types	(%)
Gasoline	Light truck	97
	Small passenger car	97
	Taxi (equal to small passenger car)	97
	Motorcycle	N/A
Diesel	Heavy truck	95
	Large passenger vehicle (buses)	95

Source: The Third PM<sub>2.5</sub> Emission Inventory Draft (2014)

Therefore, the above Equation 1 can be converted to:

$$E = \sum V_o \times P \times C \times \rho \times L \times EF (1-\eta) \times 10^2$$

*Equation 2. Converted equation of on-road vehicle PM<sub>2.5</sub> emissions*

where  $V_0$  indicates the daily traffic counts on a given street segment;  $P$  is the percentage of a given vehicle type;  $C$  is the fuel consumption per 100 kilometers of this vehicle type;  $\rho$  is the mass density of gasoline and diesel;  $L$  is the length of the street segments;  $EF$  is the emission factor of this vehicle type; and  $\eta$  is the contaminant removal efficiency of this vehicle type.

In our study, the mass density of gasoline is 0.83 g/ml and the mass density of diesel is 0.74 g/ml.

### 3.3.4. GAUSSIAN DISPERSION MODEL

Atmospheric dispersion modeling is the mathematical spatial simulation of how air pollutants disperse in the ambient atmosphere. The technical literature on air pollution is quite extensive and dates back to the 1930s and earlier. The Gaussian dispersion model is one of the oldest air pollution dispersion models and one of the most commonly and widely used models in predicting the dispersion of all kinds of air pollutants in the ambient atmosphere.

The Gaussian model assumes that the dispersion pattern of the pollutants has a Gaussian distribution, meaning that the pollutant distribution has a normal probability of distribution. Gaussian models are most often used for predicting the dispersion of continuous, buoyant air pollution plumes originating from ground level (ground-level roads) or elevated sources (elevated freeways). The basis for most of these models was the equation shown as following:

$$C = \frac{Q}{u} \cdot \frac{f}{\sigma_y \sqrt{2\pi}} \cdot \frac{g_1 + g_2 + g_3}{\sigma_z \sqrt{2\pi}}$$

Source: Beychok, 1994; Turner, 1994

*Equation 3. Gaussian model equation*

$f$  = crosswind dispersion parameter

$$= \exp [ - \mathcal{Y}^2 / (2\sigma_y^2) ]$$

$\mathcal{G}$  = vertical dispersion parameter =  $\mathcal{G}_1 + \mathcal{G}_2 + \mathcal{G}_3$

$\mathcal{G}_1$  = vertical dispersion with no reflections

$$= \exp [ - (z - H)^2 / (2\sigma_z^2) ]$$

$\mathcal{G}_2$  = vertical dispersion for reflection from the ground

$$= \exp [ - (z + H)^2 / (2\sigma_z^2) ]$$

$\mathcal{G}_3$  = vertical dispersion for reflection from an inversion aloft

$$\begin{aligned} = \sum_{m=1}^{\infty} \{ & \exp [ - (z - H - 2mL)^2 / (2\sigma_z^2) ] \\ & + \exp [ - (z + H + 2mL)^2 / (2\sigma_z^2) ] \\ & + \exp [ - (z + H - 2mL)^2 / (2\sigma_z^2) ] \\ & + \exp [ - (z - H + 2mL)^2 / (2\sigma_z^2) ] \} \end{aligned}$$

$C$  = concentration of emissions, in g/m<sup>3</sup>, at any receptor located:

$x$  meters downwind from the emission source point

$y$  meters crosswind from the emission plume centerline

$z$  meters above ground level

$Q$  = source pollutant emission rate, in g/s

$u$  = horizontal wind velocity along the plume centerline, m/s

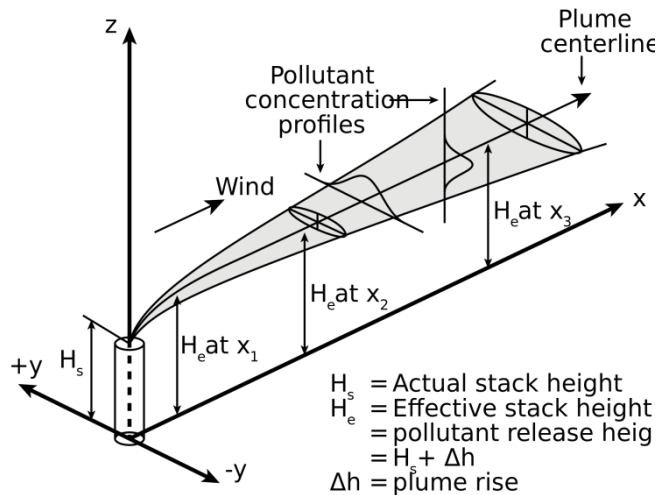
$H$  = height of emission plume centerline above ground level, in m

$\sigma_z$  = vertical standard deviation of the emission distribution, in m

$\sigma_y$  = horizontal standard deviation of the emission distribution, in m

$L$  = height from ground level to bottom of the inversion aloft, in m

exp = the exponential function



Source: Wikipedia

Figure 42. Simulation of dispersion of point pollutants with Gaussian model (Beychok, 1994; Turner, 1994).

Since the Gaussian model supposes that urban streets can be deemed line sources or strings of point sources, the dispersion model can be regarded as being associated with independent variables such as wind direction, wind speed, the weight of the particles, and the height of locations of the pollution sources (the distance to the ground). Such studies have been made on heavy metals in road traffic emissions (Johansson et al., 2008) and  $PM_{10}$  emissions on Stockholm's roads with the Gaussian air quality estimation model SMHI, Airviro (Johansson et al., 2007).

Today we can use the geographic information system (GIS) to predict air pollution dispersion in urban areas, applying the Gaussian dispersion model. GIS and its built-in geostatistical tools are widely used to predict the dispersion of specific substances in the air, depending on discrete data collected. For example, studies have been conducted in Los

Angeles on Ozone dispersion patterns because Ozone is a significant air pollutant in the Greater Los Angeles area that negatively affects human health (see ArcGIS Online for details).

In the above study, researchers collected data from a limited number of air quality monitoring stations. Using the Gaussian dispersion model, they created a smooth surface that showed a smooth transition from high concentrations to low concentrations of Ozone . By doing so, researchers could estimate the Ozone concentrations in areas without air quality monitors.

In this thesis, Gaussian dispersion model and the geostatistical tools of the GIS, including Kriging interpolation, can also be applied to studying  $PM_{2.5}$  dispersion in Shanghai, depending on both the point resource data collected at the air quality monitoring stations and the line resource data based on traffic-density data, as discussed earlier (see Section 3.2.2.4).

### **3.3.5. IMPORTANT ASSUMPTIONS AND SHORTCOMINGS OF METHODOLOGY 2**

Methodology 2, TRAP by Location, is different from Methodology 1, TRAP by Year, because it focuses on calculating the traffic-density–based  $PM_{2.5}$  emissions along the streets, which can help provide an intuitive understanding of the dispersion pattern of  $PM_{2.5}$  from a microscopic perspective.

The traffic conditions in a city and along any streets change over time. The percentages of different vehicle types on the streets vary, too. Due to the lack of detailed data, it is difficult to obtain an accurate assessment of how  $PM_{2.5}$  has been dispersed day and night over the past few years. Nevertheless, it is possible for us to obtain an annual or daily average overview of the geographical dispersion of  $PM_{2.5}$  particles in the air. To obtain that outcome, we make the following assumptions:

- a. The percentages of different vehicle types are generalized to all the streets in the study area.

- b. The average increases of traffic volume from 2003 to 2009 in all four subregions are equally applied to the streets.
- c. Among all of the vehicle population of buses, we assume that on all of the streets in our study area, 83.3% are diesel powered and 16.7% are electricity powered (*Report of the Fourth Comprehensive Traffic Survey in Shanghai 2009*, published in 2010). Because the  $PM_{2.5}$  emission factor of electricity-powered buses is 0, we can ignore electric buses in this study.
- d. Because motorcycles and heavy trucks are not allowed to enter the Central City, which is defined as the area inside the first ring road, we assume that these types of vehicles can only appear outside the first ring road.
- e. We use 2003 and 2009 as the study years because two transportation surveys were conducted during these two years and data are available.

As mentioned, Methodology 2 will be based on the assumptions above. Most of the data that we collected are average daily data, which differ from the total annual amount of  $PM_{2.5}$  particles emitted in the atmosphere. The approaches used in this study are rather experimental, requiring data sets of good quality. Because of the lack of high-quality data, such as the exact percentages of vehicle types on the road, or the exact annual average daily traffic of the primary streets, we use the above assumptions to complete this study, aiming at creating a trial to see how transportation-related  $PM_{2.5}$  emissions dispersed in 2003 and 2009 in Shanghai. Furthermore, traffic emissions are not the only source of  $PM_{2.5}$  particles. The real-time  $PM_{2.5}$  concentrations collected at the monitoring stations should be higher than the outcome of our research. All intra-regional differences that we discovered by using the data obtained at the monitoring stations may be related to other causes, such as industrial activities, energy sources, and so on, rather than to differences in traffic emissions.

Despite these shortcomings, calculating the traffic-related  $PM_{2.5}$  emissions based on traffic-density data can help depict an average dispersion pattern of  $PM_{2.5}$  particles in the city. The benefits of studying the average dispersion pattern is that a study may help those who are sensitive to air pollution, planners, urban administrators, and health practitioners identify areas with higher emissions of  $PM_{2.5}$  so that people who live and work in polluted spots can adopt mitigation measures.

## **Chapter 4 Analysis of Transportation-Related Air Pollution (PM<sub>2.5</sub>)**

### **4.1. TRANSPORTATION-RELATED AIR QUALITY IN SHANGHAI**

#### **4.1.1. VISUALIZATION OF DAILY TRAP (PM<sub>2.5</sub>) DATA UNDER THE ENVIRONMENT OF GIS**

The main focus of this chapter is to analyze the outcomes of the second methodology mentioned above. In general, this methodology discussed in the previous chapter would help show not only the geographical distribution of transportation-related PM<sub>2.5</sub> in Shanghai, but also the regional health risks due to PM<sub>2.5</sub> exposures in the central city.

The GIS data of Shanghai's street network is obtained from the Openstreet Map Database (see <http://www.openstreetmap.org/#map=2/12.7/-111.6> for more details). After calculating the total PM<sub>2.5</sub> emissions caused by the average daily 12-hour on-road traffic, we assigned the values of how many grams of PM<sub>2.5</sub> particles are generated along the main streets to the corresponding GIS features by adding a field containing the information.

For the sake of comparison, we built maps of daily transportation-related PM<sub>2.5</sub> emission for both 2003 and 2009 (see Figure 43 and 44). It is evident that, in 2009, the PM<sub>2.5</sub> emissions were more concentrated along a small number of main streets rather than being averagely dispersed in the street network, compared with the situation in 2003.

The other significant change was that the total amount of the daily transportation-related emissions in 2009 was approximately 30% of the amount of 2003. It means that, if the transportation-related PM<sub>2.5</sub> emission is the only consideration, the Inner City, defined as the area inside the first ring road, will be much cleaner than it had been six years ago.

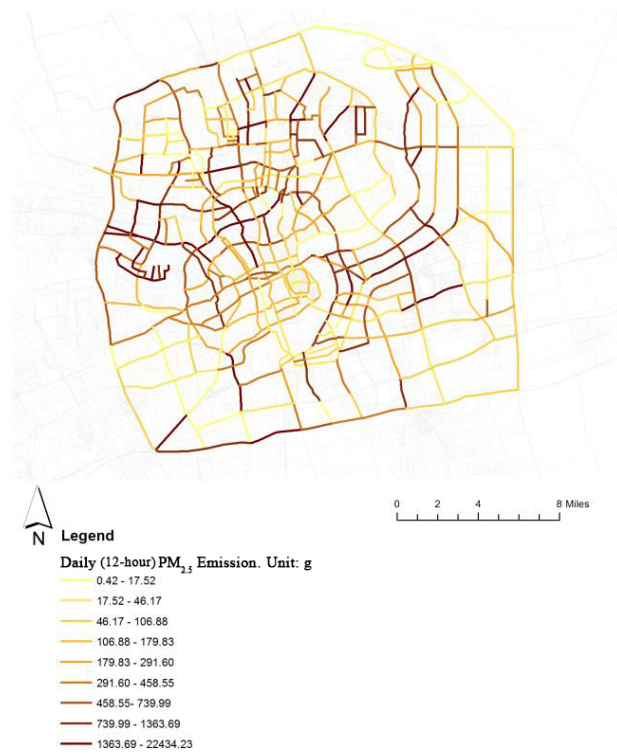


Figure 43. Traffic related  $PM_{2.5}$  emissions (g) along the main streets of Shanghai 2003

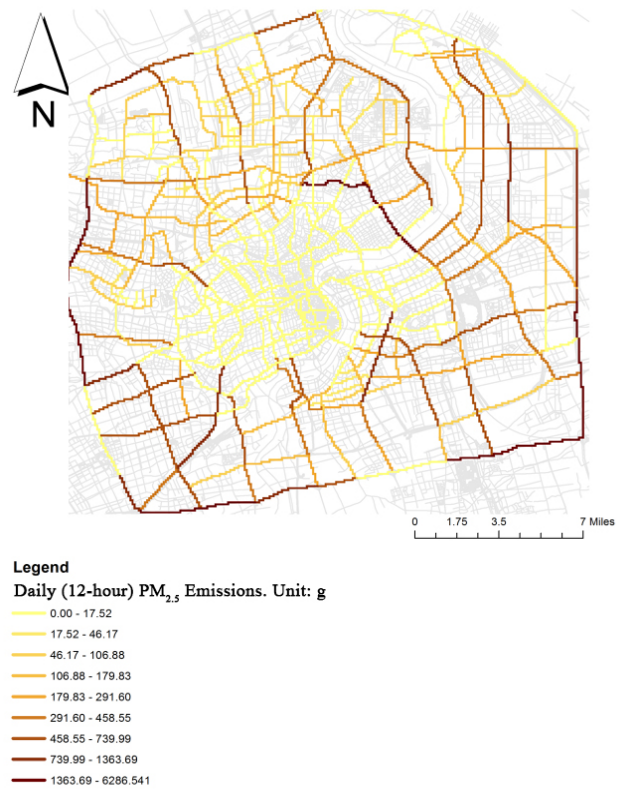


Figure 44. Traffic related  $PM_{2.5}$  emissions (g) along the main streets of Shanghai 2009

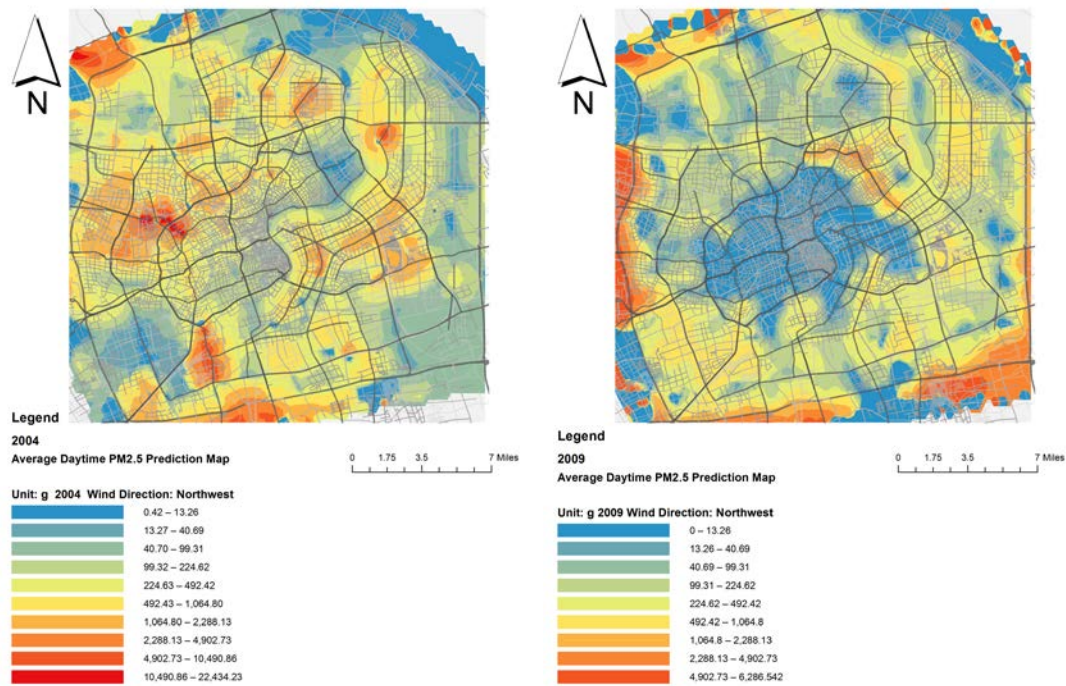


Figure 45. Traffic Related PM<sub>2.5</sub> Emission Dispersion in the Central City Area in 2003 (left) and 2009 (right).

Being one of the Geostatistical Analyst tools of the Geographic Information System (GIS), Kriging Interpolation assumes that at least some of the spatial variation observed in natural phenomena can be modeled by random processes with spatial autocorrelation (ESRI, 2012). It is widely used in the field of environmental science in describing and modeling spatial patterns, predicting values at unmeasured locations, based on a variety of spatial variation models, including the Gaussian Dispersion Model discussed above (see Section 3.3.3).

The above two PM<sub>2.5</sub> Emission Dispersion maps reveal fairly strong contrast, regarding the amount of TRAP (PM<sub>2.5</sub>) emission in the three regions of the city—(1) inside the first ring road; (2) between the first and the second ring roads; (3) out of the second ring road.

It is obvious that the  $PM_{2.5}$  emissions were evenly dispersed in the Central City (Area 1 and Area 2) in 2003. In contrast to the centralization of  $PM_{2.5}$  emissions, the north, the southeast and the southwest of the outer suburban area, which were located outside of the second ring road (Area 3), had a lower level of  $PM_{2.5}$  emissions.

On the other hand, in 2009, the central city of Shanghai showed a lower level of TRAP ( $PM_{2.5}$ ) emissions. A relatively higher concentration of TRAP ( $PM_{2.5}$ ) gathered along the second ring road. It expanded into and affected the Area 3. As a result, the outer suburban area in 2009 (Area 3) was confronted with relatively higher concentrations of transportation-related  $PM_{2.5}$  emissions.

#### **4.1.2. IMPORTANT FACTORS**

There are several reasons behind the phenomenon mentioned above:

##### **(1) Different Emission Standards**

In 2002, Shanghai adopted the National II emission standards. We assumed that all vehicles followed these emission standards until 2009 when they were changed to National III standards. Thus, the  $PM_{2.5}$  emission limits applied to the 2009 analysis were much lower than those of 2003, especially for large passenger vehicles, buses, heavy trucks and motorcycles.. This was inevitable because of the lack of detailed data on the vehicle year distribution.

##### **(2) Different Share of Vehicle Types**

The percent distribution of the vehicle types, not the numbers of vehicle types, is another important factor of the  $PM_{2.5}$  conversion equation (See Equation 2). In 2009, the percentage of heavy trucks (see Table 5) on the streets of the central city (Area 1 and Area 2, inside the second ring roads) of Shanghai was much lower (9.0%) than that of 2003 (23.6%) as well as the decline of bus shares from 10.11% to 5.99%. Because of the diesel vehicle prohibition in the central city, light trucks, which are in the same category with small

passenger vehicles in Shanghai Statistical Yearbooks, began to replace heavy trucks in the central city. All of these factors ended up with a lower transportation-related PM<sub>2.5</sub> emission level in 2009.

### **(3) Increase of Traffic Volume in Outer Suburban Areas**

Due to the urban development from 2003 to 2009, the transportation network in the outer suburban area of Shanghai had expanded greatly by 2009. For example, the construction of the southeast section of the third ring road was accomplished in 2009, carrying increasing traffic volume to the outer suburban area of Southeast Shanghai. Increasing traffic volume would always produce increasing PM<sub>2.5</sub> emissions. Therefore, the comparatively higher level of PM<sub>2.5</sub> emissions in outside of the second ring road in 2009 could also be ascribed to the increase of traffic volume in the outer suburban area.

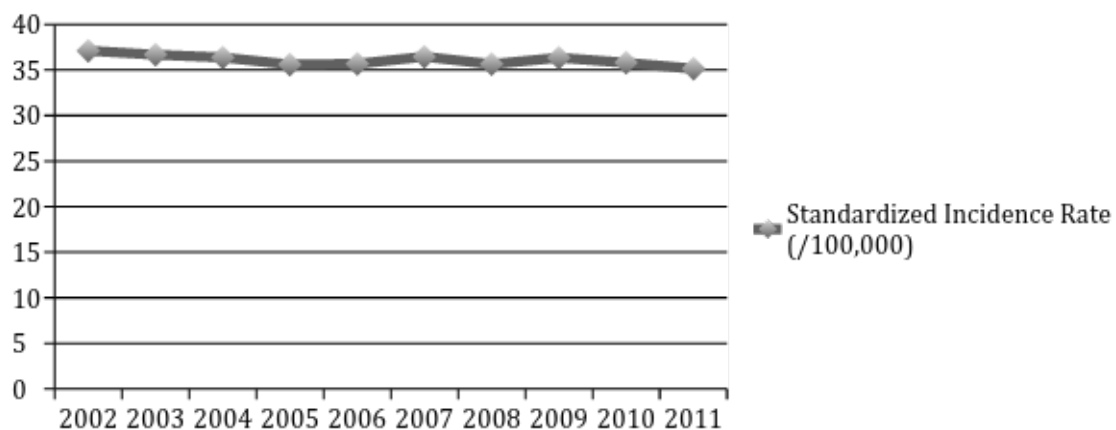
To summarize, it was the lower share of some vehicle types, the lower emission limits of National III, and the increase of the traffic volume in the outer suburban area that resulted in a different transportation-related PM<sub>2.5</sub> dispersion pattern in 2009. Under the same circumstances, such as the same wind speed as 2.8 meters per second—which is the annual average wind speed of the city calculated with multi-year wind speed data (Shanghai Meteorological Center, 上海天气网)—and the prevailing wind direction as northwest in winter, in 2009, it is predictable that the PM<sub>2.5</sub> particles would gather along the second ring road instead of spreading into the city center. In other words, the city center, which was previously occupied by the highest level of PM<sub>2.5</sub> particles in 2003, became cleaner in six years. Contrarily, the PM<sub>2.5</sub> emission levels in the outer suburban areas rose and became higher than the city center.

## 4.2. HEALTH IMPACTS OF TRANSPORTATION-RELATED PM<sub>2.5</sub> EMISSIONS IN SHANGHAI

### 4.2.1. TRENDS AND ISSUES IN PUBLIC HEALTH

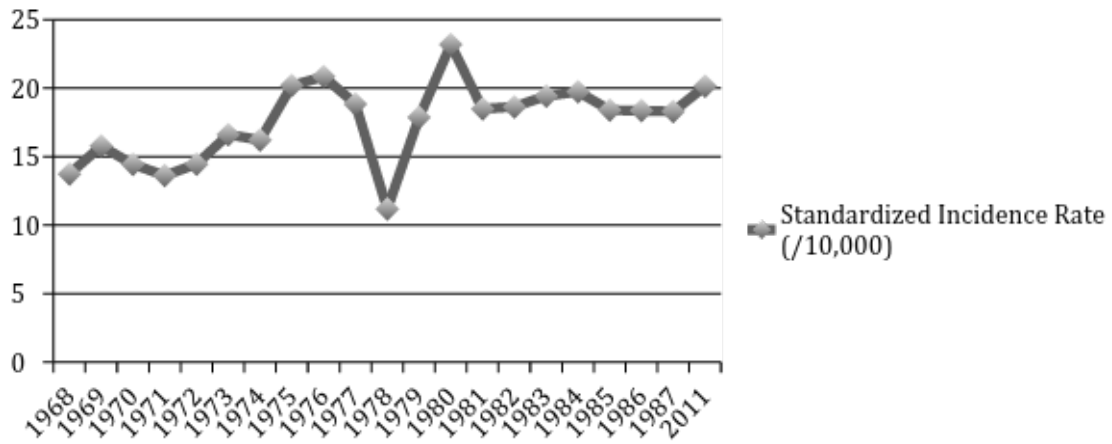
The history of urban development (see 231) shows that the growth of the city was outward from the city center. The act of constructions, the increase of street density and the growth of the traffic volume were mainly focused on the close and outer suburbs (Areas 2 and 3). As shown in the studies of Ye (Ye et al, 2003) and Feng (Feng et al, 2009), the PM<sub>2.5</sub> concentrations in suburban districts Jiading, Zhabei, Hongkou and Yangpu changed incrementally.

When we look at the records of these four districts in terms of their past years' incidences of lung cancer (see Figures 46, 47, 48 and 49), we can see that except Yangpu District, the lung incidences of the other three districts increased gradually. This means that there were specific factors that were negatively influencing people's health during the time period. In Yangpu District, the lung cancer incidence at the beginning of 21st Century was higher than current cancer incidence, showing in the last decade, there existed positive factors for the public health.



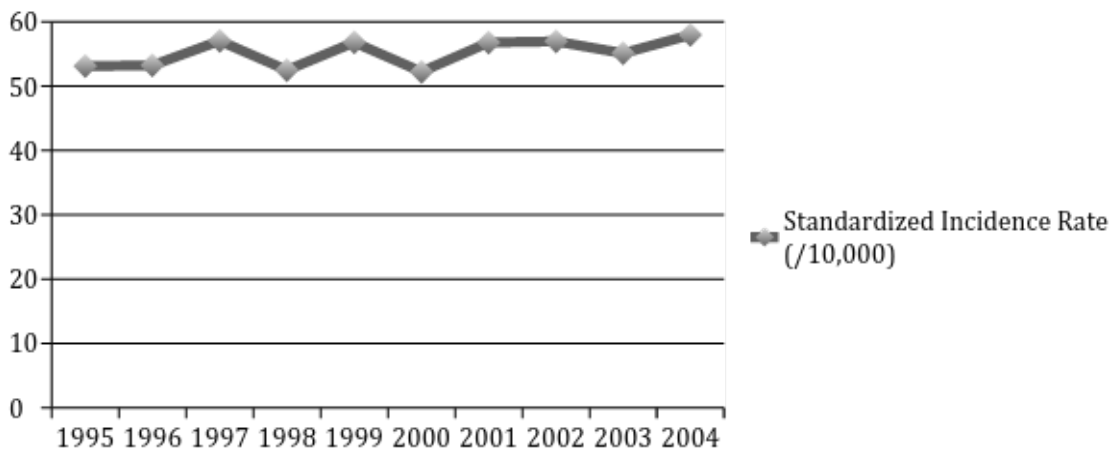
Source: Jiang et al, 2013

Figure 46. Standardized incidence rate of lung cancer in Yangpu District, Shanghai (unit: number of incidences per 100,000) (2002~2011)



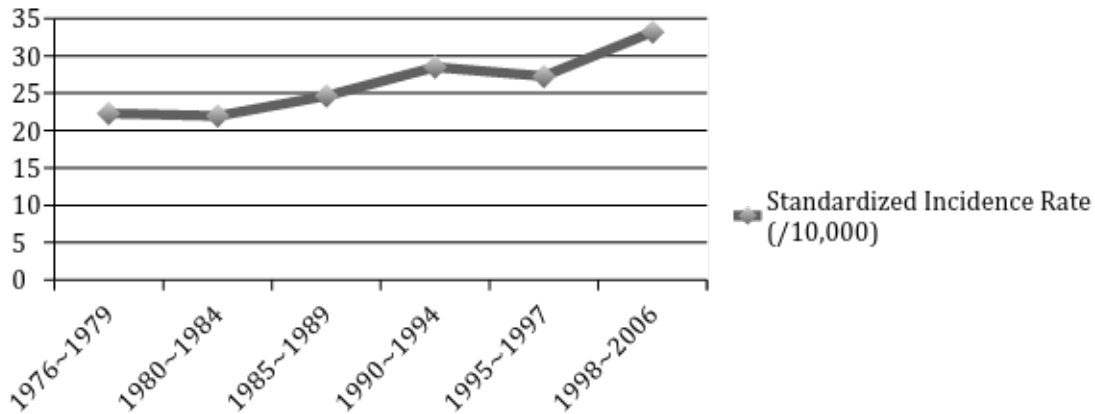
Source: Dai et al, 2013

Figure 47. Standardized incidence rate of lung cancer in hongkou district, Shanghai (unit: number of incidences per 100,000) (1968~2011)



Source: Xu et al, 2008

Figure 48. Standardized incidence rate of lung cancer in Zhabei District, Shanghai (unit: number of incidences per 100,000) (1995~2004)



Source: Dai and Peng, 1998; Peng et al, 2011

*Figure 49.* Standardized incidence rate of lung cancer in Jiading District, Shanghai (Unit: number of incidences per 100,000) (1995~2004)

Due to the lack of data, it is hard to provide statistical evidences for answering: whether it were or were not the particles, including TSP,  $PM_{10}$  and  $PM_{2.5}$ , that led to an increase or decrease of the lung cancer incidences in different locations of the city. Nevertheless, we can highlight the temporal coherence between the growth of the city, the increase of regional  $PM_{2.5}$  concentrations and the lung cancer rates. When the city 'grew' into close suburbs, the four districts subsequently saw significant increases in the number of standardized lung cancer incidences.

Accumulating evidences show that long-term exposure to  $PM_{2.5}$  cause lung cancer. For example, in 2003, a study that investigated lung cancer in relation to long-term exposure to three ambient air pollutants— $O_3$ ,  $NO_x$  and  $PM_{2.5}$ , based on a Canadian population-based case-control study, shows that lung cancer increased most strongly with  $NO_x$  and  $PM_{2.5}$  exposure (Hystad et al, 2013). Another important article examined the lung cancer cases in 23 European countries, following the World Health Organization (WHO) methodology for Health Impact Assessment (HIA) and concludes, that 1901 examined lung-cancer deaths in these 23 countries could be prevented annually if long-term exposure to  $PM_{2.5}$  could be reduced to  $15 \mu g/m^3$  (Boldo et al, 2006).

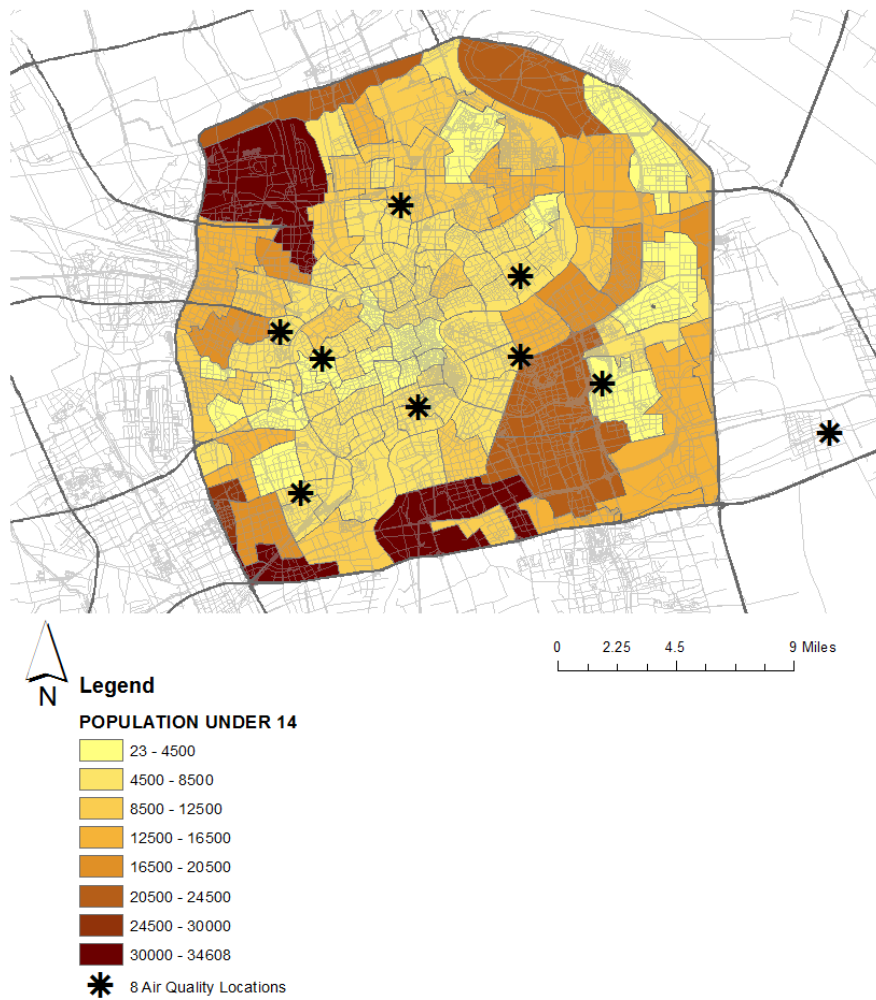
Based on increasing evidences and literatures, WHO's specialized cancer agency, the International Agency for Research on Cancer (IARC) announced, that one of the components of outdoor air pollution—the particulate matters (PM)—to be at least carcinogenic and cause cancer (WHO Regional Office for Europe, 2013).

#### **4.2.2. DISTRIBUTION OF TWO VULNERABLE GROUPS**

As Bae, et. al. state in their article, that fine particles have definitive effects on the population exposed to them, especially for those who are vulnerable to air pollution, such as children and the elderly. The effects include aggravation of asthma, depressed lung function in school children, increased risk of lung cancer and increased prevalence of bronchitis (Bae et al, 2007). For a comprehensive review of transportation-related air pollution and health articles, readers should review the 2010 report from Health Effect Institute (HEI).

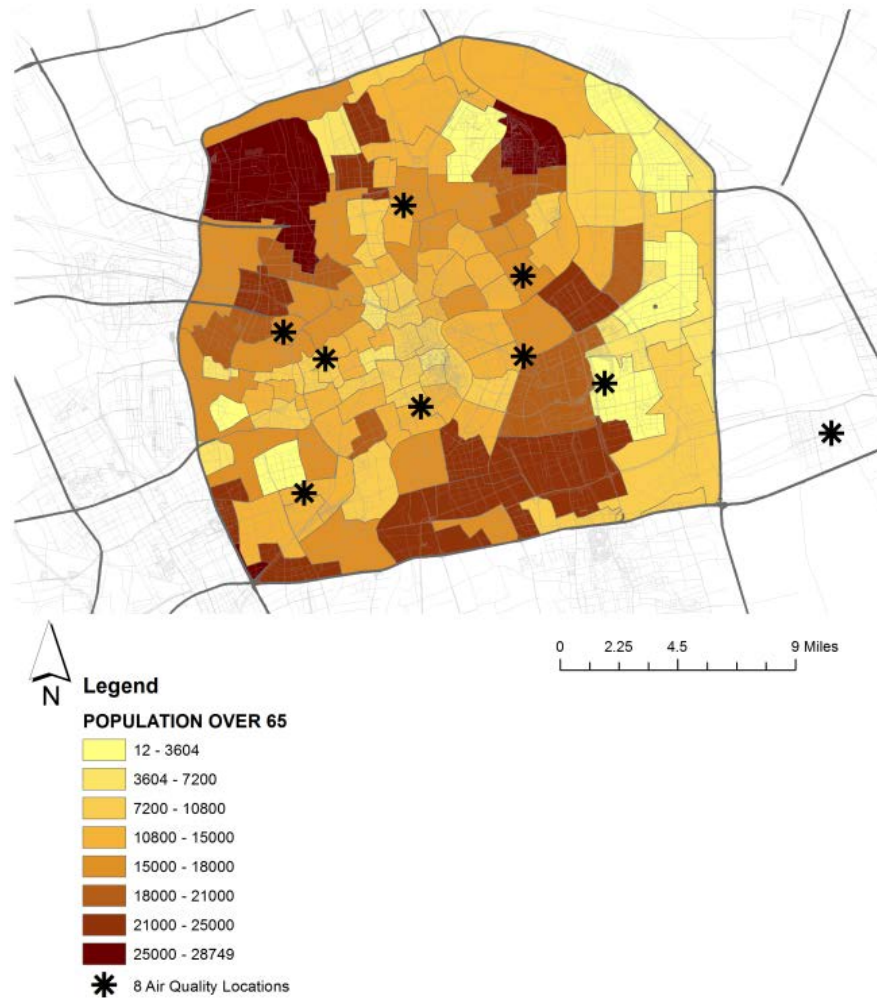
Our study assumes that two population groups—children under 14 years old and old population over 65 years old—are more vulnerable than other groups to PM<sub>2.5</sub> emissions, because children's immune systems are not fully developed and the older adults' immune systems are deteriorating. Moreover, old adults have been exposed to environmental pollution for longer periods than other age groups. They are clinically more sensitive to cancer. This thesis aims to investigate where these two vulnerable groups live and whether the places they live are strongly affected by PM<sub>2.5</sub> emissions.

By using the latest Census Investigation in 2010, which offered the census data by 'street district' (the smallest administrative districts, 街道), and GIS, we could map up the residential concentration of the children and the elderly in Shanghai (see Figure 50 and 51).



Source: Shanghai Census Investigation 2009, published in 2010.

*Figure 50.* Residential concentrations of children in Shanghai, 2009

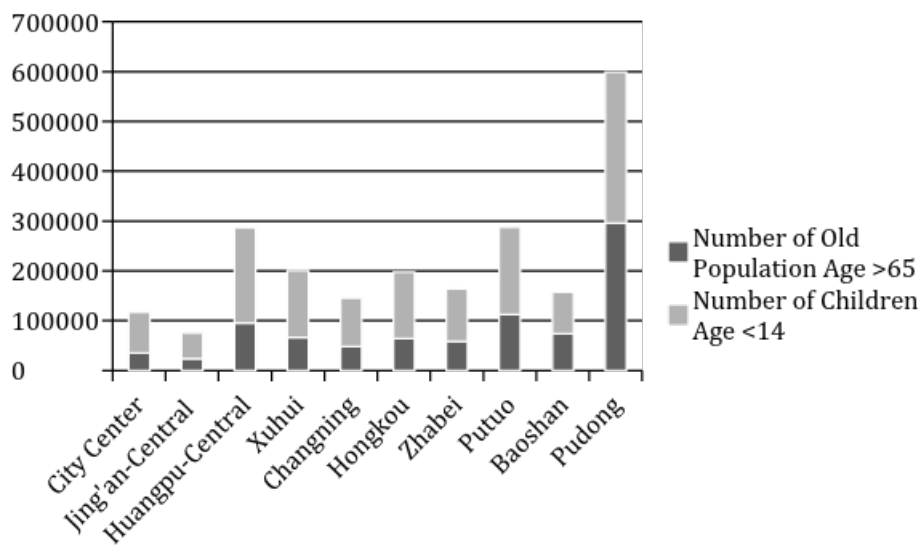


Source: Shanghai Census Investigation 2009, published in 2010.

*Figure 51.* Residential concentrations of the old adults in Shanghai, 2009

These two maps show that the young and the old are not evenly distributed throughout the city. Both of the population groups-- children under 14 years old and old adults who are over 65 years old-- are more concentrated in close suburbs between the first and the second ring roads. Yangpu District (杨浦区), Jiading District (嘉定区), Hongkou District (虹口区) and Zhabei District (闸北区), which have been previously discussed (see Section 4.2.1.) have increasing lung cancer incidences, and have relatively greater numbers

of children and elderly people (see Figures 46—49). Other non-central districts also accommodate more population with the age under 14 or above 65, such as Pudong District (浦东新区). Only a few old adults and children live closer to the city center because of the easy accessibility of medical, education, food and transportation resources in central districts. Huangpu District (黄浦区), as a result, is the only central district where a large number of children and old population live.



Source: Shanghai Census Investigation, 2010

Figure 52. Number of children (<14) and old population (>65) by districts

#### 4.2.3. SHANGHAI TRAP-SPATIAL HEALTH HAZARD PRIORITY AREAS (SHHPA)

After converting the estimated TRAP PM<sub>2.5</sub> emission dispersion (2009) map into the average TRAP PM<sub>2.5</sub> emission by street district map, we multiplied the statistics of average TRAP PM<sub>2.5</sub> emission by street district with the statistics of the total population over 65 years old (Figure 50) and under 14 years old (Figure 51).

In order to highlight whether the vulnerable population groups concentrate in areas with higher TRAP PM<sub>2.5</sub> emission levels, we create a *Shanghai TRAP-Spatial Health Hazard Priority Area (Shanghai TRAP-SHHPA)*. As stated above, we multiplied the average PM<sub>2.5</sub>

emission amount of a micro area (street district, 街道) with its total number of vulnerable population (sum of the number of children and the old adults). By doing so, we can demonstrate a spatially sensitive index showing the different concentration levels of both the vulnerable groups and the TRAP PM<sub>2.5</sub> emissions by micro area (see Figure 53).

We found that are the highest TRAP related health risks lie in the districts in the northwest (Changning District [长宁区] and Putuo District [普陀区]) and southeast (Pudong District [浦东新区] and Minghang District [闵行区]) Shanghai. The Inner City is the lowest health risk priority area along with a pocket of the East Suburbs. It reflects lower concentration of the children and the elderly coupled with the improved, lower level of TRAP. Interestingly, the current air quality monitoring stations are located in the micro areas (street districts) where the Shanghai-TRAP SHHPA scores are lower.

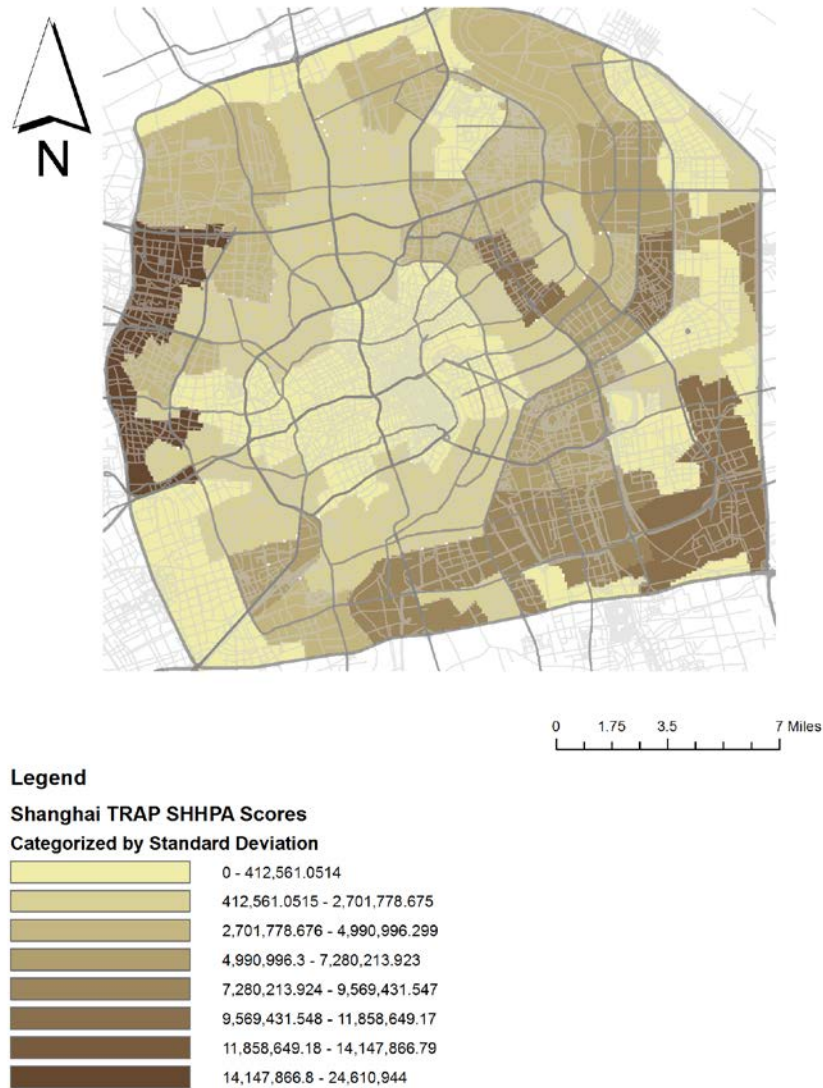


Figure 53. Spatial application of *Shanghai TRAP-Health Hazard Priority Areas*

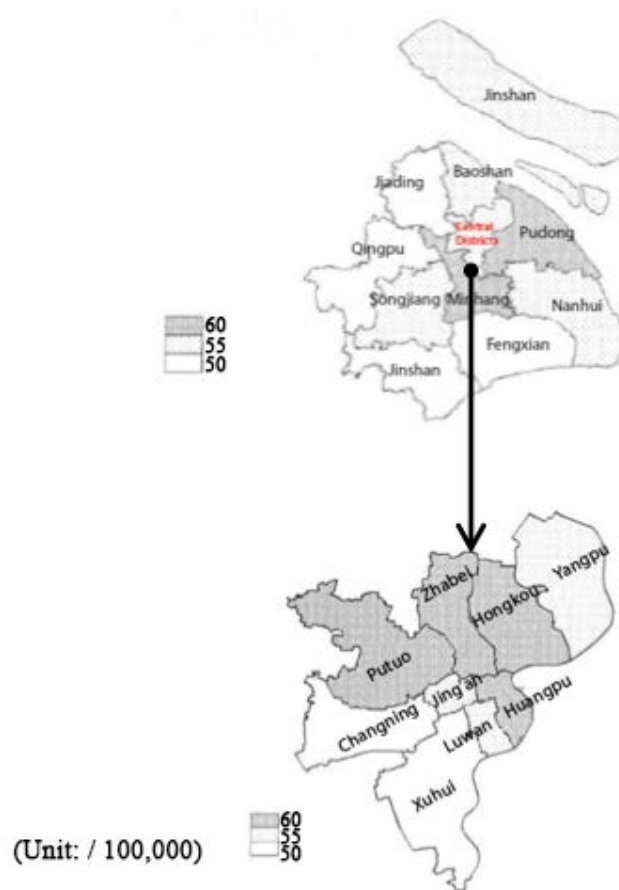
#### 4.3. SIGNIFICANCE FINDINGS OF STUDIES ABOVE

As WHO announced (see section 4.2.1), one of the components among the pollutants in the ambient atmosphere—the PM—is carcinogenic to human beings, long-term exposure to it would increase the risk of lung cancer (WHO, 2013).

By using the estimated TRAP PM<sub>2.5</sub> emission dispersion (2009) with National III, Shanghai-SHHPA analysis in the previous section, show that the exposures to PM<sub>2.5</sub>

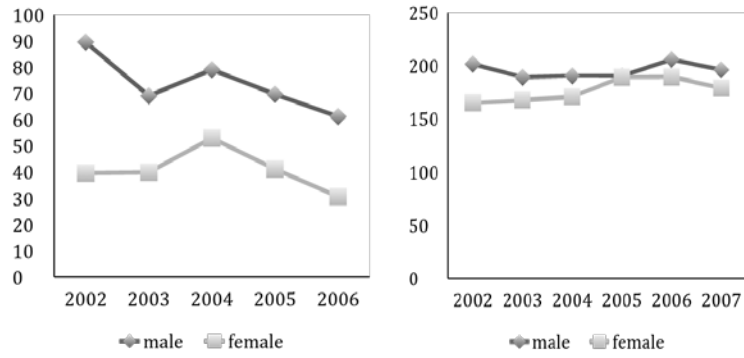
emissions in the city center were lower than the close suburbs located between the first and the second ring roads in 2009 (see Figure 53).

Below is the difference of different administrative districts in lung cancer rates—the cancer incidences among 100,000 populations in 2004 (see Figure 54). It is evident that the highest cancer rates were found in districts that were located around the city center, while the lowest cancer rates could be found in outer suburban areas. Other studies show that since 2004, the cancer rates in the central districts further decreased, compared with the lung cancer standardized incidences varying upwardly in suburban zones (see Figure 55).



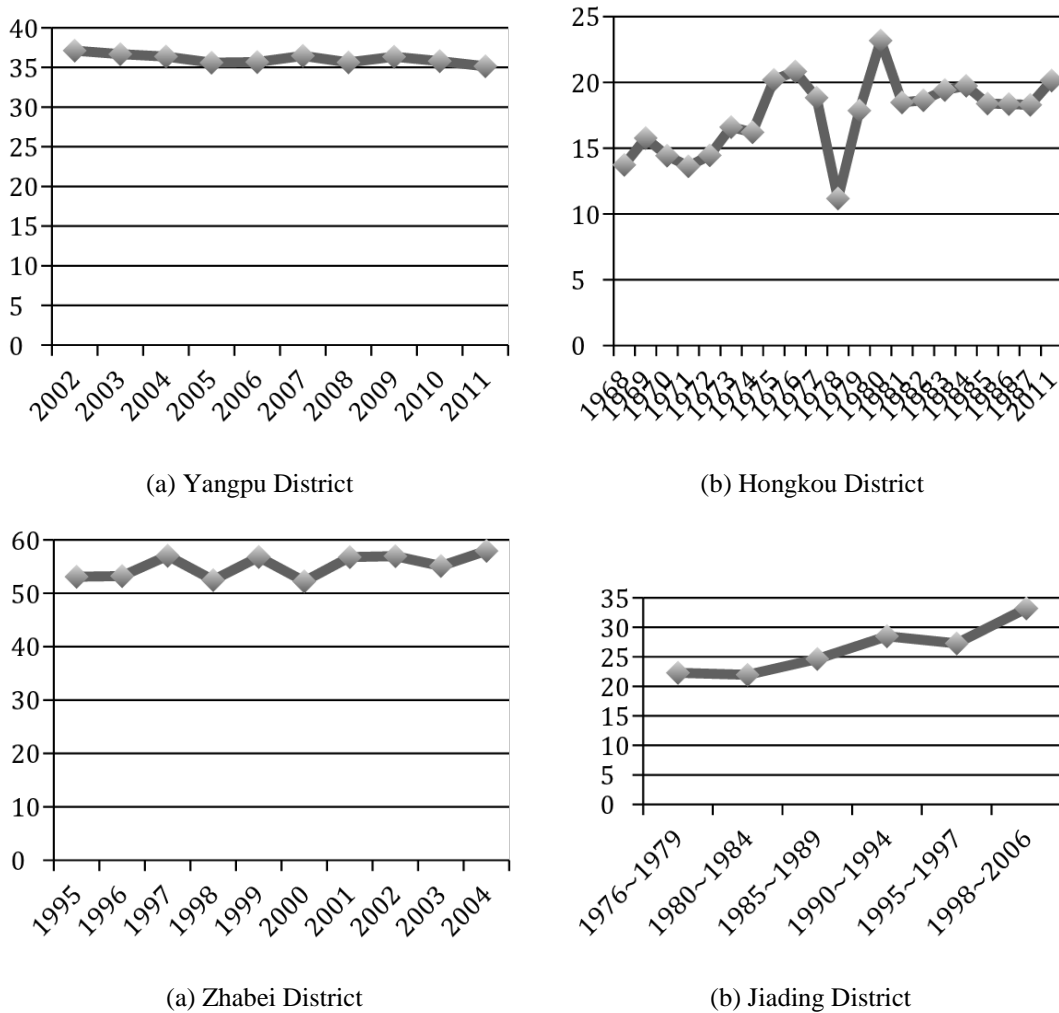
Source: Zheng et al, 2006

*Figure 54.* Different number of lung cancer incidences in different administrative districts (2004)



Source: Zhang et al, 2010; Wang and Gao, 2011

Figure 55. Lung cancer rates (/ 100,000) in two central districts—Huangpu (left) 2002~2006 and Luwan (right) 2002~2007



Source: Section 4.2.1.

Figure 56. Lung cancer rates (/ 100,000) in four suburban districts

Zhang et al (2010) and Wang and Gao (2011) suggest that the years around 2004 was a turning point. The change of the lung cancer rates in central and suburban districts was simultaneous (see Sections 4.2.1 and 4.3). It was also concurrent with the change of the TRAP PM<sub>2.5</sub> distribution pattern. Following the adoption of National II in 2002 and prohibiting heavy freight vehicles and motorcycles in the central area, the emissions in the city center declined because the PM<sub>2.5</sub> emitted per gallon decreased according to the requirements of National II standards.

The year 2003 also saw a decline of motorcycle population growth. This implied less TRAP PM<sub>2.5</sub> emissions would be found to be emitted by motorcycles. National II required that a motorcycle emission quantity was reduced to 33%, from 0.1 g/km to 0.03 g/km (Table 1). The rapid growth rate of small passenger vehicles overtook that of motor vehicles (see Figure 35). But, one should keep in mind that the number of total vehicle population for all vehicle types is still increasing. So will the total mobile source emissions.

However, when we compare the outcomes of Methodologies 1 and 2, it is undoubtedly that, although the PM<sub>2.5</sub> emissions in the city region began to ‘retreat’ from the city center, as Methodology 2 suggested, they are not disappearing because the total amount of PM<sub>2.5</sub> emissions kept increasing in the city region, as Methodology 1 suggested. It is to say, that people living in close suburbs (between the first and second ring roads) and outer suburban (out of the second ring road) zones are facing increasing health risks. This is an alarming fact because the young children and the older adult population concentrated in the suburban area.

#### **4.4. SPEED IMPACT**

The amount of pollutants emitted by vehicles are related with travel speed because incomplete fuel combustions usually provoke more PM<sub>2.5</sub> emissions. Studies show that small passenger vehicles, such as taxies and private cars, usually generate the highest levels of

PM<sub>2.5</sub> emissions when they are driven at a speed under 40 kilometers per hour (km/h) or over 60 km/h (see Figure 41 in Chapter 3.3.2.2.).

Interestingly, most of vehicle speeds in Shanghai fall below the lower speed threshold (< 40km/h). Chen et al. (2007) conducted a study regarding the driving patterns of heavy trucks on the streets of Shanghai show that a majority of the driving speeds on the streets are lower than 40km/h. The average citywide vehicle speed on arterial roads is 22.9 km/h, on residential roads is 19.9 km/h, and on highways is 36.3km/h (Chen et al, 2007).

According to the UK Department of Transport (UK National Archive website, see Figure 41), , when vehicles travel with their speeds between 40 and 60 km/h (approximately 24 and 37 mi/h), the amount of PM<sub>2.5</sub> emissions generated will be the lowest. It means that the residential streets, that usually have slower vehicle speed than 40 km/h, are filled with more PM<sub>2.5</sub> emissions, while the vehicles on highways could emit lower amounts of PM<sub>2.5</sub>. In general, residential streets are narrower and closer to homes, schools and work places, without green buffers between them (see Figure 57). In return, the built-up environment imposes negative impacts on people's health because low-speed streets—which produce more PM<sub>2.5</sub> particles than other streets—are close to them.

Figure 56 depicts the average vehicle speed in Shanghai-- the darker the color is, the more additional PM<sub>2.5</sub> emissions will be produced by vehicles. It shows that the relatively higher PM<sub>2.5</sub> exposures are in the city center because of relatively lower travel speeds. Based on this finding, we have updated the above Shanghai TRAP-SHHPA map reflecting the impact of vehicle speeds (see Figure 59). Again, the suburban area near the second ring road have higher concentration of PM<sub>2.5</sub>.



Source: Google Earth

*Figure 57.* Qixin elementary school (Xuhui District) and close to roads.

Vehicle speeds are always changing during the daytime. Studies show that during the daytime, the lowest vehicle speed occur in almost all of the traffic zones around 8am during the morning rush hour, and 6pm in the evening rush hour, which are also the times when  $PM_{2.5}$  emissions hit the peak. This means that the schools—children go to school at about 7am—should be kept distant from the busiest commute routes for exposure reduction.

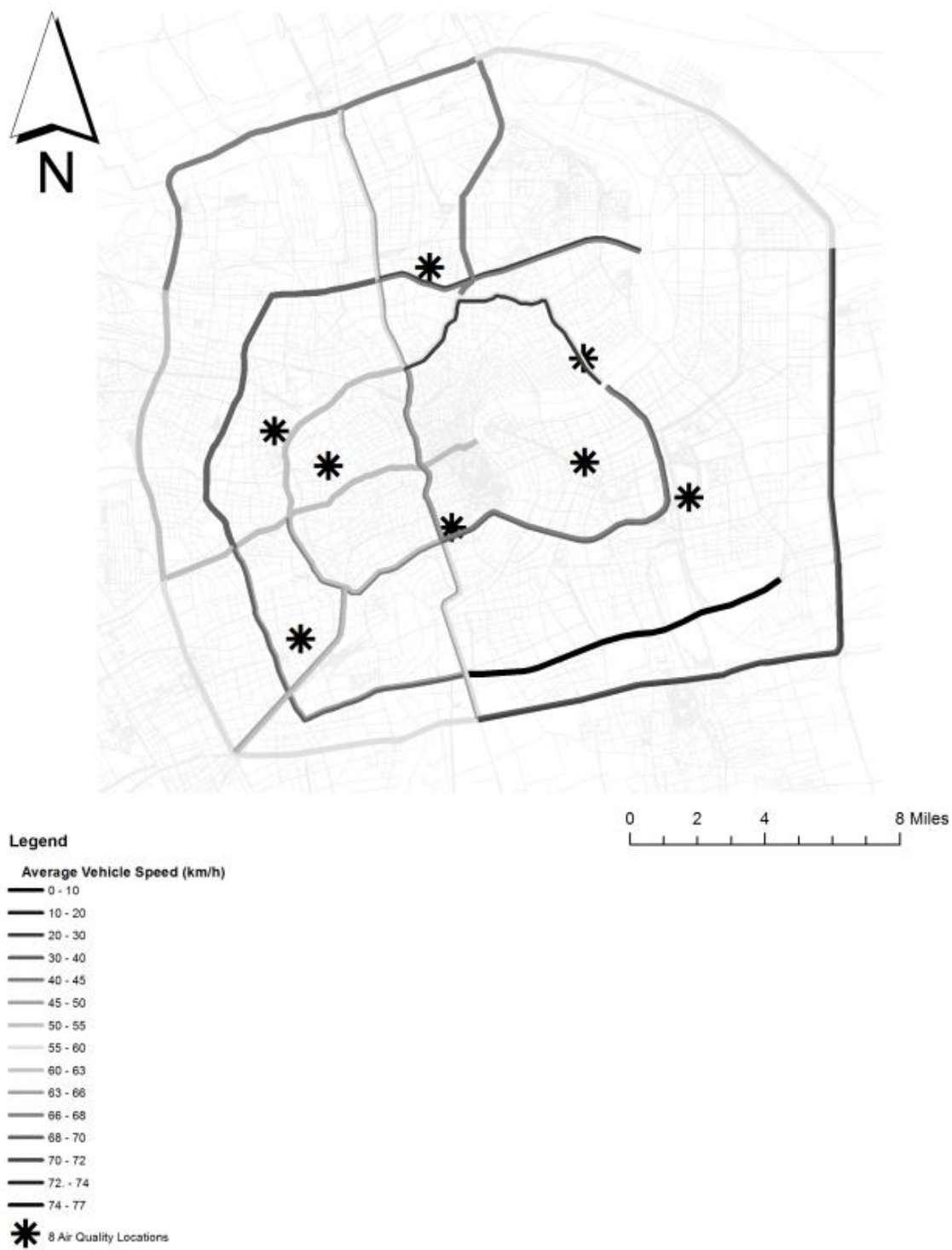


**Legend**

\* 8 Air Quality Locations

**Average Vehicle Speed (km/h)**

- 22.0
- 22.0 - 23.9
- 23.9 - 25.1
- 25.1 - 25.8
- 25.8 - 26.4
- 26.4 - 26.6
- 26.6 - 26.9
- 26.9 - 27.8
- 27.8 - 28.5
- 28.5 - 29.3
- 29.3 - 30.0
- 30.0 - 30.8
- 30.8 - 31.2
- 31.2 - 32.0
- 32.0 - 34.2



Source: 上海交通出行网

Figure 58. Average vehicle speed by street districts (based on information at the official website 上海交通出行网).



**Legend**

**Updated Shanghai TRAP SHHPA Scores  
Categorized by Standard Deviation**

	0 - 11,081.45916
	11,081.45917 - 86,494.48796
	86,494.48797 - 161,907.5168
	161,907.5169 - 237,320.5456
	237,320.5457 - 312,733.5744
	312,733.5745 - 388,146.6032
	388,146.6033 - 463,559.632
	463,559.6321 - 924,980

*Figure 59. Updated Shanghai TRAP-Spatial Health Hazard Priority Areas taking into account average vehicle speed (2009).*

## Chapter 5 Conclusions and Recommendations

The economic status of the citizens of Shanghai has been increased for the last three decades. Despite the government's effort to provide disincentives for automobile ownership, the people of Shanghai aspire to use automobiles to have greater freedom of their mobility. Coupled with robust industrial activities and increasing use of vehicles, this causes increasing concern for Shanghai's air pollution and its impact on the health of its citizens, especially vulnerable populations. This trend will continue in the future. As the citizens' income levels go up, their demands for clean air will be higher as well.

In this thesis, we mainly investigated the spatial dispersion of one component of the transportation emission—the  $PM_{2.5}$ . We developed two methodologies to investigate TRAP by year (Methodology 1) by using vehicle population and the VKT, and TRAP by location (Methodology 2) by using traffic density. We collected the data that were available to us and applied the Gaussian Dispersion Model and Kriging Interpolation, GIS Geospatial analysis tools, that analyze and visualize the intra-regional air quality variations in and around the first ring (West/East of the Inner City) and the second ring (West/East of the Suburb) in the City of Shanghai. In addition, we developed a scoring system called *Shanghai-TRAP Spatial Health Hazard Priority Areas* (Shanghai-TRAP SHHPA) to highlight the location where TRAP-  $PM_{2.5}$  emissions levels and/or the vulnerable population concentration levels are higher. For the micro area analysis, we used the smallest street level area called “street district (街道)” and for the road, we used the “ground-level” and “elevated freeway” transportation network.

One of the primary findings of our study is that there were opposite trends in the central area and in the suburban area. In about six years from 2003 to 2009, the daily transportation-related  $PM_{2.5}$  emissions in outer suburban area of the city became higher than

the central area, the daily PM<sub>2.5</sub> emissions inside the second ring road was reduced, and the annual PM<sub>2.5</sub> emissions created by the transportation sector across the whole city increased. These findings show that the outer suburban area of the city, which was known as the area out of the second ring road, bore the majority of the transportation-related PM<sub>2.5</sub> emission increases after 2003. The increasing population and residential property prices in the central city pushed population outward. Shanghai became suburbanized, and the first and the second ring roads served the interactive and communicative activities between different regions of the city. the residential areas began to cluster in close suburban areas and outer suburban areas, adding to the commuting traffic between suburban and central areas, increasing use of private/public/freight vehicles, and greatly affecting the total amount of PM<sub>2.5</sub> emissions in the outer suburban area.

Secondly, some of the transportation policies, such as the motorcycle and heavy truck restriction policy, and the adoption of different emission standards, profoundly influenced the dispersion pattern of PM<sub>2.5</sub> particles in the city. When the use of diesel vehicles was discouraged in Shanghai, the share of the heavy trucks on road was greatly reduced from 23.6% to 9%. The government encouraged using cleaner vehicles. The share of small passenger cars increased from 41.57% to 56.79%. Moreover, tougher emission standards were adopted in 2009, and the emission factors for both heavy trucks and diesel buses went down greatly. Meanwhile, the improvement of the air quality in terms of daily transportation-related PM<sub>2.5</sub> emissions should be ascribed to the adoption of a new emission standard—National III.

Thirdly, our research is also focused on the health impact of the clustering of PM<sub>2.5</sub> in different areas of the city. As said, the health impact of PM<sub>2.5</sub> is closely related to the distribution of the vulnerable groups exposed to such particles. In our study, the term ‘vulnerable groups’ refers to the old population above 65 years old along with children under 14 years old. If an urban area contains a greater concentration of vulnerable populations and

at the same time, a higher concentration of PM<sub>2.5</sub> particles in the ambient atmosphere, this area would be considered to be assigned a higher TRAP (transportation-related air pollution) Health Hazard priority area.

By using Shanghai-TRAP SHHPA score system, it was possible for us to differentiate the areas across the city in terms of to what degree that the transportation-related PM<sub>2.5</sub> particles impact people's health. In the end, we concluded that the city center was confronted with a lower degree of PM<sub>2.5</sub> related health effect comparing with the suburban areas, and the Northwest and Southeast Shanghai (Yangpu, Jiading, Hongkou, and Zhabei Districts) were the two regions that were facing the severest PM<sub>2.5</sub> effects.

Fourthly, traffic speed also plays an important role in PM<sub>2.5</sub> emission, as when vehicles operate at a speed lower than 40 kilometers per hour or higher than 60 kilometers per hour create additional PM<sub>2.5</sub> emissions because of incomplete combustion. In our study, we examine the average traffic speed in the area inside the second ring road, and conclude that the city center is much more likely than suburban and outer suburban areas, if all other things are equal, to be confront with additional transportation-related PM<sub>2.5</sub> emissions.

All in all, as we can see from the historical data of SO<sub>2</sub>, PM<sub>10</sub> and TSP, all of the air pollutants followed the environmental Kuznets Curve (the inverted-U curve). The total amount of different air pollutants increased along with GDP and began decreasing in recent years. When people paid attention to one pollutant, a variety of policies would be created and adopted to cope with it. Although long-term historical data for PM<sub>2.5</sub> do not exist in Shanghai, from the calculation with two methodologies discussed in Chapter 3, we can also see decreasing PM<sub>2.5</sub> emissions in some areas of the city. It is also evident that policies, such as emission standards, also played an important role in creating an 'inverted U curve' in PM<sub>2.5</sub> trend in some areas of the city-- for example, in the city center.

## **5.1. PLANNING IMPLICATIONS**

### **(1) Central Area vs. Suburbs: Motorcycles and Diesel Trucks in Suburban Area, and Diesel Buses in Central Area**

There are many vehicle types in the streets of Shanghai. Different types of vehicles contribute different levels of the  $PM_{2.5}$  emissions. Large freight vehicles, which follow lower emission standards and mostly use diesel fuels that generate more  $PM_{2.5}$  emissions, and motorcycles with unsophisticated emission reduction mechanisms are the primary contributors to the transportation-related  $PM_{2.5}$  emissions in the suburban area.

### **(2) Clustered Residential Areas Along The Main Freeways**

In this thesis, we found that higher concentration of vulnerable populations, who are under 14 years old, or over 65 years old, reside in the suburban areas between the First and the Second Ring Roads. We developed the Shanghai-TRAP SHHPA scoring system to highlight the location of high TRAP- $PM_{2.5}$  emission levels and the vulnerable population concentration. We found that the Northwest and the Southeast of suburban Shanghai shows the highest scores.

The second ring road is designed to help people access to the city center or other regions of the city quickly and conveniently, and the land prices are less expensive compared to the city center, many high-density suburban residential developments are clustered around the Second Ring Road. Urban planners and air quality management professionals should provide necessary services to lower the TRAP exposure levels to those who are living in these areas.

### **(3) Travel Speed and Related Higher Emissions**

While many of TRAP researches focus on the vehicle emissions from the freeways in the West, the residential streets in Shanghai generate more  $PM_{2.5}$  emissions than arterials and

highways. In this thesis, we addressed the vehicle speeds and the vehicle type of the residential areas, which are not in favor of clean air and healthy lungs of Shanghai residents. As vehicle speeds are lower in the residential areas, vehicle emission rates are higher due to incomplete combustion. Also, a large fraction of motorcycle usage is on the residential roads, emitting toxic pollutants to the residential streets to harm those who live there. The current land use practice in Shanghai does not offer any mitigation measures to ensure the health of the residents. There are schools, hospitals, and residences for the elderly located beside main commute routes without any buffers.

## **5.2. RECOMMENDATIONS AND FUTURE RESEARCH**

According to all of the analyses above, we recommend that the city of Shanghai implement the following measures so as to mitigate the health impact of transportation-related PM<sub>2.5</sub> emissions:

- a. Adjust existing land use patterns and move the residential areas out of the street canyon of the second ring road;
- b. Restrict or prohibit the usage of motorcycles in residential areas;
- c. Revise the routes of freight trucks, bus services, and commute vehicles away from the highly populated residential areas, schools, hospitals, and elderly-inhabited housing;
- d. Use landscaping measures to create buffers and public parks in areas where the average speed is lower than the citywide average;
- e. Reduce the under-14 and over-65 population in the areas with high TRAP emission zones;
- f. To give priority to low-emission, or zero-emission vehicles.

### **5.3. LIMITATIONS OF THE STUDY**

The lack of data is one of the primary obstacles of this research. The data obtained are of low accuracy and sample count. Furthermore, some of the previous studies that we referenced contain different methods. For example, the two methodologies that were used in Chapter 3 used different emission factors obtained from two different references.

We could not test the robustness of the Shanghai-TRAP SHHPA scoring system because of limited data availability and other confounding factors. However, it is a start in describing the priority regions of Shanghai where urban environmental, transportation, and land use planners can work together to introduce mitigation measures to improve air quality and the health of children and the elderly.

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