Traffic-Related $PM_{2.5}$ Air Pollution and Schools in Proximity to Major Roadways in Shanghai, China

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Abstract

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Air pollution is a major issue around the world, which affects not only climate change but also people's health. Shanghai has the one of the most serious air pollution problems in the world. Fine particulate matter ($PM_{2.5}$) is to be blamed for the main component contributing to the serious smoggy weather in recent years. Research has shown vehicle emissions are the main source of $PM_{2.5}$ emissions in Shanghai. Children are vulnerable to $PM_{2.5}$ air pollution because of their undeveloped immune system and lung function. Traffic-related air pollution levels are higher while they are in school, and the location of schools close to roadways with heavy traffic. Therefore, this study aims to explore $PM_{2.5}$ air pollution problems caused by transportation and the location of schools in proximity to major roadways in the city of Shanghai.

In this study, the traffic density data was used to calculate the traffic-related $PM_{2.5}$ emissions, and GIS Geostatistical tools and the Kriging Interpolation Tool were used to analyze traffic-related $PM_{2.5}$ dispersion in Shanghai. Schools within a distance of 100 meters to 400 meters from major roadways were selected as study samples to assess students' exposure to traffic-related $PM_{2.5}$ and health risks caused by vehicle emissions. A school hazard score map was developed to highlight the existing school sites where the highest health risks to students occur. The findings show that the west and east inner city and western suburbs have the most serious traffic-related $PM_{2.5}$ pollution in Shanghai. I also developed a school site suitability index for Shanghai based on the level of $PM_{2.5}$ emissions and distance to major roadways to help planners decide school sites in the future. Furthermore, a set of policies were proposed to mitigate traffic-related $PM_{2.5}$ emissions in Shanghai.

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CHAPTER 1. INTRODUCTION

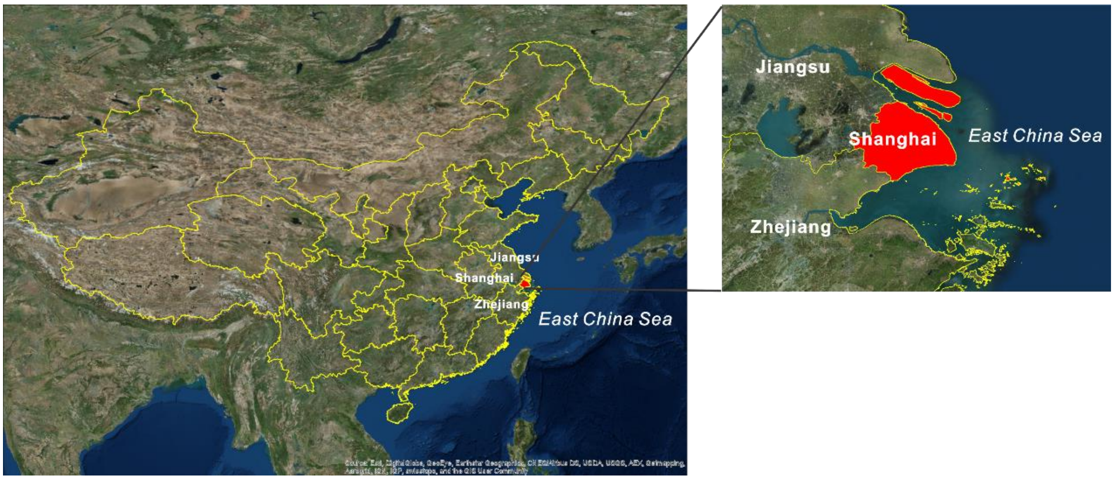
Air pollution is a major pollution issue around the world, which contributes to climate change and affects people’s health. It is well known that air pollution affects human kind greatly. Whether at a small geographic scale or at an individual level, it can cause subtle diseases like nausea and headache to critical ones like asthma and lung cancer. At the global scale, air pollution is cited as primary reason for climate change, contributing to the accumulation of greenhouse gases (GHG) and stratospheric ozone layer depletion.

China is one of the countries that have the most serious air pollution problem in the world, where $PM_{2.5}$ is the main component contributing to the nationwide smog problem. Shanghai, situated on the east coast of China and the estuary of the 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.

With the rapid urbanization process in terms of economic and population growth, Shanghai also suffers one of the most serious air pollution problems in China. Situated at the mouth of the Yangtze River Delta, which is a heavily industrialized region focused on manufacturing, much of Shanghai’s air pollution originates from the industrial area outside of the city and blows into the city. However, Shanghai is experiencing rapid growth in automobile ownership as the residents’ incomes are rising. This thesis will focus on $PM_{2.5}$, largely related to automobiles, with a focus on Shanghai.

1.1 Background of Research Area

Shanghai is the largest city in China, and is also the economic and cultural center of China. It is not only a global financial center, but also a transport hub with the world's busiest container port due to its location on the Yangtze River Delta, the largest urban agglomeration in China. More than one fifth of China’s GDP is produced here, and 11% of China’s population live in this region. Shanghai is located in the center of the Yangtze River Delta urban agglomeration, which also consists of the nearby Jiangsu province to the north and Zhejiang province to the south, and is bounded to the east by the East China Sea (see Figure 1).



Source: Google Earth

Figure 1. *Shanghai's location in China*

As in 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. The Huangpu River, a branch of the Yangtze River, traverses Shanghai and divides the city into two parts: west of the Huangpu River and east of the Huangpu River (see Figure 2).

Source: Shanghai Comprehensive Plan 1999–2020

Figure 2. *Land use structure of the Shanghai*

The total population of the city increased dramatically in recent years, from 16.08 million in 2000 to 24.15 million in 2015. Shanghai has a population density of 8,890 people per square mile (Seattle: 6,717 people/sq. mi) (Shanghai Economic and Social Development Statistical Bulletin 2015), which is one of the cities with the highest urban population density in the world. In addition, one can find that population densities in urban districts (Huangpu, Xuhui, Chnagning, Jingan, Puto, Zhabei, Hongkou, Yangpu) are two to five times higher than those of suburbs and rural areas (Pudong, Minhang, Baoshan, Jiading, Jinshan, Songjiang, Qingpu, Fengxian, Chongming) (see Figure 3). The reason is that most of Shanghai's population lives in urban districts with historical central areas, where the area is much smaller than newer suburbs and rural areas (see Figure 4).

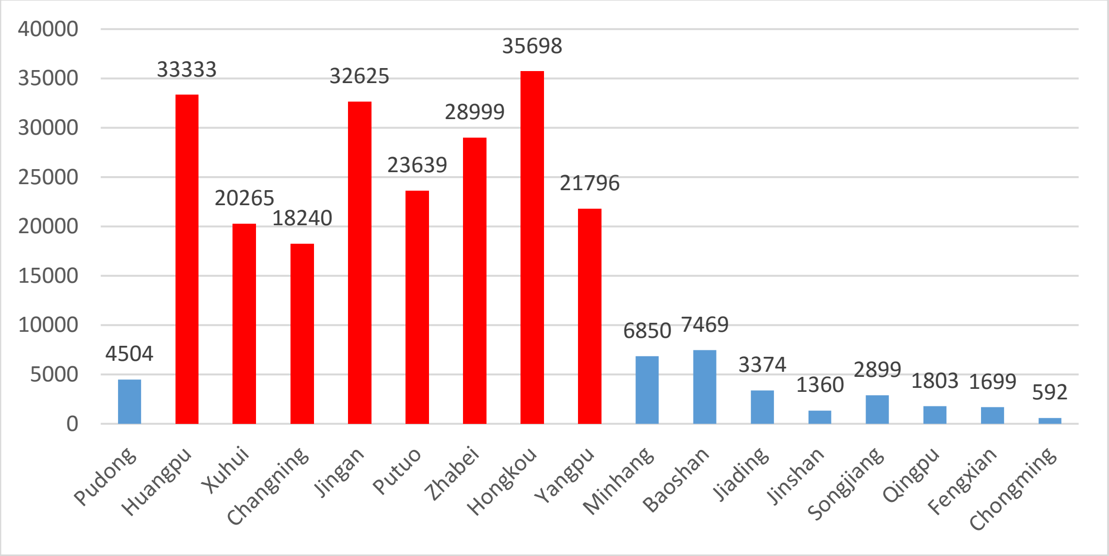
Shanghai's high population density is the result of a combination of geographic, demographic, and policy considerations. First, the geographic region has a natural scarcity of developable land. The most prevalent constraints are hilly terrain, swampy low lands, and the surrounding bodies of water. Land scarcity alone does not produce high population density, but it is combined with rapid population growth since WWII, farmland preservation for regional food security, and compact development in Shanghai. The factors that drive Shanghai's population growth have been twofold: natural increases in birthrate of the local population and a major influx of immigration from other districts. Most migrants are from nearby Jiangsu, Anhui, and Zhejiang province (Shanghai Bureau of Statistics, 2011). In addition, the rapid economic growth also attracts people from outside of the city to Shanghai.

Table 1. *Population, area and population density comparison among world's largest cities (2014)*

City	Population	Total Area(km^2)	Gross Population Density(/km^2)
Shanghai	24,256,800	6,340	3,775
Beijing	21,516,000	16,410	1,311
Hong Kong	7,298,600	1,104	6,608
Tokyo	13,297,629	2,189	6,075
Seoul	10,048,850	605	17,134
Cairo	9,278,441	3,085	3,008
New York	8,550,405	784	10,908
London	8,538,689	1,572	5,431

Source: Wikipedia, List of cities proper by population,

https://en.wikipedia.org/wiki/List_of_cities_proper_by_population

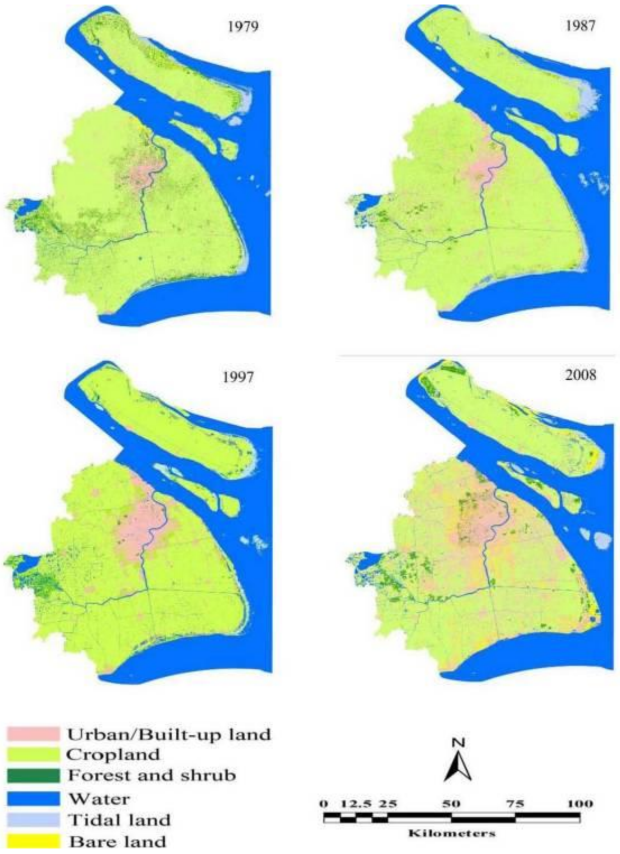


Source: Shanghai Statistical Yearbook 2015

Figure 3. *Population density by districts of Shanghai 2014 (unit: 10,000 person)*

Figure 4. *Shanghai administrative district division*

Like other high density cities, Shanghai has embraced land use policies that favor high density land use since the 1970s. The urban/built-up area grew by 1,230 km^2 (304,000 acres) between 1979 and 2008, or nearly 4,242.06 hectares per year on average. This means that the built-up area grew more than 5.7 times of Seattle land area (53,760 acres). Bare land grew by 461.7 km^2 or nearly by 1,594.66 hectares per year on average. In contrast, cropland decreased by 953 km^2 (235,491 acres) or nearly by 3,286.26 hectares per year on average, followed by forest and shrub, water, and tidal land, which decreased on average by 1,331.33 hectares per year, 903.43 hectares per year, and 315.72 hectares per year, respectively. The urban area increased from the area along the Huangpu River in the 1970s to the whole Shanghai administrative region today. Urban expansion occurred more rapidly between 1997 and 2008 (see Figure 5).



Source: Zhang et al., 2011

Figure 5. *Land use maps of Shanghai in 1979–2008*

There are five key concepts that comprise Shanghai’s high density policy: space proximity, compactness, verticality, sky city, and intensive mixed uses (Lau et al., 2003). Space proximity promotes minimal horizontal setbacks and separation between structures. Compactness promotes smaller, efficiently designed spaces to allow for more intensive use.

Verticality promotes increased height limits on buildings to allow for higher floor area ratios. Sky city is a concept that encourages linkages, transportation, amenities, and essential services to exist and be connected on multiple layers above the street level. An example of this would be sky bridges that connect multiple buildings. Also, intensive mixed use allows for a diversity of goods and services to be available within a convenient distance. All these factors have contributed to the creation of the very compact and high density development we see today in Shanghai.

This density has many benefits. Many observers have recognized and applauded Shanghai for creating a compact city that increases efficiency, decreases transportation costs, and ensures the highest and best use of available land. One benefit is that it has allowed the city to create an efficient, high capacity transit system. On the surface, this type of development delivers significant environmental benefits and is believed to be a model for a sustainable city because, by many measures, it improves the quality of life for the people living there. However, it has become apparent that certain aspects of the high density policies are creating environmental problems and lowering quality of life for residents. For example, the high density might contribute to an increase in urban air pollution. The two components of density that are most responsible for this are space proximity and verticality. Average height of Shanghai's skyscrapers can achieve 200 meters (656 feet), which is similar to Rainier Square Tower in Seattle, with closed proximity in urban area (see Figure 6). By placing tall buildings very close together, the natural wind patterns of the city have been obstructed. This prevents that wind from blowing through the city and removing stagnant, polluted air and replacing it with fresh air.

Source: Getty Images

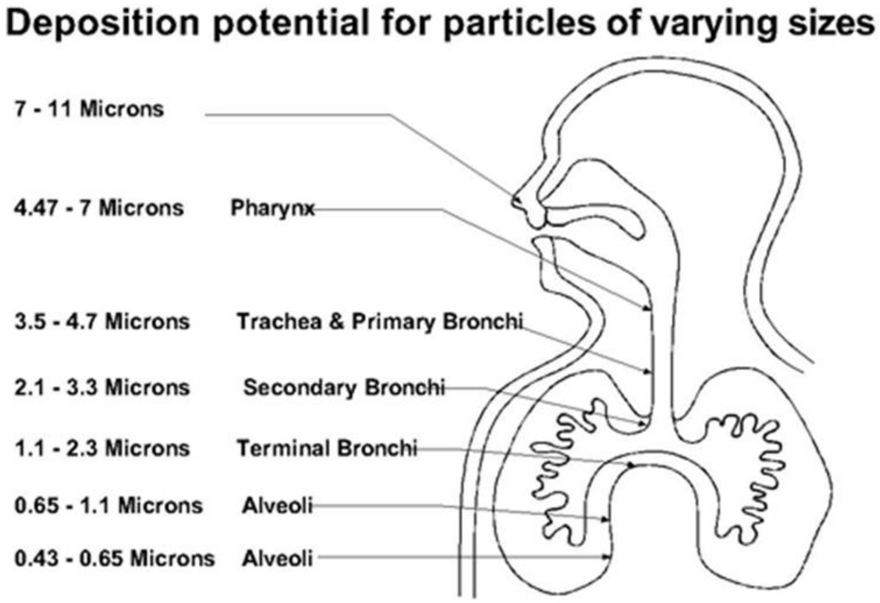
http://www.gettyimages.com/detail/photo/shanghai-city-skyline-royalty-free-image/458912579

Figure 6. *Skyline of Shanghai*

1.2 Particulate Matter

1.2.1 What Is Particulate Matter

Airborne particulates are a major component of urban air pollution. Anthropogenic sources include combustion within car engines, solid-fuel combustion in households, industrial activities (such as building, mining, manufacturing of cement, ceramics and bricks, and smelting), quarrying and mining. For particulate matter, the size of the particles is very important. It determines both how long particles remain airborne to be inhaled, and whether they reach the deep regions of the lung where they can be absorbed. Only particles smaller than about 10 microns (one thousandth of a millimeter) will reach the alveoli. Larger particles are deposited higher up in the respiratory system and removed on the mucociliary escalator, which is a major barrier against infection by the cilia (University of Colorado, 2016), but may then be swallowed and subsequently absorbed through the gastro-intestinal tract. Many researchers find that much smaller particles, called ultrafine particulate matter—like $PM_{0.1}$, whose particle size is 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).

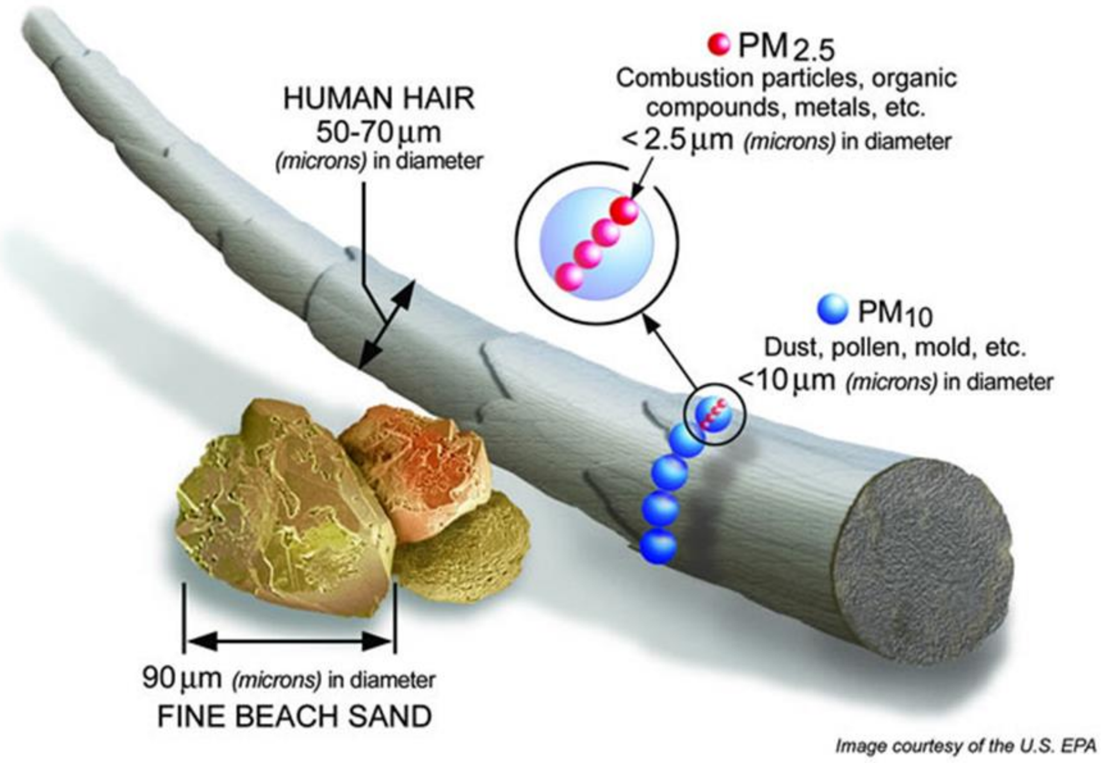


Source: ACRD website, http://www.acrd.bc.ca/particulate-matter

Figure 7. *Particulate matter sizes and potential deposition location of lung*

According to the definition given by the US Environmental Protection Agency (EPA), particles less than 10 micrometers in diameter (PM_{10}) pose a health concern because they can be inhaled into and accumulate in the respiratory system. Particles with diameters between 2.5 and 10 micrometers are referred to as "coarse." Sources of coarse particles include crushing or grinding operations, and dust from paved or unpaved roads.

There is a description in EPA’s website introducing $PM_{2.5}$: “Particles less than 2.5 micrometers in diameter ($PM_{2.5}$) 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.” (EPA, 2016(a)).



Source: US EPA, https://www3.epa.gov/pm/graphics/pm2_5_graphic_lg.jpg

Figure 8. *Particulate matter sizes and a human hair comparison*

Sources of fine particles ($PM_{2.5}$) include human activities and natural activities. Human activities include all types of combustion activities (motor vehicles, power plants, wood burning, etc.) and certain industrial processes (EPA, 2016(b)). The major natural activities responsible for airborne particulate matter include volcanic eruptions, wildfires, landslides, and seismic activity, although activities far smaller in scale and magnitude like pollination can also increase particulate matter concentration in the nearby area (WA State Dept. of Health, 2014).

Other particles may be formed in the air from the chemical change of gases. They are indirectly formed when gases from burning fuels react with sunlight and water vapor. These can result from fuel combustion in motor vehicles, in power plants, and in other industrial processes.

1.2.2 Health Impact of $PM_{2.5}$

A high concentration of fine particulate matters ($PM_{2.5}$) puts people at risk due to the harm it does to people's respiratory and cardiovascular systems. Only particles smaller than about 10 microns (one thousandth of a millimeter) will reach the alveoli. Larger particles are deposited higher up in the respiratory system and removed on the mucociliary escalator, but may then be swallowed and subsequently absorbed through the gastro-intestinal tract (See CARB report, Health Effects of Particulate Matter, for more). The particle size of 2.5 micrometers in diameter is commonly described as one tenth of the diameter of a human hair (See Figure 8). 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.

Research shows $PM_{2.5}$ may lead to acute respiratory symptoms, wheezy bronchitis among infants, and a decreased rate of lung growth in children. The vulnerable population includes the young (those under 16 years old) and the old (those over 65 years old) who live close to freeways (Bae et al., 2007). By using a geographic information system (GIS) and the US Census population data in the Seattle metropolitan area, Bae et al. demonstrated that there is an overconcentration of vulnerable residents who live near freeways, such as in the downtown International District of Seattle, where I-5 and I-90 intersect.

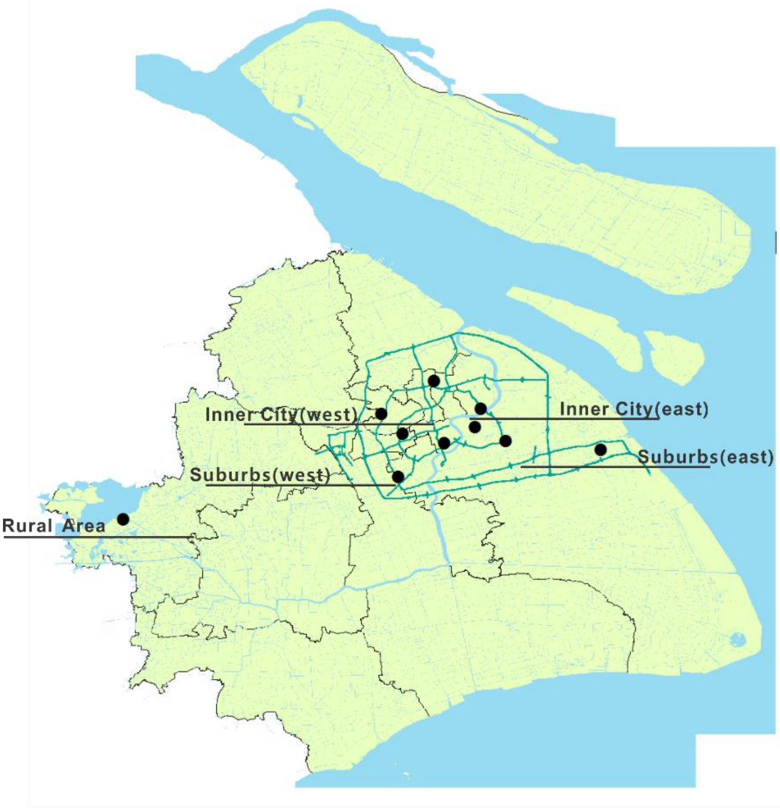
Research showed that ambient levels of both particulates (PM_{10}, and $PM_{2.5}$) and gaseous pollutants (NO_2 and O_3) are associated with childhood asthma hospital admission (Lee et al., 2006). Moreover, epidemiologic study has confirmed that $PM_{2.5}$ and PM_{10} relate to the increased incidence of various respiratory illnesses and mortality. Yin's research found that when daily $PM_{2.5}$ concentration increases 34 $\mu g/m^3$, the number of pediatric respiratory outpatients in Shanghai would increase by 3.2% (Yin et al., 2011). Moreover, researchers link traffic-related air pollution in primary schools and the pupil's cognitive development. Those who were exposed to higher levels of air pollution showed lower growth in cognitive development than those who attend schools with lower level of air pollution (Sunyer, J. et al., 2015). According to WHO guidelines, when the $PM_{2.5}$ concentration reaches 50 $\mu g/m^3$, short-term mortality will increase 2.5%. Most of these deaths are caused by lung cancer (WHO, 2005).

On the other hand, the research found that the respirable particulate level is greatly affected by the mode of transport as well as the ventilation system of the transport. Through studying Hong Kong's air pollution, Chan found that the commuter exposure in trams (175 $\mu g/m^3$) is the highest among all the monitored commuting modes, including trains, buses, taxis, and ferries. Even if commuters take the railway transportation, they are still exposed to average PM_{10} with 50 $\mu g/m^3$, which is the lowest among those transportation modes but high compared to the annual PM_{10} level (45 $\mu g/m^3$) of Hong Kong. The overall average PM_{10} concentration level is 86 $\mu g/m^3$ in public transportation mode (Chan et al., 2002).

1.3 Shanghai's $PM_{2.5}$ Air Pollution Condition

1.3.1 $PM_{2.5}$ Conditions in Shanghai

Shanghai's $PM_{2.5}$ data collection and publication began very recently. It dates back to 2011, and the data collection from all of the $PM_{2.5}$ air quality monitoring stations began one year later. Before that, most of the literature focused on studying PM_{10} and gaseous pollutants such as CO, HC, and NO_x. In 2000 the Ambient Air Quality Standard, 1996 Amendment canceled the collection of NOx concentration data and began to collect the concentration data for NO_2. At the same time, the city of Shanghai started recording PM_{10} concentrations. I compiled $PM_{2.5}$ data that have been available from June 28, 2012 to March 31, 2015, from all 10 air quality monitoring stations throughout the city (see Figure 9).



Source: http://www.zq12369.com/environment.php?tab=city&city=%E4%B8%8A%E6%B5%B7

Figure 9. *Study zones of the survey and locations of the 10 air quality monitoring stations*

Shanghai's air pollution problem is well known in the world. Table 2 shows WHO air quality guidelines, which are higher than the US EPA's National Ambient Air Quality Standards. Table 3 shows the general Shanghai air quality in 2014. The annual concentrations of PM_{10} and $PM_{2.5}$ were more than three to five times higher than the WHO standard; NO_2 is slightly higher. Only O_3 and SO_2 were lower than WHO standards.

Table 2. *WHO air quality guidelines and interim targets for particulate matter*

	PM_{10} $(\mu g/m^3)$	$PM_{2.5}$ $(\mu g/m^3)$	Basis for the selected level
Interim target-1 (IT-1)	70	35	These levels are associated with an approximately 15% higher long-term mortality risk relative to the AQG level.
Interim target-2 (IT-2)	50	25	In addition to other health benefits, these levels lower the risk of premature mortality by approximately 6% [2-11%] relative to the IT-1 level.
Interim target-3 (IT-3)	30	15	In addition to other health benefits, these levels lower the risk of premature mortality by approximately 6%

			[2-11%] relative to the IT-2 level.
Air quality guideline(AQG)	20	10	These are the lowest levels at which total, cardiopulmonary and lung cancer mortality have been shown to increase with more than 95% confidence in response to long-term exposure to $PM_{2.5}$.

Source: WHO Air quality guidelines for particulate matter, ozone, nitrogen dioxide and sulfur dioxide, Global update 2005

Table 3. *Comparison of air quality in Shanghai 2015 and the WHO standard (unit:* $\mu g/m^3$*)*

	PM_{10} annual mean	$PM_{2.5}$ annual mean	O_3 8-hour mean	NO_2 annual mean	SO_2 24-hours mean
Shanghai	69	53	89	46	17
WHO AQG	20	10	100	40	20
Shanghai/WHO comparison	3.45	5.3	0.89	1.15	0.89

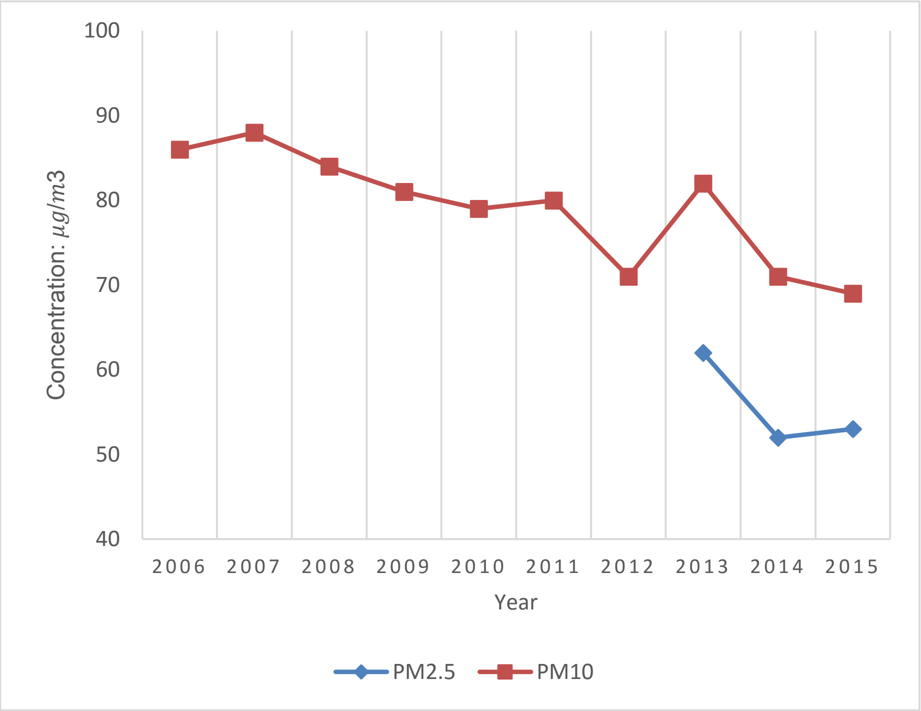
Source: Shanghai Environmental Center, WHO Air quality guidelines for particulate matter, ozone, nitrogen dioxide and sulfur dioxide, Global update 2005

When compared with other global cities in the world, Shanghai's air quality is better than Mumbai and Beijing, but much worse than other Western cities such as New York, Los Angeles, London, and Sydney, as well as the nearby Far Eastern megacities such as Tokyo and Seoul (See Table 4).

Table 4. *Comparison of* $PM_{2.5}$ *and* PM_{10} *in selective global cities, 2013-2014 (unit:* $\mu g/m^3$*)*

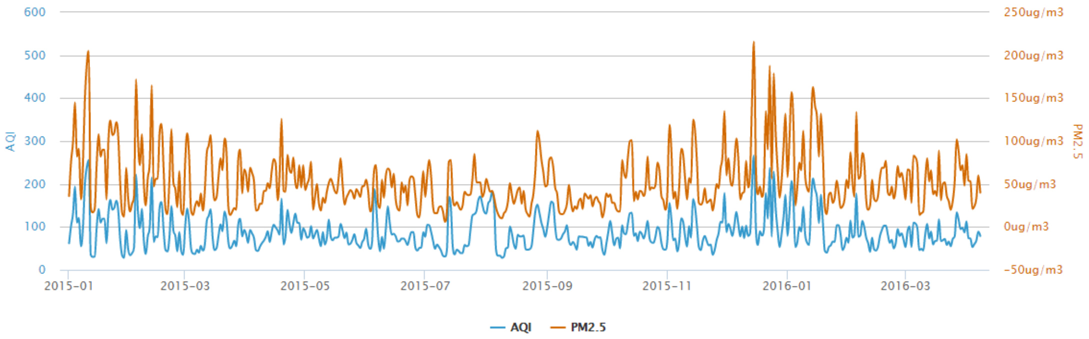
City	Annual $PM_{2.5}$ Concentration Level	Average PM_{10} Concentration Level	Level based on WHO guideline
New York	9	16	AQG
Los Angeles	11	20	IT-3/AQG
Seattle	6	12	AQG
Sydney	8	17	AQG
London	15	22	IT-3
Mumbai	63	117	None
Shanghai	52	84	None
Beijing	85	108	None
Tokyo	15	28	IT-3
Seoul	24	46	IT-2
Mexico City	20	42	IT-2

Source: WHO, Ambient (Outdoor) air pollution database, by country and city http://www.who.int/phe/health_topics/outdoorair/databases/cities/en/



Source: Shanghai Environmental Center

Figure 10. *Shanghai's annual respirable suspended particulates concentration trend (2006-2015)*



Source:http://www.zq12369.com/environment.php?tab=city&city=%E4%B8%8A%E6%B5%B7

Figure 11. *Shanghai daily $PM_{2.5}$ concentration trend from 2015.01 to 2016. 03 (unit: $\mu g/m^3$)*

Figure 10 shows the respirable suspended particulates (PM_{10} and $PM_{2.5}$) concentration in a declining trend over the last decade (2006-2015). However, the recent PM_{10} concentration maintain a level of about 70 $\mu g/m^3$, while the concentration of $PM_{2.5}$ is higher than 50 $\mu g/m^3$. According to WHO guidelines, when the PM_{10} concentration increases to 50 $\mu g/m^3$, short-term mortality will increase 2.5% due to lung cancer. Figure 11 shows the daily $PM_{2.5}$

concentration trends between 2015 and 2016, where the striking levels of $PM_{2.5}$ more than 200 μg/m^3 per day are visible. For many days, especially during the winter months, $PM_{2.5}$ concentration exceeds 100 μg/m^3, which shows the serious air pollution in Shanghai, and demands urgent research.

1.3.2 Problem Faced

It is well-known that one of the worst smog events hit Shanghai during the winter since 2013 (Huang, 2015). During January 2013, Shanghai suffered six large scale, long lasting and serious haze weather events (see Table 5 and Figure 12) (Zhou et al., 2013). It was reported that Shanghai's concentration of $PM_{2.5}$ particles even reached an unprecedented level of 602.5 μg/m^3 on the afternoon of December 6, 2013. The atmospheric visibility decreased, 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). According to Pan's research, in 2010, Shanghai $PM_{2.5}$ air pollution caused 2,980 deaths and more than USD 364 million financial loss in total (see Table 6) (Pan et al., 2012).

Table 5. *Average mass concentration of PM in haze periods in January 2013 in Shanghai*

Date	PM_{10} (μg/m^3)	$PM_{2.5}$ (μg/m^3)	$PM_{2.5}$/PM_{10}	Cumulative time of atmospheric visibility<10km (unit: hours)
1.6-1.9	138±48	96±38	69.6%	35
1.12-1.13	212±60	145±34	68.4%	26
1.14-1.17	169±68	114±52	67.5%	56
1.18-1.19	128±28	88±17	68.8%	11
1.21-1.26	187±68	132±40	70.6%	119
1.29-1.30	257±55	175±33	68.1%	25
Average	149±70	102±50	68.4%	284

Source: Zhou et al., 2013

Source: ChinaFotoPress via Getty Images

Figure 12. *Smoggy days in Shanghai*

Table 6. *2010 death number and financial loss due to* $PM_{2.5}$ *in Shanghai*

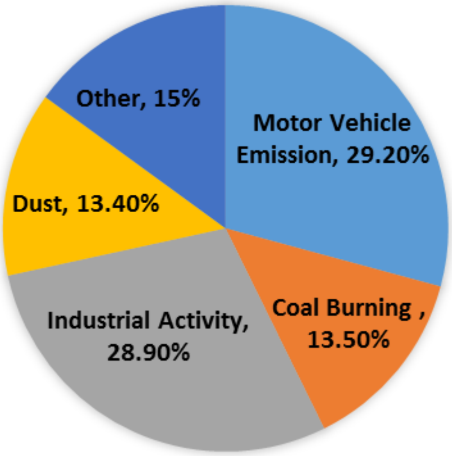
Disease Category	**Death Number**	**Financial loss/ USD**
Cyclic system	1,195	146,090,000
Respiratory system	826	101,040,000
Total Death	2,980	364,490,000

Source: Pan et al., 2012

CHAPTER 2. LITERATURE RERIEW

2.1 What Causes $PM_{2.5}$ Emissions in Shanghai

Cheng found $PM_{2.5}$ is the primary pollutant in Shanghai by applying statistical analysis to the daily air quality indicator (AQI) (Cheng and Wang, 2014). According to the analysis of $PM_{2.5}$ data by the Shanghai municipal government, there are several sources of $PM_{2.5}$ emissions in the city, including industrial activities; motor vehicle emissions; construction, coal burning emissions, such as power plants and heating burning; agricultural emissions, restaurant oil fume, and so on (Shanghai Environmental Protection Bureau, 2015). In 2014, industrial activities accounted for 28.9% of the total $PM_{2.5}$ emissions in Shanghai, and motor vehicle emissions accounted for 29.2%. The share of PM2.5 from motor vehicle emissions is larger than the share from industrial activities, which is higher than other cities' motor vehicle emissions share (See Chapter 2.3). For three other sources of $PM_{2.5}$ emission only accounts for 42% of the $PM_{2.5}$ emissions in total (see Figure 13).



Source: Shanghai Environmental Protection Bureau, 2015

Figure 13. *Source of Shanghai's $PM_{2.5}$ distribution*

2.2 Industrial Activities in Shanghai

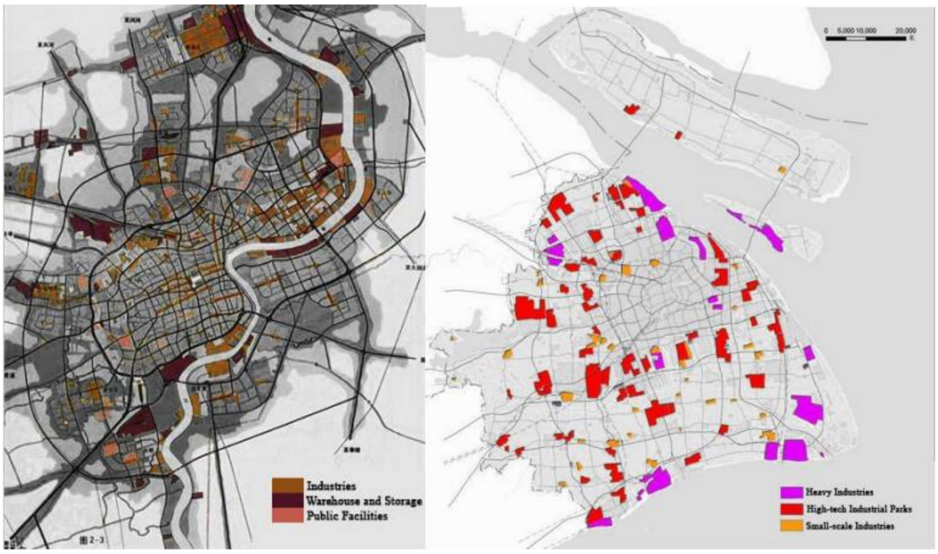
As an important industrial city in China, Shanghai's industrial development process can be traced back to the mid-nineteenth century when there was an economic reform in the late time of the Qing dynasty, but it was restricted to manually-operated processes and ultimately failed. After 1949, the establishment of the People's Republic of China, Shanghai's modern industrialization process started. The progress can be summarized into four stages by the Hoffman ratio level (Zhou, 2011).

The first stage lasted only four years between 1949 and 1952, in the earlier stage after the foundation of the People's Republic of China. In this stage, the country invested a lot into heavy industry, which aimed to encourage economic growth after the civil war. The ratio of heavy industry increased from 11.8% to 20.7% in four years. Some of industries were founded and maintained in the city center during this stage, such as cigarette factories and cotton mills (Zhou, 2011).

The second stage lasted from 1953 to 1958, which is the first "five-year plan" in China. In this stage, some heavy industries began to relocate to suburbs. In this period, the growth rate of heavy industry, such as steel and mining, exceeded light industry like manufacture for the first time. Many heavy industrial factories appear in the city center of Shanghai.

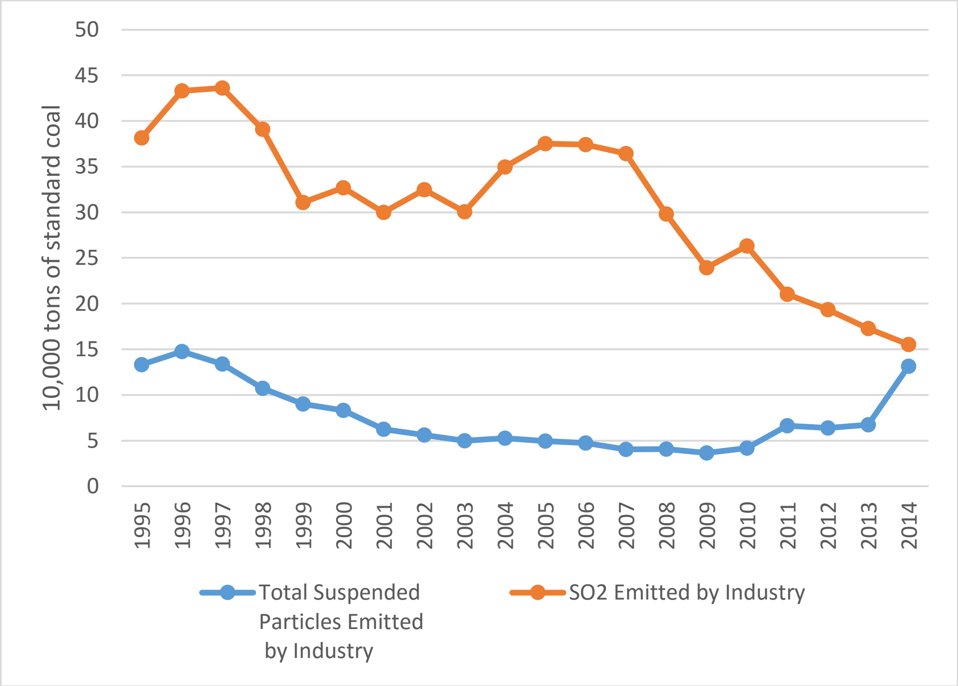
The third stage of Shanghai's industrialization began in 1959, and ended in 1991. This stage can be divided into two periods. The earlier stage was from 1959 to 1978, twenty years in total. In this period, because of the economic recession and Cultural Revolution, the production of heavy industry in Shanghai decreased dramatically. And many industrial factories closed during this time. However, after 1978, the year in which the Chinese Economic Reform started, the Shanghai government began to encourage the development of the high-tech industry, and relocate some heavy industries to suburbs.

The last stage began in 1992 and continued until the present. In recent decades, high-tech industry replaced heavy industry, being the dominant industry in Shanghai. Industrial parks were constructed by the government in order to cluster the same type of industrial. Most of old industrial plants were displaced from the city center, especially the heavy industries (see Figure 14). Heavy industrial factories moved to the rural area, or nearby cities, like Kunshan, Suzhou, and Wuxi.



Source: Ling (2014) from Shanghai Urban Planning and Design Research Institute

Figure 14. *Distribution pattern of industries in 1959 (left) and 2008 (right)*



Source: Shanghai Statistical Yearbook 2015

Figure 15. *Trends of industrial emissions (TSP and SO_2), 1995–2014*

As a result, the replacement and clustering of industrial areas in rural areas of Shanghai contribute to the decreasing of the total emissions from freight transport because of the closer transportation distances between upstream and downstream factories (see Figure 15).

Moreover, the removal of polluting industrial factories from central Shanghai is also helpful to reduce industrial impacts on the air quality of the central area.

2.3 Traffic-Related Air Pollution $PM_{2.5}$ in Shanghai

Many recent studies found that motorization is the leading cause of deteriorating air quality, and is especially the biggest contributor to $PM_{2.5}$ emissions. Li found that vehicle emission was the major contributor to fine particles ($PM_{2.5}$) in Shanghai during a heavy haze episode in December of 201,3 based on the particulate matter source apportionment technology (Li, An, and Yan, 2015). The Chinese Academy of Sciences' research indicates that motor vehicle emissions contribute most to Beijing $PM_{2.5}$ emissions, which accounts for almost 25% (Institute of Remote Sensing and Digital Earth, 2013). Bao's study shows that the motor vehicle exhaust contributes 21.6% of total $PM_{2.5}$ emissions to the air in Hangzhou, which is much higher than other sources. As far as the major contributor to PM_{10} emissions, motor vehicle exhausts also accounts for 16.9% (Bao et al., 2010). Xiao also discovered vehicle emissions account for the majority of ambient PM_{10} and $PM_{2.5}$ in urban areas (Xiao et al., 2012).

According to COPERT Ⅳ model, vehicle emissions can be divided to exhaust pipe and non-exhaust pipe emissions of $PM_{2.5}$. Exhaust pipe emissions include vehicle running emission, vehicle start emission, and fuel vaporization. Non-exhaust pipe emissions include the emission of tire wear, brake wear, and road wear. The model indicates non-exhaust pipe emissions of $PM_{2.5}$ increased with higher vehicle weight and decreased with higher speeds. Exhaust pipe emissions of $PM_{2.5}$ decreased with the speed and enhancing emission standards (Huang, Liu, and Cheng, 2014).

Travel speed is another important factor impacting the amount of pollutants emitted by automobiles because incomplete fuel combustions usually provoke more $PM_{2.5}$ emissions. Studies show that small passenger vehicles, such as taxies and private cars, usually generate the highest levels of $PM_{2.5}$ emissions when they are driven at a speed under 40 kilometers per hour (km/h) or over 60 km/h.

Shen found the PM_1, $PM_{2.5}$, and PM_{10} concentrations along motor roads are always higher than the average level of $PM_{2.5}$ in Shanghai. The major factors impacting traffic-related $PM_{2.5}$ emissions include traffic volume and transportation system (Shen et al., 2011).

In summary, transportation is the major contributor to Shanghai $PM_{2.5}$ emissions. In this research, I will focus on the traffic-related air pollution in Shanghai, especially $PM_{2.5}$ emissions, which is the main pollutant in Shanghai.

2.3.1 Transportation Development Process in Shanghai

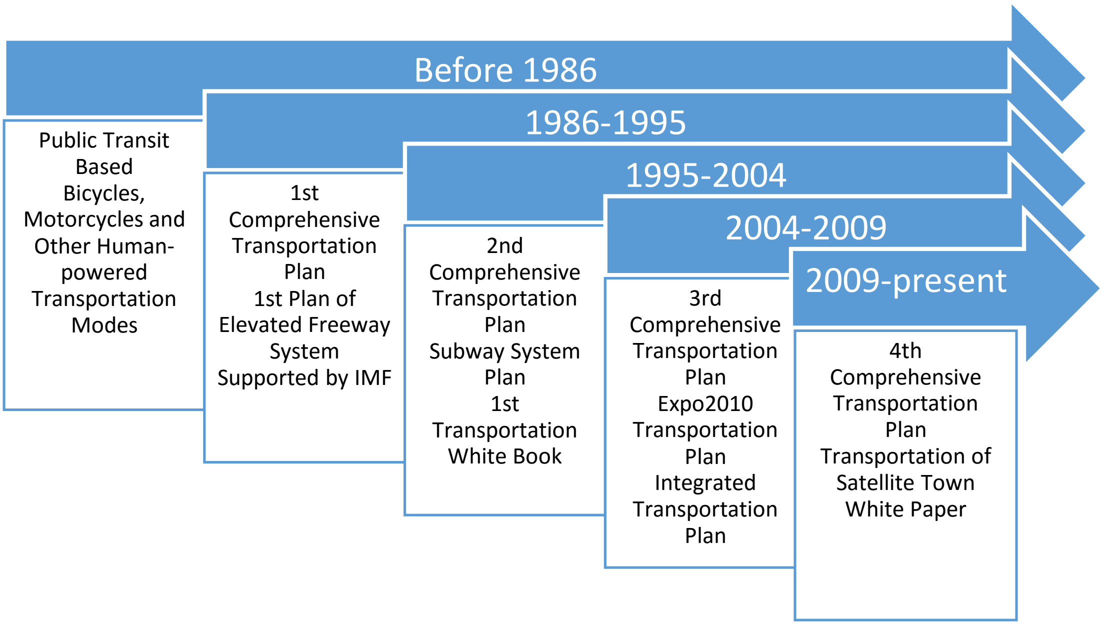
Transportation system emission is one of the most important issues facing the city due to residents' exposure to and the health impacts of $PM_{2.5}$ emissions. Shanghai developed from a public-transit based city, primarily with buses and trolley buses, to one with a multimodal transportation system with mixed ground and underground transportation.

Ling summarized four stages of Shanghai multimodal transportation plan in her thesis (Ling, 2014). The first stage consists of two periods: period before 1980 and period between 1986 and 1995. Before 1980s, most of residents relied on routine buses and bicycles to commute in Shanghai. There lacked reliable connection between the west and east city, and people had to take ferry to cross the river during that time. Meanwhile, most residents and jobs were located west of the Huangpu River (Lu and Gu, 2009). In 1986, Shanghai published its first Comprehensive Transportation Plan (*Shanghai Synthesis Transportation Strategy Plan 1990–2020*). In this plan, Shanghai planned to develop an elevated freeway system in the city, and the first subway line began construction in this year (Ling, 2014).

The second stage of transportation development began in 1995. In this stage, Shanghai adopted its second synthesis transportation plan (*Shanghai Synthesis Transportation Strategy Plan 2000–2020*), which included building a large subway system covering the whole city and connecting the west city and east city. Within ten years from 1980 to 1990, the total length of road increased from 4400 kilometers to 5400 kilometers in Shanghai. The motorcycle became a major transportation mode for people in that time (Lu and Gu, 2009).

The third stage began in 2004, with an increasing city scale and the continuous growth of vehicle ownership. The synthesis transportation plan 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 of Shanghai. Combined with the Expo 2010 Comprehensive Plan and Shanghai "eleven-five" Synthesis Transportation Plan, Shanghai strengthened the linkages between different regions, communities, and park-and-ride facilities using different transportation modes. In this stage, private vehicles replaced motorcycles as the main transportation mode (Ling, 2014; Lu and Gu, 2009).

The fourth and current stage began after Expo 2010 and is intended to lead to a system that matches the new trend of suburbanization. It focuses on not only the convenience of transportation modes, but also the service quality in this process (see Figure 16) (Lu and Gu, 2009).



Source: Ling (2014) based on Lu and Gu, 2009

Figure 16. *Stages of multimodal transportation system development in Shanghai*

2.3.2 Current Transportation in Shanghai

2.3.2.1 Street Network in Shanghai

I divided Shanghai City into five sub-regions: west inner city, east inner city, west suburbs, east suburbs, and rural area (see Figure 9, Chapter 1.3.1). As a monocentric city, the central city area is known as the identified city center in Shanghai, surrounded by the outer ring road. Currently, the central city of Shanghai consists of the inner city and suburbs (west and east inner city, and west and east suburbs).

The radial and complete street network, including expressway, highway, national road, provincial road, and county road, covers the whole city. The street network also supports quick connections between the city center and suburban areas, and ensures convenient commuting between homes and workplaces for most residents (see Figure 17) (Ling, 2014).

From Figure 18, one can see that from 1999 to 2014, the total road length in Shanghai experienced faster growth. The growth rates became lower between 2007 and 2014 than the previous decade. During this period, both the urban areas and suburban 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.

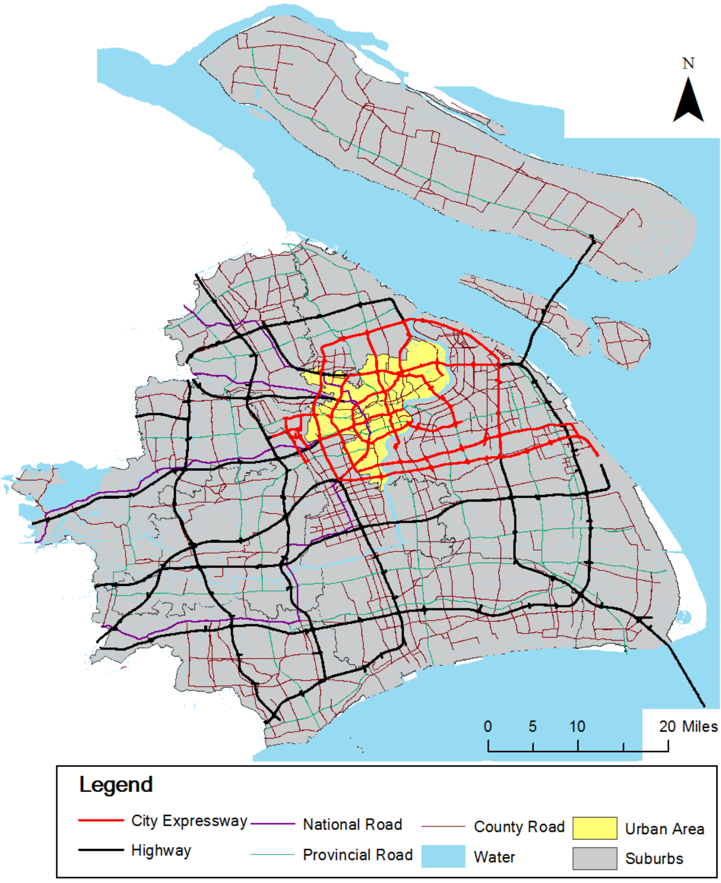
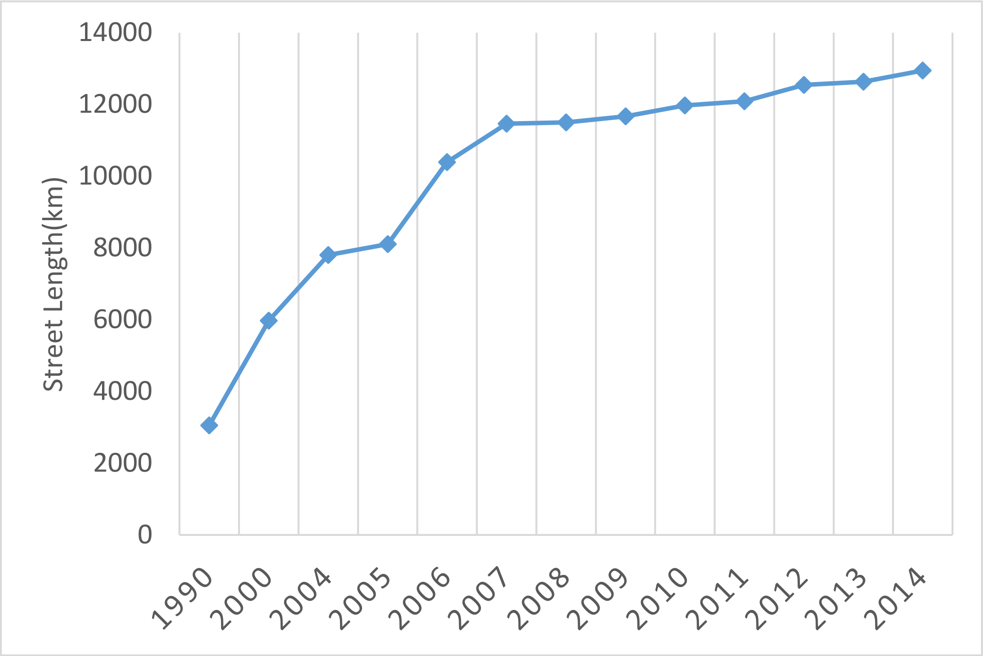


Figure 17. *Current street network and urban areas in Shanghai*

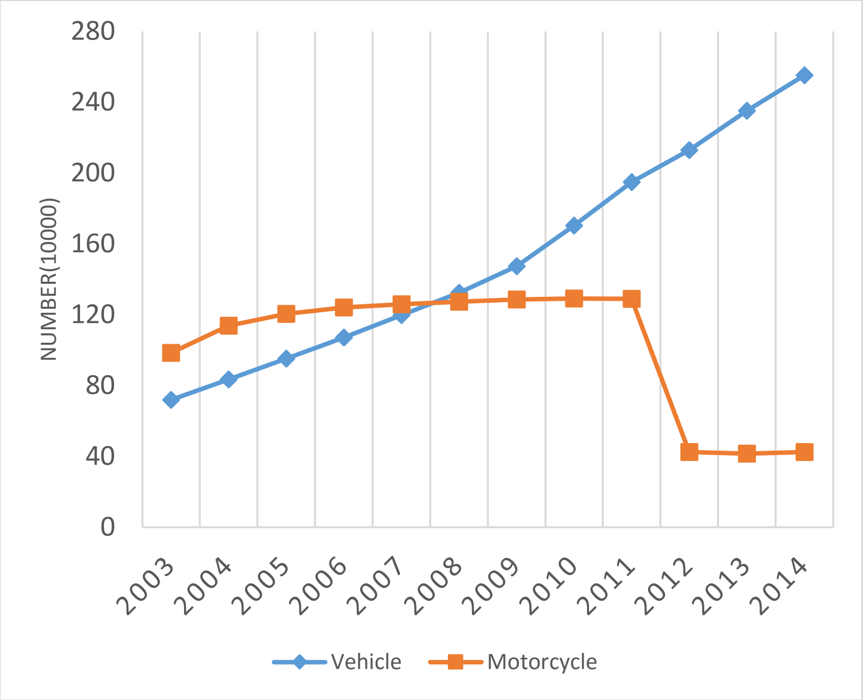


Source: Shanghai Statistical Yearbook 2006, 2008, 2010, 2013, 2015

Figure 18. *Total road lengths in kilometers (km) in Shanghai from 1999 to 2014*

2.3.2.2 Vehicle Population Growth

With complete transportation facilities, the vehicle population of Shanghai increased rapidly in the 2000s. Figure 19 shows the growth of the vehicle and motorcycle population from 2003 to 2014. Similar to the growth trend of total length of road, Shanghai's vehicle population continued to increase from 2003 to 2014, and reached more than three million in 2014. However, the population of motorcycles maintained stable at about 1.2 million by 2011, and decreased sharply to 0.4 million in 2012, which might result from the motorcycle limit policy published by Shanghai in 2012: motorcycles are forbidden in most roads in urban area (within the outer ring road) of the city.



Source: Shanghai Statistical Yearbook 2005, 2008, 2011, 2015

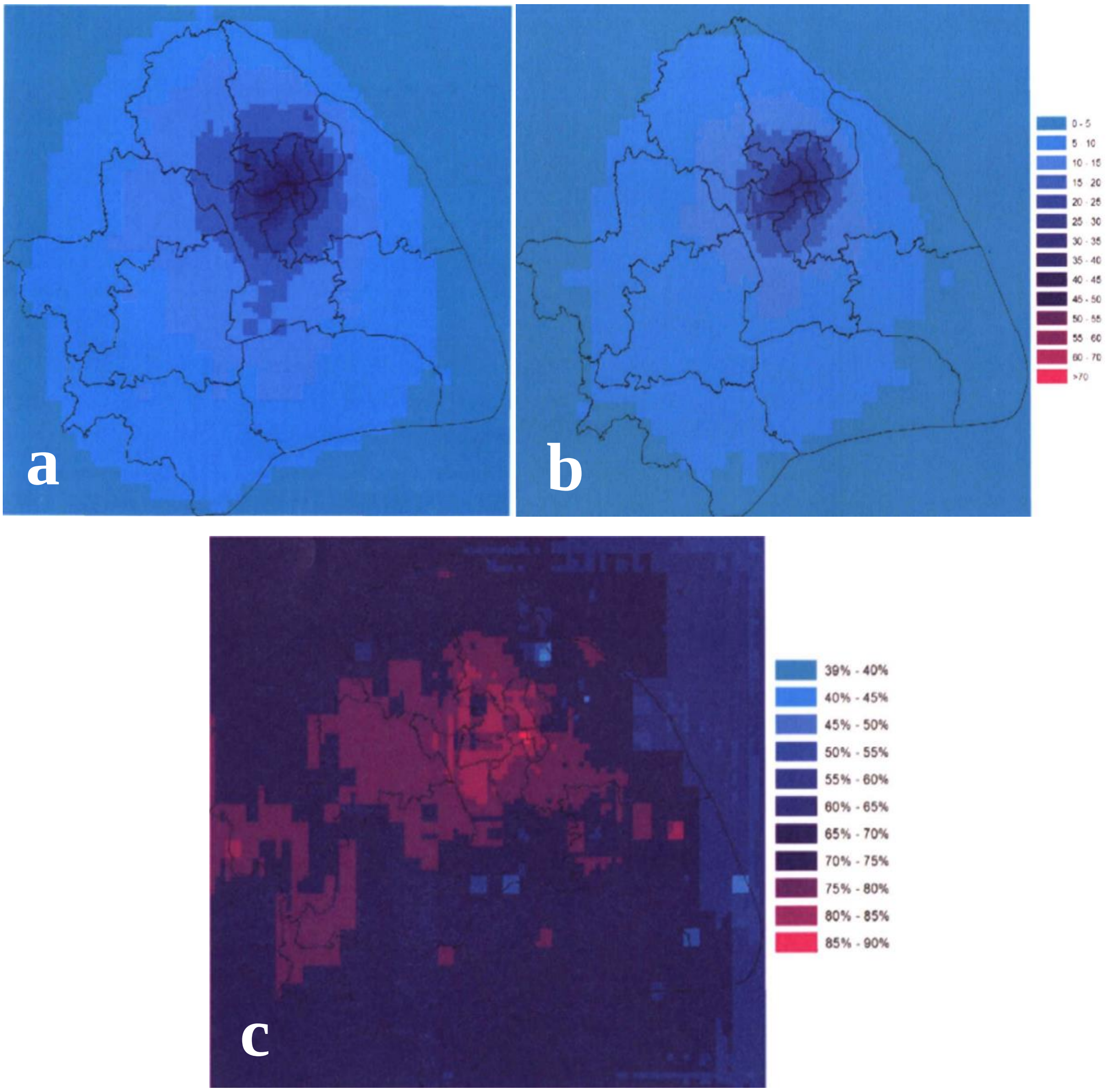
Figure 19. *Trend of vehicle and motorcycle population in Shanghai*

In 2014, the total number of vehicles reached nearly 2.8 million. The rapid growth in vehicle population brought about the overuse of street infrastructure and traffic congestion problems. In order to release the traffic burden, Shanghai adopted a bidding mechanism for allocating licenses to automobile owners to control the number of private cars in 1986 (Feng and Li, 2013). At the same time, the city also published a specific kind of license plate initiated with letter “C”. Vehicles with this specific “C” license are only being allowed in the rural area outside of the outer ring road but forbid to enter the central city. In addition, to encourage people to take public transit, Shanghai municipal government also improved the public transit system by expanding bus lines and metro lines in the city region. As of 2016, there are 15 metro lines covering the entire city from north to south and west to east, as well as a connection to Kunshan, the city west of Shanghai. Study shows that the subway system is now gradually replacing buses to become the most important transportation mode in Shanghai. Its ridership reached nearly 11 million in December 31, 2015, which is the highest ridership in the history of the system (Li, 2016).

2.3.2.3 Environmental Impacts of Growing Transportation Demand

Increased transportation demand will result in a negative effect on air quality in Shanghai. Several studies have pointed that the central districts always saw the highest frequency of motor vehicle usage and the highest $PM_{2.5}$ concentration levels in the whole city region (Ling, 2014).

Figure 20 shows documentation of fine particulate matter ($PM_{2.5}$) concentration patterns in Shanghai based on the $PM_{2.5}$ concentration data collected at different locations in the city in 2004 (Zhao, 2009). Figure 21(a) shows the distribution map of Shanghai's $PM_{2.5}$ concentration level in 2004. Figure 21(b) presents the traffic-related $PM_{2.5}$ emissions in Shanghai in 2004. And Figure 21(c) is the map of traffic-related $PM_{2.5}$ (Map b) divided by the total $PM_{2.5}$ level (Map a), which shows the share of traffic-related $PM_{2.5}$ emissions contributed to the whole concentration of $PM_{2.5}$ in Shanghai. In Shanghai, the central area's $PM_{2.5}$ concentration level is eight times higher (> 40 $\mu g/m^3$) than it is at the periphery (< 5 $\mu g/m^3$). The levels of the $PM_{2.5}$ concentration decrease further away from the center. Zhao found that in central areas, suburban areas, and rural areas, the rate of traffic-related $PM_{2.5}$ emissions contributing to the total $PM_{2.5}$ concentration are 78%, 74%, and 44% respectively. The major sources of traffic-related $PM_{2.5}$ are vehicle emissions and road dust. According to the research's outcome, central areas, suburbs in West Shanghai, districts along the expressway, and areas with dense street networks and high traffic volumes have more $PM_{2.5}$ emissions. In addition, Shen found that concentrations of PM_{10}, $PM_{2.5}$, and PM_1 along main arterials in Shanghai are always higher than those of other districts (Shen et al., 2011).



Source: Zhao, 2009

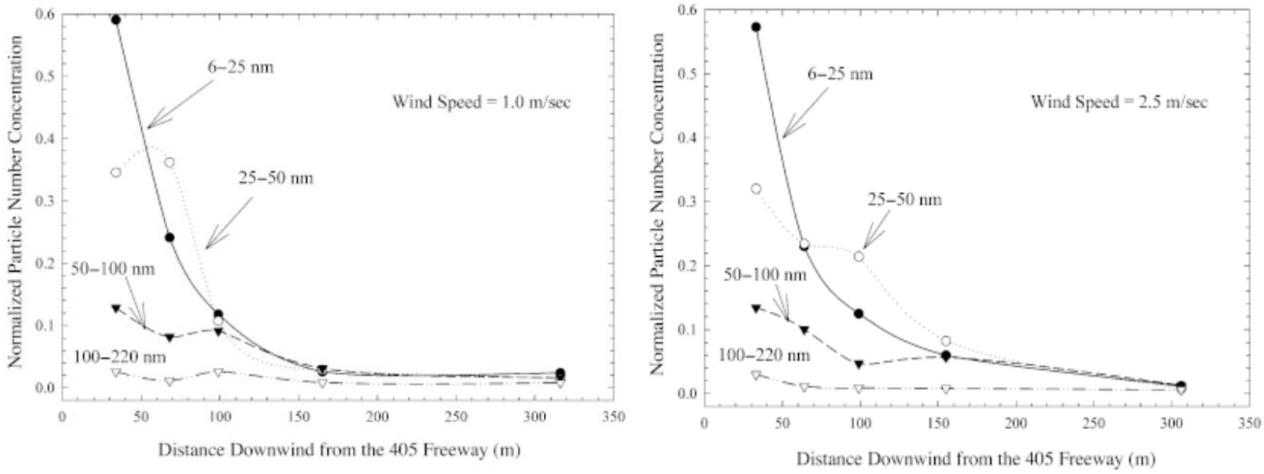
Figure 20. *(a.) Average concentration of $PM_{2.5}$ in Shanghai 2004 ($\mu g/m^3$); (b.) Traffic-related $PM_{2.5}$ emission distribution in Shanghai 2004 ($\mu g/m^3$); (c.) Traffic emission's contribution percentage to $PM_{2.5}$.*

2.4 Traffic-Related $PM_{2.5}$ Emissions Near Major Roads

Traffic-related air pollution is always an important issue for people. U.S. Centers for Disease Control (CDC) have found approximately 11.3 million people (or 3.7% of the 308.7 million U.S. population) live within 150 meters of a major highway in the U.S., with state-level estimates ranging from 1.8% in Maine to 5.6% in New York (Woghiren-Akinnifesi, 2013). Appatova et al. found that over 30% of schools fell within 400 meters of a major roadway (Interstate, U.S. and State Highways) and over 10% were within 100 meters in nine large Metropolitan Statistical Areas (MSA) of the USA (Appatova et al., 2008). These studies suggest increased exposure to traffic-related air pollution and elevated risk for adverse health outcomes among students who attend these schools.

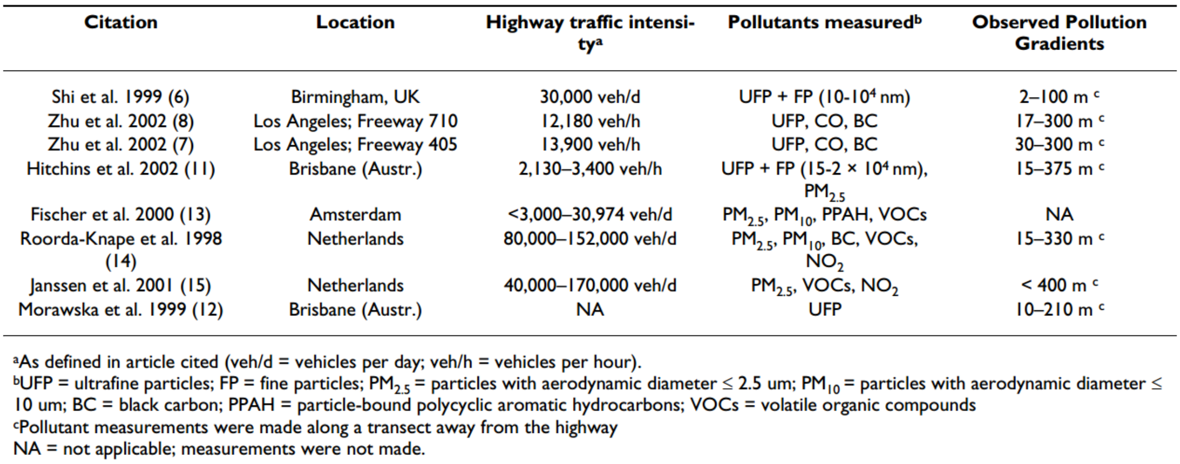
Evidence of the health hazards of traffic-related pollutants (fine and ultrafine particulate matters, black carbons, carbon monoxides, etc.) arises from studies that assess proximity to highways, actual exposure to the pollutants, or both. Several recent studies have shown that sharp pollutant gradients exist near highways. Brugge and his collaborators conclude that people living or working within about 200 meters of highways are exposed to these pollutants more than those living farther away from highways and high traffic roads in urban areas. They also report higher risks for children's asthma and reduced lung function along the freeway, as well as association with lung cancer for those who live near freeways (Brugge et al., 2007). Shi measured UFP (Ultrafine Particles) concentration and size distribution along a roadway-to-urban-background transect in Birmingham (UK), and found that particle concentrations decreased nearly 5-fold within 30 meters of a major roadway (>30,000 vehicle/day) (Shi, Khan, and Harrison, 1999). Hitchins et al. (2000) reports that particle concentration levels reach the highest within 15-375 meter range from roads. Particle concentration decreases substantially within the range of 100 to 150 meters from the freeway and the wind direction can reduce the concentration levels. For $PM_{2.5}$, if the wind blows parallel to the road, the amount decreases to 65%, as opposed to a 75% decrease when the wind blows from the road (Hitchins et al., 2000). Zhu and her colleagues measured wind speed and direction, traffic volume, UFP number concentration and size distribution, as well as BC (black carbon) and CO along transects downwind of I-405 in Los Angeles, which is dominated by gasoline vehicles (13,900 vehicles per hour (veh/h)). Relative concentrations of CO, BC, and total particle number concentration decreased exponentially between 17 and 150 meters downwind from the highways, while at 300 meters UFP number concentrations were the same as at upwind sites (Zhu et al., 2002) (see Figure 21). Brugge et al. reports the broader application of the type and the distance from the freeways in literature (See

Figure22).



Source: *Zhu et al., 2002*

Figure 21. *Normalized particle number concentration for different size ranges as a function of distance to the 405 freeway*



Citation	Location	Highway traffic intensity[a]	Pollutants measured[b]	Observed Pollution Gradients
Shi et al. 1999 (6)	Birmingham, UK	30,000 veh/d	UFP + FP (10-10^4 nm)	2–100 m [c]
Zhu et al. 2002 (8)	Los Angeles; Freeway 710	12,180 veh/h	UFP, CO, BC	17–300 m [c]
Zhu et al. 2002 (7)	Los Angeles; Freeway 405	13,900 veh/h	UFP, CO, BC	30–300 m [c]
Hitchins et al. 2002 (11)	Brisbane (Austr.)	2,130–3,400 veh/h	UFP + FP (15-2 × 10^4 nm), $PM_{2.5}$	15–375 m [c]
Fischer et al. 2000 (13)	Amsterdam	<3,000–30,974 veh/d	$PM_{2.5}$, PM_{10}, PPAH, VOCs	NA
Roorda-Knape et al. 1998 (14)	Netherlands	80,000–152,000 veh/d	$PM_{2.5}$, PM_{10}, BC, VOCs, NO_2	15–330 m [c]
Janssen et al. 2001 (15)	Netherlands	40,000–170,000 veh/d	$PM_{2.5}$, VOCs, NO_2	< 400 m [c]
Morawska et al. 1999 (12)	Brisbane (Austr.)	NA	UFP	10–210 m [c]

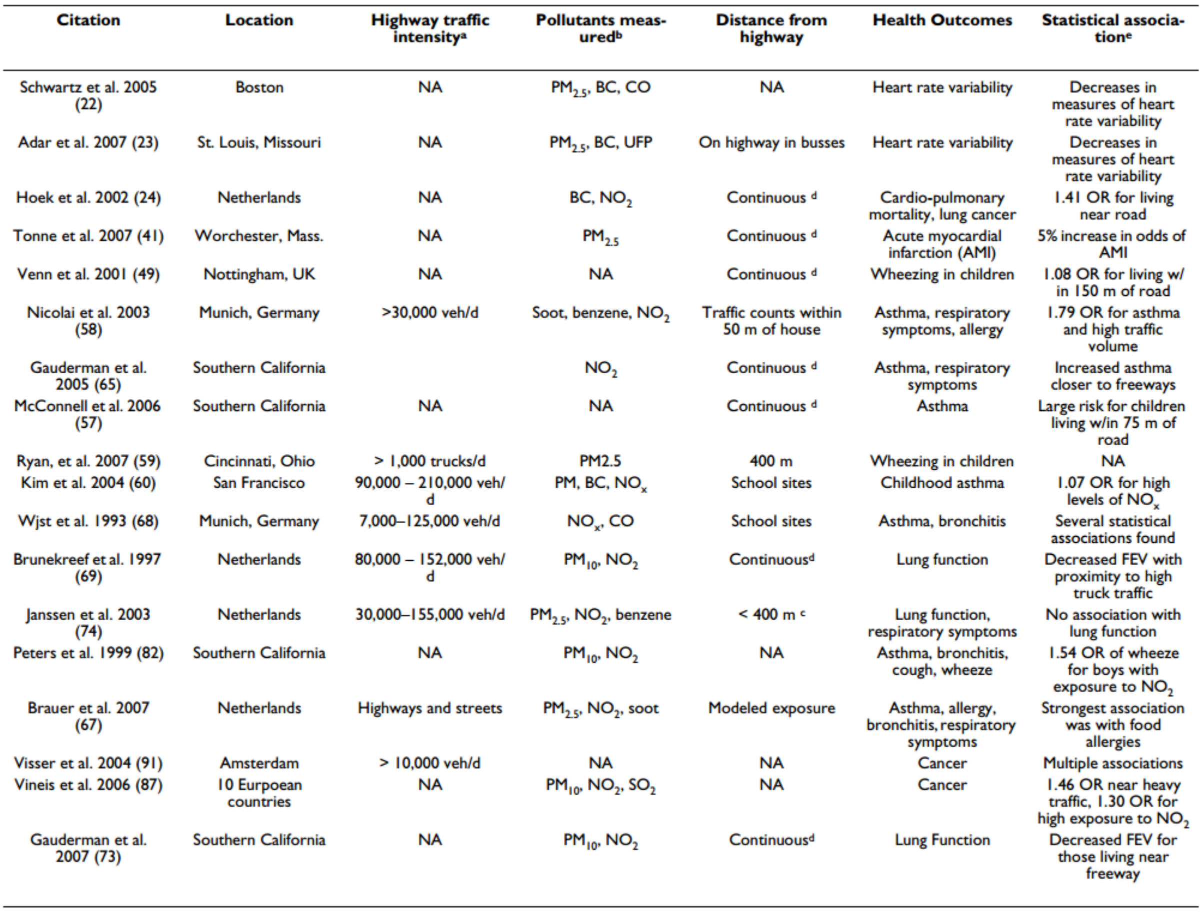
[a] As defined in article cited (veh/d = vehicles per day; veh/h = vehicles per hour).
[b] UFP = ultrafine particles; FP = fine particles; $PM_{2.5}$ = particles with aerodynamic diameter ≤ 2.5 um; PM_{10} = particles with aerodynamic diameter ≤ 10 um; BC = black carbon; PPAH = particle-bound polycyclic aromatic hydrocarbons; VOCs = volatile organic compounds
[c] Pollutant measurements were made along a transect away from the highway
NA = not applicable; measurements were not made.

Source: *Brugge et al., 2007*

Figure 22. *Summary of near-highway pollution gradients*

2.5 Health Impact Proximal to Major Roadways

International studies have shown many health risks for children from traffic-related pollutants. Children exposed to high-traffic roadways had a higher prevalence of most respiratory symptoms (Oosterlee et al., 1996). A hospital asthma-admissions survey in Birmingham (UK) revealed that the subjects were more likely to live near roads with traffic of 424,000 cars/day (Beris and Edwards, 1994). Dutch researchers indicated that cough, wheeze, runny nose, and asthma were reported significantly more often for children living within 100 meters of freeways, and that black smoke from truck traffic measured in schools was significantly associated with chronic respiratory symptoms (Janssen et al., 2001). A Swedish study suggested that exposure to combustion products containing NO_2 may be of particular importance for the development of wheezing bronchitis in girls (Pershagen et al., 1995). Asthma and wheeze in Southern Californian school children were strongly associated with residential proximity to major roads, with the effects greater in girls (Gauderman et al., 2005). Figure 23 shows the summary of previous major near-highway health studies by different scholars.



Citation	Location	Highway traffic intensity[a]	Pollutants measured[b]	Distance from highway	Health Outcomes	Statistical association[e]
Schwartz et al. 2005 (22)	Boston	NA	$PM_{2.5}$, BC, CO	NA	Heart rate variability	Decreases in measures of heart rate variability
Adar et al. 2007 (23)	St. Louis, Missouri	NA	$PM_{2.5}$, BC, UFP	On highway in busses	Heart rate variability	Decreases in measures of heart rate variability
Hoek et al. 2002 (24)	Netherlands	NA	BC, NO_2	Continuous [d]	Cardio-pulmonary mortality, lung cancer	1.41 OR for living near road
Tonne et al. 2007 (41)	Worchester, Mass.	NA	$PM_{2.5}$	Continuous [d]	Acute myocardial infarction (AMI)	5% increase in odds of AMI
Venn et al. 2001 (49)	Nottingham, UK	NA	NA	Continuous [d]	Wheezing in children	1.08 OR for living w/in 150 m of road
Nicolai et al. 2003 (58)	Munich, Germany	>30,000 veh/d	Soot, benzene, NO_2	Traffic counts within 50 m of house	Asthma, respiratory symptoms, allergy	1.79 OR for asthma and high traffic volume
Gauderman et al. 2005 (65)	Southern California		NO_2	Continuous [d]	Asthma, respiratory symptoms	Increased asthma closer to freeways
McConnell et al. 2006 (57)	Southern California	NA	NA	Continuous [d]	Asthma	Large risk for children living w/in 75 m of road
Ryan, et al. 2007 (59)	Cincinnati, Ohio	> 1,000 trucks/d	PM2.5	400 m	Wheezing in children	NA
Kim et al. 2004 (60)	San Francisco	90,000 – 210,000 veh/d	PM, BC, NO_x	School sites	Childhood asthma	1.07 OR for high levels of NO_x
Wjst et al. 1993 (68)	Munich, Germany	7,000–125,000 veh/d	NO_x, CO	School sites	Asthma, bronchitis	Several statistical associations found
Brunekreef et al. 1997 (69)	Netherlands	80,000 – 152,000 veh/d	PM_{10}, NO_2	Continuous[d]	Lung function	Decreased FEV with proximity to high truck traffic
Janssen et al. 2003 (74)	Netherlands	30,000–155,000 veh/d	$PM_{2.5}$, NO_2, benzene	< 400 m [c]	Lung function, respiratory symptoms	No association with lung function
Peters et al. 1999 (82)	Southern California	NA	PM_{10}, NO_2	NA	Asthma, bronchitis, cough, wheeze	1.54 OR of wheeze for boys with exposure to NO_2
Brauer et al. 2007 (67)	Netherlands	Highways and streets	$PM_{2.5}$, NO_2, soot	Modeled exposure	Asthma, allergy, bronchitis, respiratory symptoms	Strongest association was with food allergies
Visser et al. 2004 (91)	Amsterdam	> 10,000 veh/d	NA	NA	Cancer	Multiple associations
Vineis et al. 2006 (87)	10 Eurpoean countries	NA	PM_{10}, NO_2, SO_2	NA	Cancer	1.46 OR near heavy traffic, 1.30 OR for high exposure to NO_2
Gauderman et al. 2007 (73)	Southern California	NA	PM_{10}, NO_2	Continuous[d]	Lung Function	Decreased FEV for those living near freeway

Source: Brugge et al., 2007

Figure 23. *Summary of near-highway health effects studies*

2.6 Research Focus

This thesis focuses on studying the condition of fine particle matter ($PM_{2.5}$) produced by transportation in Shanghai. I aim to estimate the dispersion pattern of traffic-related $PM_{2.5}$ emissions in City of Shanghai, and figure out its impact to people's health, especially school children who are the most vulnerable population to air pollution. Figure 24 shows a fair amount of schools are in close proximity to major roadways (within 100 meters to 400 meters) in Shanghai (see Figure 24, Table 7). Therefore, it is very important to study the dispersion of traffic-related $PM_{2.5}$ emissions and its impact to students attending schools in proximity to major roadways in Shanghai.

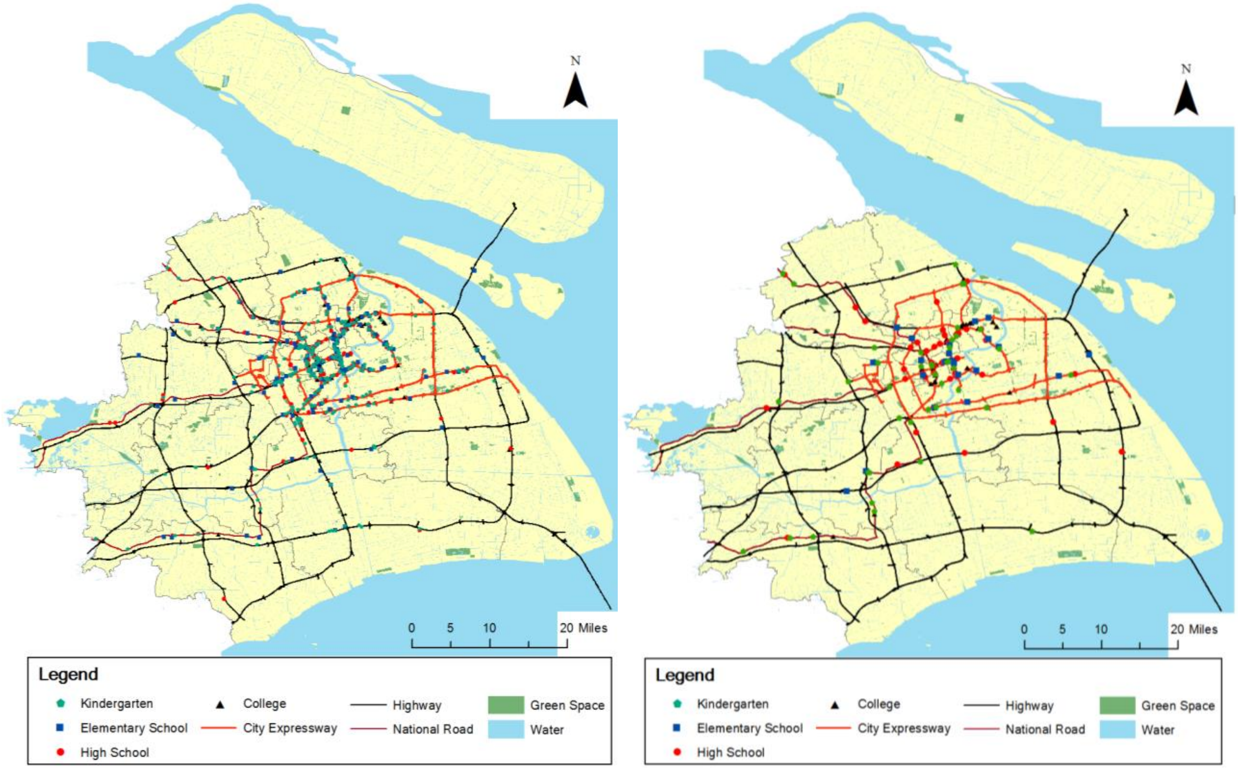


Figure 24. *Schools located within 400m of major roadways in Shanghai (left); Schools located within 100m of major roadways in Shanghai (right)*

Table 7. *Schools located within 100m and 400m of major roadways in Shanghai*

Category	100 m		400 m		Total
	Number	Percent	Number	Percent	
Kindergarten	41	2.56%	261	16.28%	1603

Elementary School	24	2.58%	128	13.73%	932
High School	50	5.43%	160	17.39%	920
College	47	11.27%	87	20.86%	417

The research questions of this study are:

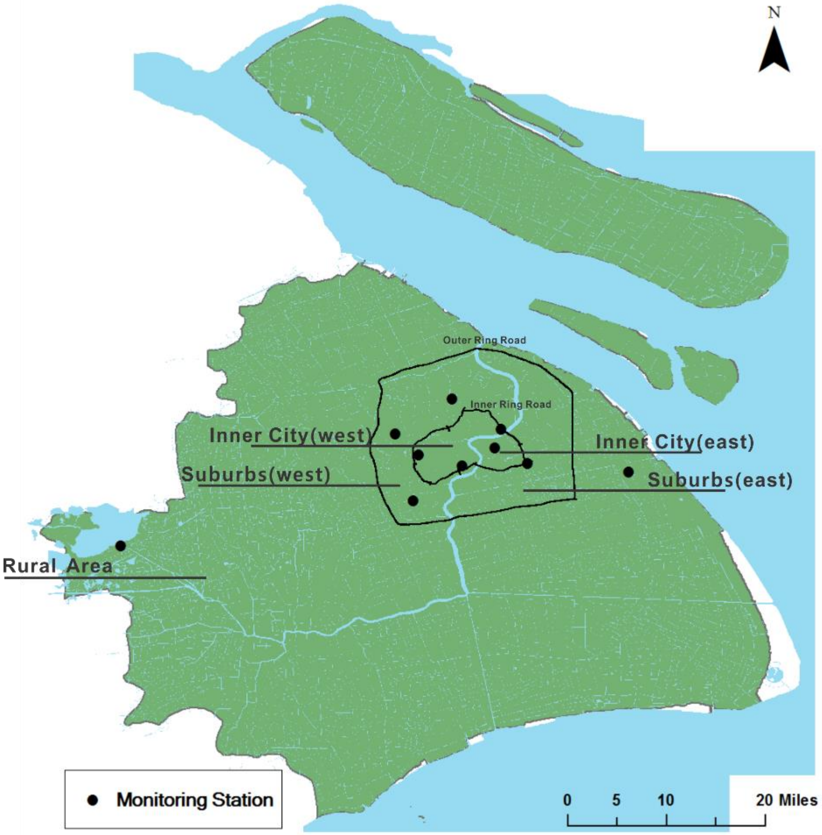
- What are the current air quality conditions in Shanghai?
- To what degree do the current on-road vehicles affect Shanghai's air quality?
- How does traffic-related $PM_{2.5}$ affect schools and students, especially those in proximity to major roadways?
- What strategies could planners employ to avoid these negative air pollution impacts?

In addition, this study will only focus on $PM_{2.5}$ particles to reveal how the motorization of Shanghai and the increase in on-road motor vehicles has affected the city's air quality.

CHAPTER 3. METHODOLOGY

3.1 Boundary of Study Area

The definition of study area is based on the availability of the traffic volume data and the location of air quality monitoring stations. In addition, the available traffic speed data and the percentages of different on-road vehicle types can be found inside administrative boundary of Shanghai. As a result, I decided to use the City of Shanghai as my study area. The study area can be divided into five sub-regions by inner ring road and outer ring road: the East and West Inner City regions (inside the Inner Ring Road), the East and West Suburbs (between the Inner Ring Road and Outer Ring Road), and the Rural Area (Outside of the Outer Ring Road) (see Figure 25).



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

Figure 25. *Map of study area*

3.2 Data Collection

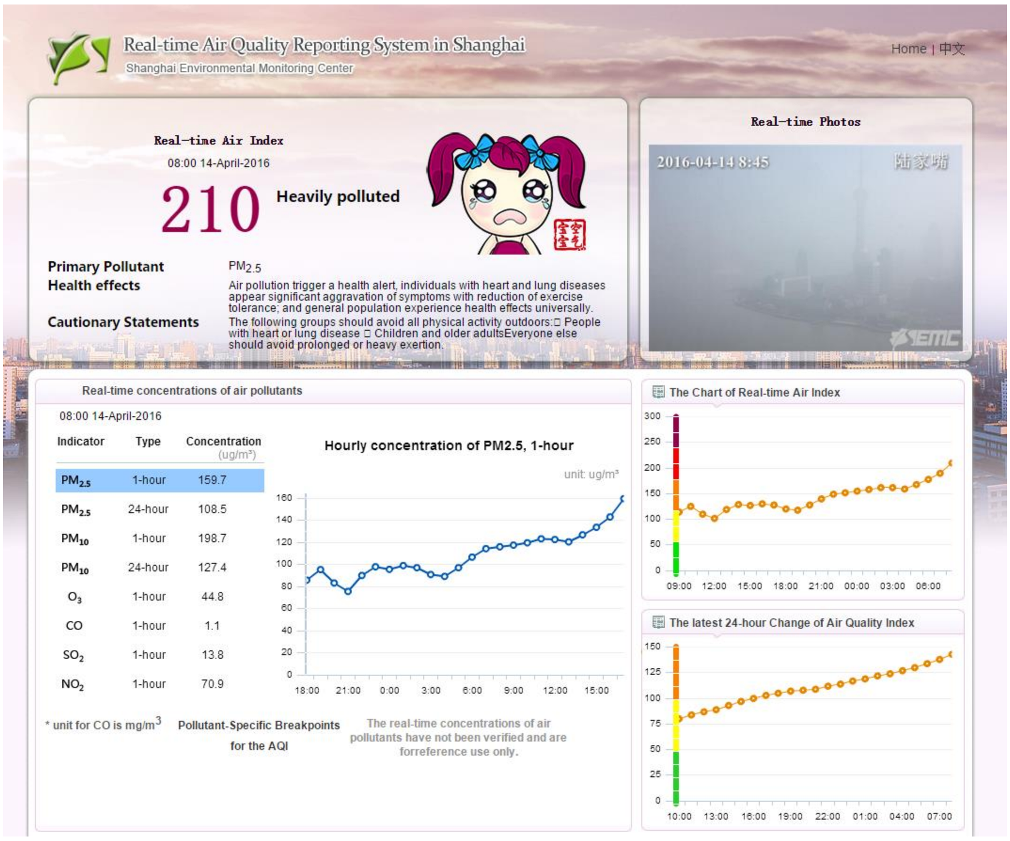
3.2.1 Air Quality Data ($PM_{2.5}$)

This thesis will address the problem of intra-regional disparities in air quality in Shanghai. I researched questions and discussions about whether there exists an imbalance among different regions of the city. To examine what is called “intra-regional air quality,” it will be necessary to analyze the $PM_{2.5}$ data obtained from the ten monitoring stations in the city of Shanghai.

It is known that Shanghai began to monitor $PM_{2.5}$ after June 2012 (Zhao, 2012). Access to the database was not readily available. I obtained the real-time $PM_{2.5}$ data from the website of Ministry of Environmental Protection of China, but could not download them directly from the website. However, I was still able to access several online databases that allowed me to collect the 24-hour, real-time $PM_{2.5}$ concentration data from June 2012 to March 2015. The following websites were used for the air quality data collection:

- Shanghai Environmental Monitoring Center
  http://www.semc.gov.cn/aqi/home/Station.aspx
- Countrywide $PM_{2.5}$ Monitoring Network
  http://www.cnpm25.cn/city/shanghai.html
- Shanghai Air Quality $PM_{2.5}$ (Blog)
  http://www.weibo.com/airquality?topnav=1&wvr=5&topsug=1

The main source of $PM_{2.5}$ data comes from Shanghai Air Quality $PM_{2.5}$ (上海空气通 $PM_{2.5}$), which is a blog recording Shanghai real-time $PM_{2.5}$ data for all ten monitoring stations every day since June 2012. To collect $PM_{2.5}$ data from the blog, I wrote programs to extract all past $PM_{2.5}$ data using Python programming language, and then summarized them in a spreadsheet. Thus, our study is based on the available Shanghai $PM_{2.5}$ data for all ten monitoring stations from June 2012 to March 2015, though we could not obtain $PM_{2.5}$ data after March 2015 because of missing data.



Real-time Air Quality Reporting System in Shanghai
Shanghai Environmental Monitoring Center

Real-time Air Index
08:00 14-April-2016
210 **Heavily polluted**

Primary Pollutant $PM_{2.5}$
Health effects Air pollution trigger a health alert, individuals with heart and lung diseases appear significant aggravation of symptoms with reduction of exercise tolerance; and general population experience health effects universally.
Cautionary Statements The following groups should avoid all physical activity outdoors:☐ People with heart or lung disease ☐ Children and older adultsEveryone else should avoid prolonged or heavy exertion.

Real-time Photos

Real-time concentrations of air pollutants
08:00 14-April-2016

Indicator	Type	Concentration (ug/m³)
$PM_{2.5}$	1-hour	159.7
$PM_{2.5}$	24-hour	108.5
PM_{10}	1-hour	198.7
PM_{10}	24-hour	127.4
O_3	1-hour	44.8
CO	1-hour	1.1
SO_2	1-hour	13.8
NO_2	1-hour	70.9

* unit for CO is mg/m^3

Pollutant-Specific Breakpoints for the AQI

Hourly concentration of PM2.5, 1-hour

The real-time concentrations of air pollutants have not been verified and are forreference use only.

Source: Shanghai Environmental Monitoring Center

Figure 26. *Screenshot of Shanghai Environmental Monitoring Center website*

3.2.2 Road Data

Road data of Shanghai is obtained from *Shanghai Institute of Technical Physics of The Chinese Academy of Science (中国科学院上海技术物理研究所)* as GIS shapefile documents. Like many other cities in China, Shanghai's road system consists of a hierarchy of six levels: city expressway, highway, national road, provincial road, county road, and local road (see Figure 29). The city expressway includes three main elevated, circular expressways surrounding Shanghai city (see Figure 27 and Figure 28): the inner ring road, the middle ring road, and the outer ring road. The highway is the toll road connecting Shanghai and nearby provinces. National roads are free roads which also connect Shanghai with nearby provinces. Provincial, county, and local roads are all local secondary roads that only serve short-distance travels inside the city.

Source: shutterstock.com, https://stock-clip.com/video-footage/yanan+road/2

Figure 27. *Elevated expressway in Shanghai*

Source: eastday.com, http://photo.eastday.com/2013slideshow/20150408_10/index2.html

Figure 28. *Traffic congestions in Shanghai inner ring road*

In this thesis, I only focus on the three main arterials—city expressways, highways, and national roads—as our study objects. These roads all have heavy daily traffic volumes .The other three kinds of roads are not being considered because they only serve short-distance travels, for which traffic volumes are low.

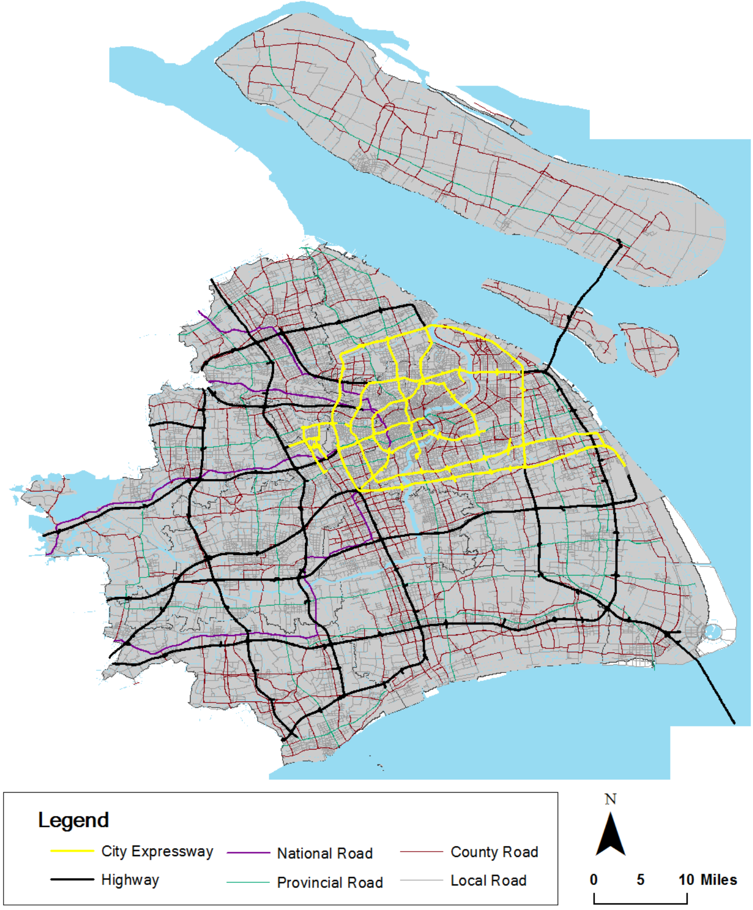


Figure 29. *Shanghai road system and network*

3.2.3 Traffic Volume Data

Traffic volume data is another important set of data needed in this thesis. It represents the average daily vehicle numbers on city streets. Researchers who studied the relationship between childhood asthma and the proximity to major roads proposed a method to measure traffic density: to multiply the traffic volume along one specific road by the length of the road (Lin et al., 2002).

The traffic flows are mixed with different types of vehicles, which occupy different path spaces. For instance, motorcycles only occupy a small area of road, but the heavy truck might occupy two lanes because of its volume and width. To make the traffic volume data indicate the real transportation status on roads, the concept of Passenger Car Equivalent (PCE) was introduced, and all vehicle types were converted to passenger cars with specific conversion coefficients (Ling, 2014). The following PCE conversion coefficients for different vehicle types are from the Code for Transport Rules and Regulations on Urban Roads (Ministry of Housing and Urban-Rural Development of P.R.C., 1995) (see Table 8). These conversion coefficients below are used to calculate the number of different types of vehicles on the road by their different volume and width.

Table 8. *PCE conversion coefficients by vehicle type (95, GB50220)*

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

Source: Ling, 2014 cited Ministry of Housing and Urban-Rural Development of P.R.C., 1995

The total traffic volume distribution data of the city region are from Shanghai Annual Comprehensive Transportation Report 2010-2015 (上海市综合交通年度报告 2010-2015) (see Table 9). It is noteworthy that the traffic volume data in Table 13 are the Passenger Car Equivalent number after being processed by the PCE conversion coefficients mentioned above. Our study will adopt the traffic volume data of 2014.

Table 9. *Traffic volume in five sub-regions of Shanghai (PCE, unit: 10,000 vehicle per day)*

Year	West Inner City	East Inner City	West Suburb	East Suburb	Rural Area	Total
2007	1,631	414	2,415	1,188	5,105	10,753
2008	1,641	438	2,596	1,370	5,800	11,845
2009	1,826	490	2,667	1,460	6,426	12,869
2010	1,833	495	2,810	1,560	7,113	13,811
2011	1,840	500	2,961	1,667	7,897	14,865
2012	1,888	503	3,109	1,726	8,847	16,073
2013	1,923	507	3,265	1,824	9,871	17,390
2014	1,931	510	3,353	2,054	10,559	18,407

Source: Shanghai annual comprehensive transportation report 2010-2015

3.2.4 Vehicle Type Distribution Data

Vehicle population grew quickly in recent years in Shanghai, especially the population of private small cars. According to Shanghai annual comprehensive transportation report 2010-2015, the number of private small passenger cars grew from 936,000 to 2,190,300, more than doubling in seven years from 2007 to 2014. In addition, the total population of vehicles also increased, reaching nearly 3 million in 2014. However, the number of motorcycles decreased from 1,029,000 in 2007 to 425,100 in 2014 (see Table 10).

Table 10. *Trend of increasing number of vehicle in Shanghai from 2007 to 2014 (Unit: 10,000 vehicle)*

Year	Private Car	Bus	Truck	Motorcycle	Total
2007	93.6	3.9	20.9	102.9	221.3
2008	104.6	4.7	21.3	97.6	228.2
2009	118.0	5.4	21.7	91.6	236.7
2010	135.52	6.32	23.07	76.44	241.35

2011	155.79	6.82	24.71	56.15	243.47
2012	177.82	7.35	25.07	43.48	253.72
2013	199.65	7.61	25.24	41.56	274.06
2014	219.03	7.75	24.80	42.51	294.09

Source: Shanghai annual comprehensive transportation report 2010-2015

There are different types of vehicles on the road with different emissions standards. Therefore, to calculate the traffic-related $PM_{2.5}$ emissions, it is necessary to know each type of vehicle's frequency on the road. This data can be obtained from the latest Shanghai transportation survey (Report of the Fifth Comprehensive Traffic Survey in Shanghai, 2015[上海市第五次综合交通调查总报告]).

The three transportation surveys of Shanghai conducted in 2003, 2009, and 2014 (Report of the Third and Fourth Comprehensive Traffic Survey in Shanghai, 2003, 2009, and 2014) can give us the different percentages of different vehicle types in our study area (see Table 11) in all three years (Ling, 2014). However, they only tell the overall percentage of each kind of vehicle at the citywide level, but not sub-region level. I have to assume that the percentage of each kind of vehicle on the road is constant in the whole study area, which is not possible in the real world.

Table 11. *Percentages of different types of vehicles Shanghai streets in 2003, 2009, and 2014 (Traffic volume unit: annual average daily 10,000 PCE kilometers)*

Vehicle Type	Traffic Volume in 2003	Volume (%) in 2003	Traffic Volume in 2009	Volume (%) in 2009	Traffic Volume in 2014	Volume (%) in 2014
Bus	550	10.11%	356	5.99%	276	3.95%
Taxi	1,210	22.47%	1,380	23.21%	1,502	21.48%
Private cars	2,243	41.57%	3,377	56.79%	4,414	63.11%
Motorcycle	104	2.25%	297	4.99%	355	5.07%
Heavy Trucks	1,278	23.60%	537	9.02%	447	6.39%

Total	5,385	100%	5,974	100%	6,994	100%

Source: Report of the Fourth Comprehensive Traffic Survey in Shanghai 2003 (published in 2004), 2009 (published in 2010), and 2014 (published in 2015).

Since detailed information about percentages of different types of vehicles on each segment of the road is unavailable at this moment, I calculate the $PM_{2.5}$ emissions based on the vehicle type percentage data from 2014, shown above.

3.2.5 Emissions Factor Data

China began to monitor $PM_{2.5}$ emissions in 2012 because of increasingly common nationwide smog. At the same time, the Department of Science and Technology and Standards (DSTS, 技术标准司) of China also began to take $PM_{2.5}$ emissions seriously and launched a study of $PM_{2.5}$ emissions inventory. At the end of 2013, a new $PM_{2.5}$ emission inventory was completed, called the Third $PM_{2.5}$ Emission Inventory Draft in China (大气细颗粒物($PM_{2.5}$)源排放清单编制技术指南(试行)) by the Ministry of Environmental Protection of the People's Republic of China (Ling, 2014).

In this inventory, the $PM_{2.5}$ emission factors were introduced in details classified by different types of vehicles with different vehicle weight, size, and fuel type. In China, most vehicles of smaller size and lighter weight are powered by gasoline, such as small passenger cars, taxis, and motorcycles. On the other hand, bigger vehicles like heavy trucks and buses are usually powered by diesel. The emissions factor and fuel consumption per hundred kilometers of these vehicle categories are related to their specific vehicle weight, size, and fuel type (Ling, 2014; Liu et al., 2013) (see Table 12).

Table 12. *China national emission standard IV*

Fuel Type	Vehicle Type	Size	$PM_{2.5}$ Emission Factor (g/kg)	Fuel Consumption per hundred kilometers (liters/100 km)
Gasoline	Small passenger car	Length<6m, seat number<9	0.02	9.2
	Taxi	Same as small passenger car	0.02	33.4
	Motorcycle	N/A	4.65	2.0
Diesel	Heavy Truck	Length ≥ 6m, Mass ≥ 12000 kg	1.35	31.8
	Large Passenger Vehicle (buses)	Length ≥ 6m, Seat Number ≥ 20	1.46	8.3

Source: Liu et al. (2013); the Third $PM_{2.5}$ *Emission Inventory Draft (2014)*

3.3 Traffic-Related $PM_{2.5}$ Emission Calculation

3.3.1 Traffic-Related $PM_{2.5}$ Emission by Traffic Density

The amount of energy consumption in the transportation sector can be obtained from Shanghai Statistics Yearbook. However, $PM_{2.5}$ emissions cannot be calculated based only on the amount of gasoline, diesel, or electricity consumption in the transportation sector.

According to the third $PM_{2.5}$ emission inventory draft published in 2014, the amount of daily $PM_{2.5}$ emissions should be based on daily traffic density along streets. It can be derived from the calculation steps shown via the equation of on-road vehicle $PM_{2.5}$ emissions:

$$E = A \times EF(1 - \eta)$$

Equation 1. *Calculation equation of vehicle* $PM_{2.5}$ *emissions* (The Third $PM_{2.5}$ Emission Inventory Draft 2014; Ling, 2014)

In this equation, E equals the amount of $PM_{2.5}$ emissions during a specific period; A signifies activity level, which is the fuel consumption of a specific type of vehicle, defined as vehicle-kilometers traveled (VKT) multiplied by fuel consumption per hundred kilometers; EF is the emission factor; and η is the contaminant removal efficiency of this vehicle type, as shown below. The removal efficiency presents the percentage of the total amount of $PM_{2.5}$ which can be transformed to harmless materials in the vehicle before they are emitted to outside.

Table 13. *Removal efficiencies of different types of vehicles*

Fuel Type	Vehicle Type	Removal Efficiencies (%)
Gasoline	Small passenger car	97
	Taxi	97
	Motorcycle	95
Diesel	Heavy Truck	95
	Large Passenger Vehicle (buses)	95

Source: Ling, 2014 cited The Third $PM_{2.5}$ Emission Inventory Draft (2014)

According to the definition of equation 1, the equation can be converted to:

$$\mathrm{E} = \sum \frac{V_0 \times P \times C \times \rho \times EF(1 - \eta) \times 10}{B \times L}$$

Equation 2. *Converted equation of on-road vehicle $PM_{2.5}$ emissions*

In the above equation, E still equals the amount of $PM_{2.5}$ emissions per kilometer during a specific period, its unit is gram per kilometer (g/km); V_0 indicates the daily traffic density on a given street segment (PCE, unit: vehicle kilometers per day); P is the percentage of traffic volume of a given vehicle type; C is the fuel consumption per 100 kilometers of this vehicle type, the unit is liter per 100 kilometers (L/100km); ρ is the mass density of gasoline and diesel (g/ml); EF is the emission factor of this vehicle type; and η is the contaminant removal efficiency of this vehicle type (see Table 13); B represents the conversion efficient in responding to different types of vehicles; and L is the length of the street segments (km).The mass density of gasoline and diesel are 0.83 g/ml and 0.74 g/ml, respectively.

In this thesis, I will use year 2014 available data to calculate the $PM_{2.5}$ emissions of on-road vehicles.

3.3.2 GIS Tool

In our study, I used Geographic Information System (GIS) to predict air pollution dispersion in urban areas, applying the Kriging Interpolation 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 (Ling, 2014; Esri, 2012).

The Kriging Interpolation predicts the value of an unmeasured location deriving from weighting the surrounding measured values. The general formula of prediction is formed as a weighted sum based on distance between the measured points, the prediction location, and the overall spatial arrangement of the measured points:

$$\mathrm{Z}(s_0) = \sum_{i=1}^{N} \lambda_i Z(s_i)$$

Equation 3. *The Kriging Interpolation formula*

In the above equation, $Z(s_i)$ is the measured value at the *i*th location; λ_i represents an unknown weight for the measured value at the *i*th location; and s_0 is the prediction location; while N equals the number of measured values.

Two tasks are necessary to make a prediction with the Kriging Interpolation method: find the dependency rules and make the prediction. The statistical dependence rule, which is also called spatial autocorrelation deriving from values and locations of a measured point, is fundamental to predict the value of an unmeasured location (Esri, 2016). In this thesis, I used the Kriging Interpolation model and the geostatistical tools of ArcGIS to study $PM_{2.5}$ dispersion in Shanghai, depending on both the point resource data collected at the air quality monitoring stations and the line resource data based on road and traffic density data.

3.3.3 Assumptions and Limits to the Methodology

The above methodology to calculate traffic-related $PM_{2.5}$ emission 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. However, there still exist some limits for this methodology.

Firstly, I only get the traffic volume for the whole city, but the detailed data of exact percentage of different vehicles for every road in our five sub-region study area are not available. Due to the lack of detailed data, I assume the percentage of different types of vehicles will be constant in every road of our study area.

On the other hand, there are four types of vehicles categorized by power: gasoline, diesel, hybrid, and electronic. The hybrid and electric vehicles hardly emit air pollutants and are friendlier to the environment. However, I cannot obtain the exact number of hybrid or electric vehicles. Therefore, it assumes that the population of buses and trucks on roads in our study area are all diesel powered, and other types of vehicles, including small passenger cars, taxis, and motorcycles, are all gasoline powered. The hybrid and electric vehicles will not be counted in this thesis.

In addition, 2014 will be taken as the study year, because the newest data is available for this year.

As mentioned, the calculation of traffic-related $PM_{2.5}$ emissions will be based on the assumptions above. Despite of these limits, I can still calculate the traffic-related $PM_{2.5}$ emissions by traffic density and depict an average $PM_{2.5}$ dispersion pattern in the city to see how it will impact students in schools close to major roads. It will help planners, urban administrators, and health practitioners identify the sites of existing schools that are exposed to serious $PM_{2.5}$ air pollution, so that they can formulate targeted measures to mitigate the air pollution. It is also helpful for planners to decide new school sites to avoid serious air pollution in the future.

3.4 Data Analysis

With the $PM_{2.5}$ data from June 2012 to March 2015, the analysis of dispersion pattern of $PM_{2.5}$ particles in the city of Shanghai can be made. As mentioned above, I divided the study area to five sub-regions: West and East Inner City, West and East Suburbs, and Rural Area, to study $PM_{2.5}$ dispersion characteristics in each district.

On the other hand, I also explored the relationship between traffic-related $PM_{2.5}$ emissions and school distribution in Shanghai to see how students might be exposed to on-road vehicle $PM_{2.5}$, and propose some recommendations to school site selections in the future.

3.4.1 General Dispersion Pattern of $PM_{2.5}$ in Shanghai

To analyze the dispersion pattern of $PM_{2.5}$ in Shanghai, I chose several representative weather condition periods: days with most serious air pollution (high $PM_{2.5}$ concentration), and days with good air quality (low $PM_{2.5}$ concentration), in Shanghai to see the fine particle matter dispersion characteristics in our study area.

Zhou found that in January 2013, there was a nationwide heavy air pollution problem in Central and Eastern China, including Shanghai. Her research showed that the average concentration of PM_{10}, $PM_{2.5}$, and PM_1 can reach (125 ± 75) $\mu g/m^3$, (82 ± 54) $\mu g/m^3$, and (44 ± 27) $\mu g/m^3$ in that period, respectively (Zhou et al., 2013). Chang also indicated that in January 2013 and December 2013, Shanghai suffered a heavy air pollution episode (Chang et al., 2016). In addition, a rare heavy haze pollution event occurred in Shanghai and the surrounding the Yangtze River Delta in early December 2013, that the hourly $PM_{2.5}$ concentration even reached 640 $\mu g/m^3$ (Li, An, and Yan, 2015).

According to the previous studies and data records, I select January 2013 and December 2013 as our study periods (worst air quality episode). The $PM_{2.5}$ data for January 2013 is from 2013.1.24 to 2013.1.30, in total seven days and each day 24 hours at ten monitoring stations. For December 2013, $PM_{2.5}$ data are recorded from 2013.12.1 to 2013.12.30, the total 30 days in December, and each day 24 hours at ten monitoring stations in Shanghai. The two periods in January and February are the most typical periods with extreme weather conditions in Shanghai. Because of the lack of data, I could only obtain seven-day air quality data for January 2013.

For the best air quality episode, I chose September 2014, from the 1st to the 23rd of September, totaling 23 days as our study time because of availability of data. This time presents a period with a relatively better air quality condition in Shanghai.

To analyze the dispersion pattern of Shanghai's $PM_{2.5}$ emissions, I use the Kriging Interpolation tool in ArcGIS to predict the general geographical dispersion pattern of $PM_{2.5}$ emissions in the city. The detailed analysis will be illustrated in next chapter.

3.4.2 Traffic-Related $PM_{2.5}$ Emissions Analysis

To estimate transportation-related $PM_{2.5}$ pollution, I use annual vehicle population and vehicle kilometers traveled (VKT). It should be helpful to see a rough dispersion pattern of $PM_{2.5}$ particles based on average daily traffic density, since such a dispersion pattern can help evaluate the regional differences in exposure risks to $PM_{2.5}$ emissions.

As analyzed above, a majority of the $PM_{2.5}$ 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 where motorcycles are able to access.

The traffic-related $PM_{2.5}$ emissions will be calculated by Equation 2, which includes the variables of traffic volume, percentage of vehicle type, fuel consumption, street length, and emission factors. The result of the calculation will be applied to a road network layer in ArcGIS, and will produce an average traffic-related $PM_{2.5}$ emissions dispersion map by sub-region through the Kriging Interpolation method.

3.4.3 Proximal Exposure and School Location Assessment

Such as the discussion in literature review part, previous studies have shown many health risks for children from traffic-related pollutants. Children exposed to high-traffic roadways had substantial deficits in lung development, and a higher prevalence of most respiratory symptoms (Oosterlee et al., 1996). A study across nine European countries revealed that for every increase of 10 $\mu g/m^3$ in PM_{10}, the lung cancer rate rose 2.2%. The smaller $PM_{2.5}$, and ultrafine particles were particularly deadly, with a 36% increase in lung cancer per 10 $\mu g/m^3$ as it can penetrate deeper into the lungs (Stokes, 2015). Therefore, it is very important to study the school distribution in Shanghai, especially those located closed to highways with heavy traffic volume.

To characterize schools located close to major highways in Shanghai, this thesis examined data from several sources using Geographical Information Systems (GIS). Three data were used for this assessment: (1) Shanghai school location data shown as a point layer in ArcGIS; (2) Shanghai road network data shown as a line layer in ArcGIS; and (3) study area data containing five sub-regions showed as a polygon layer in ArcGIS.

According to previous researches, $PM_{2.5}$ concentration decreases with the increasing distance to major roads. Reponen's study shows that Particulate Sulphur concentration will decrease by half between 50 and 100 meters from a highway but persisted until 400 meters, and hardly change when the distance exceeds 400 meters (Reponen et al., 2003). Van Vliet et al. referred to 100 meters as a benchmark distance from freeways to identify chronic respiratory symptoms in school children (Van Vliet et al., 1997).

Based on practical considerations and several studies on the environmental exposure assessment and exposure-health relationship, two distances were established in this thesis, 100 and 400 meters, as measures of proximal exposure to air pollutants originated from major roadways in Shanghai. ArcGIS software was used to create circular buffers of 100 and 400 meters around all major highways, and the proportion of schools included inside the buffer areas was calculated by each sub-region.

Moreover, the proportion of the school locating within 100 meters and 400 meters of a major highway was calculated in four different school level: kindergarten (4-7 years old), elementary school (7-12 years old), middle/high school (12-18 years old), and college (>18 years old). Each level corresponds to students in different age ranges, and the risks of exposure to traffic emissions on their health are different.

3.4.4 School Hazard Score Map and School Site Suitability Index Map

To study the relationship between schools in proximity to major roads and the traffic-related $PM_{2.5}$ dispersion pattern, I multiplied the statistics of average traffic-related $PM_{2.5}$ emissions by sub-region with the statistics of the density of schools within the 100 meters and 400 meters buffer to major roadways in each sub-region area.

This is to explore the relationship between school locations and traffic-related $PM_{2.5}$ emissions distribution. In order to highlight how many schools concentrate in areas with higher traffic-related $PM_{2.5}$ emission levels, I created a score system to show the level of $PM_{2.5}$ emission's hazard impacts to students. As stated above, I multiplied the average $PM_{2.5}$ emission amount of a micro area (sub-region) with the density of schools (kindergarten, elementary school, middle/high school, and college) within a 400 meter buffer. By doing so, I can demonstrate a spatially sensitive index showing the overlapping levels of both schools close to major roadways and the traffic-related $PM_{2.5}$ emissions by micro area.

In addition, I developed an index system to show new school site suitability considering two factors: the distance from major roads and the level of traffic-related $PM_{2.5}$ emissions. To establish the index system, I multiplied the average traffic-related $PM_{2.5}$ emission amount of a sub-region with the different level of distances to a major road. This school site suitability index system can act as a reference for decision-makers to decide new school sites in the future.

3.4.5 Analysis Process

As stated in above parts, I will choose three typical periods of the worst and the best air quality in Shanghai: January 2013, December 2013, and September 2014, to study the general $PM_{2.5}$ dispersion pattern by the Kriging Interpolation tool. On the other hand, I use Equation 2 (See Chapter 3.3.1) to calculate the traffic-related $PM_{2.5}$ emissions by traffic density of 2014 and apply results to Shanghai's major roads. After that, I compare Shanghai general $PM_{2.5}$ dispersion pattern with the traffic-related $PM_{2.5}$ emissions dispersion pattern and figure out what causes the difference between these two modes' dispersion patterns.

The school hazard map is created by the combination of the traffic-related $PM_{2.5}$ emissions dispersion pattern map and Shanghai school distribution map to show the school geographical dispersion in areas with high traffic-related $PM_{2.5}$ emissions. Based on the school hazard map, I developed the Shanghai School Site Suitability Index considering the traffic-related air pollution level and the school's distance to major roadways. The complete analysis process is shown in Figure 30.

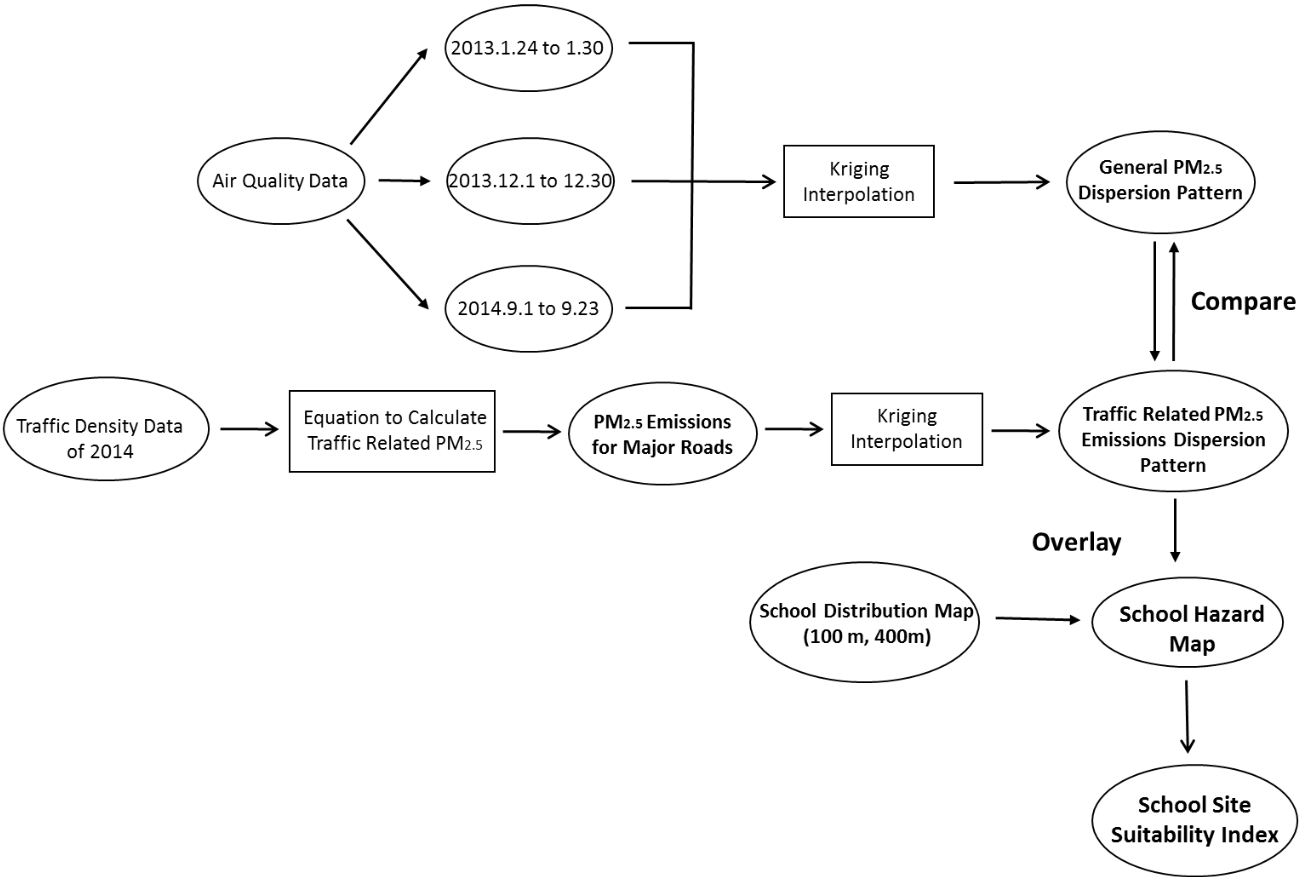


Figure 30. *Traffic-related PM$_{2.5}$ dispersion and school site analysis process flow chart*

CHAPTER 4. ANALYSIS

The main focus of this chapter is to analyze the dispersion pattern of traffic-related $PM_{2.5}$ emissions in Shanghai and its impacts to student's health. Furthermore, this chapter will also introduce the general $PM_{2.5}$ dispersion pattern in Shanghai, and analyze the developed School Site Suitability Index System.

4.1 General $PM_{2.5}$ Dispersion in Shanghai

Before analyzing the traffic-related $PM_{2.5}$ emissions in Shanghai, the general $PM_{2.5}$ emissions dispersion can help us know the common $PM_{2.5}$ concentration distribution pattern in Shanghai. The general $PM_{2.5}$ emissions may come from all possible sources, such as transportation, industry, agriculture, and so on.

As mentioned in last chapter, to analyze the general $PM_{2.5}$ dispersion pattern in Shanghai, I select three representative periods to analyze: two periods with the worst air quality in Shanghai (January 2013, and December 2013), and one episode representative of the best air quality in Shanghai (September 2014).

The $PM_{2.5}$ data of Shanghai are obtained from Shanghai Air Quality $PM_{2.5}$ Blog website (http://www.weibo.com/airquality?topnav=1&wvr=5&topsug=1). I select the data of our study period and calculate average value of each monitoring station's $PM_{2.5}$ concentration (see Table 14). After calculating the average $PM_{2.5}$ emissions by each monitoring station during our study time, I assigned the values of $PM_{2.5}$ particles by each monitoring station to the corresponding GIS features by adding a field containing the information.

Table 14. *Average $PM_{2.5}$ concentration for each monitoring station in three study periods (Unit: $\mu g/m^3$)*

Study Period Monitoring Stations		January 2013 (2013.1.24-1.30)	December 2013 (2013.12.1-12.30)	September 2014 (2014.9.1-9.23)
West Inner City	Luwan(卢湾)	119	137	40
	Jing'an(静安)	127	142	41
	Yangpu(杨浦)	135	130	44

East Inner City	Pudong(浦东)	118	134	40
West Suburbs	Hongkou(虹口)	123	134	39
	Putuo(普陀)	119	138	39
	Xuhui(徐汇)	121	143	41
East Suburbs	Zhangjiang(张江)	114	93	35
Rural Area	Dianshanhu(淀山湖)	137	164	46
	Chuansha(川沙)	117	136	37
Average $PM_{2.5}$ Concentration		123	143	40

Source: Shanghai Air Quality $PM_{2.5}$ (Blog)

For the sake of comparison, I built three maps of general $PM_{2.5}$ emissions dispersion pattern for all three study times—January 2013, December 2013, and September 2014—using the Kriging Interpolation tool in ArcGIS (see Figure 31, Figure 32, and Figure 33). Being one of the Geostatistical Analysis tools of the Geographic Information System (GIS), the Kriging Interpolation method assumes that at least some of the spatial variation observed in natural phenomena can be modeled by random processes with spatial autocorrelation. It is widely used in the field of environmental science in describing and modeling spatial patterns, as well as predicting values at unmeasured locations, based on a variety of spatial variation models.

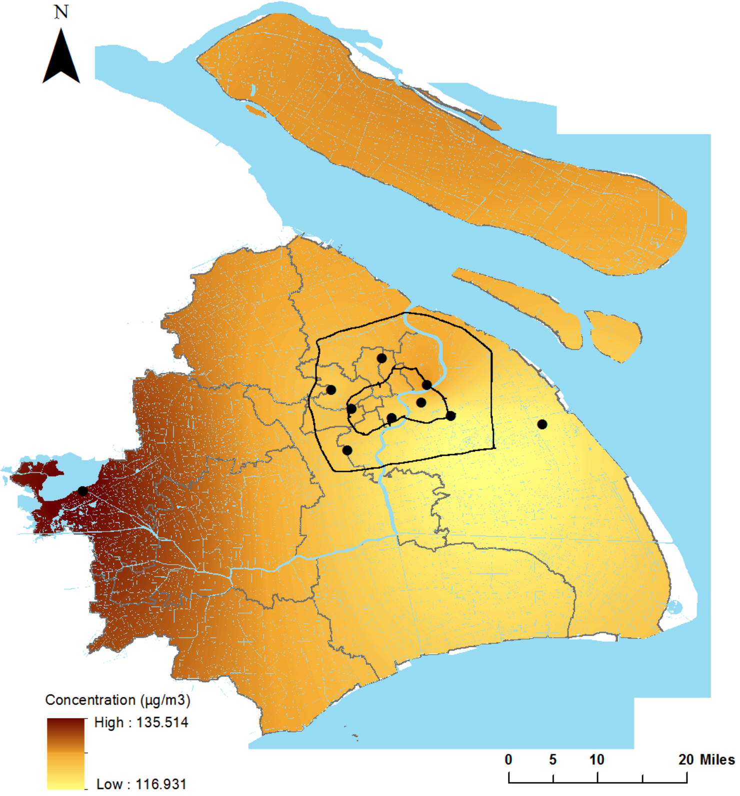


Figure 31. *PM$_{2.5}$ emission dispersion in January 2013 (1.24-1.30)*

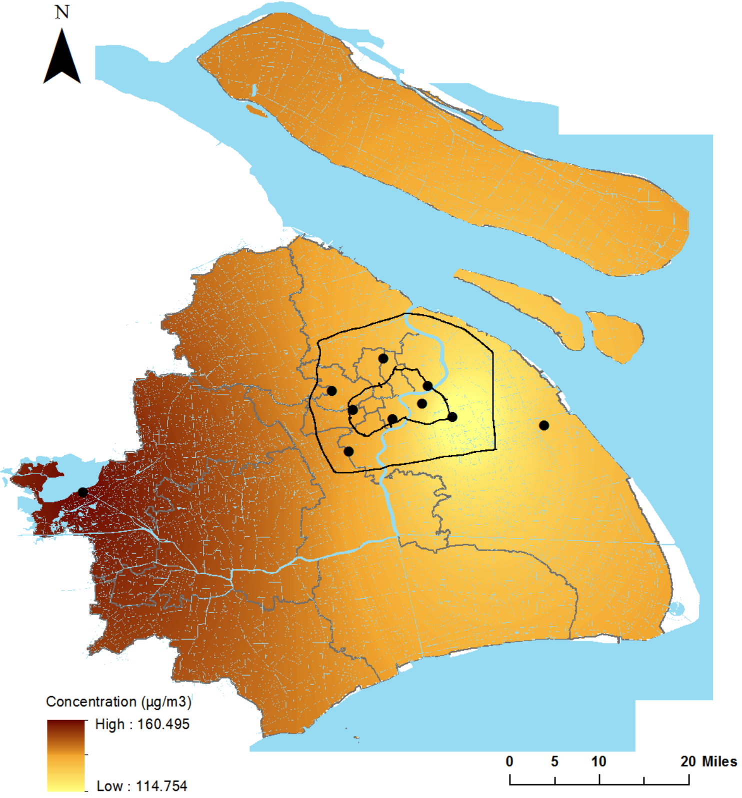


Figure 32. *PM$_{2.5}$ emission dispersion in December 2013 (12.1-12.30)*

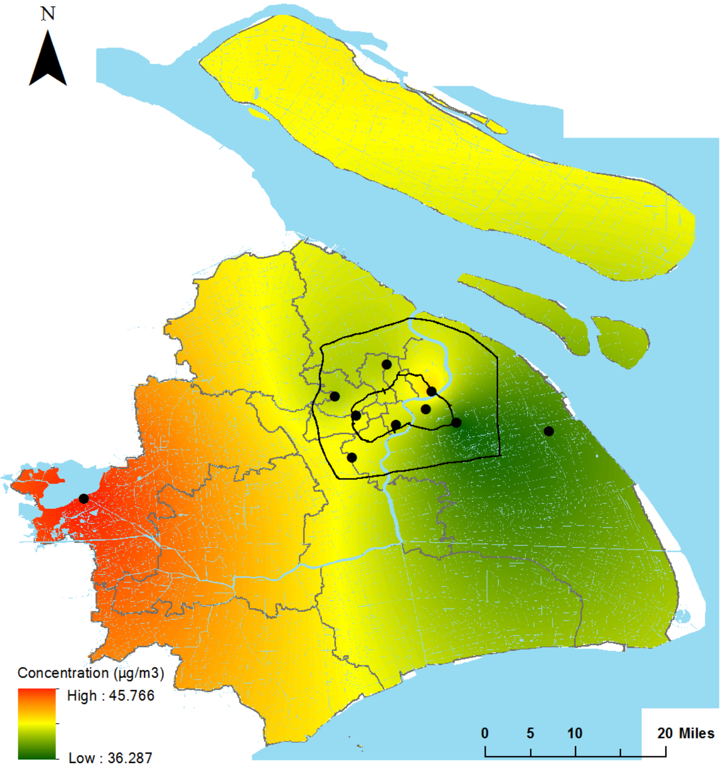


Figure 33. *$PM_{2.5}$ emission dispersion in September 2014 (9.1-9.23)*

In January 2013, and December 2013, the average $PM_{2.5}$ concentration of Shanghai reached 123 μg/m^3 and 143 μg/m^3, which are nearly four times higher than WHO's highest standard for $PM_{2.5}$ concentration (35 μg/m^3). Shanghai's average $PM_{2.5}$ emission concentration was 40 μg/m^3 even in September 2014—the period with best air quality, which is still higher than WHO's highest $PM_{2.5}$ concentration standard. It means that in the period with best air quality in Shanghai, $PM_{2.5}$ emissions still did harm resident' health (WHO, 2005). The above analysis shows $PM_{2.5}$ pollution is serious in Shanghai.

It is evident that in all three study periods, the $PM_{2.5}$ emissions were more concentrated in the west rural area (west of the Huangpu River and outside the outer ring road), especially near the west boundary of Shanghai. These three maps also show that $PM_{2.5}$ concentration level decreases from west to east, and reaches the lowest concentration level in the east coast of the rural area. The result is corresponding to the $PM_{2.5}$ concentration distribution data I got from Table 18. Dianshanhu (淀山湖) monitoring station located in the west rural area has the highest $PM_{2.5}$ concentration value of the ten monitoring stations, which was 164 µg/m^3 during December 2013. On the contrast, Chuansha (川沙) monitoring station always has the lowest $PM_{2.5}$ concentration value among all ten monitoring stations.

The high $PM_{2.5}$ emissions in west rural area might result from the dense heavy industrial parks and factories in this area, and the closed geographical location to the nearby industrial cities, like Kunshan, Suzhou, and Wuxi. Data showed that the wind direction was northwest and the average wind speed was 20 km/h during our study periods. The northwestern wind might blow some air pollutants to this district, where is near the boundary to nearby cities. On the other hand, as a traditional agricultural area in Shanghai, the agriculture in the west rural area might also contribute to the high $PM_{2.5}$ emissions because of burning and fertilization.

I found the west central city (the west inner city and west suburbs) is another district with high $PM_{2.5}$ emissions, just after west rural area. Six monitoring stations in this district also recorded high $PM_{2.5}$ concentrations. Unlike the west rural area, traffic emissions might be the main contributor to the high $PM_{2.5}$ concentrations in this area, because there are no heavy industries located in urban area. As Shanghai's city center for decades, the west central city is highly developed with a dense street network and heavy traffic volume. Nearly 70% of city roads in Shanghai are concentrated in the west central city, and the daily traffic volume reached 78,480,000 vehicles in 2014 (Shanghai Annual Comprehensive Transportation Report, 2015).

4.2 Traffic-Related $PM_{2.5}$ Emissions in Shanghai

4.2.1 Visualization of Daily $PM_{2.5}$ Emissions Dispersion

In this chapter, I focus on the outcome of on-road vehicle emissions calculation using Equation 2 mentioned above. This methodology discussed in the previous chapter would help show the geographical distribution of transportation-related $PM_{2.5}$ emissions in Shanghai.

$$\mathrm{E} = \sum \frac{V_0 \times P \times C \times \rho \times EF(1-\eta) \times 10}{B \times L}$$

Equation 2. *Converted equation of on-road vehicle $PM_{2.5}$ emissions*

In the above equation, the most important factors are the traffic volume and the percentage of different types of vehicles on road. The former factor presents the number of total vehicles on the roads, which has positive correlations with the level of traffic-related $PM_{2.5}$ emissions. The latter one shows the number of vehicles by different fuel types. It is important because vehicles powered by different fuel types have different fuel consumptions and emission standards. This will impact the final traffic-related $PM_{2.5}$ emissions. Both factors are important to our calculation result that higher traffic volumes produce more traffic-related $PM_{2.5}$ emissions. On the other hand, certain on-road vehicle types will also impact final traffic-related $PM_{2.5}$ emissions because of different fuel consumptions.

The major road traffic volume data were obtained from Shanghai Municipal Engineering Management Department Statistical Report 2015 (上海市市政工程管理处 2015 年统计报告). The total lengths of roadways in each sub-region were from Shanghai Annual Comprehensive Transportation Report 2015 (see Table 15). Each major roadway's length by automatic calculation can be obtained in ArcGIS software. After calculating the total $PM_{2.5}$ emissions caused by the average daily on-road traffic, I assigned the values of how many grams of $PM_{2.5}$ particles are generated along the main streets to the corresponding GIS features by adding a field containing these values. I then generated maps of traffic-related $PM_{2.5}$ emissions along the major roads of central city as well as the whole of Shanghai in 2014, respectively (see Figure 34 and Figure 35).

Table 15. *Road length in five sub-regions of Shanghai in 2014 (Unit: kilometers)*

	West Inner City	East Inner City	West Suburb	East Suburb	Rural Area
Expressway	43.11	17.71	94.21	70.26	0
Highway	0	0	16.78	18.74	877.94
Main Road	104.39	48.82	251.41	227.54	2,194.45
Secondary Road	654.00	200.88	1,285.54	907.53	9,414.48
Total	801.50	267.41	1,647.94	1,224.07	12,486.87

Source: Shanghai annual comprehensive transportation report 2015

Figure 34. *Daily traffic-related PM$_{2.5}$ emissions (g/km) along the main streets of Shanghai in 2014*

Figure 35. *Daily traffic-related $PM_{2.5}$ emissions (g/km) along the main streets of the central city of Shanghai in 2014*

It is evident that, in 2014, the on-road vehicle $PM_{2.5}$ emissions were more concentrated along roads in the central city (the west and east inner city, the west and east suburbs) rather than the rural area in Shanghai. When comparing the west central city and east central city, it is obvious that the west central city has higher traffic-related $PM_{2.5}$ emisssions, especially in the west inner city area. The outer ring elevated road, middle ring elevated road, inner ring elevated road, and main roads in west inner city have higher $PM_{2.5}$ pollution levels than other roads in Shanghai. The other significant highly polluted areas are bridges and tunnels crossing the Huangpu River. In other words, it shows that there are large amount of daily traffic volumes between east city and west city utilizing these bridges or tunnels.

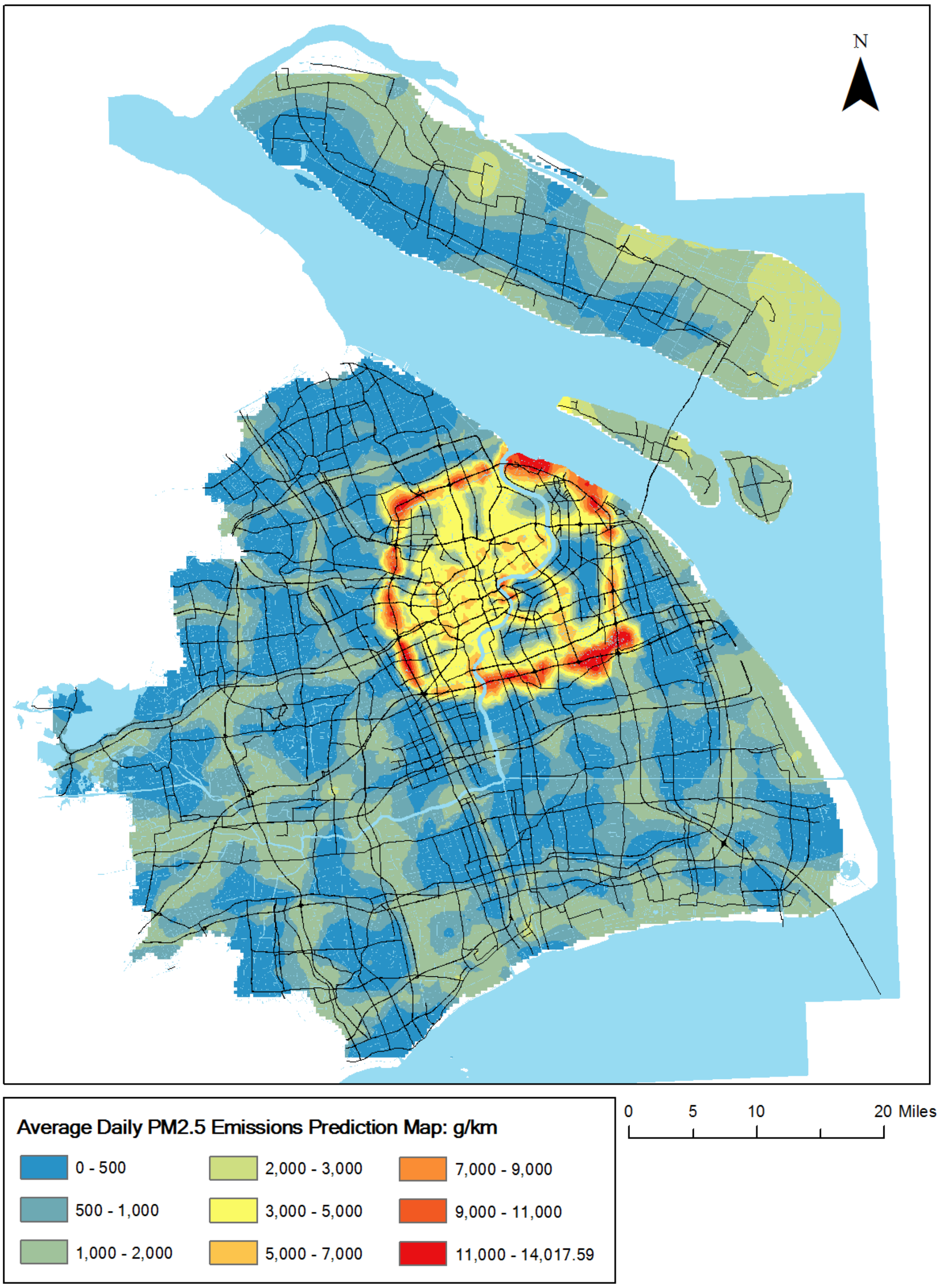


Figure 36. *Daily traffic-related* $PM_{2.5}$ *emission dispersion in Shanghai in 2014*

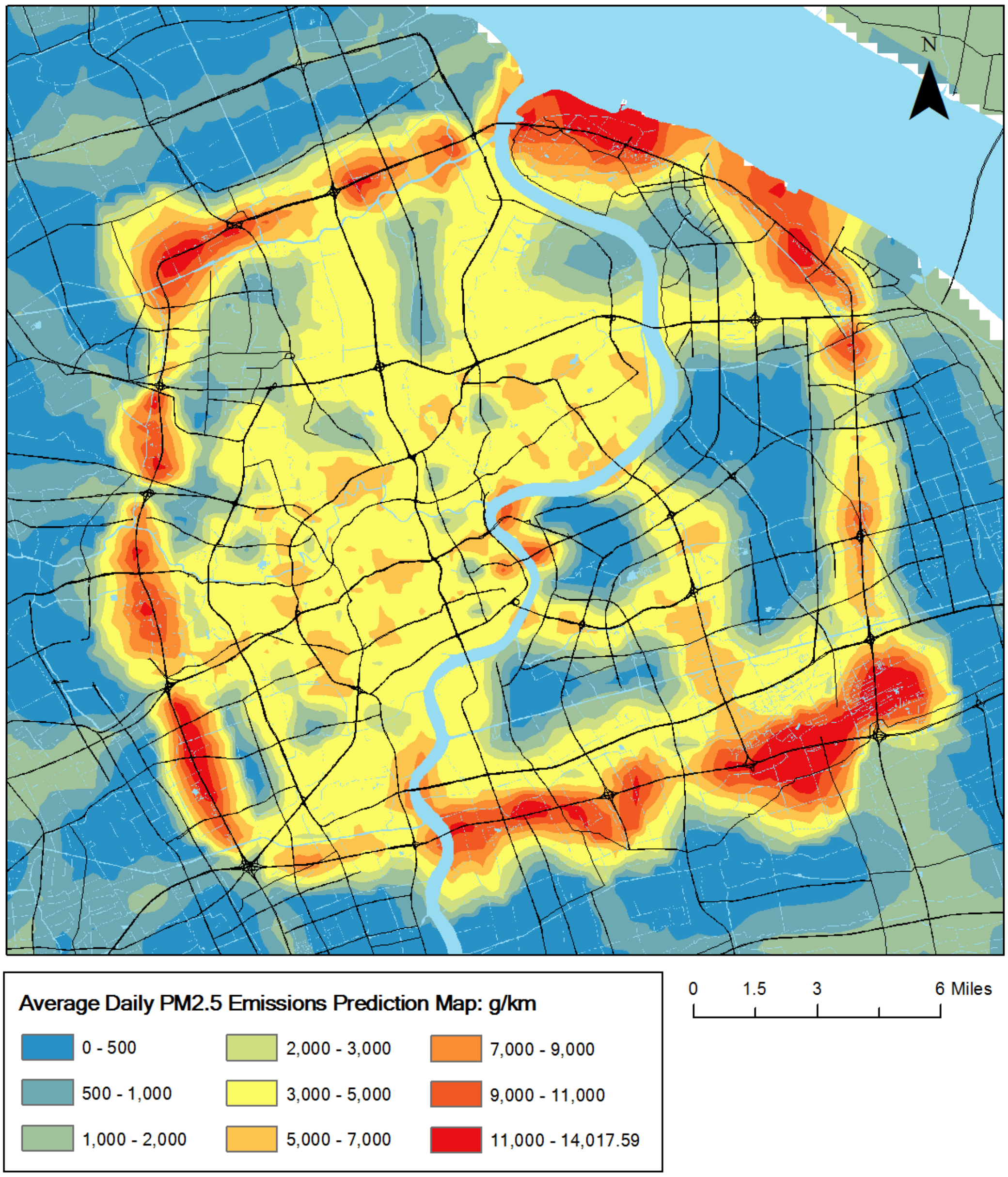


Figure 37. *Daily traffic-related $PM_{2.5}$ emission dispersion in the central city area of Shanghai in 2014*

To investigate the $PM_{2.5}$ emissions hotspot area in Shanghai, the Kriging Interpolation tool in ArcGIS software was used to predict average daily traffic-related $PM_{2.5}$ emissions in Shanghai (see Figure 36 and Figure 37).

Figure 36 shows that $PM_{2.5}$ emissions concentration levels are higher in central city areas than they are in rural areas. The higher $PM_{2.5}$ emissions in rural areas are mostly concentrated along highways. In comparison with urban areas, $PM_{2.5}$ emissions produced by transportation is not the main contributor to local $PM_{2.5}$ air pollution, which was explained in first part of this chapter.

In contrast to the rural area, the central city of Shanghai has a high level of traffic-related $PM_{2.5}$ emissions. It is evident from the map that most $PM_{2.5}$ emissions are concentrated in the west inner city (inside the inner ring road) and along the outer ring road. It's worth noting that a relatively higher concentration of traffic-related $PM_{2.5}$ emissions is found along the outer ring road, especially in crossings where several viaducts intersect.

It seems the east central city has better air quality compared to its counterpart west of the Huangpu River. However, there is a traffic-related $PM_{2.5}$ emission hotspot located in the peninsula east of the Huangpu River, which has an unusually high $PM_{2.5}$ concentration compared to the rest of east central city. The geographical location might contribute to this condition. This area, called Lujiazui (陆家嘴), is the central financial district and famous tourist attraction in the city, consisting of several landmarks and the two busiest bridges in Shanghai connecting the west inner city and east inner city. Therefore, it is understandable why this area has the unusually highest $PM_{2.5}$ emissions in the east central city.

4.2.2 Analysis of Traffic-Related $PM_{2.5}$ Emissions in Shanghai

It is obvious that Shanghai’s traffic-related $PM_{2.5}$ emissions concentrate in the central city, in particular the west inner city and the outer ring road. There are several reasons behind this phenomenon:

(1) Density of Population

In 2014, more than 51.52% of population live in central city (inside the outer ring road), but central city only accounts for 23.65% of area of Shanghai (see Figure 3) (Shanghai Statistical Yearbook 2015). Most of people’s activity areas are limited inside the outer ring road. Research shows 67.8% of people’s interactions happen among districts in central city, only 11.5% happens in the rural area (Yangtze River Delta city smart travel big data report 2016). Thus, with high population density, traffic demand is high in the central city, especially for small private vehicles, buses, and motorcycles. All these factors contribute to the higher traffic-related $PM_{2.5}$ emissions in the central city of Shanghai than in the rural area.

(2) Density of Street Network

Except for high population density, the central city also has a denser road network compared to the rural area (road/area ratio: 1.75km/km^2 versus 0.43km/km^2) (Shanghai municipal engineering management department statistical report 2015). Due to urban development in the 1990s, the transportation facilities in the central city of Shanghai had expanded greatly. The three elevated expressways with the heaviest traffic volumes in Shanghai—the outer ring road, middle ring road, and inner ring road—are all located in the central city. As the most developed district in Shanghai, the west central city (west of the Huangpu River) has a more complicated and denser street network than the east part. The three north-south and three east-west expressways, which cover the whole west central city and consist of elevated plus surface roads, act as the most important arterials in Shanghai (see Figure 38). The denser major roadways in the west central city also result in more traffic congestion and higher traffic-related $PM_{2.5}$ emissions in this area.

Source: http://www.oldkids.cn/blog/blog_con.php?blogid=968726

Figure 38. *Street network in the west central city of Shanghai*

(3) Traffic Speed

The amount of pollutants emitted by vehicles is related to travel speed because incomplete fuel combustions usually produce more $PM_{2.5}$ emissions. According to the UK Department of Transport, particle matter emission rates tend to be lowest when the average vehicle speed is around 50 km/h (45 mi/h), though they increase when the average speed is less than 40 km/h (36 mi/h) or higher than 60 km/h (54 mi/h) (US Environmental Protection Agency, 2013). Wang's research also reveals that vehicular speed can affect particulate number emission factors. She proposed that the particle number emission factor will increase with increasing traffic speed, and vice versa (Wang, Fang, and Ketzel, 2012).

According to Shanghai Municipal Engineering Management Department Statistical Report, in 2014, the average vehicle speed in the central city of Shanghai was only 17.4 km/h (10.8 mi/h) in peak hours, but the average vehicle speed in rural area achieved 50.3 km/h (31.3 mi/h), obviously higher than that of the central city. In addition, vehicle idling can cause more $PM_{2.5}$ emissions than low speeds. However, in Shanghai, vehicle idling is inevitable, because congestion is very common along main arterials like the inner ring road, outer ring road, and three north-south and three east-west expressways in the central city.

Therefore, the congestion and low vehicle speeds in the central city might be another significant factor contributing to the high traffic-related $PM_{2.5}$ emissions in the central city of Shanghai.

(4) Commute Model

In Shanghai, the high price of housing pushes more and more people outward to the suburbs and rural areas. However, most of their workplaces are still concentrated in the central city. Due to the long distance between home and work sites, most people need to drive or take public transit to commute between the central city and rural area every day. Therefore, as the only gateway to the central city, the outer ring road always has the heaviest traffic volumes in Shanghai, especially during peak times.

On the other hand, according to Yangtze River Delta City Smart Travel Big Data Report 2016(长三角城市智能出行大数据报告), average commute distance and time are 19 kilometers (11.8 mi), and 50 minutes respectively in Shanghai. The congestion index is 1.51 in peak times in Shanghai, which means people have to spend 1.51 times longer to get their destinations compared to off-peak time. In addition, most of these conditions occur in the central city of Shanghai.

4.2.3 Comparison with the General $PM_{2.5}$ Dispersion Pattern

In summary, the traffic-related $PM_{2.5}$ emissions in Shanghai are more concentrated in the central city (West and East inner city, West and East suburbs) than in the rural area, in particular in the west central city (West inner city and suburbs) and in the area along the outer ring road and inner ring road. On the other hand, the traffic-related $PM_{2.5}$ emissions in the rural area are much less than the central area, since most of $PM_{2.5}$ emissions in this area concentrate along highways.

Contrary to the traffic-related $PM_{2.5}$ emissions in Shanghai, in the general $PM_{2.5}$ dispersion pattern (see Chapter 4.1), the most serious $PM_{2.5}$ air pollution happens in the west rural area in Shanghai, and $PM_{2.5}$ concentrations get lower from west to east. It seems that central city's $PM_{2.5}$ emissions are not so high.

The different dispersion patterns of these two $PM_{2.5}$ emissions models might be attributed to the different dominant pollutant source. For the rural area, the main source of $PM_{2.5}$ emissions is mainly from industrial activities, because most factories in Shanghai are located in the rural area, especially in the western rural area close to Shanghai's satellite towns, such as Kunshan, Suzhou, and Wuxi. In addition, wind patterns might be another reason for the difference. The prevalent northwest winds in Yangtze River Delta area may bring $PM_{2.5}$ pollutants from nearby towns to the rural area of Shanghai.

However, when just considering traffic factors, the central city is the area with much higher $PM_{2.5}$ emissions than rural area because of its denser road network, higher population density, and heavier traffic volume.

Because of the limited industry data in Shanghai, this thesis aims to study the traffic-related $PM_{2.5}$ emissions in Shanghai. Thus, $PM_{2.5}$ caused by other factors except traffic will not be included in this study.

4.3 School Distribution in Shanghai

As Bae, et al. state in their article, fine particles have serious 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, decreased lung function in school children, increased risk of lung cancer, and increased prevalence of bronchitis (Bae et al., 2007). According to Gauderman, et al.'s research of exposure to traffic on lung development in children from 10 to 18 years of age in southern California, children living within 500 meters of a freeway had reduced lung development compared with children living beyond 1,500 meters from a freeway (Gauderman et al., 2007).

School attendance results in a large daily inhalation of traffic pollutants for students in schools close to highways, since students spend almost 30% of the day in the classroom and considerable time on school grounds participating in sports and other before/after-school activities (Stevenson and Nerison-Low, 2002). According to previous research, 81.7% of pupils walk to school, and other 5.9% of pupils bicycle to school, while only 12.4% of students commute to school by other modes in Shanghai, such as bus, subway, taxi, and private cars (Cai, Wei, and Zhu, 2011). Therefore, the location of school sites is important for assessing children's potential health risks.

Due to the data limit, I cannot get the data of the exact student number in each school. However, the available Shanghai school count and each school's location data could be used to analyze school dispersion patterns in Shanghai. This study divides the school types into four age ranges: kindergarten (4-7 years old), elementary school (7-12 year olds), middle/high school (12-18 years old), and college (>18 years old). Students in kindergarten and elementary school (<12 years old) are more vulnerable than the other two age groups when exposed to $PM_{2.5}$ emissions because they are younger and their immune systems are less developed than the other two student groups.

The school and complete road network data of Shanghai are obtained from Shanghai Institute of Technical Physics of The Chinese Academy of Science as the GIS shapefile documents. I defined school types as: kindergarten, elementary school, middle/high school, and college. I selected city expressway, highway, national road, and provincial road as our study's major roadways. The distance to the nearest major roads (100 m, 400 m) was estimated using ArcGIS software (version 10.2; Environmental Systems Research Institute Inc., Redlands, CA). The results are as follows (see Table 19, Table 20, Figure 35, Figure 36, Figure 37, and Figure 38).

Table 16. *Number of schools to major roadways defined as kindergarten, elementary school, middle/high school and college*

Sub-region	Distance to major roads	Kindergarten	Elementary School	Middle/High School	College
West Inner City	<100 m	9	7	20	19
	< 400 m	61	34	55	40
	Total	222	148	182	88
East Inner City	<100 m	0	1	0	0
	< 400 m	7	6	1	0
	Total	53	33	33	11
West Suburb	<100 m	9	9	17	22
	< 400 m	92	38	52	31
	Total	345	184	236	117
East Suburb	<100 m	2	2	1	1
	< 400 m	17	7	10	3
	Total	182	95	87	31
Rural Area	<100 m	20	5	12	5
	< 400 m	83	43	42	13
	Total	798	470	382	170

Table 17. *Schools within 100 m and 400 m of a major roadway in Shanghai*

Category	<100 m		<400 m		Total
	Number	Percent	Number	Percent	
Kindergarten	41	2.56%	261	16.28%	1,603
Elementary School	24	2.58%	128	13.73%	932
Middle/High School	50	5.43%	160	17.39%	920
College	47	11.27%	87	20.86%	417
Total	162	4.18%	636	16.43%	3,872

4.3.1 General School Distribution Pattern

A total of 3,872 schools in Shanghai—comprised of 1,603 kindergartens, 932 elementary schools, 920 middle/high schools, and 417 colleges—were identified from the five sub-region areas (see Table 17). As seen in Table 17, in the city region, 16.43% of schools fell within 400 meters of a major roadway and 4.18% were within 100 meters. Considering the school type, 41 kindergartens, 24 elementary schools, 50 middle/high schools, and 47 colleges are located within 100 meters to a major road; 261 kindergartens, 128 elementary schools, 160 middle/high schools, and 87 colleges are located within 400 meters of a major road. It shows that more middle/high schools are concentrated within 100 meters of major roads. However, within a distance of 400 meters from major roads, the number of kindergartens is the most among all the four school types, nearly double the number of elementary schools and middle/high schools and almost three times more than colleges.

For geographical school distribution, one can find that most of schools within 100 meters to 400 meters from major roads are concentrated in the west central city (west inner city and west suburbs), especially along the west part of inner ring road (see Figure 39-42, Table 16). There are not too many schools located in the east central city between 100 meters and 400 meters from major roads. One reason might be that the total number of schools in the east central city is much less than that of west central city. Another possible explanation might be that the east central city was just developed in recent decades, and school sites were well planned to avoid being located too close to major roadways.

For schools located within 100 meters to 400 meters from major roads in the rural area, they scatter unevenly, and I could not find an obvious school distribution pattern in the rural area. I assumed that the school distribution in rural area has no obvious characteristics because of the large area of the rural district and the uneven population distribution. However, it is evident that more schools concentrated in the west rural area than the east rural area from the above map.

In summary, from the above analysis, one can see that more middle/high schools are concentrated within 100 meters from major roads than other three types of schools. But within a distance of 400 meters from major roads, the number of kindergartens is the highest among all four school types in our study.

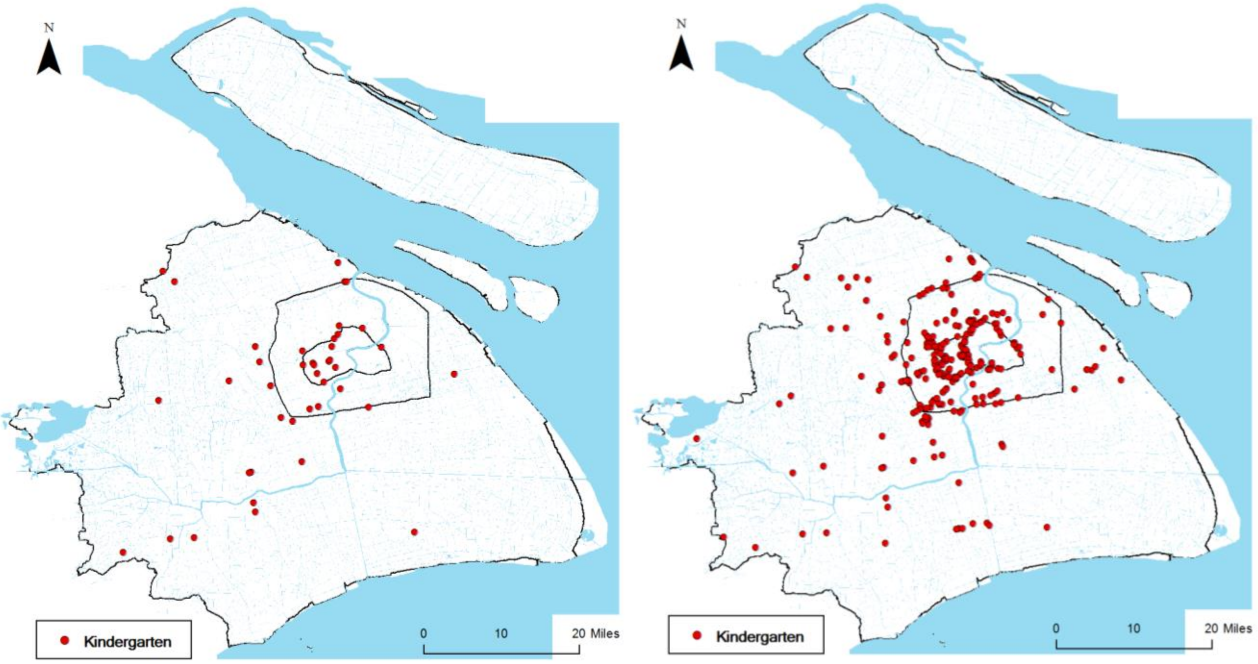


Figure 39. *Distribution of kindergatens within 100 meters (left) to 400 meters (right) from major roads in Shanghai*

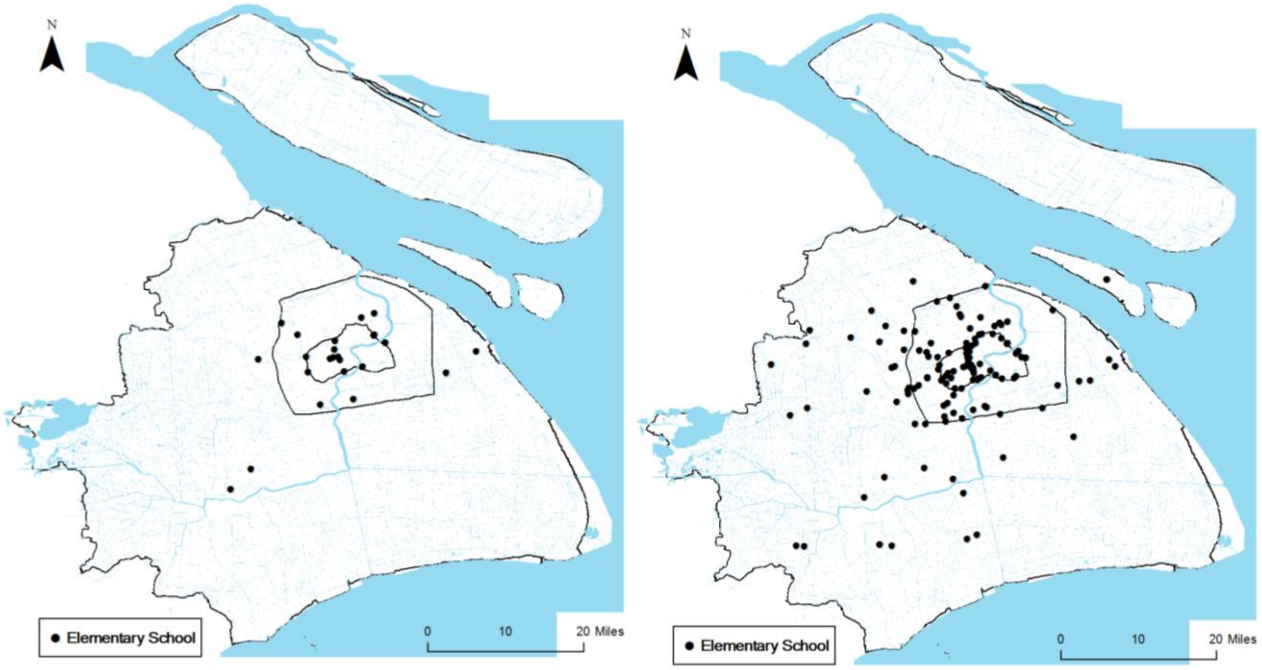


Figure 40. *Distribution of elementary schools within 100 meters (left) to 400 meters (right) from major roads in Shanghai*

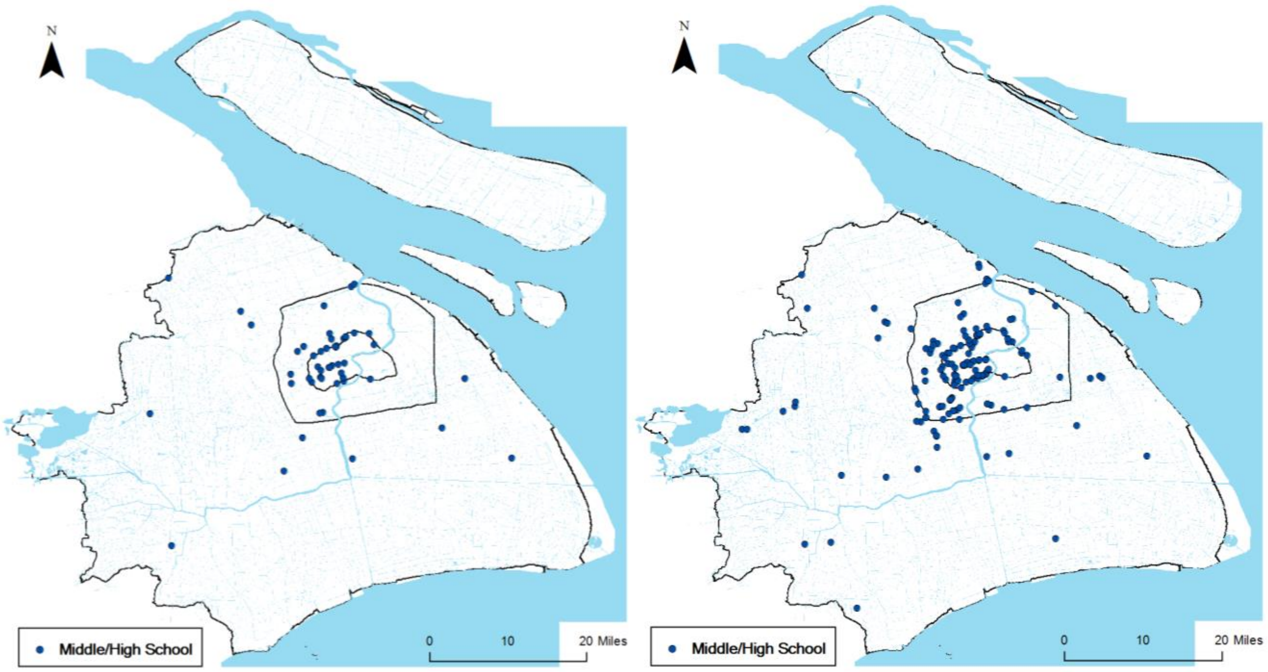


Figure 41. *Distribution of middle/high schools within 100 meters (left) to 400 meters (right) from major roads in Shanghai*

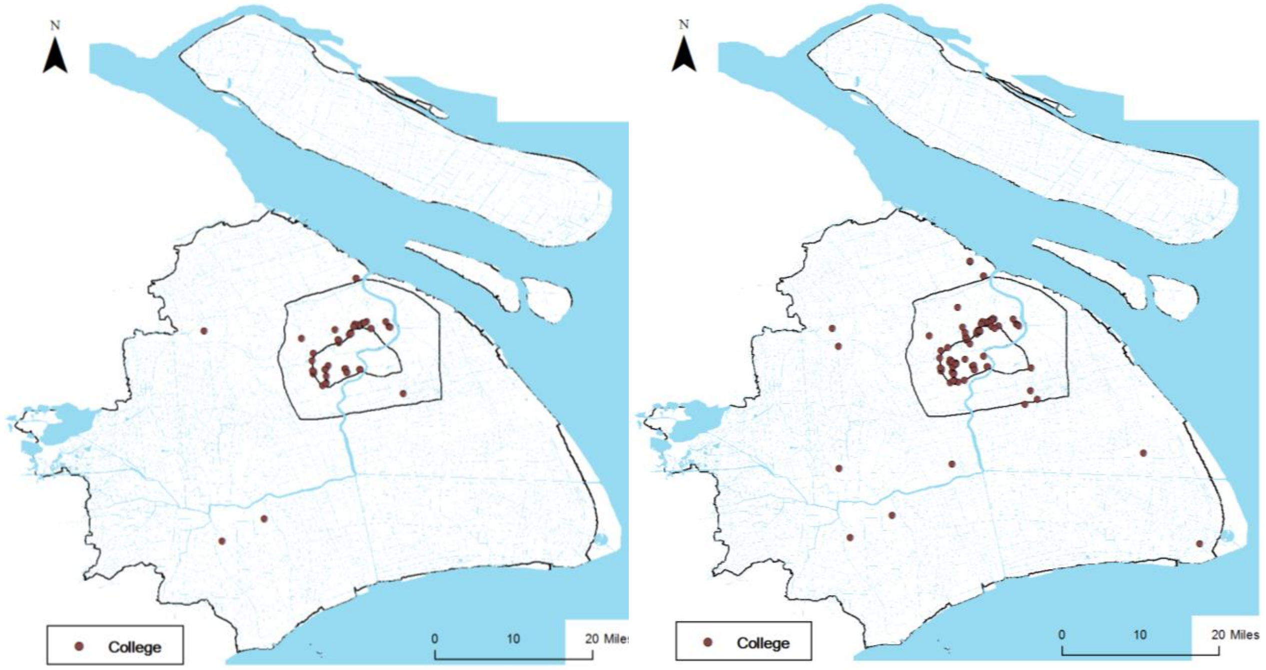


Figure 42. *Distribution of colleges within 100 meters (left) to 400 meters (right) from major roads in Shanghai*

4.3.2 Geospatial Dispersion of School

From figure 39, 40, 41 and 42, I found that no matter the school level, most schools in close proximity to a major roadway are located in the west central city, and along the inner ring road and outer ring road, which correspond to my findings of areas with highest $PM_{2.5}$ concentrations. Just a few schools scatter in the rural area randomly. Most of schools (kindergarten, elementary school, middle/high school, and college) concentrate in the west central city (west inner city, west suburb), especially close to the inner ring road.

According to our study on traffic-related $PM_{2.5}$ emissions in Shanghai, an obvious overlap can be found between locations of a large percentage of schools in close proximity to a major roadway and the areas with highest traffic-related $PM_{2.5}$ concentrations. In other words, it means a significantly high percentage of students in these schools are exposed to extremely high traffic-related $PM_{2.5}$ emissions, and their health is under serious threat.

4.4 Impact of Traffic-Related $PM_{2.5}$ Emissions to School Location

4.4.1 Shanghai School Hazard Map

With the geospatial distribution of schools in close proximity to major roadways (100 meters to 400 meters), I can produce a density map of schools located within 400 meters from a major roadway in ArcGIS software (see Figure 43). Corresponding to our analysis above, the map shows the highest school density lies in the west central city, and along the southwest outer ring road. There are a few concentrations of schools located in the east inner city, but they are not as obvious as in the west central city. However, the rural area has the lowest school density. There are just some insignificant concentrations of schools scattered throughout this area, but most areas in this district have low density of schools in close proximity to major roadways.

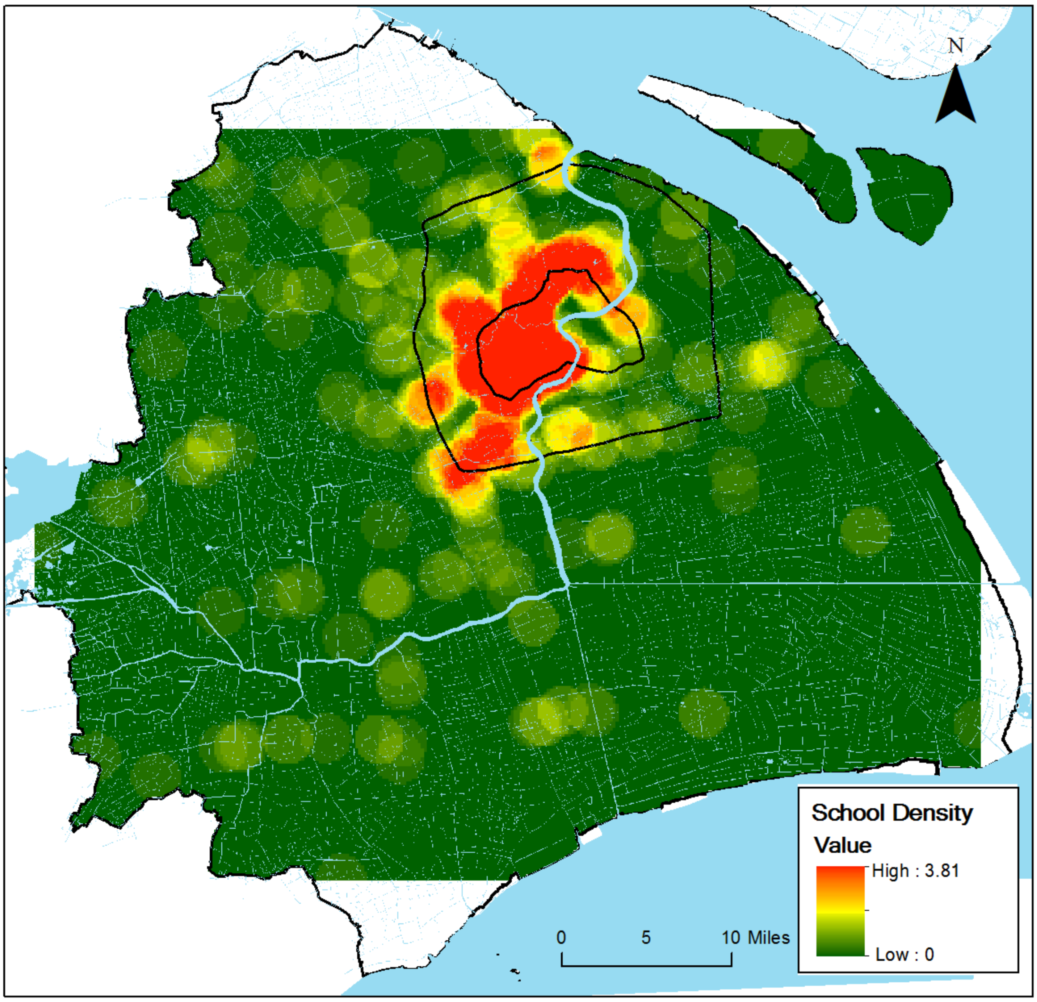


Figure 43. *Density of schools within 400 meters of major roadways in Shanghai*

In order to explore whether schools in close distance to major roads are concentrated in areas with higher traffic-related $PM_{2.5}$ emission levels concurrently, I created a Shanghai TRAP-Spatial School Hazard Priority Area Map (see Figure 44). To make this map, I multiplied the average daily traffic-related $PM_{2.5}$ emission amount in our study area with its total density of schools located within 400 meters to major roadways (see Figure 36 and Figure 43). By doing so, I can demonstrate a spatially sensitive index showing the different concentration levels of both the school location and the traffic-related $PM_{2.5}$ emissions in Shanghai.

According to the Shanghai TRAP-Spatial School Hazard Priority Area Map, one can find that the most hazardous school priority area lies in the west inner city, along the inner ring road west of the Huangpu River, and south part of west suburbs area. The rural area and most parts of the east suburbs have the lowest hazard scores. It reflects a lower concentration of schools in close proximity to major roadways coupled with the lower level of traffic-related $PM_{2.5}$ emissions in these areas.

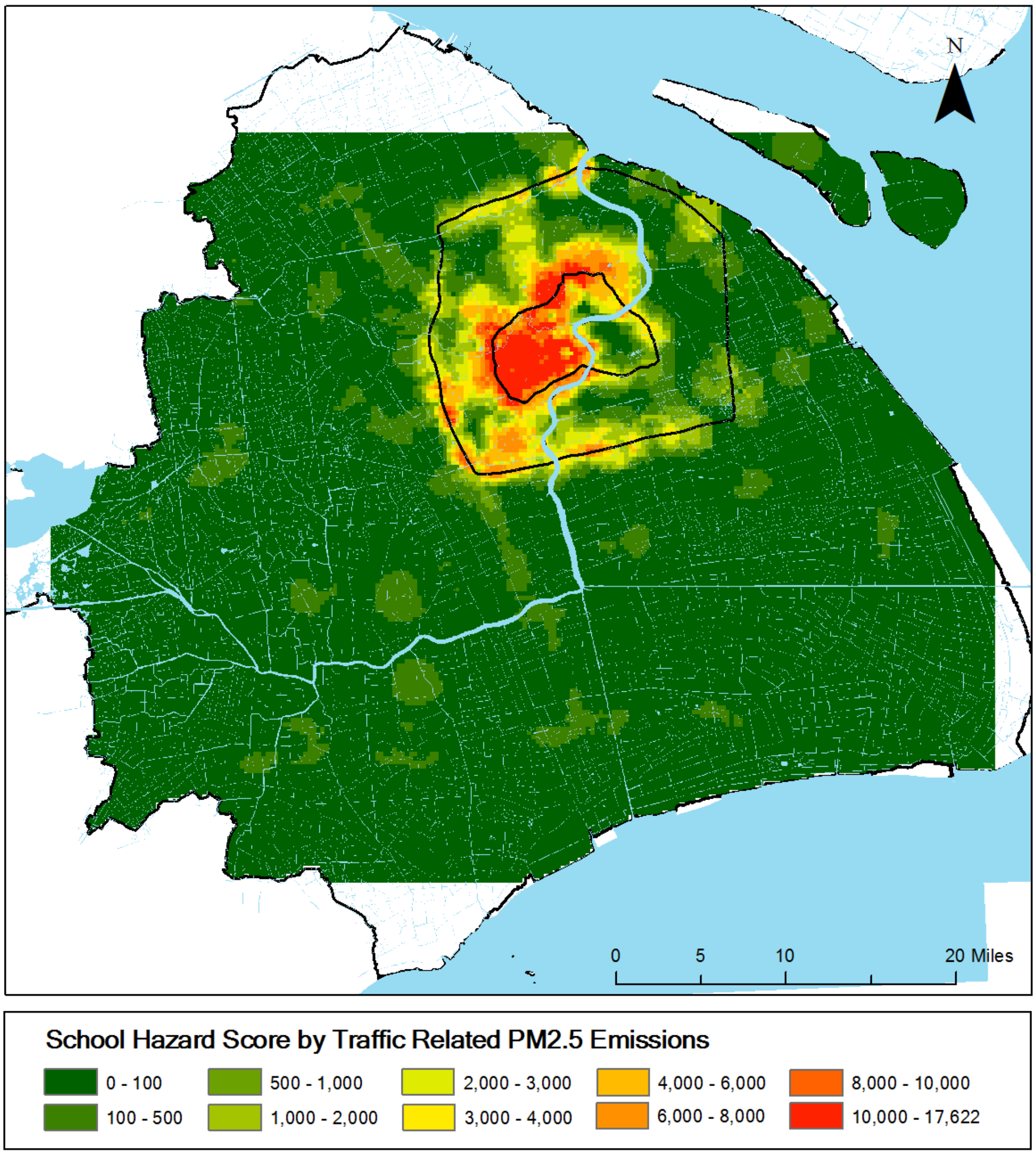


Figure 44. *Shanghai TRAP-Spatial school hazard priority area map*

4.4.2 School Site Suitability Index System of Shanghai

As stated above, schools in close proximity to major roadways are usually concentrated concurrently in areas with higher traffic-related $PM_{2.5}$ emission levels, especially in the west central city, and along the inner ring road and outer ring road. In other words, students in these schools may have high traffic-related air pollution health risks, such as asthma, respiratory system diseases, and so on. To avoid this situation happening in the future, a Shnaghai School Site Suitability Index Map could be created to show appropriate locations for school sites in Shanghai.

Two factors were considered for school site situability index: distance to major roadways, and the level of traffic-related $PM_{2.5}$ emissions. Research has shown that people’s health risks will increase while approaching highways (See Chapter 2.5, Figure 23), especially for children under 14 years old who are more vulnerable than other groups to $PM_{2.5}$ emissions because they are still growing and the immune system is developing.

After calculating the distance to major roadways in Shanghai, I multiplied the statistics of average traffic-related $PM_{2.5}$ emissions (2014) by the statistics of the distance to main roadways in Shanghai to create the Shnaghai School Site Suitability Index Map (see Figure 45).

It is obvious that areas in close proximity to major roadways are least suitable for school sites. Instead, sites located in the middle of open gaps in the road network are more suitable. From a sub-region perspective, the west and east inner city and west suburbs are less suitable to build schools than the rural area and east suburbs because of denser road networks and higher traffic-related $PM_{2.5}$ emissions.

Overall, when only considering the health impact from traffic-related $PM_{2.5}$ emissions, sites located in the rural areas and east suburbs—and far away from main roads, especially the outer ring road and inner ring road—are the best places for school construction (see Figure 45).

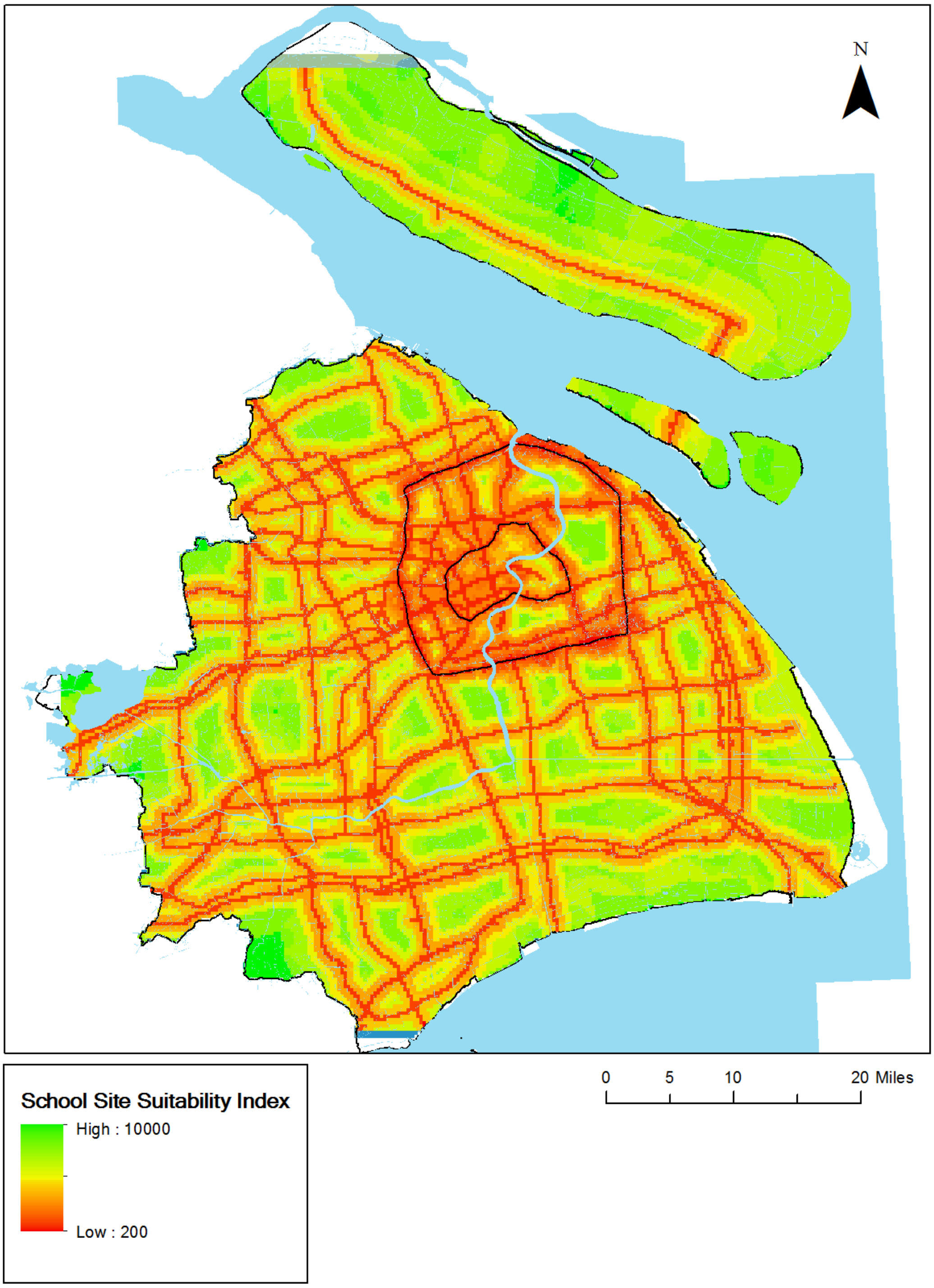


Figure 45. *School site suitability index map*

CHAPTER 5. CONCLUSION AND RECOMMENDATION

Air pollution and its impact to citizens' health has become one of the most important issues in Shanghai due to its robust industrial activities and continuously increasing vehicle use. In this thesis, I mainly investigated the spatial dispersion of one component of transportation emissions—$PM_{2.5}$—which has been found as the main contributor to the serious air pollution problem in Shanghai.

To investigate the traffic-related $PM_{2.5}$ emissions and its impacts on students, I developed a methodology to calculate traffic-related $PM_{2.5}$ emissions by traffic density, and visualized air quality variations and their connections with school distribution in Shanghai. Furthermore, I also developed a school site suitability index system to explore the best possible school sites in the future.

The findings from this study are as follows:

5.1 The General $PM_{2.5}$ Emissions in Shanghai

I chose three specific periods—January 2013, December 2013, and September 2014—to investigate Shanghai's general air quality conditions using daily data from ten monitoring stations in the city. The study result shows that in all three study periods, the $PM_{2.5}$ emissions were more concentrated in the west rural area (west of the Huangpu River and outside the outer ring road), and $PM_{2.5}$ concentrations decreased from west to east. These findings show that the rural area of the city, known as the area beyond the outer ring road, has the most serious $PM_{2.5}$ air pollution, especially near the west border of the city.

Industrial activity emissions might be the most significant contributor to this condition. Most of heavy industrial factories and industrial parks are located in the west rural area of Shanghai. In contrast, there is almost no industry settling in the central city or east rural area. Also, the prevalent north wind might blow air pollution from other nearby industrial cities, like Kunshan, Suzhou, and Wuxi, to this area.

In addition, inadequate data samples may also result in this condition. There is only one monitoring station (Dianshanhu, 淀山湖) in the west rural area. In sharp contrast, eight of ten monitoring stations are located in the central city. The lack of data could possibly contribute to the uneven geospatial dispersion of $PM_{2.5}$ emissions.

5.2 The Traffic-Related $PM_{2.5}$ Emissions in Shanghai

In this thesis, I mainly investigated the spatial dispersion traffic-related $PM_{2.5}$ emissions in Shanghai. When just considering traffic factors, I found that in 2014 the on-road vehicle $PM_{2.5}$ emissions were more concentrated along streets in the central city (the west and east inner city, west and east suburbs) rather than in the rural area around Shanghai. The west inner city and the area along the outer ring road and the inner ring road were the most severely-afflicted areas by traffic-related $PM_{2.5}$ emissions.

Unlike the general $PM_{2.5}$ emissions dispersion model, the much higher traffic-related $PM_{2.5}$ emissions in central city were caused by vehicle emissions, heavy traffic volume, dense population density and street network. Firstly, the high population density and high frequency of interactions among districts in the central city will increase people’s demand for transportation. The most common transportation types are small private vehicles, buses, and motorcycles, which contribute the most to $PM_{2.5}$ emissions.

Furthermore, with the increasing economic status of the citizens of Shanghai in the last three decades, the vehicle ownership rates in Shanghai increased dramatically. When compared to the rural area, the street network density in the central city is nearly four times higher ($1.75km/km^2$ to $0.43km/km^2$). In other words, with more vehicles and a denser street network, the traffic volume in the central city is much higher than that of the rural area around it.

In addition, traffic speed also plays an important role in $PM_{2.5}$ emissions. When vehicles operate at a speed lower than 40 kilometers per hour or higher than 60 kilometers per hour, they create additional $PM_{2.5}$ emissions because of incomplete combustion. According to my study, I examine the average traffic speed in the whole of Shanghai, and find that average traffic speed in the central city is only 17.4 km/h in rush hour when that of rural area is 50.3 km/h. If all other things are equal, the central city is to be confronted with more traffic-related $PM_{2.5}$ emissions than the rural area.

Lastly, the increasing population and residential property prices in the central city pushed the population outward into the rural area. It causes more frequent commuting traffic between rural areas and the central city, which results in an increase of $PM_{2.5}$ emissions in the central city.

5.3 The Impact of Traffic-Related $PM_{2.5}$ Emissions to Schools

The other focus of this thesis is to explore the effect of urban planning and road development on the health risks to students attending schools near major roadways in Shanghai. It was concluded that proximity to major roadways should be an important factor in considering sites for new schools and developing policies for reducing the air pollution exposure in existing schools.

The study shows a high percentage of schools in Shanghai located in close proximity (<400 m) to major roadways, including 16.28% of kindergartens, 13.73% of elementary schools, 17.39% of middle/high schools, and 20.86% of colleges. Most of these school sites are in west central city along the inner ring road and outer ring road. The study found these school locations are highly overlapped with areas with high traffic-related $PM_{2.5}$ emissions. As a result, the high traffic-related $PM_{2.5}$ emissions will result in a potentially increased risk for asthma and other chronic respiratory problems for those students who attended schools near (<400 m) major roadways.

Taking two factors—distance to main roadways, and the level of traffic-related $PM_{2.5}$ emissions—into consideration, I developed a school site suitability index system. By using the school site suitability index system, it was possible for me to differentiate the areas across the city in terms of the degree of impact that the traffic-related $PM_{2.5}$ particles had on students' health. Through this index system, I found the most suitable sites for schools are the rural area and east suburbs because of the less dense street network and fewer traffic-related $PM_{2.5}$ emissions. These findings can provide an important reference point for coordinating future urban development, transportation, and environmental policies.

5.4 Planning Policies and Recommendations to Mitigate the Current Situation

It is unpractical to recommend that all existing schools within 400 meters of major roadways in Shanghai move to new sites because of the large cost and lack of vacant lands. However, planners can adopt mitigation policies to reduce on-road $PM_{2.5}$ emissions.

The Shanghai municipal government has employed several policies to restrain vehicle use and ownerships of vehicles, such as license plate auction, banning out of town vehicles entering the central city of Shanghai, and so on. However, people in Shanghai still aspire to use automobiles to have greater freedom of their mobility and the ownership of vehicles increases. Therefore, Shanghai needs more effective policies to reduce traffic-related $PM_{2.5}$ emissions. My recommendations are the following:

1) **Adopt higher vehicle emission standards and encourage use of electric and hybrid power vehicles**

There are many vehicle types on the streets in Shanghai. Different types of vehicles contribute different levels of $PM_{2.5}$ 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. Different emission standards have different restrictions on $PM_{2.5}$ emissions. To reduce vehicle emissions, Shanghai should adopt higher emission standards for vehicles. On the other hand, Shanghai should also encourage the use of environmentally friendly vehicles, like electric and hybrid power automobiles, which will produce no or fewer emissions.

2) **Provide better public transit service and increase parking fees**

Another recommendation is to develop Shanghai public transit system in priority to encourage people to ride more public transit rather than drive private vehicles, which includes developing Shanghai's subway system, increasing bus routes and its frequency, setting the specific bus lanes, popularizing electric buses, and so on. The wide coverage and convenient public transit could increase the ridership of public transit, and reduce the use of private vehicles. Also, the government can raise parking fees to discourage the use of private vehicles.

3) Congestion pricing and other restrictions on vehicle use

To reduce traffic-related $PM_{2.5}$ emissions, the city can also charge congestion fees and set vehicle restriction areas in the targeted areas, like the area with high traffic volume and vehicle emissions, and areas near schools, hospitals, or some air pollution sensitive public facilities. However, this solution may only be effective to the targeted area and have a counter effect outside the target area, because cars are rerouted around the priced and restricted zones.

4) Restrict new school sites in certain distance to major roadways

It is unpractical to remove existing schools near major roadways to new sites, but we can avoid the unscientific school site decision in the future. It was concluded that proximity of major roadways should be considered when deciding sites for new schools. To reduce the health impacts of $PM_{2.5}$ emissions to students, the sites for new schools should be kept away from major roadways. If possible, the government should settle them in the rural area or east suburbs where the traffic-related $PM_{2.5}$ emissions are low.

5) Open air quality data to the public and create air pollution warning system

It is very difficult for the public to obtain air quality data of Shanghai. Shanghai's air quality data are not so transparent like most cities in the U.S. For Shanghai municipal government, it is necessary to open its air quality database and share the real-time air pollution conditions with the public. On the other hand, the government should create a warning system for air pollution levels, especially for people who have respiratory and cardiovascular diseases and are sensitive to the air pollution. To deal with this problem, three solutions should be considered. The first one is to utilize smart phone technology to crowd source data collection on air pollution that will improve research and allow more information to be collected. Secondly, when air pollution reaches an unhealthy level to those who have sensitive respiratory systems and/or vulnerable populations such as children and the elderly, the warning messages could be transmitted via smart phones to the public. Thirdly, the city should also create widespread education programs to raise the awareness and information about how people can protect themselves from the air pollution.

6) Build more air quality monitoring stations in Shanghai

It is unthinkable that as the largest city in China, Shanghai, with a population of more than 20 million, only has 10 air quality monitoring stations. This means that one monitoring station covers two million residents on average. As discussed in this thesis, traffic-related $PM_{2.5}$ levels are distance sensitive, and associated with traffic volumes and vehicle fuel types. The lack of air quality monitoring stations might result in the inaccuracy of citywide air quality data and reduce the reliability of government's evaluation on Shanghai air pollution condition. With similar population and city size, Shanghai can learn from Hong Kong's air quality monitoring stations distribution mode. There are 15 monitoring stations covering the whole Hong Kong City with a population of 7.2 million: 12 general stations scattering in the urban and rural area, and 3 roadside stations located along the major roadways with heavy traffic. The comparison between air quality data detected by general stations and those of roadside stations is helpful to study traffic-related air pollution. With more serious air pollution, Shanghai should learn the lesson from Hong Kong, or other cities in the world, and build more air quality monitoring stations. The city can divide them into the general stations in residential areas and roadside stations close to main arterials.

5.5 Future Research and Limitations

The lack of data is one of the primary obstacles of this research. I cannot obtain $PM_{2.5}$ data emitted by industrial activities in Shanghai, so I am not able to compare industrial vs traffic-related $PM_{2.5}$ emissions in Shanghai at the present time. In addition, there also lacks the exact distribution data of different vehicles on roads, which could affect the result of traffic-related $PM_{2.5}$ emissions dispersion patterns.

In addition, we could not test the robustness of the Shanghai school site suitability index system because of limited data availability. The limit of this index system is that I only considered two factors, which are not sophisticated enough to apply to the real world. In the future study, more factors can be added into consideration, such as the number of students per school, student age groups, students' health information (asthma, or other respiratory problems), student's commuting mode, and local resident density. On the other hand, I think the method used in this thesis and the School Site Suitability Index System can be applied to other cities in the world where better air quality and school data are available, such as New York, London, Los Angeles and so on. The School Site Suitability Index System could be an excellent guidance for planners and government staff to select new school sites in urbanizing areas in the future.

However, even though with sevral limitations, 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 students.

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