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Transportation Situation and Traffic Air Pollution Status in Shanghai

Vehicle Emissions Control and Health Benefits; Technical and Policy Barriers to Sustainable Transport

(Part One Report, Draft)

Shanghai Academy of Environmental Sciences

Shanghai, P.R. China

January 27, 2005

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Team Leaders:	Changhong CHEN	Professor/Deputy Chief Engineer Shanghai Academy of Environmental Sciences (SAES)
	Bingheng CHEN	Professor School of Public Health (SOPH) Fudan University
	Qingyan FU	Senior Engineer Shanghai Environmental Monitoring Center (SEMC)
Team Members:	Qiguo JING,	Assistant Engineer, SAES
	Haidong KAN	Ph.D., SOPH, Fudan University
	Lily	Assistant Engineer, SAES
	Hansheng PAN	Assistant Engineer, SAES
	Guohai CHEN	Senior Engineer, SEMC
	Haiying HUANG	Assistant Engineer, SAES
	Bingyan WANG	Assistant Engineer, SAES
	Minghhua CHEN	Senior Engineer, SAES
	Jibing QIU	Engineer, SAES
	Cheng HUANG	Masters Student, East China University of Science and Technology (ECUS&T)
	Yi DAI	Masters Student, ECUS&T
	Haikun WANG	Masters Student, ECUS&T
	Jing ZHAO	Masters Student, ECUS&T

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Authors

Changhong CHEN, Jiguo JING, Lyli, Cheng HUANG,
Hansheng PAN, Haikun WANG, Yi DAI, Haiying HUANG,
Jing ZHAO

Co-Authors

Guohai CHEN, Bingyan WANG, Hua QIAN, Haixia DAI,

Hongyi LIN, Shaojun WANG

Shanghai Academy of Environmental Sciences

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Contacts

This report was prepared by the Shanghai Academy of Environmental Sciences. Questions and comments about this report, including inquires regarding specific information, may be directed as follows:

Shanghai Academy of Environmental Sciences

Add: 508 Qiznhou Road

Shanghai 200233, P. R. China

Tel: +86-21-6408 5119

Fax: +86-21-6484 7827

To Changhong CHEN

Tel: +86-21-6408 5119, Ext. 2506

Fax: +86-21-6484 7827

Email: chench@saes.sh.cn

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Executive Summary

1. Background

Shanghai is a megacity with the highest population and most developed economy in China. As the economy flourishes and incomes rise, the demand for transportation increases. By the end of 2003, the urban vehicle population had reached two million (including mopeds). Since then, the number of vehicles has continued to rise sharply.

Although Shanghai phased-out the use of leaded gasoline and implemented Euro-I and Euro-II standards on July 1, 1999 and March 1, 2003, respectively, environmental monitoring data taken in 2004 revealed little improvement in Shanghai's air quality. The concentration of NO_x continues to rise, and PM pollution is still high. Despite such discouraging news, Shanghai's government and urban management personnel remain committed to reducing vehicle emissions, improving air quality, and creating a healthier environment for Shanghai's citizens before the 2010 World Expo.

Funded by the United States's Energy Foundation and World Resources Research Institute (EMBARQ), the Shanghai Academy of Environmental Sciences (SAES) launched two projects, "Shanghai Vehicle Pollution and Health Benefit" and "Sustainable Transport and Environment Indicators," to help Shanghai reach these goals and develop its transportation system in a sustainable and environmentally-friendly way. This integrated report combines the results of the first phase of both of these projects. The report provides results of research into of the state of Shanghai's transportation system and its environmental and health impact. This preliminary research will subsequently be used for health-benefit analysis the development of sustainable transport and environmental indicators.

2. Purpose

The purpose of the "Shanghai Vehicle Pollution and Health Benefit" project was to evaluate the relationship between Shanghai's economic development and its vehicle population and determine the exposure–response relationships of air pollution. To do this, we analyzed vehicle driving behavior, vehicle technology, air pollution, and epidemiology. Then, using recent transportation research and predictions of future growth rates of Shanghai's vehicle population, we applied IVE and air quality models to analyze vehicle emission control scenarios, study air pollution exposure levels, and conduct health-benefit analyses.

Because the 2010 World Expo is of great importance to Shanghai, we studied the prospect and potential health benefits of implementing Euro-IV emission standards for light-duty vehicles and emission control measures for heavy-duty vehicles by the year 2010.

The purpose of the "Shanghai Sustainable Transport and Environment Indicators" project was to establish a system of sustainable transport and environmental indicators that will "review the past, analyze the current, and guide the future." We first identified basic traffic and heavy-duty vehicle emission indices, based on the "Shanghai Vehicle Pollution and Health Benefit" project. The objective of phase one for both projects was to collect traffic environment data, study vehicle driving behavior, and establish a vehicle emissions inventory.

3. Process

The following has been accomplished in one year of work, February 1, 2004 to January 31, 2005:

(1) SAES collected and analyzed data on Shanghai's social and economic development and air pollution monitoring.

(2) In June 2004, with help from the American Energy Fund, SAES worked with the University of California at Riverside (UCR) to investigate vehicle driving behavior, traffic flow, vehicle start-up frequency, and vehicle technology classification. This research showed the diurnal mileage distribution of vehicles on Shanghai roads, vehicle fleet classification, the diurnal change in vehicle speed, and detailed vehicle technology classification, all of which laid a foundation for the development of Shanghai's vehicle emission inventory.

(3) During Fall 2004, working with EMBARQ and the United States Environmental Protection Agency (USEPA), SAES used SE MTECH-D to conduct mid- and heavy-duty vehicle emissions testing on highways, arterial roads, and residential roads. The data collected will provide important technical information for China's vehicle pollution control.

(4) We then collaborated with UCR to set up an air pollutant emissions model based on vehicle miles traveled, traffic flow distribution, vehicle technology classification, and vehicle power change. A vehicle emissions inventory was also developed.

(5) We investigated the vehicle pollution levels at 18 traffic intersections in Shanghai to learn the air pollution situation on main traffic roads.

(6) We collected documents about air pollution and epidemiology from both within China and abroad, and authored the following reports: "Analysis of Exposure-Response Functions between PM_{10} pollution and Adverse Health Outcomes," "Analysis of Exposure-Response Functions between NO_2 pollution and Adverse Health Outcomes," and "Application of DALYs in Measuring the Health Burden of Ambient Air Pollution."

4. Main Results

Our efforts have yielded the following results:

(1) Shanghai's GDP and vehicle population are skyrocketing. For each of the past 12 years, Shanghai's GDP has grown by at least 10 percent, with the vehicle population increasing proportionally. Thus, as GDP and income continue to rise, Shanghai's transportation demand and vehicle population are bound to continue increasing as well.

(2) Over the past ten years, average road area both per person and per vehicle has increased. At the same time, the widths of non-mobile roads and sidewalks have narrowed, suggesting Shanghai is increasing vehicle roads at the expense of areas for pedestrians, bicycles, and other non-vehicular traffic. This decrease in non-mobile roads and sidewalks has increased traffic congestion, offsetting some of the positive effects of increased road area.

(3) Average traffic speed in Shanghai is low: the average speed of buses is 12.0 km/h; trucks, 18.3 km/h; and taxis, 28.3 km/h. On arterial roads in the center of Shanghai, average vehicle speed is only 10.0 km/h; in business areas, 13.2 km/h; in the city outskirts, 18.1 km/h.

(4) On some roads in Shanghai, it is common for both mobile and non-mobile vehicles to drive in the same lanes. This means that vehicles must frequently accelerate/decelerate, significantly raising vehicle emissions. On average, empty trucks on integrated roads emit 5.6 g/km of CO, 2.1 g/km of THC, and 6.5 g/km of NO_x. Fully-loaded trucks emit 22.5 g/km of CO, 2.4 g/km of THC, and 7.4g/km of NO_x. Buses on their routine route on average emit 3.6 g/km of CO, 2.1 g/km of THC, and 4.7 g/km of NO_x. Finally, light-duty vehicles emit 1.0 g/km of CO, 0.6 g/km of THC, and 4.0 g/km of NO_x on average.

(5) Each year, 2.1×10^4 tons of CO, 6.4×10^4 tons of VOC, 6.6×10^4 tons of NO_x, 0.17×10^4 tons of PM, and 753×10^4 tons of CO_2 are emitted by

vehicles in Shanghai. Twenty to thirty percent of the total CO, VOC, and PM emitted is produced at start-up. Heavy-duty vehicles are responsible for a large proportion of total vehicular air pollution: they account for 40 percent of CO emissions, 67 percent of NO_x emissions, and 53 percent of PM emissions.

(6) Among 18 traffic pollution monitoring sites set up throughout Shanghai, 16 reported an average hourly concentration of NO_x exceeding the second-class national air-quality standard. The maximum average hourly concentration was nearly 0.5 mg/m^3, 1.6 times the second-class national standard (0.30 mg/m^3). The maximum average hourly concentration of NO_x was almost 1.0 mg/m^3, 3.3 times the second-class national standard (0.30 mg/m^3). Average daily concentration of PM_{10} reached 0.32 mg/m^3, 2.1 times the second-class national standard (0.15 mg/m^3); the maximum average daily concentration of PM_{10} was nearly 1.2 mg/m^3, eight times the second-class national standard.

(7) Nitrogen dioxide (NO_2) is the main component of traffic-related air pollution. We examined the relationship between NO_2 and mortality and morbidity, especially lower respiratory disease in children. The effects of NO_2 on mortality and morbidity seemed confounded by other pollutants; thus, the effect of NO_2 on mortality requires additional investigation. For children aged 5 to 12 years, each increase of 28.3 $\mu g/m^3$ in 2-week average NO_2 exposure corresponds to an increase of about 20 percent in the odds of developing lower respiratory symptoms and disease. No consistent relationship was found between estimates of NO_2 exposure and the prevalence of respiratory symptoms and disease for young children (2 years of age or younger). The exposure-response functions derived in this part can also be applied to health risk assessments of traffic-related air pollution.

(8) Among all air pollutants, particulate matter shows the most consistent association with adverse health outcomes. Thus, in an effort to make a health-based risk assessment of air pollution in China, we conducted research to determine the exposure-response function for each health outcome associated with exposure to air particulate matter, using meta-analysis when there were several studies describing the same health endpoint. We were able to estimate the health risks associated with varying concentrations of air particulate matter. The exposure-response functions suggested in this part can also be applied to health-risk

assessment of air pollution (including traffic-related air pollution) in China.

(9) We also analyzed the use of a new indicator, disability-adjusted life years (DALYs), in the quantitative evaluation of the health impact of ambient air pollution. We used epidemiology-based exposure-response functions to calculate the number of reported health problems attributable to air pollution in Shanghai in 2000, and then we estimated the number of DALYs lost due to health damage caused by air pollution. We estimated that ambient air pollution caused the loss of 103,064 DALYs in Shanghai in 2000 alone. Premature death and chronic bronchitis accounted for the majority of DALYs lost. This analysis shows air pollution continues to damage Shanghai residents' health and strengthens the rationale further limiting air pollution levels in Shanghai. The approach used here will also be applied in the next step of the project, "Traffic air pollution and health in Shanghai."

(10) In order to reduce vehicle emissions, improve air quality by the 2010 World Expo, and raise citizens' living standard, Shanghai should consider taking the following measures:

(1) Transfer more urban construction from Shanghai's central area to peripheral districts.

(2) Leave enough space for non-mobile vehicles and pedestrians on Shanghai streets. This will reduce the interference of non-mobile vehicles and pedestrians with vehicles, improving their driving efficiency.

(3) Consider the health impact of vehicle emissions when making policy decisions. Implement Euro-IV emission standards.

(4) Establish an Inspection and Maintenance (IM) program as soon as possible.

(5) In order to effectively control vehicle emissions in Shanghai and improve air quality in the Yangzi delta region as a whole, work with surrounding provinces to establish a regional vehicle emission control network.

5. Composition of the Report

This report is composed of ten chapters. Chapter one describes the state of Shanghai's economic and social development. Chapter two discusses Shanghai's urban traffic situation, including transportation use levels and traffic conditions. Chapter three analyzes vehicle driving cycles, frequency of start-ups, vehicle technology classifications, and some key parameters like speed–acceleration distribution. Chapter four discusses the results of on-road heavy–duty vehicle emission testing using SEMTECH-D. Chapter five mainly introduces the Shanghai vehicle emission inventory calculated using SIVEM. Chapter six describes the traffic pollution situation on Shanghai roads. Chapters seven and eight introduce the exposure–response relationships involving NO_2 and PM_{10}. Chapter nine discusses the application of DALY in measuring the health effects of ambient air pollution. Finally, chapter ten offers some suggestions and conclusions coming from this first phase of work.

6. Work Plan for Next Phase

We will start the second phase of research for “Shanghai Vehicle Pollution and Health Benefit” in February 2005. Phase two includes the following tasks:

1. Predict increases in vehicle population and transportation use by applying SIVEM.
2. Use SIVEM to analyze various vehicle emissions control scenarios, including business-as-usual, establishment of an IM program, strengthening of emission standards, and total emission control.
3. Predict the exposure level of various air pollutants by applying air quality models.
4. Use DALYs to measure the health impact of ambient air pollution and health benefits that would come through various emission-control scenarios. In addition, we will analyze health and economics calculations.

Main tasks in the second phase of “Shanghai Sustainable Transport and Environment Indicators” are as follows:

1. Update the existing traffic data according to the Origin-Destination (OD) survey conducted in Shanghai in 2004.
2. After research and discussion between China and foreign countries, identify the objective of Shanghai’s sustainable traffic-environment development.
3. Consult with experts and apply an Analytical Hierarchy Process (AHP) to calculate the weight of each indicator.
4. Using results from the “Shanghai Vehicle Pollution and Health Benefit” study, analyze the sustainability of various traffic development scenarios.

5. Develop graphical methods for expressing sustainable transport and environmental evaluation indicators.

Chapter 1. Social Economics and Transportation Environment in Shanghai

1. Shanghai Administrative Region

Shanghai, or "Hu," is an important economic, navigational, historical, and cultural center in China. Located at 31°14' North latitude and 121°29' East longitude, Shanghai has the Yangtze River to the north, East China Sea to the east, Hangzhou Bay to the south, and Jiangsu and Zhejiang Provinces to the west. This is an extremely favorable geographic location; Shanghai is situated in the center of China's coastline from north to south, making communication convenient, and it has a good harbor and vast hinterland. Shanghai averages four meters above sea level. It lies on the edge of the broad flat alluvial plain of the Yangtze Delta with a few remnant hills to the southwest. Covering a total area of 6,340 square kilometers, 6,218 square kilometers of which is land and 122 square kilometers of which is water, Shanghai occupies 0.06 percent of China's total territory. The city is about 100 kilometers in width and 120 kilometers in length.

Land in Shanghai is either state- or collectively-owned. Commerce, industry, storage, municipal virescence, residence, transport, water area, and agriculture are the main uses of Shanghai's land. Among these, water and industry together use the most land, 4,628 square kilometers, 72 percent of Shanghai's total area. Residential land use ranks third.

1.1 Central business district

The central business district (CBD) is composed of Xiaolujiazui in the Pudong region and the area enclosed by the Bund, Henan Road, Renmin Road, Tiantong Road, Changzhi Road, Gongping Road, and Fuxing Road in Puxi region. Covering about five square kilometers, this business region is key to the establishment of "Three Centers."

1.2 Central commercial region

The central commercial region is the area enclosed by Tianmu Road and the old North Station to the north, Urumchi Road and Wanhangdu Road to the west, Fuxing Road and Lujiabang Road to the south, and Lujiazui to the east. It covers an area of 30 square kilometers. With the highest population density, this region is rich in commerce, trade, and finance.

1.3 Region inside the inner ring road

This region comprises the 100-square-kilometer doughnut-shaped zone lying between the central commercial region and the inner ring road. It is dominated by tertiary industry, with industry most concentrated in one urban area. Three thousand of the industries in the region account for 60 percent the area's gross output value and profit, while using a little over 30 percent of the area's total land. Within the region, there are both quite concentrated and relatively decentralized industrial areas. Given the demands future development will place on this area, it should move toward wholesale commerce, partially pollution-free urban industry, and residential areas.

1.4 Region between the inner and outer ring roads

This region includes the Pudong new area, part of Minhang district, and most of Baoshan district, an area of 620 square kilometers. It includes nine industrial parks near the city edge, several large-scale residential districts, various kinds of wholesale markets, and transportation centers. A better infrastructure, including roads, culture, education, and sanitation, is needed to improve this area's infrastructure to the level of a medium-sized city. If such improvements were made, sub-zones within the region could be integrated, with opportunities to both live and work within the region itself, lessening pressure on the central city.

1.5 Region outside the outer ring road

Although this region has several large industrial bases, such as Jinshan, Baoshan and Anting, it is mostly suburban, including most of Jiading district and several suburban counties that have been reformed and changed into districts. A number of industrial parks for township enterprises and some modernized grain and sideline products manufacturing bases are being constructed in order to adapt to the development of the mega city.

2. Population density and distribution

In 2003, the registered population of Shanghai was 13.42 million with an additional floating population of nearly five million. As shown in table 1-1, the average population density is close to 3,000 persons per square kilometer. The highest population density, over 42,000 persons per square kilometer, exists in Jing'an district. The land area of nine central urban districts—Huangpu, Luwan, Xuhui, Changning, Jing'an, Putuo, Zhabei, Hongkou, and Yangpu—is 289 square kilometers, 4.5 percent of the city; its total population, however, is 7.5 million, 41 percent of Shanghai's total population.

Table 1-1 Land area and population density of each district in Shanghai in 2003

District	Land area (km^2)	Total households (10^4)	Year-end registered population (10^4 persons)	Average number of persons per household (person)	Population Density (person/km^2)	Migratory population (10^4 persons)	Year-end total population (10^4 persons)

Total	**6340.50**	**486.06**	**1341.77**	**2.8**	**2116**	**498.79**	**1840.56**
Pudong New Area	522.75	65.23	176.69	2.7	3 380	102.34	279.03
Huangpu	12.41	21.00	61.87	2.9	49854	10.01	71.88
Luwan	8.05	11.68	32.84	2.8	40793	5.12	37.96
Xuhui	54.76	31.95	88.61	2.8	16181	20.50	109.11
Changning	38.30	21.69	61.71	2.8	16113	17.31	79.02
Jing'an	7.62	11.08	32.07	2.9	42084	4.25	36.32
Putuo	54.83	30.81	84.53	2.7	15417	23.36	107.89
Zhabei	29.26	25.86	70.79	2.7	24192	14.63	85.42
Hongkou	23.48	28.61	79.22	2.8	33741	14.74	93.96
Yangpu	60.73	37.99	108.17	2.8	17812	20.34	128.51
Baoshan	415.27	32.29	85.43	2.6	2057	43.98	129.41
Minhang	371.68	28.32	75.12	2.7	2021	73.38	148.50
Jiading	458.80	17.27	51.18	3.0	1115	40.01	91.19
Jinshan	586.05	17.36	52.71	3.0	899	7.52	60.23
Songjiang	604.71	16.77	50.68	3.0	838	32.55	83.23
Qingpu	675.54	14.86	45.83	3.1	678	27.01	72.84
Nanhui	687.66	27.66	69.91	2.5	1017	16.56	86.47
Fengxian	687.39	20.53	50.87	2.5	740	19.77	70.64
Chongming	1041.21	25.10	63.54	2.5	610	5.41	68.95

Figure 1-1 shows that Shanghai's registered population has become progressively less agricultural since the 1980's. By 2003, the agricultural population had decreased to 22 percent percent.

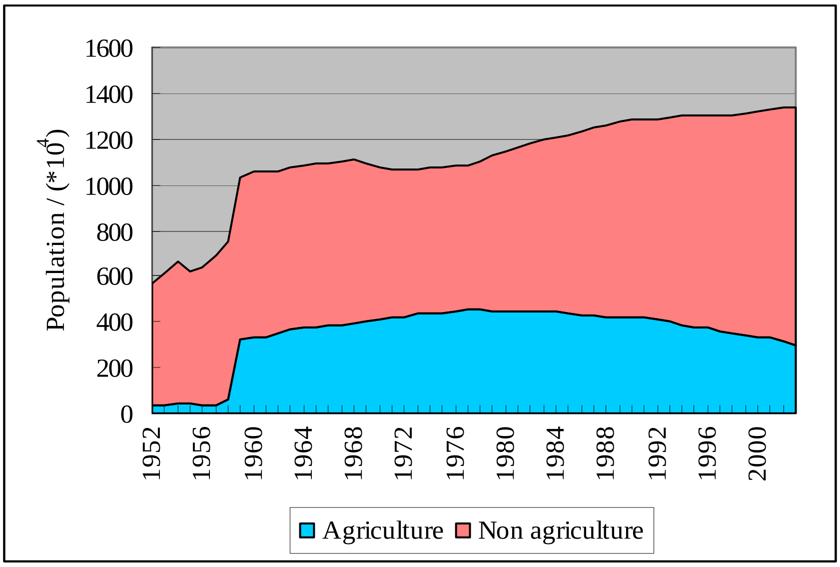

Figure 1-1 Composition of Shanghai's registered population, 1952-2003

3. Development of the Shanghai's economy

Shanghai's economy has been developing quickly since the 1990's. GDP growth rate exceeded 10 percent every year from 1992-2003, reaching 62.5 billion RMB, about 7.57 billion dollars, by the end of 2003. Per capita GDP (considering both the registered and floating populations) is more than $4,000; it is $5,600 if only the registered population is considered.

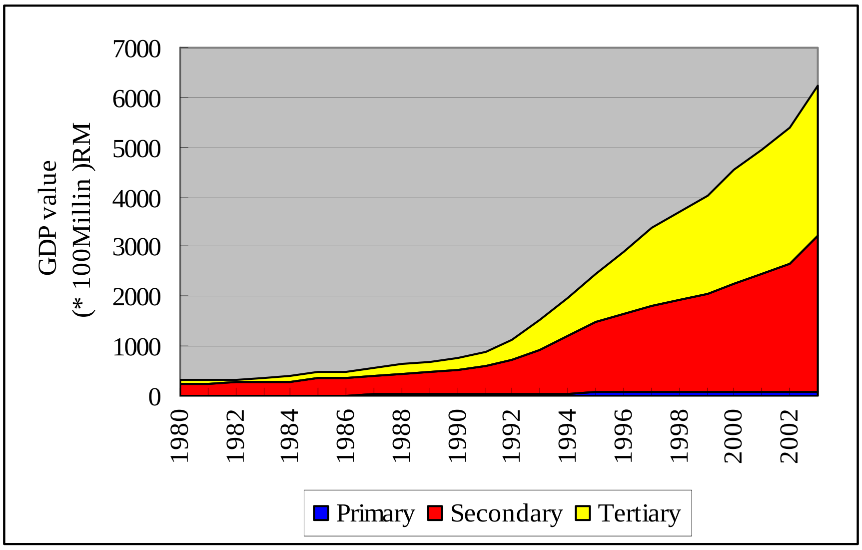

Figure 1-2 Gross Domestic Product in Shanghai, 1980-2003

Figure 1-3 shows changes in the composition of Shanghai's industry from 1980-2003. During that time, Shanghai steadily changed from an industrial city to an industrial and commercial seaport. By 2003, GDP of primary industry made up 1.5 percent of Shanghai's total GDP; secondary industry, 50.1 percent; and tertiary industry, 48.4 percent. Now secondary and tertiary industry are growing at roughly the same rate. It is anticipated that the proportion of tertiary industry will keep increasing, with high-technology industries constituting a growing proportion.

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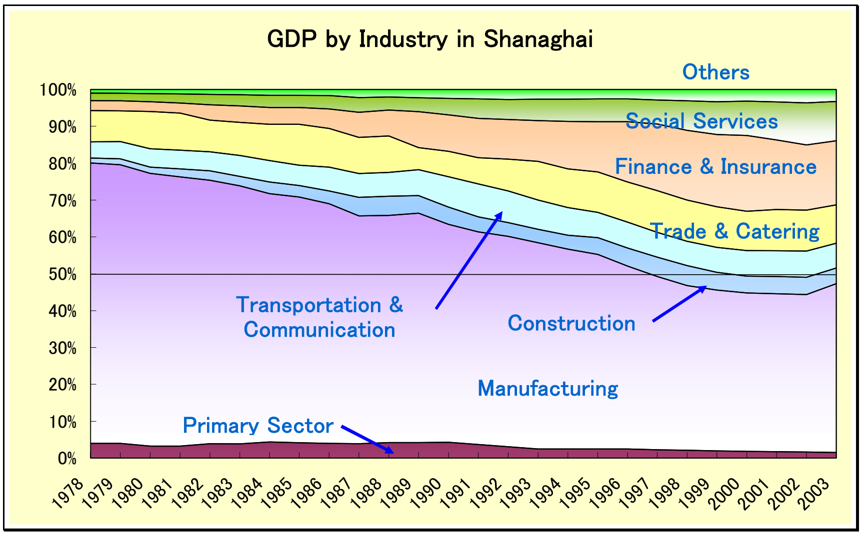


Figure 1-3 Shanghai's industrial structure, 1980-2003

4. Labor force and employment positions

In 2003, there were 8.13 million people, equal to 44 percent of the total population, working in Shanghai. Seventy-four thousand of them, constituting 9 percent of the total workforce, worked in agriculture; 3.17 million, about 39 percent of the total workforce, worked in secondary industry; 4.22 million, 52 percent, worked in tertiary industry. Thirty-four percent of the labor force worked in manufacturing, 14 percent in wholesale and retail, nine percent in residences and other services. No other single position accounted for more than five percent of the total labor force.

Table 1-2 Number of employees (10,000s) in different sectors in Shanghai, 2003

Industry	Staff and workers	Classified according to the categories of registration				
		State-owned Units	Collectively-owned Units	Others	of which	
					A	B
Total	813.05	163.69	240.12	409.24	160.73	81.62
Grouped by industry						
Primary industry	73.72	1.07	71.92	0.73	0.29	0.02
Secondary industry	317.12	43.88	104.77	168.47	45.66	68.55
Tertiary industry	422.21	118.74	63.43	240.04	114.78	13.05

A: urban privately-run businesses

B: units with investment from Hong Kong, Macao, Taiwan, or foreign countries

5. Income of urban residents

The average annual wage for all working residents of Shanghai was 22,160 RMB (about $2,686) in 2003. Employees in state-owned agencies averaged 22,541 RMB (about $2,732); those in collectively-owned companies, 9,844 RMB (about $1,193); and those in corporations with investment from Hong Kong, Macao, Taiwan, or abroad, 27,976 RMB (about $3,391). Calculated by comparable price, the average annual wage of workers in 2003 was 2.5 times their wage in 1990.

6. Consumptive expenditures of urban residents

The disposable income of Shanghai urban households increased steadily from 1980 to 2003. By 2003 it had risen to 14,867 RMB (about $1,802), five times that of 1980, calculated by comparable price. Consumptive expenditures likewise increased, rising from 553 RMB in 1980 to 11,040 RMB (about $1,338) in 2003, an increase of 3.8 times.

As income increased, the proportion of income spent on food decreased. The United Nations Food and Agriculture Organization (FAO) uses the Engel coefficient (the ratio of food expenditures to total expenses) to describe the level of individuals' quality of life in the following way:

- above 59 percent: living in poverty,
- 50-59 percent: warmly dressed and well fed,
- 40-50 percent: comparatively well off,
- 30-40 percent: affluent,
- below 30 percent: rich.

By this standard, the average urban household in Shanghai has been comparatively well off since 1998 (see figure 1-4).

Table 1-3 Disposable income and consumptive expenditures of urban residents in Shanghai

Year	A	B	C	D	E
1980	637	553	100	100	56.0
1985	1 075	992	140.72	149.53	52.10
1990	2 182	1 937	167.93	171.68	56.50
1995	7 172	5 868	254.60	239.97	53.40
2000	11 718	8 868	356.19	310.52	44.50
2001	12 883	9 336	391.61	326.90	43.40
2002	13 250	10 464	449.38	362.45	39.40
2003	14 867	11 040	497.76	384.27	37.20

A: Average disposable per capita income, RMB

B: Average per capita consumptive expenditures, RMB

C: Index of average per capita disposable income (1980=100)

D: Index of average per capita consumptive expenditures (1980=100)

E: Engel coefficient

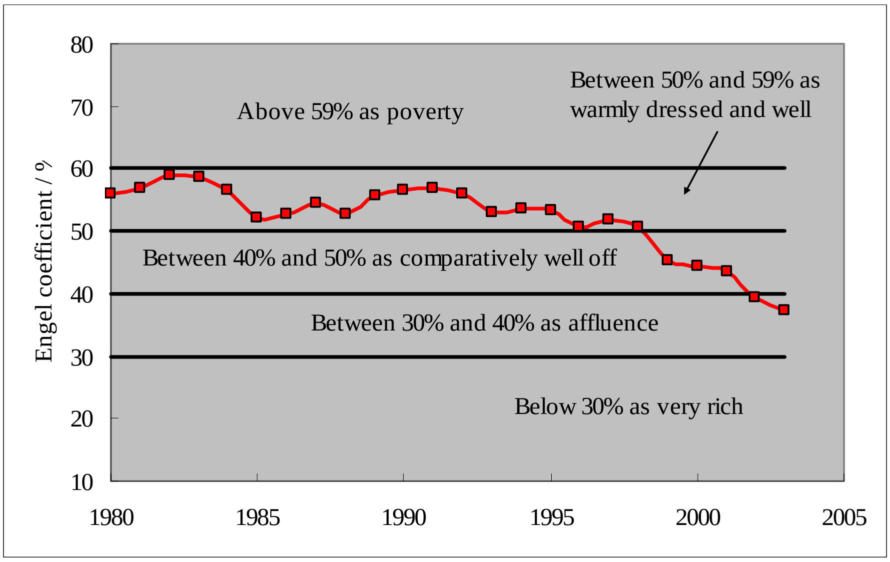


Figure 1-4 Living quality of urban residents in Shanghai

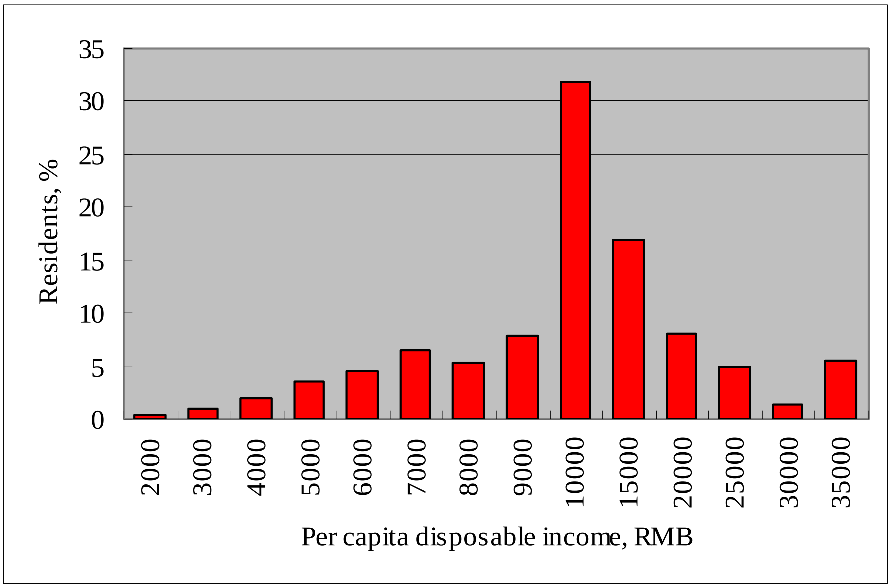


Figure 1-5 Disposable income distribution of urban residents in Shanghai

Table 1-4 shows the incomes and expenditures of rural households in Shanghai. The per capita income of rural households was 7,260 RMB (about $880) in 2003, only 48.8 percent that of urban households. However, income distribution in Shanghai is skewed; 30 percent of urban households in Shanghai have a disposable income less than 10,000 RMB (about $1,212) while over 35 percent have a disposable income more than 15,000 RMB (about $1,818).

If we also include Shanghai's agricultural population (22.4 percent of the total population), the proportion of households whose disposable income is lower than 10,000 RMB rises to 45.7 percent, more than 4.86 million households.

Table 1-4 Disposable incomes and consumptive expenditures of rural residents in Shanghai

Year	A	B	C	D	E
1990	1990	1665	1592	100	100
1995	4861	4246	4041	255	267
2000	6400	5565	5578	336	328
2001	6827	5850	6353	351	377
2002	7080	6212	6988	373	421
2003	7260	6658	6931	400	449

A: Average per capita disposable income, RMB

B: Average per capita consumptive expenditure, RMB

C: Average per capita total expenditure, RMB

D: Index of average per capita disposable income (1990=100)

E: Index of average per capita consumptive expenditures (1990=100)

Chapter 2. Urban Traffic Environmental Status

1. Economic development and transportation

Urban transportation in the Shanghai area includes both passenger and freight transport. For each of the past 20 years, daily traffic volume has increased. Around the turn of the century, Shanghai freight transportation grew extremely rapidly; the total annual freight transportation volume in 2000 was four times that in 1986 (see table 2-1).

Table 2-1 Economic, population, transportation, and vehicle numbers in Shanghai

Year	GDP* (10^8 Yuan)	Population (10^4)	Daily traffic volume** (million passenger times)	Outgoing time per person per day*** (times)	Annual freight amount (10^8 kilometers)	Vehicle population (10^4)
1986	1144	1352	23.06	1.71	12.6	15.81
1995	2658	1463	28.38	1.94	9.3	41.99
1998	3727	1489	32.83	2.20	49.4	58.27
2000	4551	1522	35.00	2.30	56.4	103.77

* 2000 prices

** includes the outgoing times of floating population

*** data based on total population

Figure 2-1 shows the changes in Shanghai's economic development, annual roadway passenger transport amount, and vehicle population from 1986 to 2003. In order to accommodate the growing demand for transportation, Shanghai's vehicle population has greatly increased.

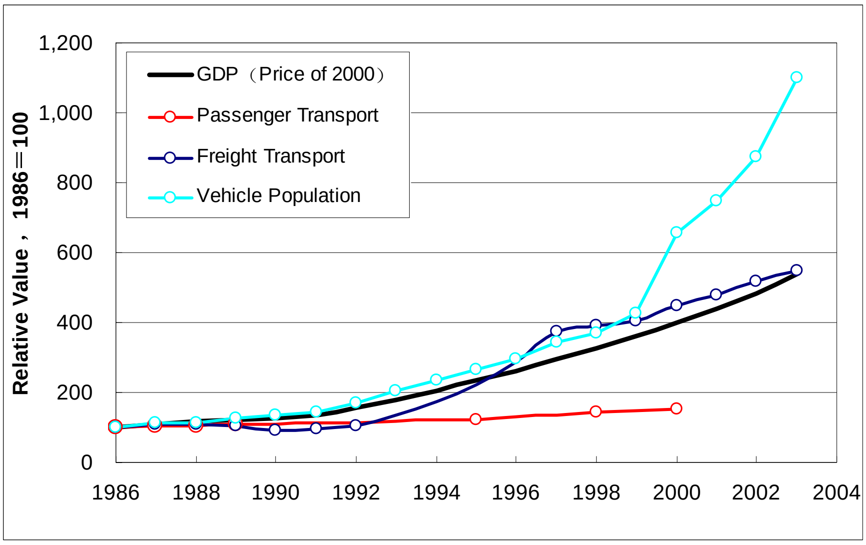


Figure 2-1 GDP, transportation volume, and vehicle population in Shanghai, 1986-2003

1.1 Economic development and passenger volume

Figure 2-2 shows the relationship between Shanghai GDP and passenger volume.

As the economy continues to flourish, total passenger volume in Shanghai is likewise increasing. The daily volume in 1986 was 23.06 million passenger-times; in 2000 it reached 35.0 million, with an average annual increase of three percent. The relationship between GDP and passenger transport volume is parabolic.

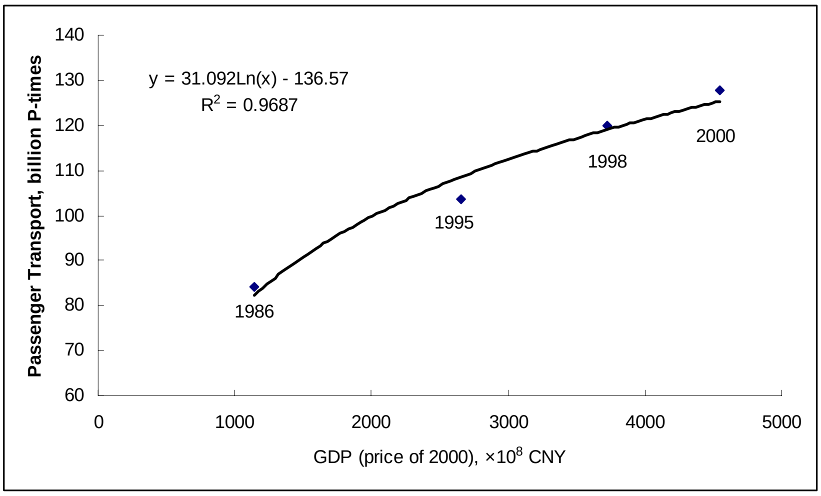


Figure 2-2 Relationship between GDP and annual passenger volume, 1986-2000

1.2 Economic development and freight volume

Figure 2-3 shows the relationship between Shanghai's annual freight volume and GDP from 1986 to 2003. During this period, freight volume in Shanghai increased steadily alongside GDP growth. The rate of increase was fastest from 1990 to 1995. Recently, the amount of freight transported in the Shanghai area has stabilized, due to a series of policies in the early 1990s that, among other things, introduced foreign investment to Shanghai and opened Pudong. From 1986 to 2003, the volume of freight on Shanghai's roadways increased with GDP roughly logarithmically; the freight volume growth rate is lower than the rate of economic development and recently growing more steady.

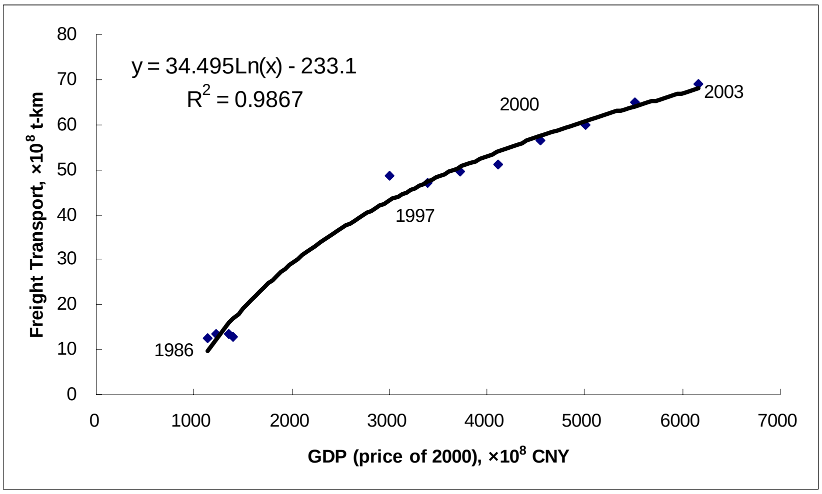


Figure 2-3 Relationship between Shanghai's GDP and freight volume, 1986-2003

2. Urban roadway transport conditions

2.1 Road construction

In order to meet traffic demands, Shanghai has increased urban road construction since middle 1990s. A highway road network, arranged like the word '申', was scheduled for completion by the end of 2004. Now, the ground arterial roads in Shanghai's urban center, arranged in the "Three Horizontal and Three Vertical" road pattern, are 55 kilometers in length, and have helped raise average vehicle speed. Particularly in the last five years, Shanghai has constructed several new roads connecting Puxi and Pudong and crossing the Huang Pu River, including Fuxing East Road tunnel, Dalian Road tunnel, Outer Ring Road tunnel, Yan-an East Road tunnel, Xupu Bridge, and Lupu Bridge. These improvements have increased transportation capacity crossing the river and accelerated the formation of east-west axes. Furthermore, the construction of the Outer Ring Road is helping facilitate the development of Shanghai's outer areas.

By the end of 2004, Shanghai's construction reached a milestone when construction on most aspects of its original plan was completed. Now Metro Line No. 1 (including the extended line) is 15.2 kilometers in length, Line No. 2 is 16.3 km, Phase 1 of the Mingzhu Line (Line No. 3) is 25.0 km, and the Xinmin Line (Line No. 5) is 17.0 km, bringing the total length of Shanghai rail transit to about 121.8 kilometers (see Table 2-2).

Shanghai's government has also recently rebuilt 2,117.01 kilometers of roadway, particularly highways. The building of Hu Ning, Hu Hang, and Jia Liu Highways has made communication between Shanghai and neighboring provinces more convenient and efficient.

Table 2-2 Mileage (in kilometers) of Shanghai metro transportation, 1995-2004

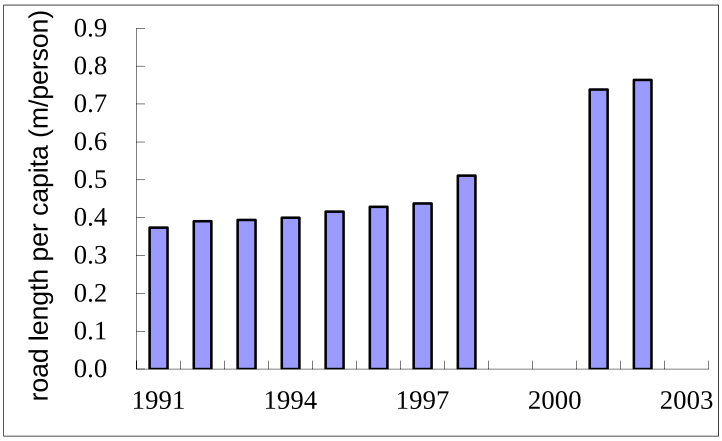
	Line No. 1	Line No. 2	Line No. 3	Line No. 5	Maglev	Total Length of the rail transit
1995	15.2					15.2
1997	21.0					21.0
2000	21.0	16.3	25.0			62.2
2003	21.0	16.3	25.0	17.0	30.0	109.2
2004	33.5	16.3	25.0	17.0	30.0	121.8

2.2 Roadway network

Currently, the roadway network in Shanghai is composed of "Three Horizontal and Three Vertical Roads" and "Three Rings and Ten Radiative Roads". The "Ring and Cross" highway in Shanghai's center, which includes the Inner Ring Road, North and South Viaduct, and Yan-an Road Viaduct, is the backbone of the city's road system. The previously-separate Outer Ring Roads were fully connected in 2003. The construction of the Medium Ring Road was started in 2004 and will be completed by 2007. By then, the "Three Ring and Ten Radiative Roads" will be about 300 km in length. The "Three Horizontal and Three Vertical Roads" in the city center includes nine arterial roads, all of which are connected. Total length of arterial roads in the city center will reach 690 km by 2005. In the city center, the main roads are only for vehicle use, and sub-main roads will be expanded. In Shanghai's outer areas, main goals include constructing new radiative roads, upgrading roadway network density, and connecting segmented roadways. When these goals are completed, the total length of suburban roadways will reach 2304 km, including 540 km of highways.

2.3 Roadway indicies

Road length and road area per capita increased remarkably from 1991 to 2003. Road length per capita was 0.37 meters in 1991; by 2003 it had increased more than two-fold, to 0.76 m. Road area per capita was 11.46 m^2 in 2002, 2.5 times that in 1991 (see Figure 2-4). Road length and road area per vehicle, on the other hand, fluctuated greatly between 1991 and 2003 (see Figure 2-5). Over those 12 years, road length and road area ranged between 6.0 and 9.1 meters and 69.2 and 112.0 m^2, respectively, per vehicle. Despite these fluctuations, in general the vehicle population is increasing faster than roadway length.



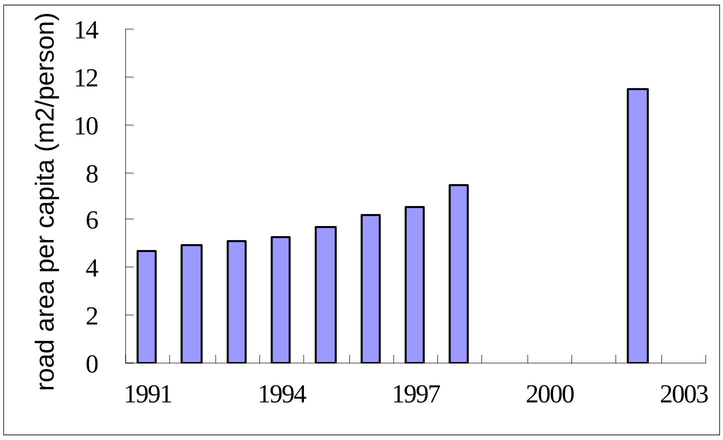
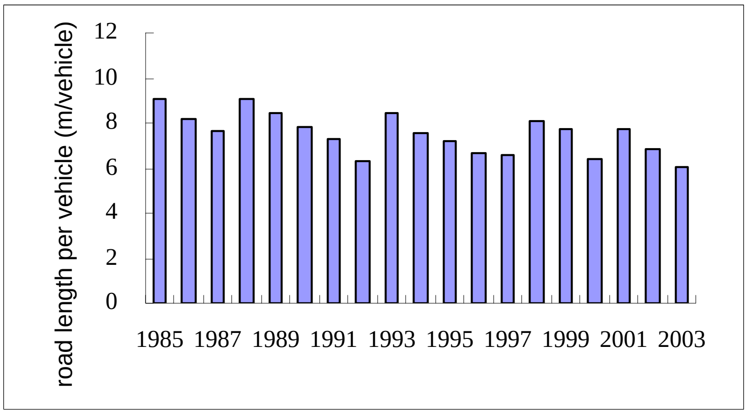


Figure 2-4　　Road length and road area per capita in Shanghai, 1991-2003



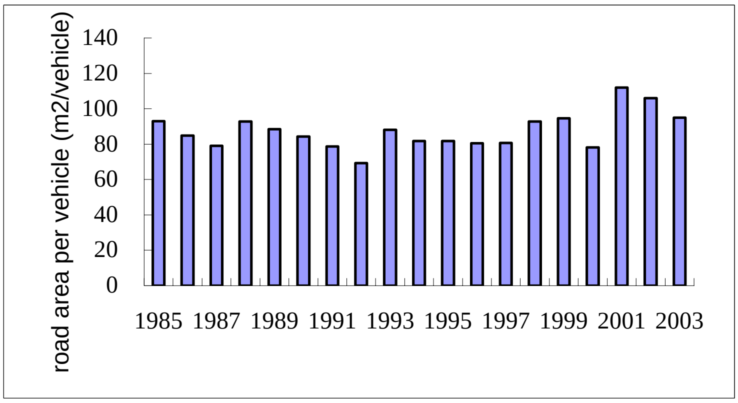


Figure 2-5　　Road length and road area per vehicle in Shanghai, 1985-2003

2.4 Road length of urban public transit

Figure 2-6 shows public bus route length in Shanghai from 1996 to 2003. From 1996 to 2001 bus route length increased relatively quickly; for instance, the length in 1998 is four percent greater than that in 1997. However, this rapid growth ceased after 2001, decreasing seven percent from 2001 to 2002, and increasing only 105 km between 2002 and 2003.

Planners hoped that lengthening bus routes would streamline urban transport and reduce the use of private vehicles. This hope did not materialize. Blindly extending public bus operation length will not, in itself, improve urban transport. It is more effective to optimize bus routes, develop BRT (bus rapid transit), and diversify modes of transportation.

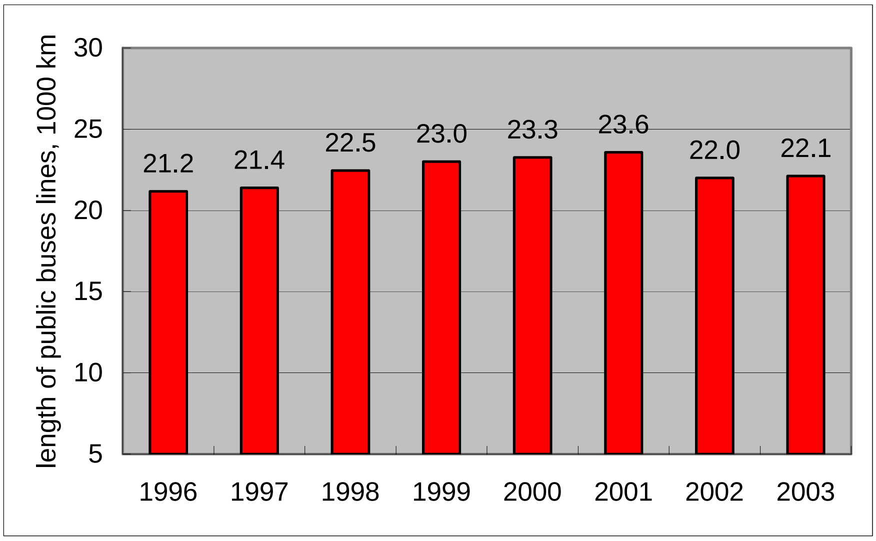


Figure 2-6 Road length of public bus routes in Shanghai, 1996-2003

3. Vehicle population and composition

3.1 Growth of vehicle population

As noted earlier, the vehicle population in Shanghai is growing at a torrid pace. The growth rate of the vehicle population has recently even outpaced GDP growth, substantially so in the late 1990s. Shanghai's per capita GDP increased 1.82 times from 1990 to 1995; the vehicle population increased 1.99 times over the same period. Per capita GDP increased 1.68 times from 1995 to 2000; vehicle population increased 2.47 times. Per capita GDP in 2003 was $5,618 USD, 1.68 times that in 2000; vehicle population in 2003 was 1.738 million, 1.66 times that in 2000.

Table 2-3 Vehicle population and per capita GDP in Shanghai, 1960-2003

Year	GDP Per capita (2000 price, USD)	Vehicle population (1000s)
1960	349	13
1965	251	15
1970	388	23
1975	533	52
1980	750	91
1985	1091	125
1990	1363	212
1995	2476	421
1996	2791	466
1997	3143	538
1998	3458	583
1999	3792	676

2000	4174	1043
2001	4581	1198
2002	5053	1390
2003	5618	1738

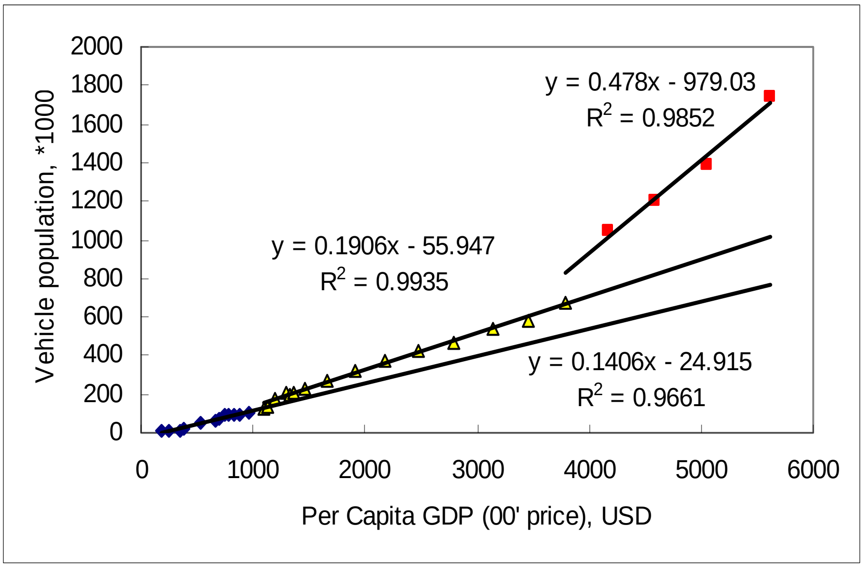


Figure 2-7 Relationship between vehicle population and per capita GDP, 1950-2003

Figure 2-7 plots vehicle population versus per capita GDP. Vehicle growth can be divided into three phases. Phase one is the period before 1984. During this period, the social economic activity level in Shanghai was low, per capita GDP was lower than $1,000, the growth rate of the vehicle population was limited by the planned economy, and vehicles were owned mainly by the government and state-owned enterprises. Phase one is characterized by very slow growth in the vehicle population.

Phase two is the period from 1985 to 1998. During this period, per capita GDP increased from $1,000 to $4,000, and multi-component economic entities including both state- and privately-owned enterprises were founded. During this phase, the vehicle population increased at a slightly higher rate than during the first phase.

Phase three is the period from 1999 to 2003. During this period, per capita GDP rose beyond $4,000, quality of life substantially improved, and the demand for cars increased each year, as most Shanghai citizens were already comfortably housed. In 2003, the number of new private vehicle registrations reached 5,000-6,000 vehicles per month. During this phase, the vehicle population grew remarkably fast, and vehicles became the major source of urban air pollution in Shanghai.

3.2 Vehicle Composition

According to research conducted in 2002 by the Shanghai Public Security Bureau’s Traffic Police, medium and heavy-duty vehicles make up nine percent of all the vehicles in Shanghai; light-duty vehicles, 36 percent; motorcycles, 54 percent; and other vehicles, including tractors, trailers, and professional machines, only one percent. Table 2-8 shows the change in vehicle composition of the whole city from 1998 to 2002.

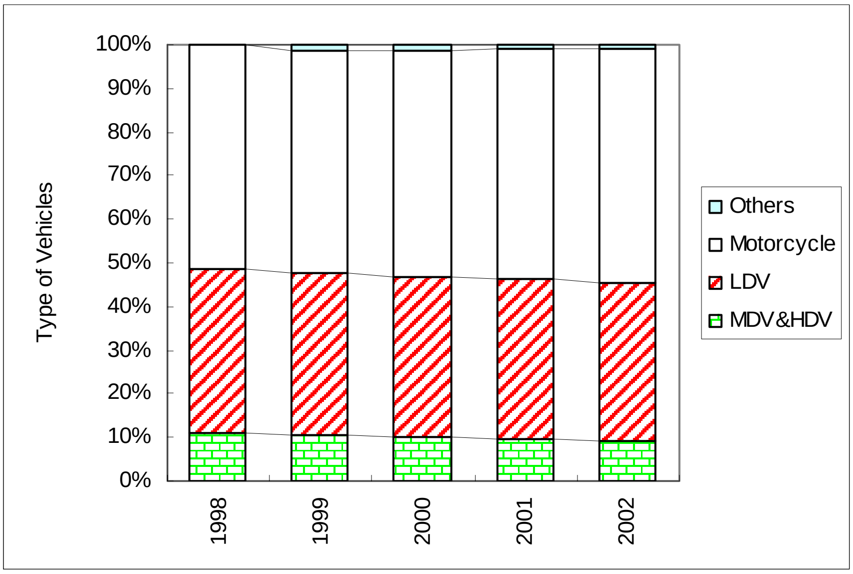


Figure 2-8, Vehicle composition in Shanghai, 1998-2002

4. Passenger traffic modal split and transportation capacity

Figure 2-9 shows recent trends in passenger modal split in Shanghai. In the 1980s, riding bicycles, walking, and taking public transportation were the predominant means of transportation. In the 1990s, Shanghai's government began gradually decreasing subsidies given to public transit companies in order to enhance the market competence of the public transportation system. At the same time, many industrial and residential areas on the city center were changed into commercial areas. As a result, many residents moved away from the city center, leaving the public transportation system unable to meet commuting residents' increasing demand. Therefore, more residents began using private transportation.

By 1995, fewer people were biking, walking, and using public transportation, and more were riding mopeds and motorcycles. As living quality rose, incomes increased, and public transportation improved, Shanghai residents gradually turned from non-mobile transportation, such as walking and riding bicycles and motorcycles, to public transit and other mobile patterns. By 2000, about 54 percent of passengers took public transportation or cars, with only 34 percent taking non-mobile transportation. In recent years, the use of public transportation has grown, indicating some improvement has been made since 2000.

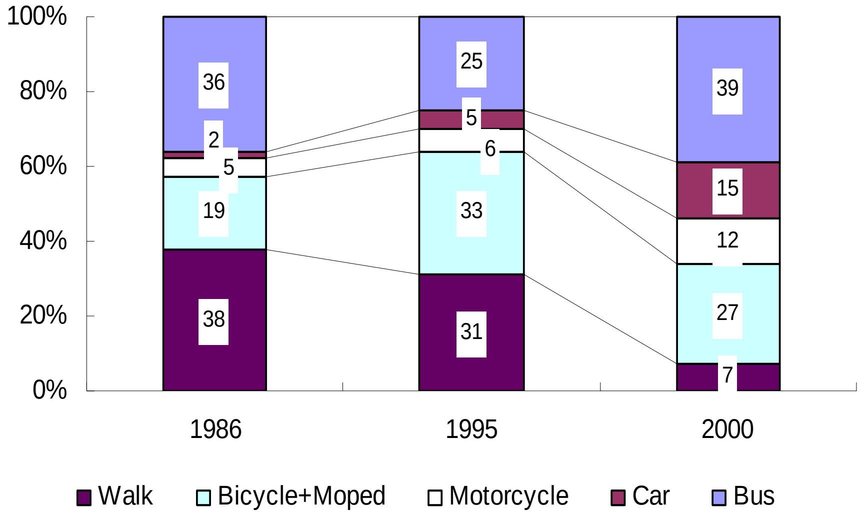


Figure 2-9 Passenger modal split in Shanghai, 1986-2000

4.1 Public transportation

Table 2-4 shows the major indices of Shanghai's public transportation. By 2003, there were 952 public transportation lines, the total length of which was 22,110 km. There were 18,625 buses, a slight increase from 2002. However, the number of passengers taking buses decreased from 2.775 billion in 2002 to 2.731 billion in 2003. With the economic development and living quality improvement, public transportation is becoming less attractive, while the usage of more convenient, private transportation, like private cars and motorcycles, is growing.

Table 2-4 Major indices of Shanghai public transportation, 1996-2002

	Unit	1996	1997	1998	1999	2000	2001	2002	2003
Road length of Public transit	km	45,840*	51,220*	53,901*	23,007	23,260	23,586	22,005	22,110
Number of lines	line	1,058	1,078	1,098	976	978	991	951	952
Number of vehicles	vehicle	13,323	14,207	15,282	16,661	17,939	18,083	18,541	18,625
Number of passengers	billion passenger times	2.307	2.378	2.488	2.420	2.649	2.684	2.775	2.731

*including long-distance transportation lines

4.2 Taxis

Compared with public transportation, taxis handle very few passengers but, nonetheless, occupy an important transportation niche. Table 2-5 shows the operation indices of Shanghai taxis. There were 48,672 taxis in Shanghai in 2003, 1,163 more than a year prior. The driving mileage increased from 5.137 billion km in 2002 to 5.645 billion km in 2003. According to data from the Shanghai Comprehensive Transportation Planning Institute, the daily passenger-times in 2003 was 2.45 million, an

18.7 percent increase from 2001. The average mileage in 2003 was 6.3 km per passenger-time, with most trips being medium or short distance. In general, Shanghai taxi usage is slightly, steadily increasing.

Table 2-5 Operation indices of Shanghai taxis, 1996-2002

	Unit	1996	1997	1998	1999	2000	2001	2002	2003
Number of taxis	Vehicle	38,554	40,977	41,183	42,056	42,943	46,921	47,509	48,672
Number of passengers taken	Million passenger-times	186.13	223.87	273.68	311.09	375.99	367.84	440.92	497.29
Operation mileage	billion km	2.743	2.967	3.5.94	4.005	4.648	4.607	5.137	5.645

4.3 Railway transportation

In recent years, the Shanghai government has increasingly turned to rail transit as one solution to its traffic problems. The total length of rail transit lines was 109 km in 2003, 45.73 km longer than in 2002. In 2003, the 17 km-long Xinmin Line (No. 5 line) and 30 km-long Maglev Line were completed. Then, in 2004, the extension of Line No. 1 (from Shanghai railway station to the Tonghe New Village Station) went into operation, increasing the total length of rail transit lines in Shanghai to 121.8 km. In 2003, the total number of passengers transported by rail reached 406 million passenger-times, 13.6 percent higher than in 2002. Rail transit is an increasingly important aspect of Shanghai's public transportation system, and given its efficiency and relative cleanness, the growth of rail transit is a positive development for Shanghai sustainable transport.

Table 2-6 Daily passengers transported by rail transit in Shanghai, 1996-2002

	Unit	1996	1997	1998	1999	2000	2001	2002	2003
Operation vehicles	cars	96	96	96	96	216	216	330	445
Length of operation lines	km	15.21	20.06	20.06	20.06	62.92	62.92	62.92	109.2
Operation mileage	million km	1.287	1.758	2.115	2.239	3.246	5.390	6.333	8.132
Total passenger times	hundred million persons	0.89	1.12	1.26	1.09	1.36	2.83	3.57	4.06

4.4 Private transportation

Private transportation refers mainly to private light-duty passenger cars, motorcycles, light-duty motorcycles, and mopeds. In 2003, the number of private light-duty passenger cars was 221,000, the daily average operation mileage per vehicle was 49 km, and the total passenger-times was about 485 million. The total number of motorcycles and light-duty motorcycles was about 980 thousand, their daily average mileage was 12 km, and the total passenger-times was about 898 million. The number of registered mopeds in Shanghai was about 350,000, their daily average mileage was around 12 km, and the total passenger-times was about 380 million.

Table 2-7 shows the fast rate of private transportation usage growth. Since the use of public transportation is growing slowly in comparison, citizens are using private transportation in greater and greater proportions. Although it is necessary during the urban mobilization process, the fast growth of Shanghai's private car fleet poses a serious challenge to Shanghai given its limited land and dense population. The sustainable development of Shanghai's private transportation is an important research field.

Table 2-7 Number of private vehicles and passenger times in Shanghai, 1996-2002

		Unit	1996	1997	1998	1999	2000	2001	2002	2003
Private light-duty passenger cars	Vehicle number	thousand	8.1	8.6	19.7	30.9	42.0	81.0	140	221
	Passenger times	10^8	0.18	0.19	0.43	0.68	0.92	1.77	3.07	4.85
Motorcycle + light motorcycle	Vehicle number	10^4	15	41	45	49	54	64	76	98
	Passenger times	10^8	1.35	3.75	4.13	4.51	4.89	5.81	6.92	8.98
Mopeds	Vehicle number	10^4	47.8	49.0	48.0	42.5	37.0	37.4	36.4	35
	Passenger times	10^8	5.2	5.4	5.3	4.7	4.1	4.1	4.0	3.83

4.5 Official vehicles

An official vehicle is one owned by a company, agency, or the government. In the 1990s, official vehicles accounted for a large proportion of light-duty passenger cars. More recently, because the demand for private cars is increasing rapidly while the demand for official vehicles is relatively stable, official cars account for a smaller proportion of total light-duty passenger cars. In 2003, the total number of official vehicles was about 270,000, and the total number of passenger-times was about 600 million.

Table 2-8 Number of official vehicles and passenger-times transported in Shanghai, 1996-2002

		Unit	1996	1997	1998	1999	2000	2001	2002	2003
Official vehicles	Vehicle number	10^4	12.6	15.2	16.2	18.1	20.2	22.4	23.1	27.0
	Passenger times transported	10^8	2.76	3.34	3.55	3.97	4.42	4.91	5.06	5.91

4.6 Bicycles

Bicycles remain an important mode of transportation in Shanghai. By the end of 2002, there were 7.640 million bicycles in Shanghai, and bicycle transport volume was about 669 billion passenger-times per year. Table 2-9 shows amount of bicycle usage from 1996-2002.

Table 2-9 Number of bicycles and passenger-times transported in Shanghai, 1996-2002

		Unit	1996	1997	1998	1999	2000	2002
Bicycle	Numbers	10^4	589	175	332	500	660	764

	Passenger times transported	10^8	51.6	15.3	29.1	43.8	57.8	66.9

5. Traffic saturation situation

In early 1990s, Shanghai increased road construction, significantly improving all road traffic indices. However, as transportation demand grows faster than supply, the Shanghai traffic environment has been facing a new and more serious challenge since 2004.

Road width is good indicator of traffic saturation. Figure 2-10 shows there are three phases in the traffic situation between 1990 and 2002. During the first phase, 1991-1997, roads throughout the city were widened and transit capacity steadily increased. This changed during the second phase, 1998-2000. During this phase, road construction decreased as the vehicle population grew at unprecedented rates, decreasing relative road transit capacity. The increase in traffic did not receive enough attention at this time.

During the third phase, 2001-present, the vehicle population was growing much faster than road construction, particularly during 2003 and 2004. Shanghai continued to construct new road and widen existing ones; however, roads were often widened at the expense of non-mobile sections. Thus, although road area for vehicles increased, the transportation situation actually worsened.

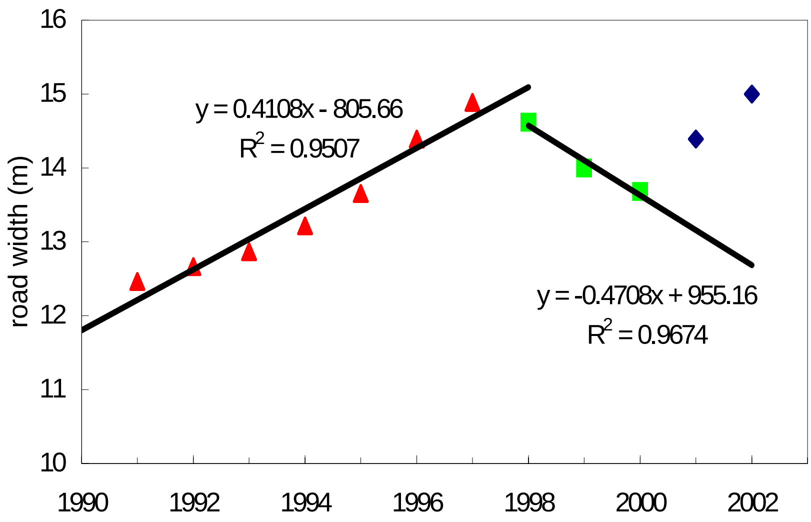


Figure 2-10 Road widths in Shanghai, 1990-2002

Figure 2-11 shows traffic volume comparison data from the Shanghai Police Security Bureau.

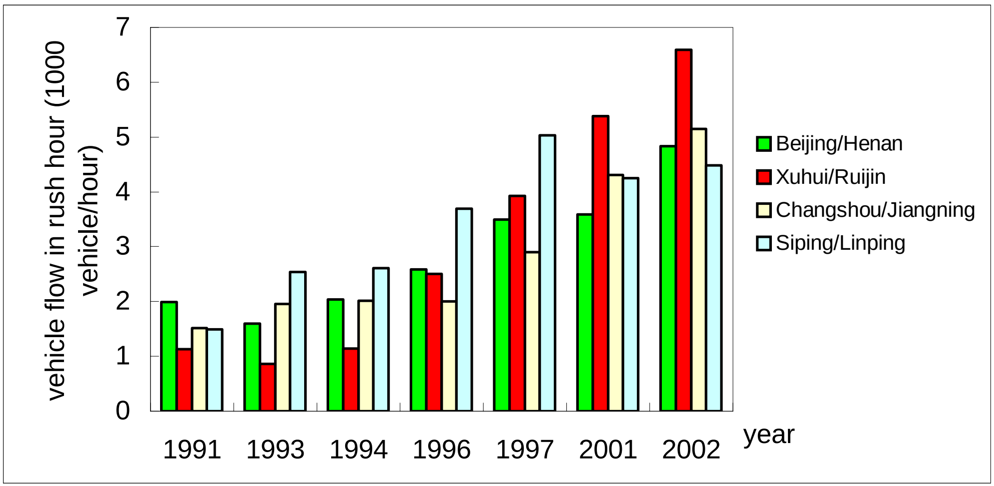


Figure 2-11 Vehicle flow during rush hour at monitoring points in Shanghai, 1991-2002

The four monitoring points were located in Huangpu, Luwan, Putuo, and Hongkou districts. Vehicle flow during rush hour at the Beijing-Henan Roads and Xuhui-Ruijin Roads intersections decreased from 1991 to 1993, but it has been increasing rapidly since 1994; vehicle flow during rush hour at the Changshu-Jiangning Roads intersection has been continually increasing; vehicle flow at the Siping-Linping Roads intersection increased steadily from 1991 to 1997, but decreased slightly from 1997 to 2002. In general, the vehicle flow during rush hour at the monitoring points is continually increasing, since the vehicle population of the whole city is rapidly growing.

Since April 2004, vehicle flow on highways during the day has been growing and most parts of the highways are saturated all day. Traffic conditions are relatively good on the east-north part of the Inner Ring Road (from Yangpu Bridge to Da-Baishu) but the section from Guangzhong Road to North Xizhang Road is quite crowded. Traffic conditions in other parts in the city are bad for the most part. North-South Highway near Yan-an Cross road is saturated; likewise, East-West Highway, particularly the section around Tongren Road, has been quite saturated since the middle part was completed.

The traffic capacity crossing the Huang Pu River is representative of traffic flowing west to east through the city center. In 2001, the average number of vehicles crossing the river daily was 370,923, 30 percent more than in 2000. Now, besides Dalian and Fuxing Road tunnels, all cross-river routes have reached or surpassed designed capacity, with two bridges and two tunnels particularly overwhelmed.

North to south traffic in the city center is mainly borne by four main roads: Chengdu Road (including the North-South Highway), Zhongshan West Road (including the Inner Ring Highway), the east vertical arterial road (Wai-Bai-du Bridge, Wusong switch bridge, and Zhongshan East One Road), and the west vertical arterial road (Cao-yang Road, Wu-ning Road, and Jiang-su Road). In whole Shanghai area, three highways, Hu-Ning, Hu-Hang, and Hu-Jia, bear one-third of total traffic, altogether about 25 million vehicles a year, 20,000-30,000 a day.

Although the transit capacity of public transportation has increased somewhat, it still cannot match increasing demand. During the first nine months of 2004, the number of passengers taking public transportation grew, the daily average reaching 12.05 million (1.28 taking railway transit; 7.72 million, ground public transportation; and 3.05 million, taxi).

Traffic in the second half of the year is generally slightly heavier than in the first half. There is little seasonal change in traffic volume; although, traffic is generally slightly lower in January and February and generally peaks in November.

6. Traffic safety

According to data from the Shanghai Public Security Bureau, there were 47,088 traffic accidents in Shanghai in 2002. Of these, automobiles (including both heavy-duty and light-duty vehicles) caused 85 percent; motorcycles, 5 percent; non-motor vehicles, 6 percent; passengers on foot and bike, 3 percent; and other vehicles (including tractors), 1 percent.

Table 2-11 and Figure 2-12 show the relationship between the motor vehicle population and the number of casualties in traffic accidents from 1990 to 2002. As expected, as the vehicle population increases, there are more casualties. However, the ratio of casualties to vehicle population is actually falling, perhaps due to Shanghai's traffic management improvements. Figure 2-12 shows that, in recent years, the traffic accident percentage in Shanghai has remained at about 12 persons per 1000 vehicles, including 11 injured and 1 death.

Table 2-11 Traffic Accidents and Vehicle Population in Shanghai, 1990-2002

Year	Vehicle Population (1000s)	Traffic accidents (100s of cases)	Deaths	Injuries
1990	212	76	608	4,710
1991	229	75	594	4,450
1992	266	45	591	3,570
1993	321	81	699	2,880
1994	372	126	722	3,310
1995	420	167	788	3,770
1996	466	201	783	4,380
1997	538	216	781	5,830
2002	1,390	471	1,400	15,690

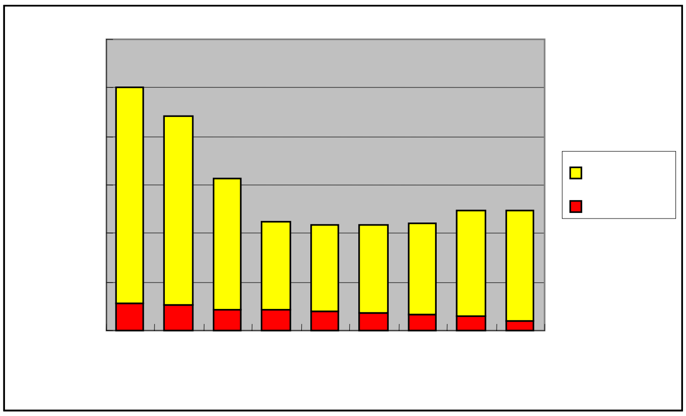


Figure 2-12　Number of Casualties in Traffic Accidents in Shanghai, 1990-2002

Most traffic accidents are of light or medium severity; serious accidents are relatively rare.　Most accidents are caused by either mixed traffic flow (vehicle and non-vehicle mixed traffic) or traffic rule infractions.

7. Parking lots

Figure 2-13 shows the number and capacity of on-road parking spaces.　From 1991 to 1997, the number of on-road parking spaces increased; however, the number and capacity of on-road parking spaces decreased significantly from 1997 to 2002, decreasing to approximately their 1994 levels.

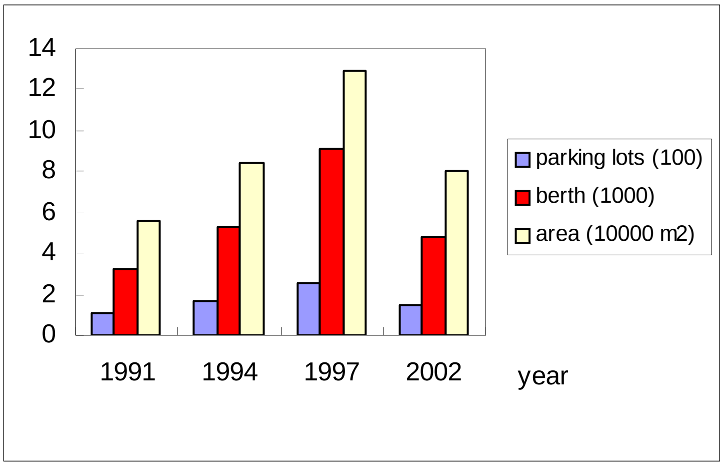


Figure 2-13　On-Road Parking Capacity in Shanghai

In 2003, there were 1.5 million motor vehicles in Shanghai, 0.8 million of which were automobiles and 0.7 million of which were motorcycles.　However, currently the total number of parking spots is only about 490,000, including 123,000 off-street public parking spaces and about 4,300 on-road spaces.　About 109,000 of these parking spaces lie within a central 4.240 million-square-meter area.　The ratio of public parking stalls to vehicle population (one motorcycle equals 0.5 automobiles) is 10.7 percent.　The ratio of basic parking stalls to vehicle population is about 60 percent.

Experience from overseas shows that when the ratio of public parking spaces to vehicle population reaches 15-20 percent and the ratio of basic parking spaces to vehicle population is around 100 percent, parking capacity is no longer a problem. Estimating an increase in 70,000 vehicles per year over the next five years, the vehicle population will reach to two million by 2010. To reach the ideal number of public parking spaces (15 percent of the vehicle population), 120,000 new spaces will need to be added by 2010.

Due to a lack and poor distribution of parking spaces, parking in Shanghai is extremely difficult, leading most people to park their cars on roadways. This causes already narrow roads to become even more crowded and diverts bicycle traffic into vehicle lanes. Thus, parking deficiencies lead to even greater traffic problems.

Table 2-12 Shanghai's Productive Parking Lots, 2003

Items/Region	Number of Parking Spaces				Parking Area (hectares)
	Large	Small	Mid-Size	Total	
Within Inner Ring Road	828	54,022	661	55,511	211.6
Between Inner and Outer Ring Road	8029	24,638	1,279	33,946	133.4
Outside Outer Ring Road	5,287	11,184	1,895	18,366	79
Total	14,144	89,844	3,833	107,823	424

8. Conclusions

Over the past 20 years, Shanghai's economy has developed rapidly, and there has been a concomitant increase in vehicle population, road construction, and transportation use. By the end of 2003, Shanghai's per capita GDP reached $5,618 USD; its vehicle population, 1.738 million. Its total road length (including urban roads and highways) reached 10,451 km, an increase of 260 km over 2002; and total road area reached 16,510 hectares, 12,361 hectares of which is vehicle-way area.

About 37 percent of motor vehicle transportation is centralized in the downtown area, but the total traffic capacity in this area is only about 18 percent of the total capacity of Shanghai's road network. Since the outgoing times of vehicles are mainly focused in the central area of Puxi but the traffic capacity of this region is quite limited, the traffic situation in this region is serious and traffic jams frequent. Currently, public transport is over-loaded during rush hour, and most roads in Shanghai are saturated all day long.

Parking lots also have an important effect on traffic conditions. Well-planned parking will not only reduce traffic and mitigate urban air pollution, it will also improve people's living quality, optimize city land use, and promote sustainable development. By 2003, the area of parking lots in Shanghai was 424 hectares, an increase of 73 hectares over 2002, but it is still not sufficient to meet growing parking demand.

Chapter 3. Vehicle Driving Cycles and Technology Survey

1. Introduction

Vehicle emission rates are closely related to the vehicles' on-road driving conditions, such as speed, acceleration, ratio of idle time, time-speed distribution, and speed-acceleration distribution. When driving conditions are poor, e.g., vehicles must frequently accelerate, emissions will increase. Thus, poor driving conditions not only create traffic and waste time, they also substantially increase vehicle emissions. Besides driving conditions, vehicle technologies--e.g., engine size, vehicle age, air conditioning, fuel/air control, and exhaust control--impact vehicle emissions levels.

In order to measure vehicle emissions and the influence of driving conditions and vehicle technology on emission levels, we used the International Vehicle Emissions Model (IVEM) to develop a vehicle emissions inventory. IVEM was developed by the University of California at Riverside, College of Engineering-Centre for Environmental Research and Technology (CE-CERT), Global Sustainable System Research (GSSR), and the International Sustainable Systems Research Centre (ISSRC). IVEM has been already been successfully used in Los Angeles, Santiago, Mexico City, and other large cities. Because the Shanghai-specific data needed for IVEM, location, fleet, and base adjustment files, can be collected relatively easily through vehicle information gathering, investigation, and emissions testing, IVEM is ideal for use in Shanghai.

On-road driving cycles data, including vehicle speed, longitude, latitude, and altitude, were collected second-by-second using Global Positioning System (GPS) equipment. Using this equipment, speed and acceleration data for each of the main types of vehicles was gathered on nine representative roads from 7:00 to 21:00. Engine start-up and shut-off data was collected using the Vehicle Operating Characteristics Enunciator (VOCE). Using VOCE, the number of start-up times and vehicle operation and engine stall time distributions were obtained. Finally a fleet file was created by investigating the kinds of vehicle technology in use.

2. Roads selected for investigation

In order to collect data that accurately represents traffic conditions in Shanghai, we conducted our research in three districts: Putuo, a low-income area; Xuhui, a high-income area; and Huangpu, a commercial area. One highway (red line), one arterial road (blue line), and one residential road (green line) were chosen in each district. The areas and roads selected are shown below.

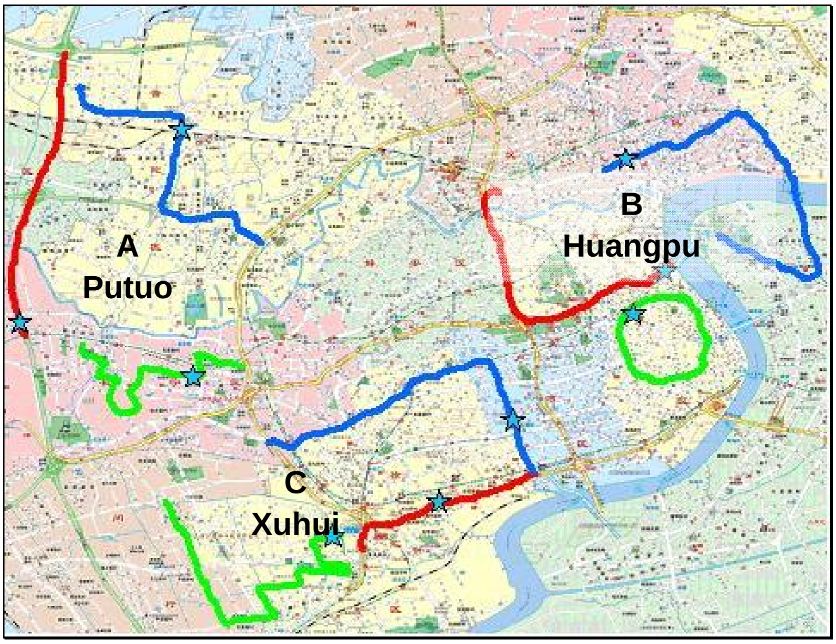


Figure 3-1 Areas and roads selected for Shanghai vehicle driving pattern survey

Table 3-1 Roads selected for Shanghai vehicle driving pattern survey

Road	Location
Highway A1	Outer ring——Putuo district
Highway B1	East Yanan road——Huangpu district
Highway C1	Second south Zhongshan road——Xuhui district
Arterial A2	Zhennan road——Putuo district
Arterial B2	Nanlin road——Hongkou district
Arterial C2	Huaihai road——Xuhui district
Residential A3	Maotai road——Putuo district
Residential B3	Zhonghua road——Huangpu district
Residential C3	Tianlin road——Xuhui district

3. Investigation methods

3.1 Investigation of driving cycles

Because different types of vehicles have very different driving behavior, we used GPS to test the driving patterns of several vehicles: passenger cars, buses, trucks, taxis, and motorcycles. We first tested three passenger cars. The cars were driven for 40 minutes each on each of the three types of roads in each of the three districts. The specific routes and schedules are shown in Tables 3-2 to 3-7. (A, B, C represent Putuo, Huangpu, and Xuhui districts, respectively; 1, 2, 3 represent highway, arterial road, and residential road, respectively.) Data was gathered for six days, seven hours each day.

Table 3-2, Day 1 Schedule (June 9, 2004)

Time	Car 1	Car 2	Car 3
07:00-08:00	A-1	B-1	C-1
08:00-09:00	A-2	B-2	C-2
09:00-10:00	A-3	B-3	C-3
10:00-11:00	A-1	B-1	C-1
11:00-12:00	A-2	B-2	C-2
12:00-13:00	A-3	B-3	C-3
13:00-14:00	A-1	B-1	C-1

Table 3-3, Day 2 Schedule (June 10, 2004)

Time	Car 1	Car 2	Car 3
07:00-08:00	C-2	A-2	B-2
08:00-09:00	C-3	A-3	B-3
09:00-10:00	C-1	A-1	B-1
10:00-11:00	C-2	A-2	B-2
11:00-12:00	C-3	A-3	B-3
12:00-13:00	C-1	A-1	B-1
13:00-14:00	C-2	A-2	B-2

Table 3-4, Day 3 Schedule (June 11, 2004)

Time	Car 1	Car 2	Car 3
14:00-15:00	A-1	B-1	C-1
15:00-16:00	A-2	B-2	C-2
16:00-17:00	A-3	B-3	C-3
17:00-18:00	A-1	B-1	C-1
18:00-19:00	A-2	B-2	C-2
19:00-20:00	A-3	B-3	C-3
20:00-21:00	A-1	B-1	C-1

Table 3-5, Day 4 Schedule (June 12, 2004)

Time	Car 1	Car 2	Car 3
07:00-08:00	B-3	C-3	A-3
08:00-09:00	B-1	C-1	A-1
09:00-10:00	B-2	C-2	A-2
10:00-11:00	B-3	C-3	A-3
11:00-12:00	B-1	C-1	A-1
12:00-13:00	B-2	C-2	A-2
13:00-14:00	B-3	C-3	A-3

Table 3-6, Day 5 Schedule (June 13, 2004)

Time	Car 1	Car 2	Car 3
14:00-15:00	C-2	A-2	B-2
15:00-16:00	C-3	A-3	B-3
16:00-17:00	C-1	A-1	B-1
17:00-18:00	C-2	A-2	B-2
18:00-19:00	C-3	A-3	B-3
19:00-20:00	C-1	A-1	B-1
20:00-21:00	C-2	A-2	B-2

Table 3-7, Day 6 Schedule (June 14, 2004)

Time	Car 1	Car 2	Car 3
14:00-15:00	B-3	C-3	A-3
15:00-16:00	B-1	C-1	A-1
16:00-17:00	B-2	C-2	A-2
17:00-18:00	B-3	C-3	A-3
18:00-19:00	B-1	C-1	A-1
19:00-20:00	B-2	C-2	A-2
20:00-21:00	B-3	C-3	A-3

Tests were then repeated on two buses, two trucks, two taxis, and one motorcycle. The driving patterns of each type of vehicle naturally matched its operation character. For example, buses generally are driven on roads with large traffic flow and frequently decelerate, accelerate, and idle. Trucks usually run on the Outer Ring Road at high speeds. The vehicles tested were operated normally, and the testing schedule for each lasted for 6 days, always between 07:00 and 21:00.

3.2 Vehicle technology survey

To find out vehicle technology levels in Shanghai, we conducted several parking lot surveys in Putuo, Huangpu, and Xuhui districts. We surveyed mainly light-duty vehicles, which make up the largest proportion of vehicles in Shanghai and accurately represent the technology levels of on-road vehicles. More than 1,200 vehicles were investigated. Because it is difficult to investigate the taxis, buses, and trucks in parking lots, the technology data for these vehicles were attained from Shanghai taxi, bus, and truck companies Vehicle technologies measures and their classifications are shown below.

Table 3-8 Vehicle technology classifications

Fuel	Engine size	Fuel/air system	Emission control	Air-conditioner
Gasoline	Liter	4C, Cab.	No	Yes
Diesel		2C, Cab.	2W	No
LPG		SI	3W	
		MI	EuroⅠ	
		PI	EuroⅡ	
		DI	EuroⅢ	
		MX	EuroⅣ	

3.3 Traffic flow video

In order to observe traffic flow and ascertain vehicle type distributions on each representative road in the three chosen typical districts, video taping points were set up on sidewalks beside or overpasses above selected routes. These taping points are designated on Figure 3-1 with a star sign, "☆". Traffic flow and vehicle type ratios were recorded in 20-minute segments each hour. Two video cameras were used at each taping point, one recording traffic flow and vehicle types, the other recording vehicle license plate numbers (in order to later get detailed information about the vehicles' technologies). The vehicles were classified as either passenger car, taxi, motorcycle, moped, heavy-duty bus, medium-duty bus, light-duty bus, heavy-duty truck, medium-duty truck, or light-duty truck. The video taping schedule and locations are shown in Table 3-9.

Table 3-9 Video taping schedule and locations

Road type	Location	Date/time
A：highway	Overpass of Beidi road (outer ring)	Wed, Jun 9 @ 07:00, 10:00, 13:00 Fri, Jun 11 @ 14:00, 17:00, 20:00
B：highway	East Yanan road	Mon, Jun 14 @ 08:00, 11:00 Wed, Jun 16 @ 15:00, 18:00
C：highway	7th floor in Xuhui Education Bureau	Thu, Jun 10 @ 09:00, 12:00 Tue, Jun 15 @ 16:00, 19:00
A：arterial road	Overpass of Jiaotong road	Wed, Jun 9 @ 08:00, 11:00 Fri, Jun 11 @ 15:00, 18:00
B：arterial road	Overpass of Henan road and Haining road	Mon, Jun 14 @ 09:00, 12:00 Wed, Jun 16 @ 16:00, 19:00
C：arterial road	Overpass of Zhaojiabang road and Ruijin road	Thu, Jun 10 @ 07:00, 10:00, 13:00 Tue, Jun 15 @ 14:00, 17:00, 20:00
A：residential road	Intersection of Maotai road and Gubei road	Wed, Jun 9 @ 09:00, 12:00

		Fri, Jun 11 @ 16:00, 19:00
B：residential road	Intersection of Henan and Zhonghua road	Mon, Jun 14 @ 07:00, 10:00, 13:00 Wed, Jun 16 @ 14:00, 17:00, 20:00
C：residential road	East Tianlin road	Thu, Jun 10 @ 08:00, 11:00 Tue, Jun 15 @ 15:00, 18:00

3.4 Vehicle start-up survey

Emissions become worse during vehicle start-up, due to the poor mixing conditions of air and fuel. Emissions are even worse in cold weather, when engine temperature is too low for the catalyst to work. In order calculate exact start-up frequencies, VOCE was used to calculate total number of start-ups and average time between start-ups. Seventy vehicles were tested continually for seven days.

4. Equipment used for the survey and testing

The instruments used in this investigation are listed in the Table 3-10.

Table 3-10 Instruments used in the investigation of driving patterns

No.	Name of the Equipment	Type	Quantity	Production Location	Remarks
1	GPS		10	USA	Records driving conditions, like speed, second-by-second
2	Vidicon	SONY DCR-PC110	2	Japan	Records traffic flow and vehicle license plate numbers
3	Tape-reading machine	SONY GV-D100	2	Japan	Reads video tapes
4	Notebook	SONY	2	Japan	Reads GPS data
5	VOCE		70	USA	Records vehicle start-ups
6	Personal Computer		2		Data processing

A total of 840 minutes of videotape, 10 sets of GPS data (1,024,078 pieces of data), and 70 sets of VOCE vehicle start-up data were collected during this investigation.

5. Results

5.1 Speed-acceleration distributions for each vehicle type.

We obtained a wealth of data over the course of the six days we conducted driving pattern tests. Here, we will examine the driving patterns of each vehicle type obtained on one day of testing, June 9, 2004, to represent their respective driving patterns.

5.1.1 Bus driving pattern distributions

The driving pattern distributions of buses are shown in Figures 3-2 and 3-3. The figures show that the average speed of buses is 12.05 km/h, and the maximum speed is less than 55 km/h. Bus speeds are mainly distributed between 0 and 20 km/h; bus acceleration is mainly distributed between -1.0 m/s^2 and 1.0 m/s^2. Because buses must stop frequently and provide a safe, comfortable ride, they are usually driven at a low speed and frequently accelerate and decelerate. Table 3-11 gives the specific parameters regarding the driving pattern of buses.

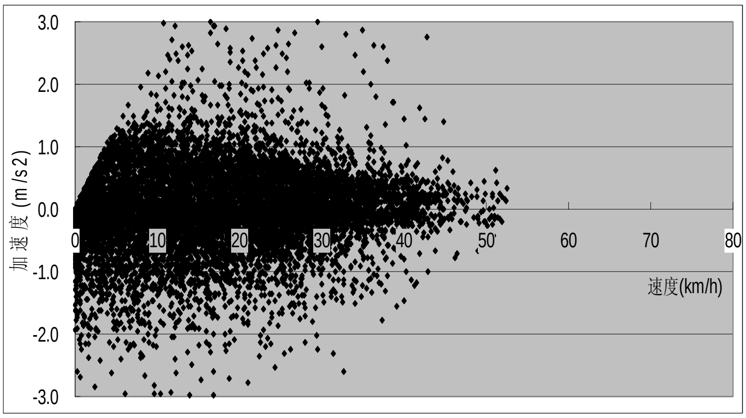


Figure 3-2 Speed-acceleration distribution of buses

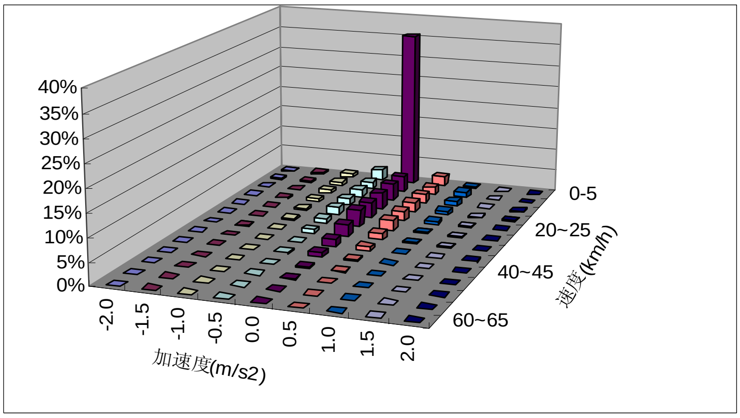


Figure 3-3 Driving pattern distribution of buses

Table 3-11 Parameters of bus driving patterns

Points	$V_{aver.}$ （km/h）	$V_{aver.\ driving}$ （km/h）	$V_{maxi.}$ （km/h）	Idle （%）	Accelerating （%）	Decelerating （%）	Steady （%）
16050	12.05	15.82	52.59	29.3	26.3	23.6	20.7

5.1.2 Truck driving pattern distributions

The driving pattern distributions for trucks are shown in Figures 3-4 and 3-5. The speed distribution range of trucks is wider than that of buses: speeds are mainly distributed between 0 and 40 km/h. Maximum speed is over 60km/h, and acceleration is mainly distributed between -0.5 m/s^2 and 0.5 m/s^2. Trucks are not allowed to enter areas within the Inner Ring Road during the day, and then, traffic conditions in the urban center at night are much better than during the day. As a result, trucks have a higher average speed than buses and the absolute value of their acceleration (and deceleration) is very low: they are typically driven on highways during the day, only entering the city center when traffic is relatively light. Table 3-11 gives the specific parameters regarding the driving patterns of trucks.

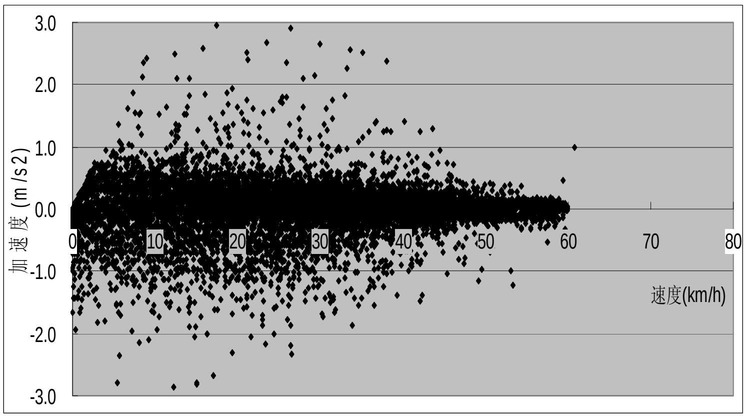


Figure 3-4 Speed-acceleration distribution of trucks

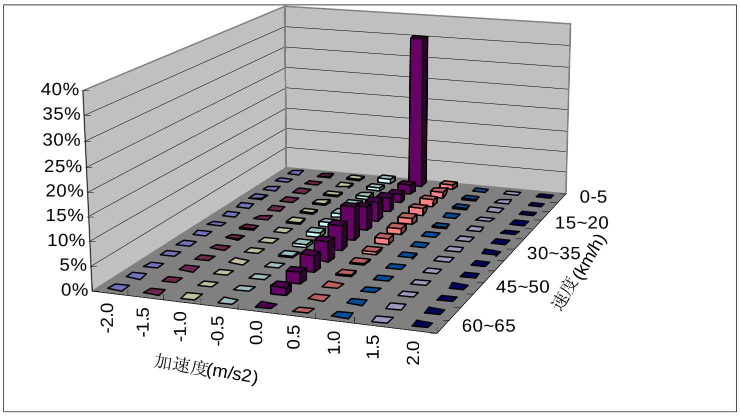


Figure 3-5 Driving pattern distribution of trucks

Table 3-12 Parameters of truck driving patterns

Points	$V_{aver.}$ （km/h）	$V_{aver.\ driving}$ （km/h）	$V_{maxi.}$ （km/h）	Idle （%）	Accelerating （%）	Decelerating （%）	Steady （%）
16352	18.29	26.16	60.85	33.1	19.7	14.1	33.1

5.1.3 Taxi driving pattern distributions

Figures 3-6 and 3-7 show taxi driving pattern distributions. Taxi driving speeds are mainly distributed in two discrete ranges, 0-40 km/h and 60-100 km/h; the maximum speed is nearly 120 km/h. Taxi acceleration lies mainly between -0.5 m/s^2

and 0.5 m/s^2 when the taxi is being driven at high speeds, and between -1.0 m/s^2 and 1.0 m/s^2 when driven at low speeds. The character of these two distributions is due to taxis' driving conditions: taxis are driven mainly on the highway—at high speeds—or residential roads—at relatively low speeds. The average and maximum speeds of taxis are much higher than those of both buses and trucks. Table 3-13 gives the specific parameters for taxi driving patterns.

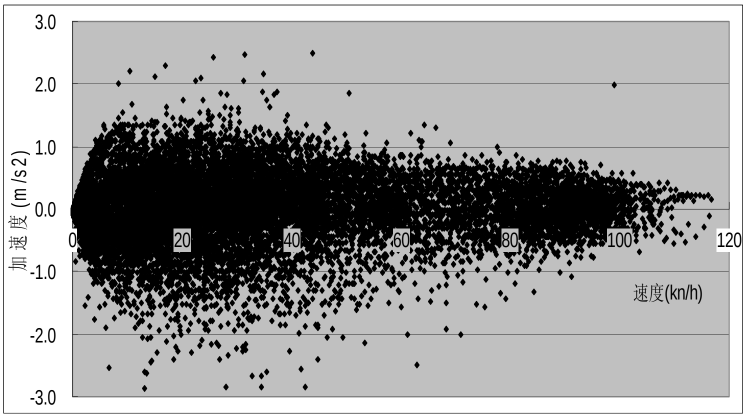


Figure 3-6 Speed-acceleration distribution of taxis

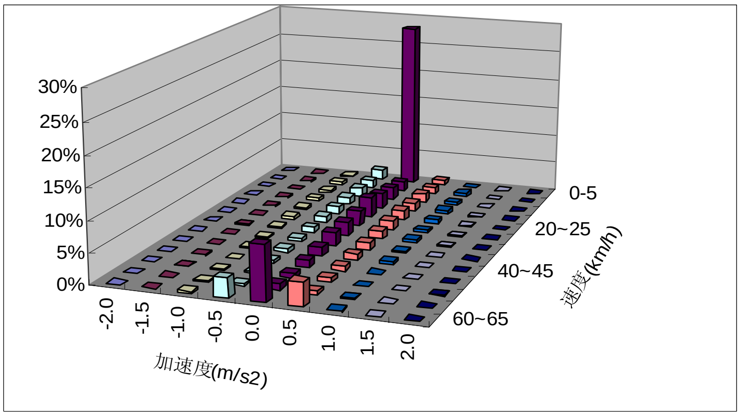


Figure 3-7 Driving pattern distribution of taxis

Table 3-12 Parameters of taxi driving patterns

Points	$V_{aver.}$ (km/h)	$V_{aver.\ driving}$ (km/h)	$V_{maxi.}$ (km/h)	Idle (%)	Accelerating (%)	Decelerating (%)	Steady (%)
20087	28.29	31.71	116.82	20.6	28.4	25.4	25.5

5.1.4 Motorcycle driving pattern distributions

Motorcycle driving pattern distributions are shown in Figures 3-8 and 3-9. Speeds are mainly distributed between 0-5 km/h and 10-20 km/h; the maximum speed of motorcycles is over 50 km/h. Acceleration figures lies mainly between -1.0 m/s^2 and 1.0m/s^2. Since motorcycles do not have a regular driving cycle, their speeds and acceleration widely vary. Table 3-14 gives the specific parameters regarding motorcycle driving patterns.

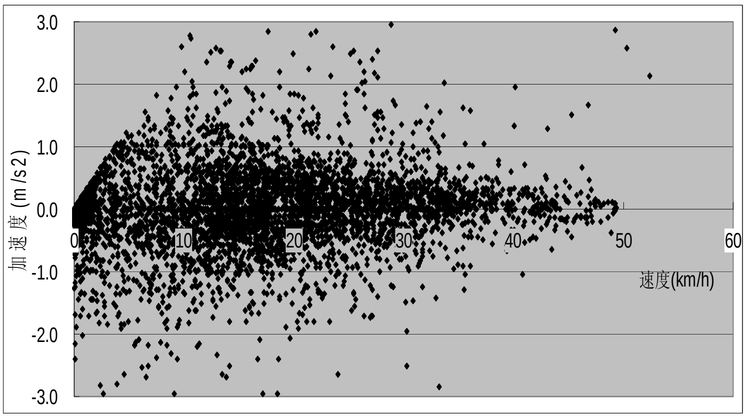


Figure 3-8 Speed-acceleration distribution of motorcycles

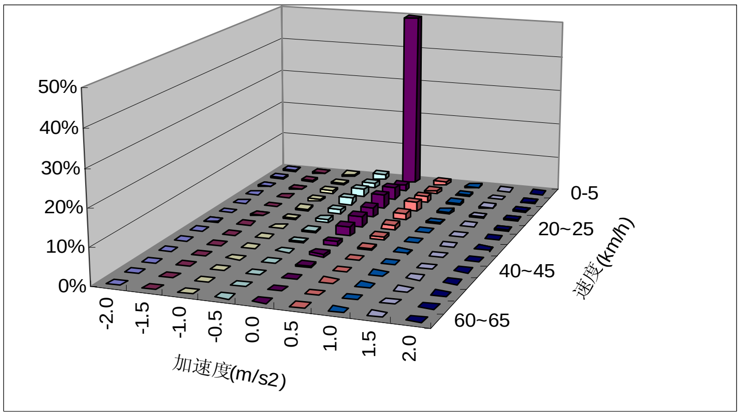


Figure 3-9 Driving pattern distribution of motorcycles

Table 3-14 Parameters of taxi driving patterns

Points	$V_{aver.}$ (km/h)	$V_{aver.\ driving}$ (km/h)	$V_{maxi.}$ (km/h)	Idle (%)	Accelerating (%)	Decelerating (%)	Steady (%)
9182	9.63	12.95	52.40	40.2	20.4	18.8	20.6

5.2 Time-speed and driving pattern distributions on various roads

5.2.1 Central city (high income area)

- Urban highways

Figure 3-10 shows the distribution of speed and acceleration for vehicles on Shanghai urban highways. Speeds are mainly distributed between 20 km/h and 50 km/h; acceleration, between -0.5 m/s^2 and 0.5 m/s^2. Most highways in central Shanghai are elevated roads with good driving conditions. Vehicles are often driven at medium or high, relatively steady speeds and have little idle time.

The maximum speed of vehicles traveling on the highways tested was 77.84 km/h; the average speed, 31.27 km/h; and the idle time ratio, only 5.7 percent.

Figure 3-10 Speed-acceleration distribution for vehicles on urban highways in Shanghai's center

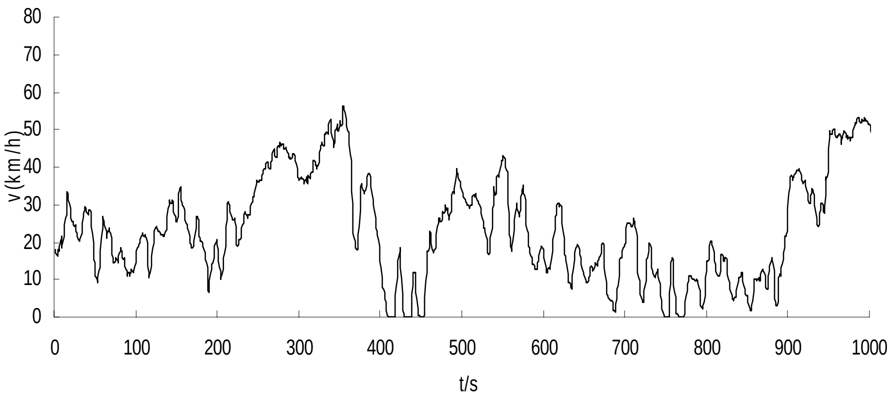


Figure 3-11 Driving cycle for vehicles on urban highways in Shanghai's center

Table 3-15 Parameters of driving patterns on urban highways in Shanghai's center

Points	$V_{aver.}$ (km/h)	$V_{aver.\ driving}$ (km/h)	$V_{maxi.}$ (km/h)	Idle (%)	Accelerating (%)	Decelerating (%)	Steady (%)
11144	29.49	31.27	77.84	5.7	33.7	34.0	26.6

- Urban arterial roads

Figure 3-12 shows that, the speeds on the urban arterial roads are mainly distributed between 0 km/h and 10 km/h and between 30 km/h and 40 km/h; acceleration, between -1.0 m/s^2 and 1.0 m/s^2. There are many vehicles and many traffic lights on urban arterial roads. Therefore, traffic on these roads is bad: vehicles cannot run steadily and the idle time ratio is very high. Since the number of vehicles on the road grows and traffic management system is poor, arterial roads are gradually becoming ineffective and traffic jams are becoming quite serious.

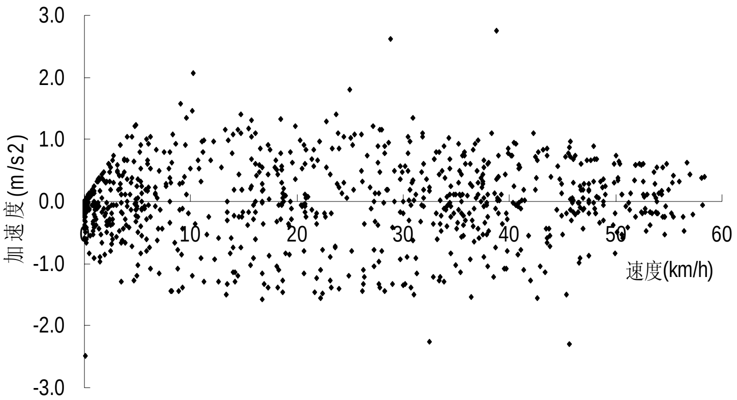


Figure 3-12 Speed-acceleration distribution for vehicles on urban arterial roads in Shanghai’s center

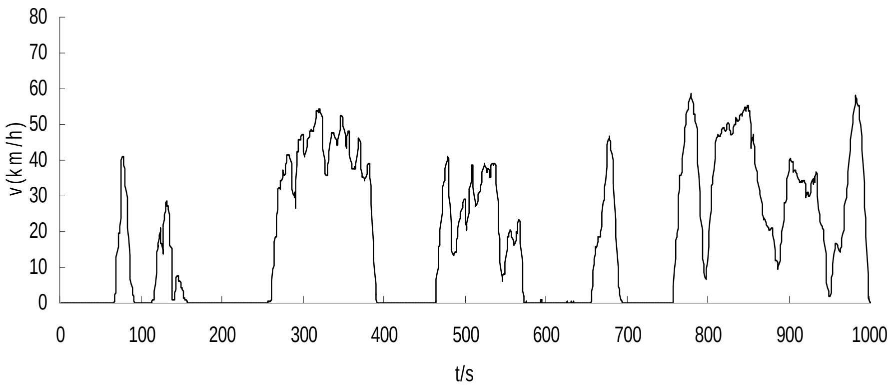


Figure 3-13 Driving cycle for vehicles on urban arterial roads in Shanghai’s center

The specific parameters for vehicles running on this type of road is shown in Table 3-16: the maximum speed is 68.30 km/h, the average speed is 10.01 km/h, and the idle time ratio is 54.8 percent.

Table 3-16 Parameters of driving patterns on the urban arterial roads in Shanghai’s center

Points	$V_{aver.}$ （km/h）	$V_{aver.\ driving}$ （km/h）	$V_{maxi.}$ （km/h）	Idle （%）	Accelerating （%）	Decelerating （%）	Steady （%）
29266	10.01	20.60	68.30	54.8	17.0	17.7	10.5

- Urban residential roads

Figure 3-14 shows that speeds on residential roads range relatively uniformly primarily between 10 km/h and 30 km/h. Vehicle speeds on residential roads are rather low since the residential roads are generally near residential areas, but traffic conditions are good and the idle time ratio is low.

The specific parameters for vehicles running on residential roads are shown in Table 3-17. The table shows that the maximum speed is 52.98 km/h, the average speed is 14.93 km/h, and the idle time ratio is 23.3 percent. Traffic conditions are better on residential roads than on arterial roads.

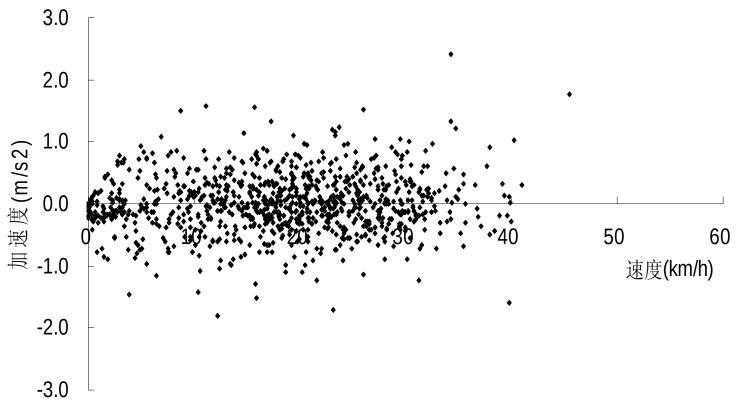


Figure 3-14 Speed-acceleration distribution for vehicles on urban residential roads in Shanghai's center

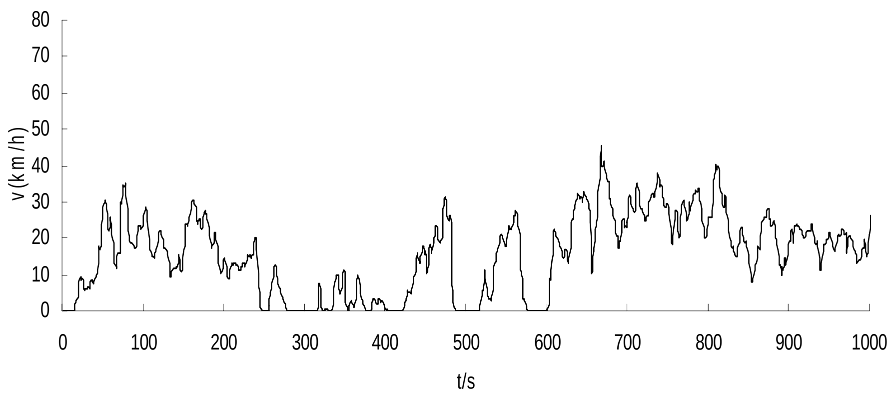


Figure 3-15 Driving cycle for vehicles on urban residential roads in Shanghai's center

Table 3-17 Parameters of driving patterns on urban residential roads in Shanghai's center

Points	$V_{aver.}$ (km/h)	$V_{aver.\ driving}$ (km/h)	$V_{maxi.}$ (km/h)	Idle (%)	Accelerating (%)	Decelerating (%)	Steady (%)
17752	14.93	19.46	52.98	23.3	26.7	27.8	22.2

5.2.2 Commercial area (medium income area)

- Highways

As shown in Figure 3-16, vehicle speeds on highways in Shanghai's commercial areas are relatively high. Speeds are mainly distributed between 10 km/h and 30 km/h and between 40 km/h and 60 km/h. Highways in commercial areas are also usually elevated. Traffic conditions on these roads are good and the idle time ratio is low.

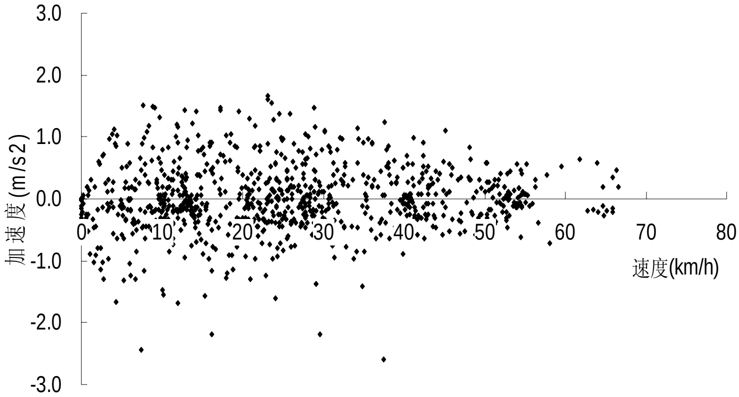


Figure 3-16 Speed-acceleration distribution for vehicles on Shanghai commercial area highways

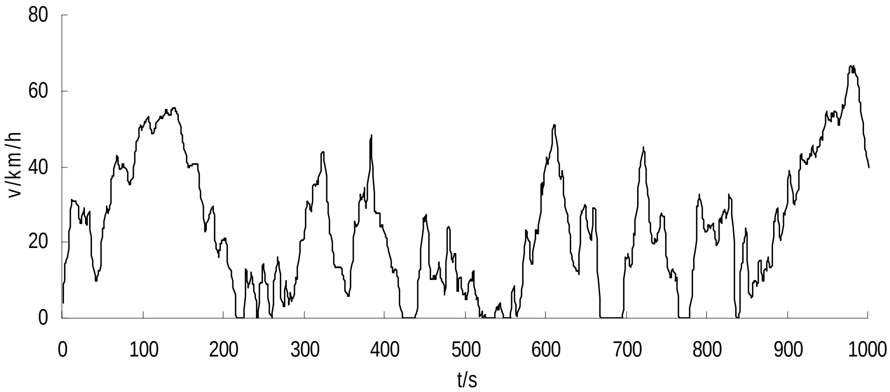


Figure 3-17 Driving cycle for vehicles on Shanghai commercial area highways

The specific parameters for vehicles running on this type of road are shown in Table 3-18; the maximum speed is 83.71 km/h; average speed, 22.48 km/h; and idle time ratio, only 11.5 percent.

Table 3-18 Parameters of driving patterns on highways in Shanghai commercial areas

Points	$V_{aver.}$ （km/h）	$V_{aver.\ driving}$ （km/h）	$V_{maxi.}$ （km/h）	Idle （%）	Accelerating （%）	Decelerating （%）	Steady （%）

10937	22.48	25.40	83.71	11.5	30.4	31.3	26.8

- Arterial roads

The driving patterns on the arterial roads in commercial areas and those in the central city are similar; traffic congestion on arterial roads in both commercial areas and the center of Shanghai is serious, and the idle ratios of vehicles traveling on them are high. Vehicles on these roads are generally driven at low speeds, usually between 0 and 10 km/h or 20 and 30 km/h.

The specific parameters for vehicles traveling on this type of road is shown in Table 3-19; the maximum speed is 61.85 km/h; average speed, 13.22 km/h; and idle time ratio, 32.4 percent.

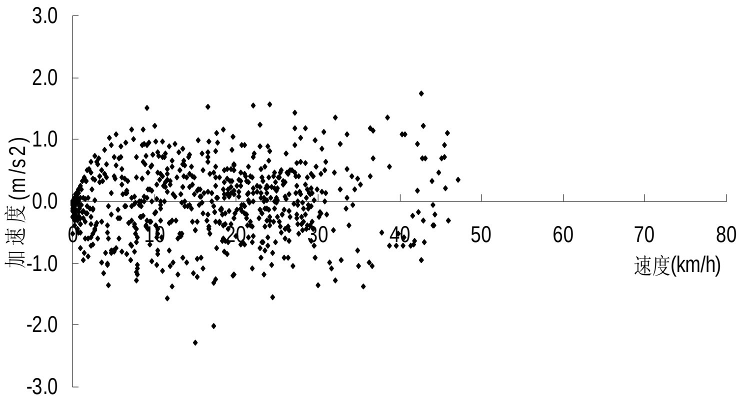


Figure 3-18 Speed-acceleration distribution for vehicles on Shanghai commercial area arterial roads

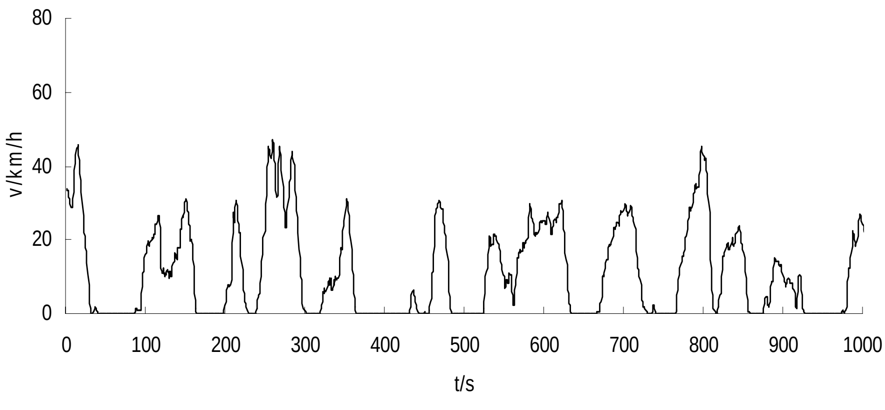


Figure 3-19 Driving cycle for vehicles on Shanghai commercial area arterial roads

Table 3-19 Parameters of driving patterns on Shanghai commercial area arterial roads

Points	$V_{aver.}$	$V_{aver.\ driving}$	$V_{maxi.}$	Idle	Accelerating	Decelerating	Steady

	（km/h）	（km/h）	（km/h）	（%）	（%）	（%）	（%）
22965	13.22	19.55	61.85	32.4	24.6	25.6	17.4

- Residential roads

Figures 3-20 and 3-21 show that traffic conditions on commercial area residential roads is better than those on commercial area arterial roads, but worse than those on commercial area highways. Vehicle speeds on commercial area residential roads are mainly distributed between 20 and 50 km/h.

Specific parameters for vehicles running on this type of road are shown in Table 3-20; the maximum speed is 76.76 km/h; average speed, 21.0 km/h; and idle time ratio, 22.5 percent.

Figure 3-20 Speed-acceleration distribution for vehicles on Shanghai commercial area residential roads

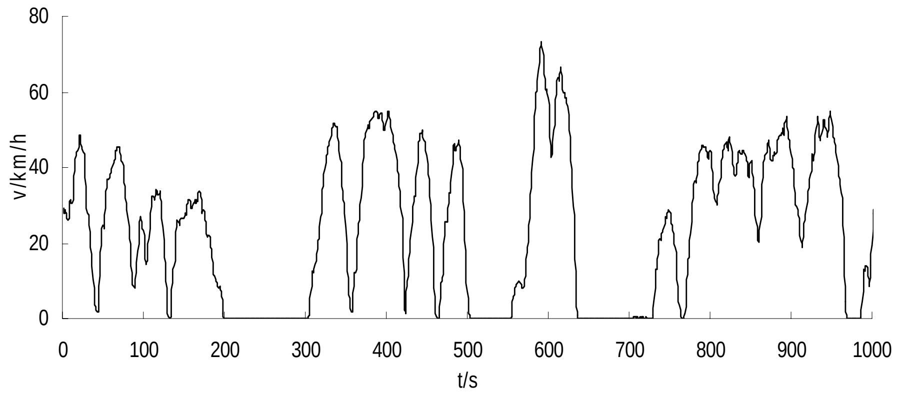


Figure 3-21 Driving cycle for vehicles on Shanghai commercial area residential roads

Table 3-20 Parameters of driving patterns on commercial area residential roads

Points	$V_{aver.}$ （km/h）	$V_{aver.\ driving}$ （km/h）	$V_{maxi.}$ （km/h）	Idle （%）	Accelerating （%）	Decelerating （%）	Steady （%）

22536	21.0	27.1	76.76	22.5	29.6	29.7	18.2

5.2.3 Outskirts of Shanghai (low income area)

- Highways

Highways in the outskirts of Shanghai refer mainly to Shanghai's outer-ring roads. Figures 3-22 and 3-23 show that traffic conditions on these roads are good; vehicles on these highways run at high speeds, distributed mainly between 50 and 70 km/h. Traffic conditions on these highways in the outskirts of Shanghai are obviously better than those in the central city or commercial areas.

Specific parameters for vehicles running on this type of road are shown in Table 3-21. These vehicles' average speed is 47.76 km/h. Traffic is quite smooth; the idle time ratio is only 7.7 percent.

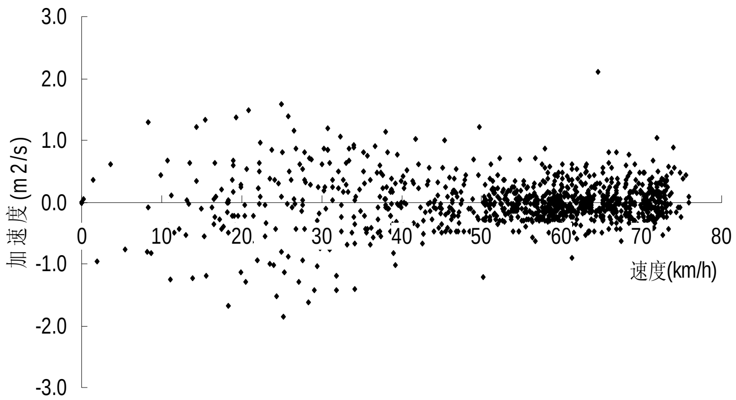


Figure 3-22 Speed-acceleration distribution for vehicles on highways in the outskirts of Shanghai

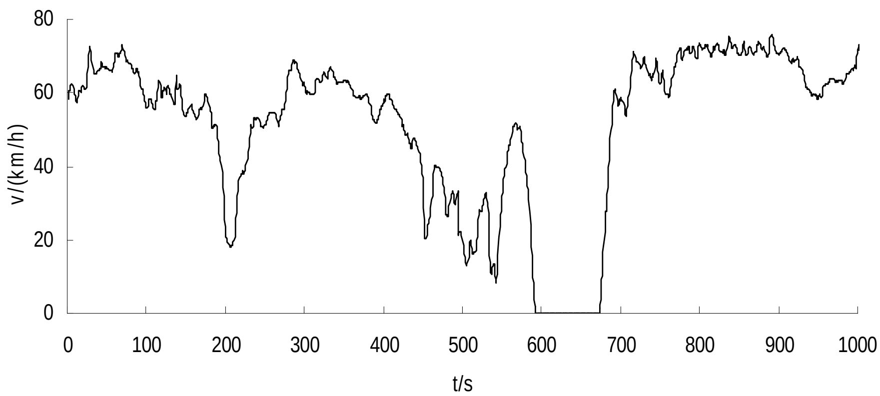


Figure 3-23 Driving cycle for vehicles on highways in the outskirts of Shanghai

Table 3-21 Parameters of driving patterns on highways in the outskirts of Shanghai

Points	$V_{aver.}$ (km/h)	$V_{aver.\ driving}$ (km/h)	$V_{maxi.}$ (km/h)	Idle (%)	Accelerating (%)	Decelerating (%)	Steady (%)
8861	47.46	51.43	92.55	7.7	29.5	29.4	33.4

- Arterial Roads

Figures 3-24 and 3-25 show that traffic on arterial roads in the outskirts of Shanghai is still dense and idle time ratios are high; nevertheless, the traffic conditions on arterial roads in Shanghai's outskirts are still better than those on arterial roads in the central city or commercial areas. The average vehicle speed is low, mainly distributed between 0 and 10 km/h and 30 and 40 km/h.

Specific parameters for vehicles running on this type of road are shown in Table 3-22; average speed is 18.13 km/h and the idle time ratio is close to 30 percent.

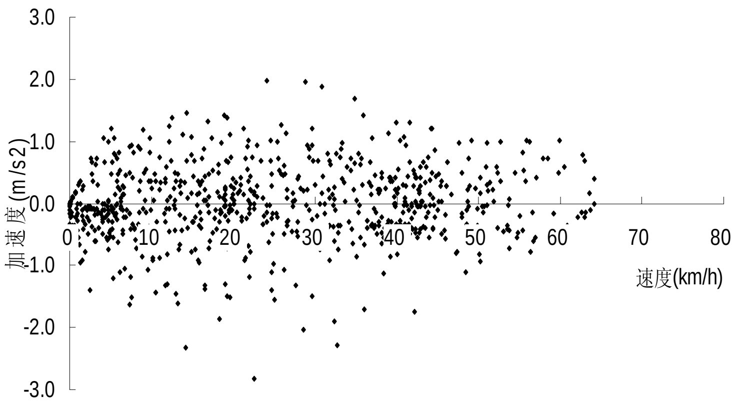


Figure 3-24 Speed-acceleration distribution for vehicles on arterial roads in the outskirts of Shanghai

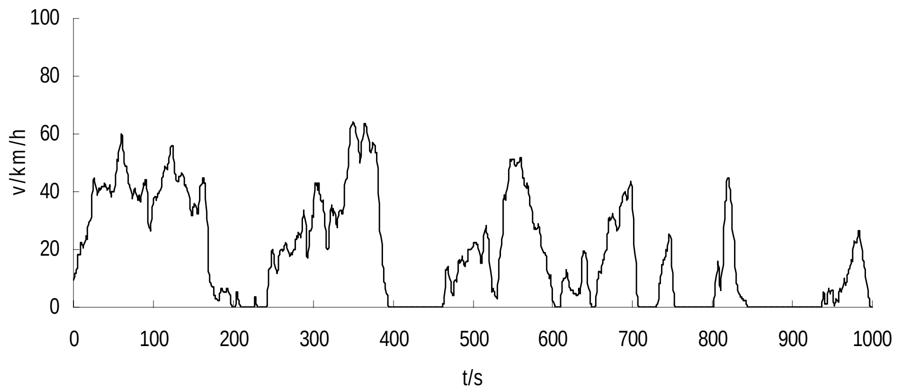


Figure 3-25 Driving cycle for vehicles on arterial roads in the outskirts of Shanghai

Table 3-22 Parameters of driving patterns on arterial roads in Shanghai's outskirts

Points	$V_{aver.}$ (km/h)	$V_{aver.\ driving}$ (km/h)	$V_{maxi.}$ (km/h)	Idle (%)	Accelerating (%)	Decelerating (%)	Steady (%)

24229	18.13	25.51	69.39	28.9	25.3	26.7	19.1

- Residential roads

Figures 3-26 and 3-27 show the traffic conditions on the residential roads in the outskirts of Shanghai. The traffic conditions on these roads are worse than those on highways but better than those on arterial roads. The average speed of vehicles on residential roads in Shanghai's outskirts is low, mainly distributed between 10 and 20 km/h.

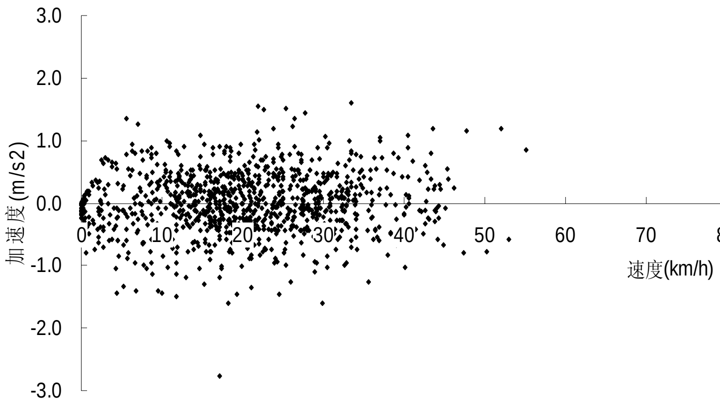


Figure 3-26 Speed-acceleration distribution for vehicles on residential roads in the outskirts of Shanghai

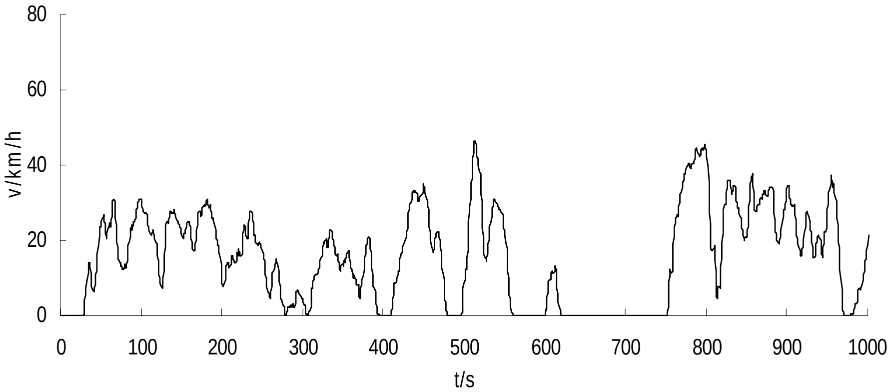


Figure 3-27 Driving cycle for vehicles on residential roads in the outskirts of Shanghai

Specific parameters for vehicles running on this type of road are shown in Table 3-23; the average speed is 16.10 km/h and the idle time ratio is 26.1 percent.

Table 3-23 Parameters of driving patterns on residential roads in Shanghai's outskirts

Points	$V_{aver.}$ （km/h）	$V_{aver.\ driving}$ （km/h）	$V_{maxi.}$ （km/h）	Idle （%）	Accelerating （%）	Decelerating （%）	Steady （%）

16198	16.10	21.79	59.65	26.1	28.1	28.3	17.5

5.3 Distribution of Vehicle Ages in Shanghai

5.3.1 Distribution of Vehicle Mileage Travel in Shanghai

Figure 3-28 shows that 80 percent of passenger cars in Shanghai travel less than 30,000 kilometers per year, with 40 percent traveling less than 10,000 kilometers per year. A very small percentage of cars travel more than 40,000 kilometers per year.

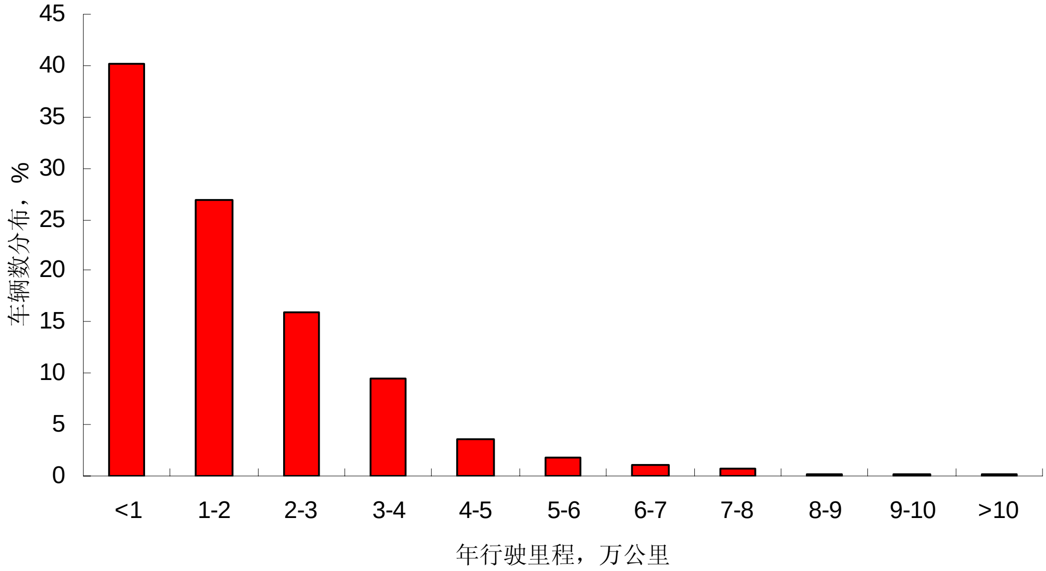


Figure 3-28 Distance traveled annually by passenger cars in Shanghai (10,000 km)

5.3.2 Distribution of Vehicle Ages

The ages of passenger cars and taxis in Shanghai are shown in Figure 3-29. It shows that more than 50 percent of vehicles in Shanghai were produced in 2002 and 2003. As the Euro-I emissions standard has been in place in Shanghai since 1999 and the Euro-II emissions standard has been in place since 2003, most vehicles in Shanghai currently meet the Euro-I or Euro-II standards. The average age of vehicles in Shanghai is 3.65 years, lower than the average age of vehicles in Beijing and other similar cities abroad. This is in great part due to the speed with which Shanghai's vehicle population is growing. With increasing numbers of new cars and old caras being phased out each year, the ratio of new cars to old ones is becoming quite high.

Unlike passenger cars, the average distance traveled by taxis each day is over 300 km due to frequent use. Therefore, taxis are usually phased out when they reach five years of age. Most taxis are three or four years old. Taxis produced in 2001 and 2002 represent more than 80 percent of all taxis in Shanghai (see Figure 3-29).

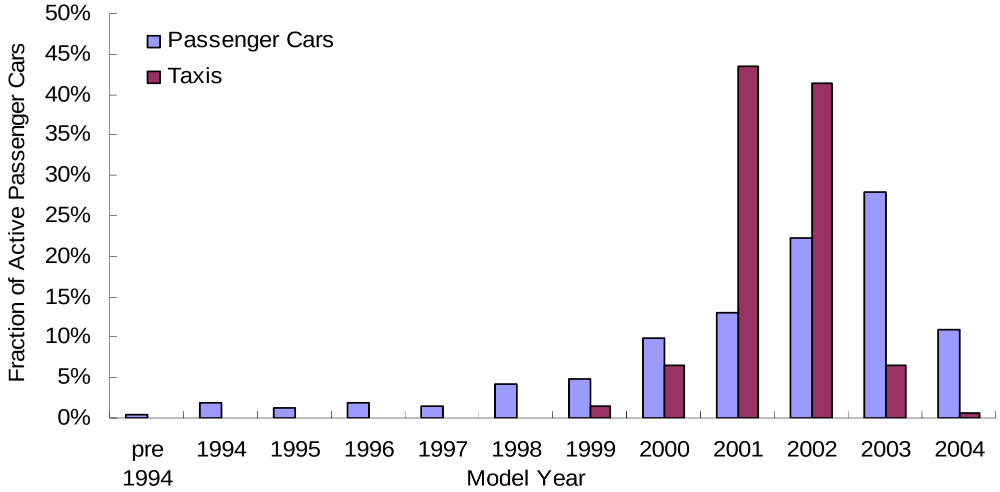


Figure 3-29 Ages of passenger cars and taxis in Shanghai

5.4 Vehicle technology characteristics in Shanghai

According to the vehicle technology classifications in the IVE model and the technology investigation results in parking lots, the technology distribution of various vehicles are shown as follows.

5.4.1 Technology distribution of passenger cars

Table 3-24 shows that 98% of passenger cars in Shanghai run on gasoline, and only less than 2% use diesel. Among cars running on gasoline, 5% are equipped with carburetors and 95% are fuel-injecting cars. Among all the passenger cars examined, 6% have no emission control technology, 9% are equipped with a 2-way catalyst device and 85% have a 3-way catalyst device.

In general, most passenger cars are relatively new in Shanghai. For this reason the emission control levels of most cars are relatively high and meet or even exceed Euro II standards.

Table 3-24 Technology distribution of passenger cars

Fuel	Weight	Air/Fuel Control	Exhaust Control	Evaporative Control	Age (K km)	Fraction of Miles Driven	Fraction with AC
Petrol	Light	Carburetor	None	PCV	80-161	0.09%	100%
Petrol	Light	Carburetor	None	PCV	>161	0.09%	0%
Petrol	Medium	Carburetor	None	PCV	<79	1.41%	100%
Petrol	Medium	Carburetor	None	PCV	80-161	1.22%	100%
Petrol	Medium	Carburetor	None	PCV	>161	2.25%	96%
Petrol	Light	Carburetor	3-Way	PCV	<79	0.09%	100%
Petrol	Light	Single-Pt FI	2-Way	PCV	<79	0.37%	100%
Petrol	Light	Single-Pt FI	2-Way	PCV	>161	0.09%	100%
Petrol	Medium	Single-Pt FI	2-Way	PCV	<79	3.19%	100%
Petrol	Medium	Single-Pt FI	2-Way	PCV	80-161	2.53%	100%
Petrol	Medium	Single-Pt FI	2-Way	PCV	>161	2.25%	100%

Petrol	Heavy	Single-Pt FI	2-Way	PCV	<79	0.19%	100%
Petrol	Heavy	Single-Pt FI	2-Way	PCV	80-161	0.09%	100%
Petrol	Heavy	Single-Pt FI	2-Way	PCV	>161	0.09%	100%
Petrol	Medium	Single-Pt FI	3-Way	PCV	<79	3.09%	100%
Petrol	Medium	Single-Pt FI	3-Way	PCV	80-161	1.12%	100%
Petrol	Medium	Single-Pt FI	3-Way	PCV	>161	0.37%	100%
Petrol	Heavy	Single-Pt FI	3-Way	PCV	>161	0.09%	100%
Petrol	Medium	Multi-Pt FI	none	PCV	<79	0.19%	100%
Petrol	Medium	Multi-Pt FI	none	PCV	80-161	0.19%	100%
Petrol	Medium	Multi-Pt FI	none	PCV	>161	0.19%	100%
Petrol	Light	Multi-Pt FI	3-Way	PCV	<79	3.75%	100%
Petrol	Medium	Multi-Pt FI	3-Way	PCV	<79	54.73%	100%
Petrol	Medium	Multi-Pt FI	3-Way	PCV	80-161	8.15%	100%
Petrol	Medium	Multi-Pt FI	3-Way	PCV	>161	3.00%	100%
Petrol	Heavy	Multi-Pt FI	3-Way	PCV	<79	7.97%	100%
Petrol	Heavy	Multi-Pt FI	3-Way	PCV	80-161	1.12%	100%
Petrol	Heavy	Multi-Pt FI	3-Way	PCV	>161	0.84%	100%
Diesel	Medium	Pre-Chamber Inject.	None	None	<79	0.09%	100%
Diesel	Medium	Pre-Chamber Inject.	None	None	80-161	0.28%	100%
Diesel	Medium	Pre-Chamber Inject.	None	None	>161	0.09%	100%
Diesel	Heavy	Pre-Chamber Inject.	None	None	<79	0.09%	100%
Diesel	Heavy	Pre-Chamber Inject.	None	None	80-161	0.19%	100%
Diesel	Heavy	Pre-Chamber Inject.	None	None	>161	0.09%	100%
Diesel	Medium	Direct Injection	EGR+Improv	None	80-161	0.19%	100%
Diesel	Heavy	Direct Injection	EGR+Improv	None	<79	0.09%	100%
Diesel	Heavy	Direct Injection	EGR+Improv	None	>161	0.09%	100%

5.4.2 Technology distribution of taxis

Table 3-25 shows that among all taxis currently in use, 73 percent use gasoline and 27 percent use both gasoline and CNG. Since taxis are usually phased out after a 5 year period, as opposed to passenger cars which average 15 years of use, the average taxi is a much newer car than most passenger cars on the road. Almost all taxis are installed with a 3-way catalyst device.

Table 3-24 Technology distribution of taxis

Fuel	Weight	Air/Fuel Control	Exhaust Control	Evapor-ative Control	Age (K km)	Fraction of Miles Driven	Fraction with AC
Petrol	Medium	Carburetor	None	PCV	>161	2.16%	100%
Petrol	Medium	Single-Pt FI	3-Way	PCV	<79	1.44%	100%
Petrol	Medium	Single-Pt FI	3-Way	PCV	80-161	4.32%	100%
Petrol	Medium	Single-Pt FI	3-Way	PCV	>161	46.76%	100%
Petrol	Heavy	Single-Pt FI	3-Way	PCV	<79	1.44%	100%
Petrol	Medium	Multi-Pt FI	3-Way	PCV	<79	2.88%	100%
Petrol	Medium	Multi-Pt FI	3-Way	PCV	80-161	1.44%	100%
Petrol	Medium	Multi-Pt FI	3-Way	PCV	>161	12.95%	100%
Propane	Medium	FI	3-Way	PCV	<79	2.88%	100%
Propane	Medium	FI	3-Way	PCV	>161	23.74%	100%

5.4.3 Technology distributions of buses

Table 3-26 shows that 76% of buses in Shanghai run on diesel. Nearly 30% of buses do not meet Euro 1 emission standards yet, meaning that those buses have no emission control measures in place whatsoever. Furthermore, since the buses are usually not well maintained and frequently start up and stop (frequent acceleration, deceleration and idle), the release significant amounts of emissions (especially PM and VOC).

Table 3-26 Technology distribution of buses

Fuel	Weight	Air/Fuel Control	Exhaust Control	Evaporative Control	Age(K km)	Fraction of Miles Driven	Fraction with AC
Petrol	Medium	FI	none	PCV	<79	4.51%	60%
Petrol	Medium	FI	none	PCV	80-161	1.53%	60%
Petrol	Medium	FI	Euro I	PCV	<79	13.60%	60%
Petrol	Medium	FI	Euro I	PCV	80-161	4.51%	60%
Diesel	Light	Direct Injection	Improved	None	<79	3.22%	60%
Diesel	Medium	Direct Injection	Improved	None	<79	11.34%	60%
Diesel	Medium	Direct Injection	Improved	None	80-161	3.78%	60%
Diesel	Heavy	Direct Injection	Improved	None	<79	2.33%	60%
Diesel	Heavy	Direct Injection	Improved	None	80-161	0.80%	60%
Diesel	Medium	FI	Euro I	None	<79	33.95%	60%
Diesel	Medium	FI	Euro I	None	80-161	11.34%	60%
Diesel	Heavy	FI	Euro I	None	<79	6.84%	60%
Diesel	Heavy	FI	Euro I	None	80-161	2.25%	60%

5.4.4 Technology distribution of trucks

Table 3-27 shows that 70% of trucks in Shanghai use diesel fuel while trucks using gasoline only account for 30%. Only 10% of trucks on the road meet Euro 1 emission standards, meaning 90% do not have any emission control measures in place. This illustrates that there are no strict emission controls for heavy-duty vehicles, such as trucks and buses. As a result, the emissions from heavy-duty vehicles are very serious. Therefore, more research needs to be dedicated to heavy-duty vehicle emissions and emission control measures must be implemented.

Table 3-27 Technology distribution of trucks

Fuel	Weight	Air/Fuel Control	Exhaust Control	Evaporative Control	Age (K km)	Fraction of Miles Driven
Petrol	Light	Carburetor	None	PCV	<79	1.35%
Petrol	Light	Carburetor	None	PCV	80-161	2.70%
Petrol	Light	Carburetor	None	PCV	>161	9.45%
Petrol	Medium	Carburetor	None	PCV	<79	1.35%
Petrol	Medium	Carburetor	None	PCV	80-161	2.70%
Petrol	Medium	Carburetor	None	PCV	>161	9.45%
Petrol	Light	FI	Euro I	PCV	<79	1.50%
Petrol	Medium	FI	Euro I	PCV	<79	1.50%
Diesel	Light	Direct Injection	Improved	None	<79	3.15%
Diesel	Light	Direct Injection	Improved	None	80-161	6.30%
Diesel	Light	Direct Injection	Improved	None	>161	22.05%

Diesel	Medium	Direct Injection	Improved	None	<79	3.15%
Diesel	Medium	Direct Injection	Improved	None	80-161	6.30%
Diesel	Medium	Direct Injection	Improved	None	>161	22.05%
Diesel	Light	FI	Euro I	None	<79	3.50%
Diesel	Medium	FI	Euro I	None	<79	3.50%

5.4.5 Motorcycle and moped

Since there isn't enough statistical data on motorcycles or mopeds, technology classifications for them are not particularly detailed. The classifications below are based on empirical data. The majority of motorcycles have a 4-cycle carburetor, while most mopeds are equipped with 2-cycle gasoline engines and LPGs. The specific classifications are shown in table 3-28 and table 3-29.

Table 3-28 Technology distribution of motorcycles

Fuel	Weight	Air/Fuel Control	Exhaust Control	Evaporative Control	Age (K km)	Fraction of Miles Driven
Petrol	Light	4-Cycle, Carb	None	None	26-50	100%

Table 3-28 Technology distribution of mopeds

Fuel	Weight	Air/Fuel Control	Exhaust Control	Evaporative Control	Age (K km)	Fraction of Miles Driven
Petrol	Light	2-Cycle	None	None	>50	50%
CNG/LPG	Light	4-Cycle, Carb	Improved	None	26-50	50%

5.5 VSP Bins distributions of vehicles

VSP is the abbreviation for Vehicle Specific Power. In the past, the relationship between speed and emissions and the relationship between acceleration and emissions were usually used to study emissions under different driving patterns. However, the amount of emissions released is actually related to the output power of the engine. When engine power is high, the amount of pollutants being released into the environment can be expected to increase. However, the lower the VSP, the less emissions there will be. The theory of VSP has been widely used in the study of vehicles in the USA (José L. Jiménez, 1999). The IVE model uses VSP to improve the impact of driving patterns on emissions. The equations about VSP are shown as follows:

$$VSP= v*[1.1*a+9.81*(atan(sin(G)))+0.132]+0.000302*v^3$$

V= velocity, m/s

a= acceleration, m/s^2

G= grade = $(h_{t=0} - h_{t=-1}) / v_{t=-1to0}$

h= altitude, m

Changes in VSP create different reactions in vehicle engines. If VSP changes sharply (which generally occurs with a bigger torque), the engine load becomes higher. In order to develop a more accurate relationship between emissions and driving patterns, another parameter known as engine stress is used in addition to VSP. In the equation, RPMindex refers to torque parameter; PreaveragePower refers to the average specific power during 25th to 5th second before the instantaneous power and it is used to describe changes of VSP during this period. The equation for engine stress is shown as follows:

Engine Stress=RPMIndex + 0.08*PreaveragePower

PreaveragePower = Average ($VSP_{t=-5sec\ to\ --25sec}$) ， Kw/ton

RPMIndex = Velocity $_{t=0}$/SpeedDrivider ， unit less

Minimum RPMIndex = 0.9

Table 3-30 shows instructions on distribution of the RPMIndex in IVE.

Table 3-30 Cut points used in RPMIndex calculations

Speed Cutpoints (m/s)		Power Cutpoints (kW/ton)		Speed Divider (s/m)
Min	Max	Min	Max	
0.0	5.4	-20	400	3
5.4	8.5	-20	16	5
5.4	8.5	16	400	3
8.5	12.5	-20	16	7
8.5	12.5	16	400	5
12.5	50	-20	16	13
12.5	50	16	400	5

The GPS data of various vehicles are divided into 20 kinds of VSP and 3 kinds of Engine Stress. The driving patterns of each kind can be assigned to the 60 Bins as shown in table 3-31. In the IVE model, the driving patterns are divided into different Bins. This allows for accurate estimation of the relationship between emissions and driving patterns.

Table 3-31 Boundaries assumed in VSP/Engine Stress Binning

Bin	VSP (kW/Ton) Lower	Upper	Engine Stress Lower	Upper
0	-80.0	-44.0	-1.6	3.1
1	-44.0	-39.9	3.1	7.8
2	-39.9	-35.8	7.8	12.6
3	-35.8	-31.7		
4	-31.7	-27.6		
5	-27.6	-23.4		
6	-23.4	-19.3		
7	-19.3	-15.2		
8	-15.2	-11.1		
9	-11.1	-7.0		
10	-7.0	-2.9		
11	-2.9	1.2		
12	1.2	5.3		
13	5.3	9.4		
14	9.4	13.6		
15	13.6	17.7		
16	17.7	21.8		
17	21.8	25.9		
18	25.9	30.0		
19	30.0	1000.0		

Figure 3-30 shows the relationship between emissions and VSP. When VSP is high, emissions will increase sharply. Some emission points are more than 200 times that of general ones.

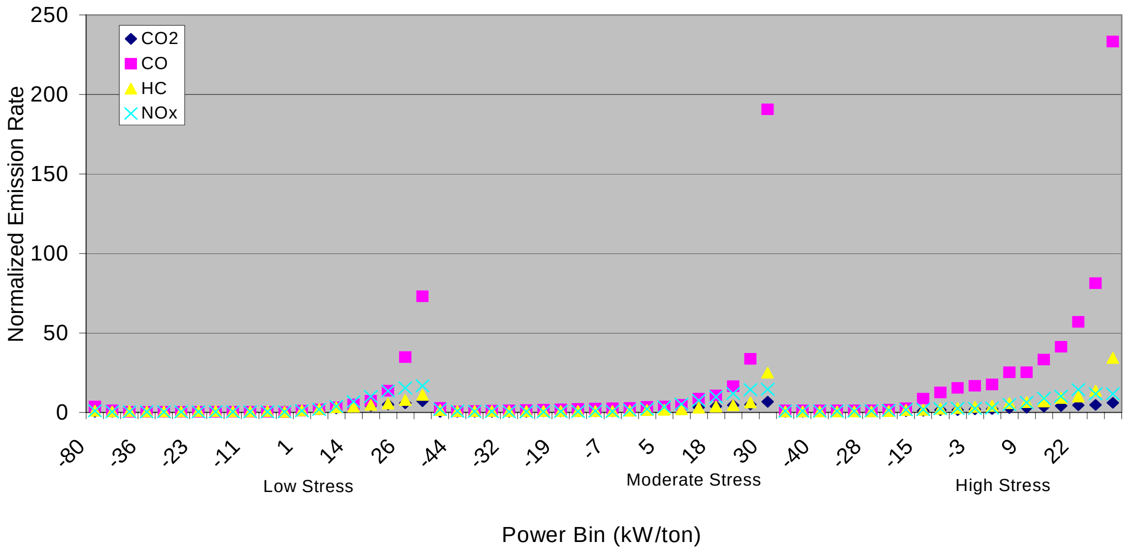


Figure 3-30 The relationship between various emissions and VSP

5.5.1 VSP Bins distributions of various vehicle types

The VSP distributions of all kinds of vehicles in Shanghai are shown in table 3-32 to table 3-38, which demonstrates that VSP distributions of all kinds of vehicles are concentrated around Bin 12. For passenger cars, 42.88 percent of passenger cars traveling on highways fall into Bin 12; 69.91 percent of passenger cars traveling on arterial roads fall into Bin 12; and 57.83 percent of passenger cars traveling on residential roads fall into Bin 12. buses, trucks and motorcycles, the values are 57.19 percent of taxis, 63.25 percent of buses, 55.48 percent of trucks, and 64.08 percent of motorcycles fall into Bin 12. Bin 12 represents the VSP state, which is close to idle. It shows that vehicles in Shanghai run very slowly most of the time and velocities are often close to zero. Only a few driving patterns are distributed in the medium load of engine.

Table 3-32 Distribution of VSP Bins for Passenger cars on Highways

(average speed: 31.97 km/hour)

Stress Group	Power Bins									
Low	1	2	3	4	5	6	7	8	9	10
	0.00%	0.00%	0.01%	0.03%	0.04%	0.07%	0.15%	0.37%	0.78%	2.36%
	11	12	13	14	15	16	17	18	19	20
	9.35%	42.88%	22.83%	12.68%	5.33%	1.57%	0.12%	0.04%	0.01%	0.02%
Med	1	2	3	4	5	6	7	8	9	10
	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
	11	12	13	14	15	16	17	18	19	20
	0.00%	0.00%	0.00%	0.01%	0.01%	0.55%	0.56%	0.19%	0.03%	0.02%
High	1	2	3	4	5	6	7	8	9	10
	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
	11	12	13	14	15	16	17	18	19	20
	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%

Table 3-33 Distribution of VSP Bins for Passenger cars on Arterial Roads

(average speed: 12.61 km/hour)

Stress Group	Power Bins									
Low	1	2	3	4	5	6	7	8	9	10
	0.04%	0.01%	0.01%	0.01%	0.02%	0.01%	0.04%	0.20%	0.57%	1.76%
	11	12	13	14	15	16	17	18	19	20
	5.84%	69.91%	12.13%	6.19%	2.26%	0.60%	0.13%	0.04%	0.02%	0.03%
Med	1	2	3	4	5	6	7	8	9	10
	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
	11	12	13	14	15	16	17	18	19	20
	0.00%	0.00%	0.00%	0.00%	0.00%	0.05%	0.06%	0.02%	0.00%	0.02%
High	1	2	3	4	5	6	7	8	9	10
	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
	11	12	13	14	15	16	17	18	19	20
	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%

Table 3-34 Distribution of VSP Bins for Passenger cars on Residential Roads

(average speed: 17.11 km/hour)

Stress	Power Bins

Group										
Low	1	2	3	4	5	6	7	8	9	10
	0.00%	0.02%	0.01%	0.01%	0.01%	0.04%	0.08%	0.25%	0.75%	2.38%
	11	12	13	14	15	16	17	18	19	20
	8.06%	57.83%	17.54%	8.03%	3.05%	1.03%	0.27%	0.06%	0.03%	0.06%
Med	1	2	3	4	5	6	7	8	9	10
	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
	11	12	13	14	15	16	17	18	19	20
	0.00%	0.00%	0.00%	0.00%	0.00%	0.14%	0.22%	0.09%	0.01%	0.03%
High	1	2	3	4	5	6	7	8	9	10
	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
	11	12	13	14	15	16	17	18	19	20
	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%

Table 3-35 Distribution of VSP Bins for Taxis

(average speed: 20.48 km/hour)

Stress Group	**Power Bins**									
Low	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
	0.02%	0.01%	0.01%	0.03%	0.05%	0.11%	0.23%	0.47%	1.03%	2.45%
	11	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**
	6.37%	57.19%	16.30%	8.66%	4.17%	1.28%	0.14%	0.05%	0.02%	0.05%
Med	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.02%
	11	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**
	0.02%	0.03%	0.03%	0.05%	0.06%	0.39%	0.51%	0.18%	0.05%	0.03%
High	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
	11	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**
	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%

Table 3-36 Distribution of VSP Bins for Buses

(average speed: 15.42 km/hour)

Stress Group	**Power Bins**									
Low	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
	0.00%	0.00%	0.01%	0.02%	0.02%	0.04%	0.08%	0.14%	0.43%	1.51%
	11	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**
	5.33%	63.25%	21.62%	6.22%	0.95%	0.20%	0.05%	0.04%	0.02%	0.03%
Med	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
	11	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**
	0.00%	0.00%	0.00%	0.00%	0.00%	0.02%	0.01%	0.01%	0.00%	0.02%
High	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
	11	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**
	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%

Table 3-37 Distribution of VSP Bins for Trucks

(average speed: 23.61 km/hour)

Stress Group	Power Bins									
Low	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
	0.00%	0.00%	0.00%	0.00%	0.01%	0.02%	0.04%	0.08%	0.26%	0.70%
	11	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**
	2.63%	55.48%	34.21%	5.94%	0.48%	0.07%	0.02%	0.01%	0.00%	0.01%
Med	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
	11	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**
	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.01%	0.01%	0.00%	0.01%
High	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
	11	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**
	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%

Table 3-38 Distribution of VSP Bins for Motorcycles

(average speed: 13.46 km/hour)

Stress Group	Power Bins									
Low	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
	0.01%	0.01%	0.01%	0.02%	0.04%	0.08%	0.08%	0.21%	0.60%	1.73%
	11	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**
	5.89%	64.08%	19.32%	5.74%	1.26%	0.36%	0.16%	0.12%	0.04%	0.08%
Med	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
	11	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**
	0.00%	0.02%	0.01%	0.02%	0.00%	0.01%	0.01%	0.01%	0.03%	0.04%
High	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
	11	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**
	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%

5.6 Distribution of Vehicle Stagnation Time

Table 3-39 shows the distribution of vehicle start up time and soak time, which are recorded by VOCE. In general, passenger vehicles are started 5.2 times per day. Most of these start-ups occur during 06:00-09:00 and 15:00-18:00, which directly corresponds to the time when people start and finish work. 6:00-9:00 in the morning is a particular peak for emissions as vehicles are turned after a whole night of being off. Thus, nearly 35.97 percent of cars being started up are cold starts (Soak Time>18hr), which strongly impacts the overall level of vehicle emissions in Shanghai.

Table 3-29 Passenger Vehicle Start and Soak Patterns in Shanghai

Soak Time (hrs)	Overall	06:00-08:59	09:00-11:59	12:00-14:59	15:00-17:59	18:00-20:59	21:00-23:59	00:00-2:59	03:00-05:59
0.25	24%	23.73%	26.69%	25.75%	26.88%	24.85%	18.80%	32.96%	20.27%
0.5	11%	10.06%	19.45%	9.90%	12.95%	8.37%	6.55%	7.70%	8.87%
1	13%	6.55%	16.97%	12.63%	11.02%	16.20%	10.10%	14.28%	11.39%

2	13%	4.85%	13.46%	19.21%	14.33%	19.05%	18.80%	7.70%	8.88%
3	9%	1.04%	5.29%	8.00%	7.95%	9.54%	13.80%	5.50%	16.41%
4	3%	0.16%	0.87%	6.74%	4.83%	2.29%	5.80%	0.00%	2.51%
6	6%	0.52%	0.52%	6.14%	3.94%	3.72%	10.90%	14.28%	6.28%
8	3%	2.94%	0.17%	2.12%	5.55%	1.77%	1.45%	2.20%	5.10%
12	7%	14.18%	2.46%	1.26%	8.59%	8.99%	5.05%	10.98%	7.62%
18	12%	35.97%	14.12%	8.23%	3.95%	5.22%	8.75%	4.41%	12.66%
Events	1426	289	284	238	289	174	184	46	40
Fraction		20%	20%	17%	20%	12%	5%	3%	3%

6. Summary

The results of the vehicle driving pattern and technology distribution survey show that the traffic flows in different hours and in various areas in Shanghai vary greatly. However, changes of traffic flow with time are similar in various areas. Traffic flow for the most part peaks at 8:00-9:00, 11:00-12:00, 15:00-16:00 and 18:00-19:00, which correspond to the time when people start and finish work.

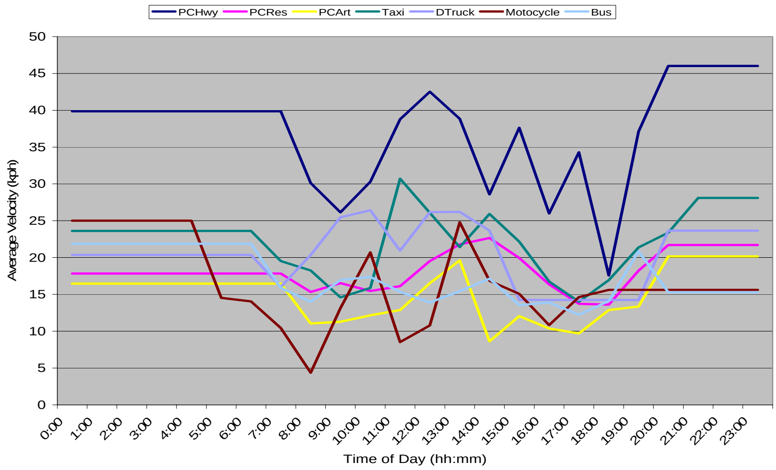


Figure 3-31 Change of vehicle speeds with time

Figure 3-31 shows the change in average speed of different vehicle types over time. It reveals that the average speed is highest on highways and lowest on arterial roads. This is mainly because arterial roads are in areas where traffic flow tends to be very congested.

Using the research on driving patterns on nine roads in three different areas (the city center, the commercial area and the outskirts) of Shanghai, we can see that the driving patterns differ greatly depending on which part of the city one is in. The traffic conditions are best in the outskirts of Shanghai and worst in the city center. This is mainly because the traffic flow is very congested in the city center and comparatively sparse in the outskirts although roadway development in the outskirts is not as advanced as that found in the city center. Various driving patterns can be distinguished by different road types. The driving cycles are best on highways, where the average speed is highest and the idle-speed ratio is lowest. This is in stark contrast to arterial roads.

The driving patterns of various vehicle types are also different. However, for the most part their accelerations occur mostly between -0.5 m/s^2 and 0.5 m/s^2. The speed-acceleration distributions are obviously different, which determines the emission characteristics of vehicles. The average age of passenger cars is 3.65 years in Shanghai, meaning most cars are quite new. 80 percent of passenger cars were put on the market after 2000. The average VMT of those cars is 49.2 km. Most passenger cars in Shanghai meet Euro-I or Euro-II emissions standards. However, emission control of heavy duty vehicles, such as trucks and buses, is very limited. Therefore, much greater attention needs to be paid to implementing emission control measures on these vehicles and to further researching the impact these vehicles have on the environment and public health in Shanghai.

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Chapter 4. Vehicle Emission Factors Measurement

1. Introduction

Since the 1990s, the number of vehicles in China has been increasing rapidly, with an annual growth rate of 10 percent. The total number of vehicles in China reached 16.09 million (NBSC, 2001) in 2000, which is 2.9 times more than in 1999. Due to the rapid growth in the number of vehicles, the local environment was heavily polluted. Not surprisingly, vehicle emissions have become the dominant source of urban air pollution (Xie, et al. 2000). In order to control vehicle emissions, domestic experts launched relative pollution control studies, and conducted strategies for vehicle emissions control in Beijing, Guangzhou, and Shanghai respectively in the middle of the 1990's (THU-DEST, et al. 1997; SAES, 1997).

The study approach for vehicle emission estimation includes model forecasts and real world testing on the factors behind vehicle emissions. There are five approaches that are frequently used in vehicle emission studies. The first is the US Mobile emission model which is a popular modeling tool in China (Fu, et al. 1997; Fu, et al. 2000; He, et al. 1998; Zhu, et al. 1997; Li, et al. 2001). The second is the laboratory testing approach which uses a chassis dynamometer. It was used in Shanghai in 1994 and 1996 (Chen, et al. 1997; Dai, et al. 1997), in Beijing (Zhou, et al. 2000), and in Xian (Deng, 1999). The third is remote sensing (Dong, et al. 2003; Zhang, et al. 1996), which is becoming more and more popular in China. The fourth is the five gas analyzer (Hu, et al. 2004) whichuses an out of date technology for vehicle emission measurement but is still a useful tool for this type of study. The fifth one is the tunnel approach which was used extensively in China (Wang, et al. 2001; Wang, et al. 2001). However, all these methods possess certain limitations to some degree. Although chassis dynamometer tests take many driving cycles into account, they can not reflect the complex situation on the road completely. Remote sensing and five gas analyzer methods are changing in favor of real-road testing, but they still have great limitations in the methods they use in analysis. Both of the methods apply NDIR to analyze all the basic pollutants, including CO, NO_x and HC, which will certainly contain errors when it comes to the measurement of NO_x and HC. Tunnel technology must resolve the problem of accuracy and how to test emissions for a single vehicle.

Most of the existing research in China focuses on emission testing of light-duty vehicles due to a lack of measurement equipment for heavy-duty vehicles. The Mobile Emission Lab, developed by CE-CERT, UCR, not only solved the above problem, but also offers opportunities to test heavy-duty vehicles on real roads (http://www.cert.ucr.edu/emissions/). Many researchers will recoil at the significantly higher costs associated with this type of testing system though, particularly in China.

Base on the current research status, various trends, and policy requirements for vehicle emission control, heavy-duty diesel trucks, diesel buses and light-duty diesel vehicles have been selected for on the road emission testing using Sensors' SEMTECH-D technology. These studies will be conducted by the Atmospheric Environment Institute (AEI) at the Shanghai Academy of Environmental Sciences (SAES), with the support of The World Resource Institute (WRI) and USEPA. The study will examine the characteristics of real world emissions and provide basic data to develop medium- and long-term vehicle emission strategies in Shanghai.

2. Testing Equipment

The real world vehicle emission factor measurement was done using SEMTECH-D equipment，**Se**nsors **E**mission **Tech**nology-**D**iesel, provided by USEPA and Sensors and designed by Sensors for diesel vehicle emission testing. The filter membranes of particulates were provided by Sensors while the standard gases were produced by Fitzpatrick Container in England.

3. Testing Methodology

To measure the concentration of pollutants accurately, SEMTECH-D must apply NDIR to the CO and CO_2 tests, NDUV to NO and NO_x, FID to HC and the electrochemical method to O_2. Moreover, it will use Global Positioning System (GPS) technology to measure vehicle speed, and temperature and humidity testing instrument to measure environmental temperature and relative humidity. Before each test, accuracy and precision are adjusted during the warm-up procedures, and the objective pollutants concentrations are zeroed. This allows for simultaneous recording of driving speed, pollutant concentration, vehicle location and environmental situation second by second.

Figure 4-1 shows the real-road testing system for heavy-duty diesel vehicles.

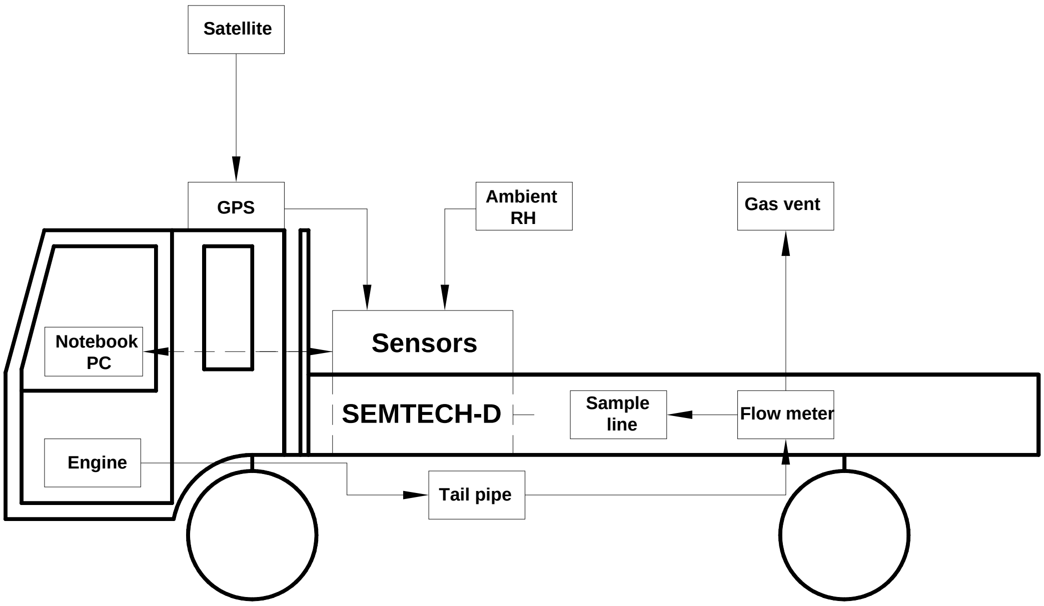


Figure 4-1 Diagram of Vehicle Emissions Measurement System

4. Tested vehicles

From September 26, 2004 to October 26, 2004, ten diesel trucks, two diesel taxis and one diesel bus were tested. The tested route of trucks and taxis were carefully designed and were composed of freeways, arterial roads, and residential roads. The route of the bus was chosen based on its routine route. The loaded trucks and driving cycles were tested in fixed routes. Table 4-1 shows the information about all the tested vehicles.

Table 4-1 Information about tested vehicles

License	Vehicle type				Type of engine	Engine power hp	Model year	Vehicle miles traveled km	Catalyst	F/A	Maintenance
	Type of vehicle	Load T	Mass T	Max.Carring Capacity T							
A H8396	Diesel truck	3	3.4	6.4	Jianghuai 4105	88.4	2000	350,000	None	Direct injection	Good
A E6022	Diesel truck	6.9	5	11.9	Dongfeng 109233	130	2002	78,240	None	Direct injection	Good
A 84645	Diesel truck	2	3	5	Jiefang 4110	95	2001	107,298	None	Direct injection	Good
A D4705	Diesel truck	4	4	6	Jiefang 6110	145	1999	200,000	None	Direct injection	Good
A 99738	Diesel truck	3	3	8	Yuejin 4102	70	2001	149,000	None	Direct injection	Middle
A H4627	Diesel truck	5	5	6	Dongfeng E020820 1360	135	2000	84,000	None	Direct injection	Good
A E5399	Diesel truck	8	5.2	10	Jiefang 6113	235	2002.1	>100,000	None	Direct injection	Middle
A C7856	Diesel truck	5	5.9	13.2	Dongfeng YC6108	158	2001	172,251	None	Direct injection	Middle
A C9192	Diesel truck	5	4.8	10.9	Dongfeng EQ6102	128	1999.12	205,250	None	Direct injection	Middle
A E9864	Diesel truck	5	10.93	15.9	Jiefang CA12521A2 6110	167	2002.2	162,067	None	Direct injection	Good
A X9265	Diesel taxi	5 person	0.475	2.495	Futian BJ5027V2SD5	76	2002.12	198,602	None	Direct injection	Good
A X9931	Diesel taxi	5 person	0.55	2.495	Jianglingbaodian JX 93Q1	76	2003.2	N/A	Euro II	Direct injection	Middle
A B5851	Diesel bus	95 person	9.4	6.65	Shangchai6114	203	1998.9	415008	Euro I	Direct injection	Good

5. Data Processing

In order to convert pollutant concentrations into emission factors, the raw data must be processed in four ways.

5.1 Correction of NO_x Humidity

Because NO_x is influenced by the cooling effect of humidity, the NO_x humidity correction factor, Kh, should be applied to the instantaneous concentration, CFR40-86.1342-94, which defines the current NO_x humidity correction factor, Kh, for diesel engines.

$$Kh = \frac{1}{[1 - 0.0182(H - 10.71)]}$$

Where, H the absolute humidity（g/kg dry air）

$$H = \frac{6.211(RH)(P_d)}{P_{baro} - (P_d)(RH/100)}$$

when RH, relative humidity, is expressed in a percentage, and P_d is the saturation vapor pressure (Kpa)，the following empirical equation can be used:

$$P_d(KPa) = EXP\left[\frac{16.78T_{sample} - 116.9}{T_{sample} + 237.3}\right]$$

5.2 Instantaneous mass emission (g/s) using the exhaust flow method

Instantaneous mass emission refers to the mass emission of pollutants recorded second by second during the driving process. Calculation of this figure is based on the exhaust flow method, which includes the following three steps.

- Step 1: Application of dry-wet correction factors to gas concentration

When the concentration of pollutants that is to be measured by the instrument is dry, the concentration must be converted into a wet state in order to calculate it. With respect to the objective pollutant M, the conversion formula is as follows:

$$[M]_{wet} = [M]_{dry} \times Kw$$

Kw--- conversion factor, a function of the concentration of water vapor that was removed from the sample by condensation.

$$Kw = 1 - [H_2O]_{condensed}$$

$$[H_2O]_{condensed} = [H_2O]_{exhaust} - [H_2O]_{residual}$$

- Step 2： Computation of volumetric exhaust flow rate under standard conditions

The Sensors electronic mass flow meter provides a direct mass measurement of the exhaust, M_f, which should be converted into a standard volumetric flow rate at 20℃ and 1 standard atmospheric pressure. This can be done using the gas continuity equation:

$$M_f = \rho Q = \rho_{std} Q_{std}$$

$$Q_{std} = \frac{M_f}{\rho_{std}}$$

To compute the density of exhaust gases under standard conditions, the molecular weight of the exhaust $WM_{exhaust}$ needs to be calculated first

$$WM_{exhaust} = \frac{1}{100}\sum \{[CO]_{wet} \times 44.01 + [O_2]_{wet} \times 32.0 + [N_2]_{wet} \times 28.013 + [H_2O]_{wet} \times 18.015\}$$

Using the equation of ideal gas under standard conditions, we can get the density of exhaust gases under the same conditions:

$$\rho_{std} = \frac{P(WM_{exhaust})}{RT}$$

- Step 3： Instantaneous mass emission calculation

Calculation of the instantaneous mass emission of objective pollutants is as follows:

$$NO(g/s) = \frac{[NO]_{wet}}{100} \times Q_{std} \times \rho_{NO,std}$$

$$NO_2(g/s) = \frac{[NO_2]_{wet}}{100} \times Q_{std} \times \rho_{NO_2,std}$$

$$CO(g/s) = \frac{[CO]_{wet}}{100} \times Q_{std} \times \rho_{CO,std}$$

$$HC(g/s) = \frac{[HC]_{wet}}{100} \times Q_{std} \times \rho_{HC,std}$$

5.3 Instantaneous fuel-specific mass emission (g/kg fuel)

Fuel-specific emissions are the mass fractions of each pollutant in relation to the combusted fuel in the air/fuel mixture. To express fuel-specific emissions in terms of pollutant per gram of fuel, the mole fraction of the pollutant to the fuel burned must be computed. This is simply the ratio of the measured concentration of pollutants to the sum of the CO, HC1, and CO2 concentrations in the exhaust, which reflects the number of moles of fuel that is consumed per mole of exhaust. The ambient CO2 concentration must be focused on the instrument or subtracted from the exhaust measurement. Ambient CO and HC are not subtracted from raw exhaust concentrations because it is assumed these are destroyed in the combustion process. The mass fraction of each pollutant to combusted fuel is then computed as follows:

$$NO_{fs}\left(\frac{g\_NO}{g\_fuel}\right) = \left(\frac{[NO]}{[CO]+[HC_1]+[CO_2]-[CO_2]_{ambien}}\right) \times \left(\frac{MW_{NO}}{MW_{fuel}}\right)$$

$$NO_{2\,fs}\left(\frac{g\_NO_2}{g\_fuel}\right) = \left(\frac{[NO_2]}{[CO]+[HC_1]+[CO_2]-[CO_2]_{ambien}}\right) \times \left(\frac{MW_{NO_2}}{MW_{fuel}}\right)$$

$$CO_{fs}\left(\frac{g\_CO}{g\_fuel}\right) = \left(\frac{[CO]}{[CO]+[HC_1]+[CO_2]-[CO_2]_{ambien}}\right) \times \left(\frac{MW_{CO}}{MW_{fuel}}\right)$$

$$HC_{1\,fs}\left(\frac{g\_HC_1}{g\_fuel}\right) = \left(\frac{[HC_1]}{[CO]+[HC_1]+[CO_2]-[CO_2]_{ambien}}\right) \times \left(\frac{MW_{HC_1}}{MW_{fuel}}\right)$$

NO_x is calculated based on the ratio of NO_2/NO_x as 5% .

5.4 Cumulative distance-specific mass emission（g/km）

Once the instantaneous mass emissions have been computed, it is a simple task to compute distance-specific emissions.

$$NO_x = \frac{\sum NO_x\ mass}{\sum kilometers\ stravelled}$$

$$CO = \frac{\sum CO\ mass}{\sum kilometers\ stravelled}$$

$$HC = \frac{\sum HC\ mass}{\sum kilometers\ stravelled}$$

6. Results

With the exception of the loss of data for one of the trucks, these tests provided excellent results and insight into various vehicle pollutants. The total length of the tested roads was 704.811 km, of which 1,947,114 datum were obtained for 107.136 effective driving seconds. The test involved ten researchers and lasted for almost 2 months. All the raw data was compiled and examined after processing. Since there is a immense amount of data that was derived from this study, three typical trucks will be selected as our focus for the purpose of this paper. They are the AX84645, AX9265 and AB5851.

6.1 Characteristics of driving pattern distribution

Driving patterns that were examined mainly included vehicle speed, acceleration and fuel consumption, which can be described in terms of the percentage of time spent idle, acceleration, deceleration and cruise time. They are described in speed-acceleration- driving distribution figures. See Figure 4-2 to 4-4, and Figure 4-5 to 4-7.

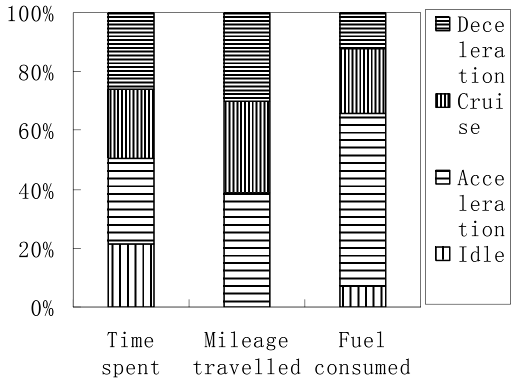


Figure 4-2 Contributions of Different Driving Patterns of

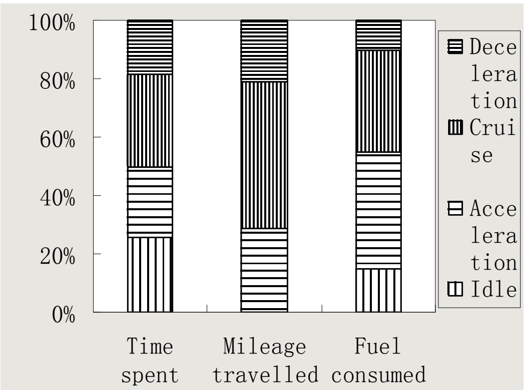


Figure 4-3 Contributions of Different Driving Patterns of

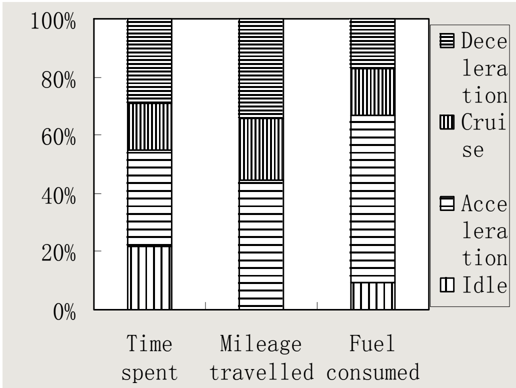


Figure 4-4 Contributions of Different Driving Patterns of Tax

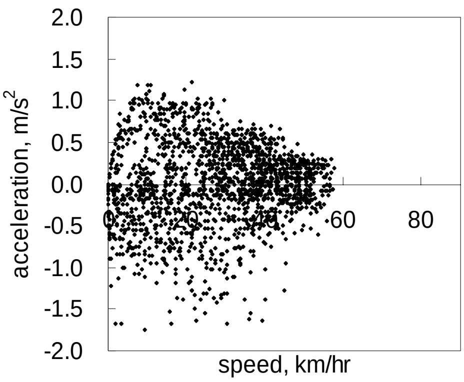


Figure 4-5 Speed-acceleration-driving pattern dots of truck

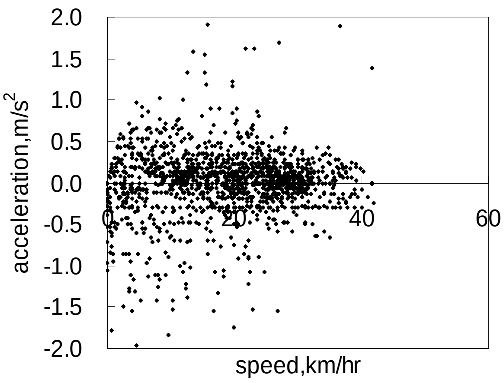


Figure 4-6 Speed-acceleration-driving pattern dots of bus

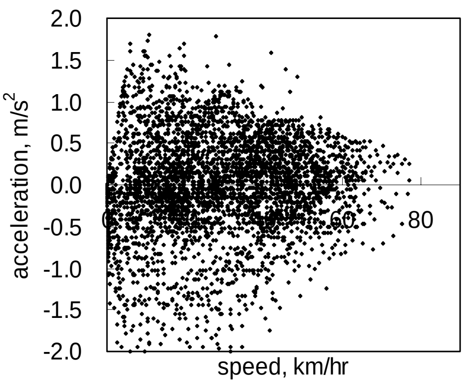


Figure 4-7 Speed-acceleration-driving pattern dots of taxis

Different vehicle types have different driving pattern distributions on various urban roads. Figures 4-8 and 4-10 shows the phenomenon.

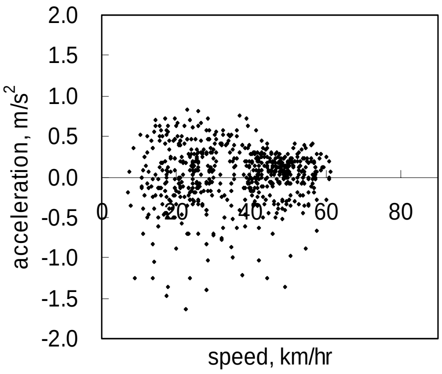


Figure 4-8 Distribution of driving pattern dots of trucks on highway

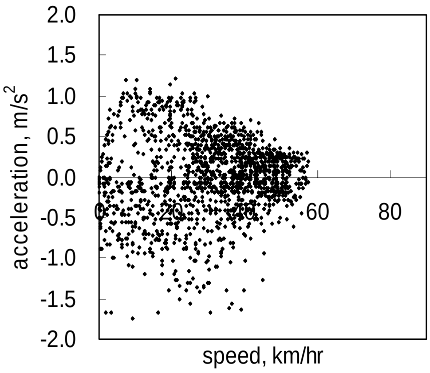


Fig.4-9 Distribution of driving pattern dots of trucks on arterial road

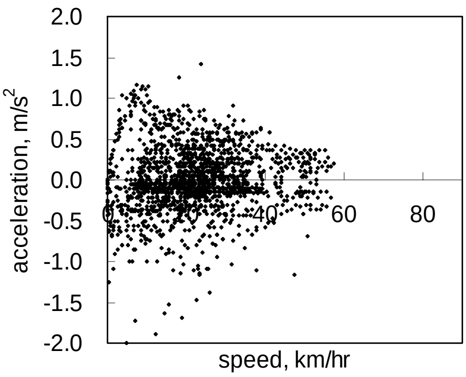
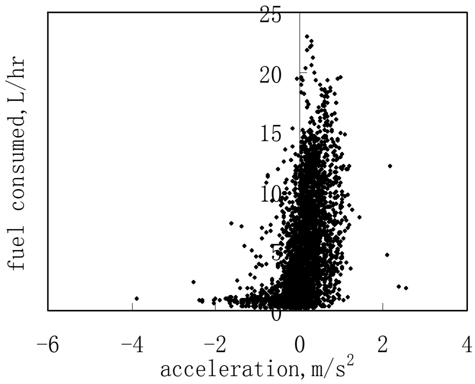


Fig.4-10 Distribution of driving pattern dots of trucks on residential road

6.2 Characteristics of acceleration-fuel consumption distribution

The acceleration-fuel consumption distribution is aimed at learning the relationship between vehicle fuel consumption and acceleration, as displayed in Figures 4-11 to 4-13.



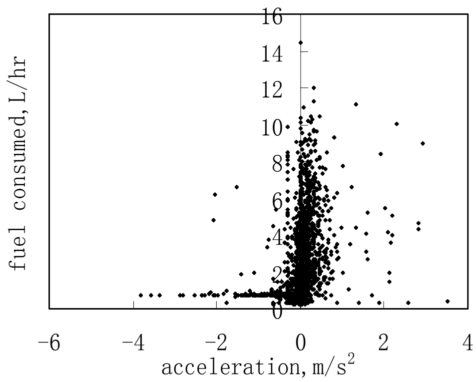


Fig.4-11 Distribution of acceleration-fuel consumed of trucks Fig.4-12 Distribution of acceleration-fuel consumed of buses

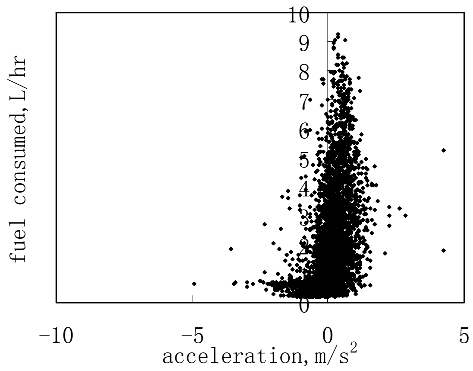
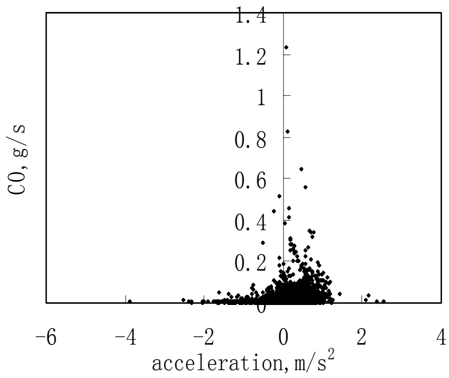


Fig.4-13 Distribution of acceleration-fuel consumed of taxis

6.3 Distribution of instantaneous emission concentration

The study of instantaneous emission concentration is aimed at learning the relationship between instantaneous emission of pollutants and acceleration. Figures 4-14 to 4-16 show the phenomenon using a heavy duty vehicle as an example.



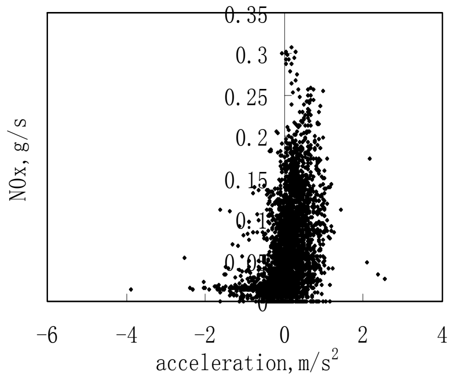


Fig.4-14 Distribution of instantaneous acceleration-CO of trucks Fig.4-15 Distribution of instantaneous acceleration-NO_x of trucks

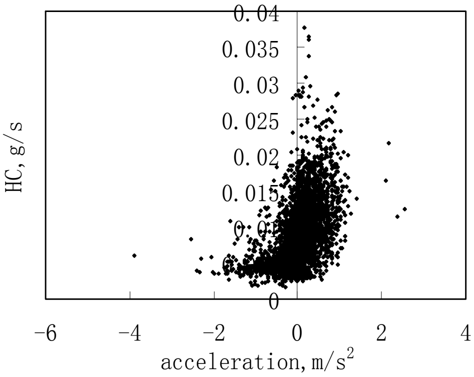


Fig.4-16 Distribution of instantaneous acceleration-HCof trucks

The tested vehicles used in this study lack OBD equipment. In other words, it was not possible to obtain driving speed directly from the vehicles. Consequently, the vehicle speeds were recorded with GPS, which has a delay of 3-5 seconds. But since vehicle speed and exhaust mass flow rate are linearly-related, the distribution of mass flow rate-emission can replace that of speed-emission (see Figures 4-17 to 4-19).

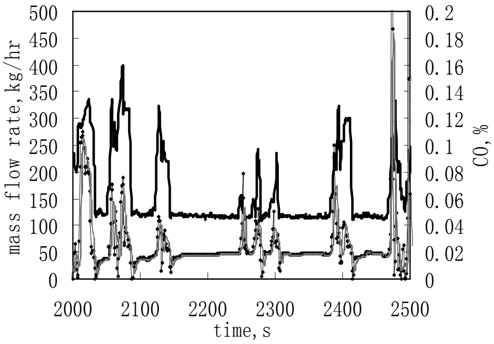


Fig.4-17 Instantaneous mass flow rate-CO concentration

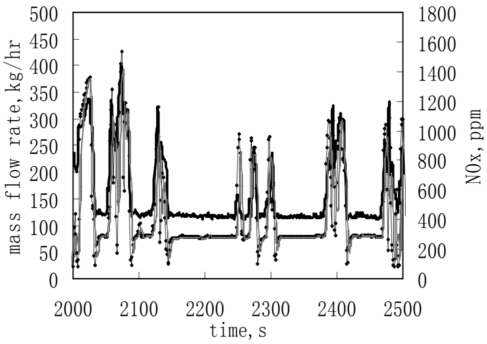


Fig.4-18 Instantaneous mass flow rate-NO_x concentration

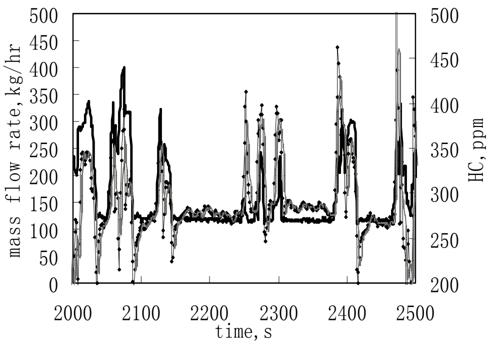


Fig.4-19 Instantaneous mass flow rate-HC concentration

6.4 Emission factors

The factors behind emissions are the most fundamental element in understanding vehicle emissions, which are usually expressed in terms of mass emission per mile. Emission factors are notable in that they vary depending on type of vehicle, roads and driving patterns. In this case, the mean emission factors for different vehicle types are displayed and standard deviations are computed.

6.4.1 Trucks

- Highway

Table 4-2 Emissions factors of trucks on throughways

Item	CO（g/km）	NOx（g/km）	HC（g/km）
Mean Emission Factors	4.68	9.38	1.22
Standard Deviations	2.70	2.55	0.28

- Arterial road

Table 4-3 Emissions factors of trucks on backbone roads

Item	CO（g/km）	NOx（g/km）	HC（g/km）
Mean Emission Factors	2.69	8.75	1.65
Standard Deviations	0.27	0.58	0.24

- Residential road

Table 4-4 Emissions factors of trucks on second-class roads

Item	CO（g/km）	NOx（g/km）	HC（g/km）
Mean Emission Factors	3.19	8.74	1.38
Standard Deviations	0.4	0.67	0.10

6.4.2 Buses

Table 4-5 Emissions factors of buses

Item	CO（g/km）	NOx（g/km）	HC（g/km）
Mean Emission Factors	3.56	4.75	2.05
Standard Deviations	0.89	1.04	0.52

6.4.3 Taxis

Table 4-6 Emissions factors of taxis

Item	CO（g/km）	NOx（g/km）	HC（g/km）
Mean Emission Factors	0.89	2.31	0.66
Standard Deviations	0.25	0.49	0.17

6.5 Results on driving cycles and emission factors

Tables 4-7 to 4-9 show the driving cycles and emission factors of various vehicle types.

Table 4-7 Characteristic parameters and emission factors of trucks on different roads under various driving patterns

Item	Driving pattern dots	speed/(km·h^{-1})		Time spent/%				Distance travelled /km				Fuel Consumption /(L·h^{-1})				Fuel economy /(L·100km^{-1})
		Average	Maximum	Idle	Acceleration	Cruise	Deceleration	Idle	Acceleration	Cruise	Deceleration	Idle	Acceleration	Cruise	Deceleration	
Highway	26724	22.7	68.5	20.4	19.6	32.3	27.6	67.8	47.1	51.1	166.0	1.2	8.1	4.7	1.9	19.1
Arterial road	6376	44.6	84.2	5.6	37.6	30.3	26.5	16.0	30.9	18.2	65.1	1.2	7.9	5.9	3.0	14.9
Residential road	23575	19.8	67.1	20.3	22.1	29.7	27.9	48.6	37.5	39.8	125.8	1.0	7.0	3.6	1.5	18.2
Integrated	61061	22.8	84.2	20.1	22.2	30.4	27.2	143.3	119.9	114.5	377.6	1.1	7.6	4.4	1.8	18.0

Item	CO emission rate/(mg·s^{-1})				HC emission rate/(mg·s^{-1})				NOx emission rate/(mg·s^{-1})				CO emission factor/(g·km^{-1})				HC emission factor/(g·km^{-1})				NOx emission factor/(g·km^{-1})			
	Idle	Acceleration	Cruise	Deceleration	Idle	Acceleration	Cruise	Deceleration	Idle	Acceleration	Cruise	Deceleration	Acceleration	Cruise	Deceleration	Integrated	Acceleration	Cruise	Deceleration	Integrated	Acceleration	Cruise	Deceleration	Integrated
Highway	12.2	72.3	40.7	21.4	8.5	21.1	15.7	9.5	14.2	74.6	47.4	21.8	9.2	4.5	3.1	6.4	2.7	1.7	1.4	2.3	9.5	5.3	3.2	6.8
Arterial road	13.9	59.1	38.6	24.6	8.5	17.0	16.2	12.3	14.5	84.5	57.4	31.9	7.1	3.0	2.3	3.9	2.1	1.3	1.1	1.5	10.2	4.5	3.0	5.5
Residential road	10.9	51.5	28.3	15.0	8.6	22.4	17.1	11.4	13.4	67.2	37.3	19.5	7.4	3.9	2.5	5.2	3.2	2.4	1.9	2.9	9.7	5.2	3.2	6.8
Integrated	11.7	62.2	37.1	19.4	7.5	17.6	14.8	9.9	13.9	71.3	44.7	21.8	8.1	4.2	2.8	5.6	2.3	1.7	1.4	2.1	9.2	5.1	3.2	6.5

Table 4-8 Characteristic parameters and emission factors of loaded trucks on different roads under various driving patterns

Item	Driving pattern dots	speed/(km h^{-1})		Time spent/%				Distance travelled /km				Fuel Consumption /(L·h^{-1})				Fuel economy /(L·100km^{-1})
		Average	Maximum	Idle	Acceleration	Cruise	Deceleration	Idle	Acceleration	Cruise	Deceleration	Idle	Acceleration	Cruise	Deceleration	
Highway	7992	23.3	56.4	17.1	25.1	34.0	23.8	20.8	17.9	12.6	51.3	1.4	13.8	8.0	2.8	32.8
Arterial road	1294	53.1	71.0	0.0	53.9	30.5	15.5	5.4	10.7	3.0	19.1	N/A	15.1	13.5	7.1	24.4
Residential road	7916	20.0	59.7	17.5	28.0	31.4	23.0	17.0	16.0	10.7	43.6	1.3	12.6	5.5	1.9	31.2
Integrated	19146	23.3	71.0	16.7	28.1	32.2	23.1	46.7	47.9	29.1	123.7	1.4	13.3	7.5	2.5	31.0

Item	CO emission rate/(mg·s^{-1})				HC emission rate/(mg·s^{-1})				NOx emission rate/(mg·s^{-1})				CO emission factor/(g·km^{-1})				HC emission factor/(g·km^{-1})				NOx emission factor/(g·km^{-1})			
	Idle	Acceleration	Cruise	Deceleration	Idle	Acceleration	Cruise	Deceleration	Idle	Acceleration	Cruise	Deceleration	Acceleration	Cruise	Deceleration	Integrated	Acceleration	Cruise	Deceleration	Integrated	Acceleration	Cruise	Deceleration	Integrated
Highway	16.1	272.2	134.2	61.1	6.7	22.7	18.6	12.1	15.1	85.2	53.8	23.2	35.5	15.0	9.2	22.3	3.0	2.1	1.8	2.6	11.1	6.0	3.5	7.9
Arterial road	N/A	340.0	384.0	134.5	N/A	19.0	19.8	17.3	N/A	92.9	83.2	52.0	24.8	25.1	9.0	22.5	1.4	1.3	1.2	1.3	6.8	5.4	3.5	5.5
Residential road	11.5	288.2	101.7	31.1	6.3	20.1	15.6	9.7	14.6	75.9	37.7	18.1	42.2	14.1	5.3	23.3	2.9	2.2	1.7	2.6	11.1	5.2	3.1	7.5
Integrated	14.0	273.6	154.7	49.4	6.5	21.4	17.2	11.1	14.8	81.8	49.4	22.2	36.1	17.4	7.5	22.5	2.8	1.9	1.7	2.4	10.8	5.6	3.4	7.4

Table 4-9 Characteristic parameters and emission factors of buses on different roads under various driving patterns

Driving pattern dots	speed/(km h^{-1})		Time spent/%				Distance travelled /km				Fuel Consumption/(L·h^{-1})				Fuel economy /(L·100km^{-1})
	Average	Maximum	Idle	Acceleration	Cruise	Deceleration	Idle	Acceleration	Cruise	Deceleration	Idle	Acceleration	Cruise	Deceleration	
4188	14.0	42.9	28.0	22.6	30.5	19.0	5.7	7.0	3.7	16.3	1.3	3.7	3.3	1.2	17.4

CO emission rate/(mg·s^{-1})			HC emission rate/(mg·s^{-1})				NOx emission rate/(mg·s^{-1})				CO emission factor/(g·km^{-1})				HC emission factor/(g·km^{-1})				NOx emission factor/(g·km^{-1})				
Idle	Acceleration	Cruise	Deceleration	Idle	Acceleration	Cruise	Deceleration	Idle	Acceleration	Cruise	Deceleration	Acceleration	Cruise	Deceleration	Integrated	Acceleration	Cruise	Deceleration	Integrated	Acceleration	Cruise	Deceleration	Integrated
7.9	20.4	18.1	7.3	4.8	11.5	10.4	5.0	10.4	25.9	25.2	10.3	4.6	2.4	1.6	3.6	2.6	1.4	1.1	2.1	5.8	3.4	2.2	4.7

Table 4-10 Characteristic parameters and emission factors of taxis on different roads under various driving patterns

Item	Driving pattern dots	speed/(km h^{-1})		Time spent/%				Distance travelled /km				Fuel Consumption/(L·h^{-1})				Fuel economy /(L·100km^{-1})
		Average	Maximum	Idle	Acceleration	Cruise	Deceleration	Idle	Acceleration	Cruise	Deceleration	Idle	Acceleration	Cruise	Deceleration	
Highway	5702	20.5	75.6	25.9	16.0	32.8	25.3	14.3	7.4	9.6	1.1	2.9	8.7	0.9	5702.0	20.5
Arterial road	1601	23.1	68.4	13.7	22.3	35.0	29.0	4.3	3.0	3.0	10.3	0.7	2.9	1.8	1.1	7.9
Residential road	2515	31.3	77.2	20.9	20.6	30.5	28.1	7.0	5.7	6.0	18.7	0.7	3.3	2.1	1.1	7.0
Integrated	11161	23.0	77.2	21.2	19.2	33.1	26.5	30.2	19.9	21.4	71.5	1.0	3.0	1.9	1.0	7.9

Item	CO emission rate/(mg·s^{-1})				HC emission rate/(mg·s^{-1})				NOx emission rate/(mg·s^{-1})				CO emission factor/(g·km^{-1})				HC emission factor/(g·km^{-1})				NOx emission factor/(g·km^{-1})			
	Idle	Acceleration	Cruise	Deceleration	Idle	Acceleration	Cruise	Deceleration	Idle	Acceleration	Cruise	Deceleration	Acceleration	Cruise	Deceleration	Integrated	Acceleration	Cruise	Deceleration	Integrated	Acceleration	Cruise	Deceleration	Integrated
Highway	4.4	7.7	6.4	4.7	3.1	5.0	4.3	3.3	12.7	38.9	23.5	15.5	1.0	0.8	0.7	1.1	0.7	0.5	0.5	0.7	5.1	2.9	2.3	4.3
Arterial road	4.2	8.5	9.1	6.2	2.6	4.9	4.0	3.1	11.8	40.8	32.4	22.6	1.1	1.1	1.0	1.1	0.6	0.5	0.5	0.6	5.3	3.9	3.5	4.6
Residential road	4.0	9.1	8.4	5.5	1.9	4.9	4.7	3.2	15.1	57.5	28.1	21.5	1.0	0.8	0.6	0.9	0.5	0.4	0.4	0.5	6.3	2.5	2.5	4.4
Integrated	4.3	8.1	7.5	5.1	2.8	5.0	4.5	3.3	12.8	41.7	25.2	17.3	1.0	0.8	0.7	1.0	0.6	0.5	0.5	0.6	5.1	2.7	2.4	4.0

7. Summary

(1) When the vehicles are tested on real road conditions, it was found that the distribution of speed, acceleration, and driving pattern points varied with road type. As far as vehicle types are concerned, light-duty vehicles have relatively high speeds, with an average speed of 23 $km \cdot h^{-1}$ and a maximum speed of 77.2 $km \cdot h^{-1}$. In terms of road types, it was discovered that the average vehicle speed on throughways is higher than that on backbone roads, which is in turn higher than that found on second-class roads. The vehicles used in this study were carefully tested to ensure that they reflected the traffic situation found on real roads. For this reason, periods of idleness, acceleration and deceleration for the vehicles tested were all characteristics reflected in real traffic situations.

(2) The response of fuel consumption changes and air/fuel ratio to engine power causes differences in speed and rates of acceleration when vehicles are in motion. This in turn influences vehicle emissions. The instantaneous concentrations of CO, THC and NO_x vary with vehicle speed by certain rules.

(3) Even when accelerating at the same rate, the emission rates of CO, THC, and NOx are different at different speeds. Results show that driving at low speeds while frequently acceleration negatively effect fuel economy and vehicle emissions. Therefore, strengthening traffic management would not only improve traffic capacity but can also have a positive effect on reducing vehicle emissions.

(4) The emission factors of vehicles tested vary with road type and vehicle driving mode, and are strongly influenced by load. Results show that the average emission factors of CO for empty trucks on integrated road is 5.6 $g \cdot km^{-1}$, while THC is 2.1 $g \cdot km^{-1}$ and NOx is 6.5 $g \cdot km^{-1}$. When the trucks are fully loaded, CO is 22.5 $g \cdot km^{-1}$ while THC is 2.4 $g \cdot km^{-1}$ and NOx is 7.4$g \cdot km^{-1}$. The average emission factors of CO for buses on their routine route is 3.6 $g \cdot km^{-1}$ while THC is 2.1 $g \cdot km^{-1}$ and NOx is 4.7 $g \cdot km^{-1}$. The average emission factor of CO for light-duty vehicles is 1.0 $g \cdot km^{-1}$ while THC is 0.6 $g \cdot km^{-1}$ and NOx is 4.0 $g \cdot km^{-1}$. This study essentially reflects the emission situation on real roads.

(5) Not taking into account CO, THC, and NOx emissions, the exhaust of diesel vehicles also contains PM10, which are fine pollutants harmful to human health. However, due to the limitation of the equipment and methodology available to us, we were unable to measure emission factors of PM10 from vehicles. Future studies should be able to take this factor into consideration.

References

CE-CERT. *Mobile heavy-duty diesel emissions laboratory* [EB/OL]. http://www.cert.ucr.edu/ emissions/

Chen, C., Fang, C., Bao, X., 1997. *Estimation of motor vehicle emissions in Shanghai proper*. Shanghai Environmental Science 16, 26-29.

Cheng C., Jing Q., Wang H., ect., In press. *Research on On-road Emission Characteristics of Heavy-duty Vehicles and Its Affection Factors.* Acta Scientiae Circumstantiae.

Dai, L., Hu, X., Gu, Y., 1997. *Building the emission test cycle of Shanghai district*. Shanghai Auto 81, 5-6.

Deng, S., Shi, B.,1999. *An experimental study on pollutant emission factors of light duty vehicles in China*. China Environmental Science 19, 176-179.

Dong, G., Chen L., Zhang Z., 2003. *Remote Sensing Measurement of On-Road Motor Vehicle Emission and Estimate of Emission Factors.* Transactions of CSICE 21(2), 115-119.

Fu, L., He, K., He, D., Tang, Z., Hao, J., 1997. *A study on models of MOBILE source emission factors*. Acta Scientiae Circumstantiae 17, 474-479.

Fu, L., Hao, J., He, D., He, K.,2000. *The emission characteristics of pollutants from motor vehicles in Beijing*. Environmental Science 21,68-70.

He, D., Hao, J., He, K., Fu, L.,1998. *Vehicle emission factors determination using model calculation*. Environmental Science 19, 7-10.

Hu J., Hao J., Fu L., Wu Y., etc, 2004. *Study on On-road Measurement and Modeling of Vehicular Emissions.* Environmental Sience 25(3), 19-25.

Li, X., Yang, X., Wang, W., Deng, X., 2001. *Motor vehicles' exhaust emission factors for urban transportation planning*. Journal of Traffic and Transportation Engineering 1, 87-91.

NBSC, 2001. China Statistical Yearbook 2001. National Bureau of Statistics of China, Beijing, P.R.China.

SAES, 1997. *Strategy for Reducing Dangerous Vehicle Emissions in City of Shanghai*. Shanghai Academy of Environment Sciences, Shanghai, P. R. China.

THU-DEST, BARI, CRAES-ARI, 1997. *Strategy Research for Vehicle Emission Pollution Control in Model City of China*. Tsinghua University-Department of Environmental Science and Engineering, Beijing Auto Research Institute, Chinese Research Academy of Environmental Sciences-Atmospheric Research Institute, Beijing, P. R. China

Xie, S., Zhang, Y., Tang, X.,2000. *Current situation and trend of motor vehicle exhaust pollution in urban areas of China*. Research of Environmental Sciences 13, 22-25.

Wang W., Liu H., Ding Y., etc., 2001. *Means of Investigation of Air Pollution from Traffic Sources by Highway Tunnel Experiments*. Research of Environmental Science 14(4), 1-4.

Wang W., Ye H., Li Y., etc., 2001. *Study on Emission Factors of CO ,SO2 and NOx in Tanyugou Highway Tunnel.* Research of Environmental Science 14(4), 5-8.

Zhang Y., Donald H. Stedman, Gray A. Bishop, etc., 1996. *On-Road Evaluation of Inspection/Maintenance Effectiveness*. Environ. Sci. Technol. 30, 1445-1450

Zhou, Z., Yuan Y., Liu, X., Wang, R., Cen, Y., 2000. *The study of driving cycle and emission factor of vehicle in Beijing city*. Acta Scientiae Circumstantiae 20, 48-53.

Zhu, C., 1997. *Coefficient of vehicular emission discharge and trend of pollution in Guangzhou City*. China Environmental Science 17, 216-219.

Chapter 5. Vehicle Emission Inventory

The IVE model was used to evaluate vehicle emissions in Shanghai. The parameters in this model were renewed by using the results of the driving patterns and technology distribution as described in Chapter 3 and the emission factor testing described in Chapter 4. Thus, the model was localized and used to prepare the vehicle emission inventory for Shanghai.

IVEM (International Vehicle Emission Model) was developed under the joint cooperation of the University of California at Riverside, the College of Engineering-Centre for Environmental Research and Technology (CE- CERT), the Global Sustainable System Research (GSSR) and the International Sustainable Systems Research Centre (ISSRC). Figure 5-1 shows the main interface of IVEM.

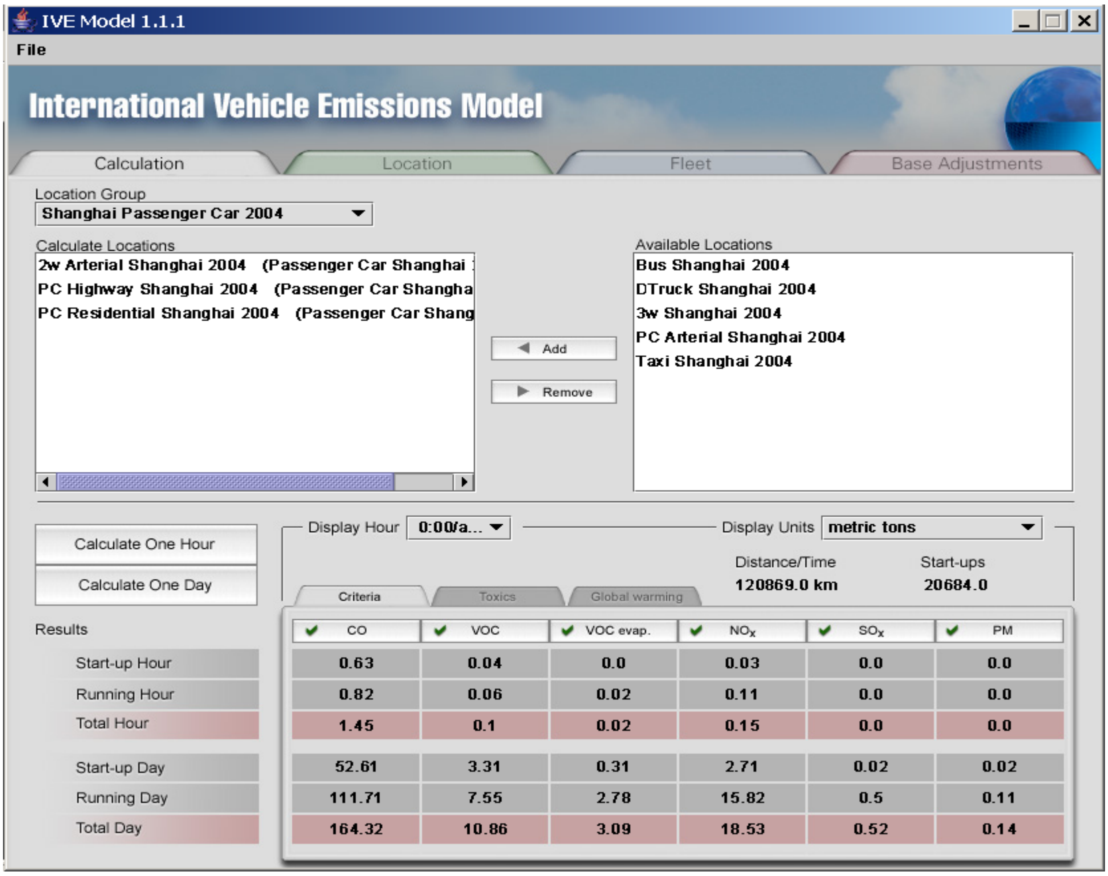


Figure 5-1 The main interface of IVEM

1. Structure of IVEM

Figure 5-2 illustrates the process of emission estimation in the IVE model. The core of the emission calculation process of the IVE model is a basic emission factor. A series of correction factors for various vehicle types are applied to the estimation. There are three critical parts in the IVE model needed to create accurate emission inventories:

- Vehicle emission rates (Including Basic Emission Factors and Correction Factors of various vehicle types);
- Vehicle activity (Location Input Data shown in Yellow Box); and
- Vehicle fleet distribution (Fleet Input Data shown in Yellow Box)

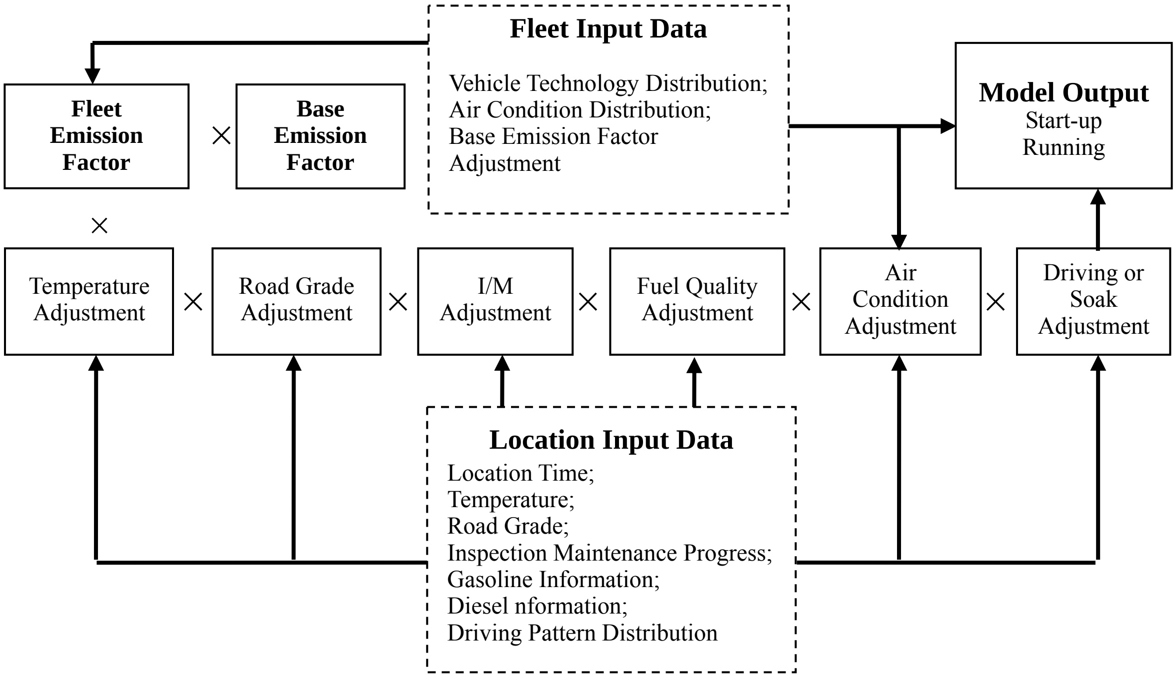


Figure 5-2 The Structure of the IVE Model

Figure 5-2 shows the structure of the IVE model. The IVE model is designed to use existing and easily collectable local data to quantify these three essential input files. Once the information has been collected, appropriate mobile source inventories can be easily developed and modified for alternative scenario evaluations. Generally, when the IVE model is applied to estimate emissions in one city or district, the input parameters can be modified to represent the local situation. Thus, a relatively accurate inventory of local vehicle emissions can be obtained.

2. Calculation Methods

The process of emission calculation in the IVE model is to multiply the basic emission factor by its correction factor and vehicle miles traveled for each type of vehicle with different technology. Thus, the total emission amount is obtained. The correction factor differs with the definition of various vehicle technologies. The calculation process of correction factors for the model is shown in Equation 1.

$$Q_{[t]} = B_{[t]} \times K_{(1)[t]} \times K_{(2)[t]} \times \ldots \times K_{(x)[t]} \quad (5\text{-}1)$$

When, $Q_{[t]}$ is the real emission factor; $B_{[t]}$ is the basic emission factor, which is based on a USFTP driving cycle. The correction factors can be divided into several categories (Table 5-1) and can also be modified in the Location File and saved in the model.

Table 5-1 Correction Factors for Location Specific Information in the IVE Model

Local Variables	**Fuel Quality Variables** $K_{(Fuel)[t]}$	**Power & Driving Variables** $K_{[dt]}$
Ambient Temperature $K_{(Tmp)[t]}$	Gasoline Overall	Vehicle Specific Power*
Ambient Humidity $K_{(Hmd)[t]}$	Gasoline Sulfur	Road Grade
Altitude $K_{(Alt)[t]}$	Gasoline Lead	Air Conditioning Usage
Inspection/Maintenance Programs $K_{(IM)[t]}$	Gasoline Benzene	Start Distribution
Base Emission Adjustment $K_{(Cntry)[t]}$	Gasoline Oxygenate	
	Diesel Overall	
	Diesel Sulfur	

Emission quantities and characteristics vary when a vehicle is running and when it is starting up. Due to incomplete combustion and low temperatures in the engine, the emissions released during start-up are much more than when running. Therefore, the emissions released when starting up a vehicle and running a vehicle are calculated separately in the IVE model. Equation 5-2 weighs the adjusted emission rate by the travel fraction and driving cycles for each type of vehicle. The travel fraction is obtained from traffic flow surveys. After weight estimation, the result is multiplied by ratio of the average speed under the LA4 driving cycle and the simulated driving cycle. This figure is then multiplied by the number of miles traveled (emission under running). Equation (5-3) shows the emission calculation process at starting up.

$$Q_{running} = \bar{U}_{FTP} \times D/\bar{U}_{C} \times \Sigma_t \{f_{[t]} \times Q_{[t]} \times \Sigma_d [f_{[dt]} \times K_{[dt]}]\} \quad (5\text{-}2)$$

$$Q_{start} = \Sigma_t \{f_{[t]} \times Q_{[t]} \times \Sigma_d [f_{[dt]} \times K_{[dt]}]\} \quad (5\text{-}3)$$

Where: $\bar{U}_{FTP}$ ——Average speed under LA4 driving cycle, km/h

D —— Vehicle miles traveled (VMT), km

$\bar{U}$ C —— Average speed under on-road driving cycle, km/h

$f_{[t]}$ —— Fraction of vehicle miles traveled among total VMT of a specific vehicle technology

$Q_{[t]}$ —— Real emission factor of a vehicle type, g/km (running condition) or g (starting up condition).

$f_{[dt]}$ —— Fraction of each type of driving or idling by a specific technology

$K_{[dt]}$ —— Correction factors at running or idling (including influence from air-conditioning and road conditions)

3. Results

3.1 VMT and vehicle start-up distribution

The VMT (Vehicle miles traveled) was obtained by integrating vehicle population, fleet distribution and the number of miles traveled on average each day of each fleet. Data regarding the number of vehicles and technology distribution was obtained from the Institute of Vehicle Management, the Shanghai Public Security Bureau, while the daily VMT of various vehicle types was obtained during this survey. The results are shown in table 5-2 and reveal that the vehicles travel about 5,085 kilometers per day in Shanghai. Passenger cars and small vans occupy the largest proportion, at about 35.7%. Taxis account for 28%. There are also a large number of mopeds in Shanghai, which account for 15% of the total vehicle miles traveled.

Table 5-2 VMT distribution of various vehicle types in Shanghai

Fleet	Population	VMT/d	Total VMT/d	Proportion
	10^4	Km/d	10^4 km/d	%
Passenger Car	37.1	49	1817.9	35.7
Taxi	4.75	300	1425	28.0
Motorcycle	12.5	12	150	2.9
Moped	63.3	12	759.6	14.9
Bus	3.23	130	419.9	8.3
Truck	5.7	90	513	10.1
Total	126.58		5,085	100

Both traffic flow and VMT differ with time of day. The VMT distribution is achieved through weighted calculation of traffic flow in various hours on different roads (refer to Chapter 3). Figure 5-3 illustrates that there are three peaks of traffic flow in Shanghai, namely 9:00-10:00, 14:00-15:00 and 17:00-18:00. The specific results are shown in table 5-3. The last two columns refer to the distribution of vehicles starting up.

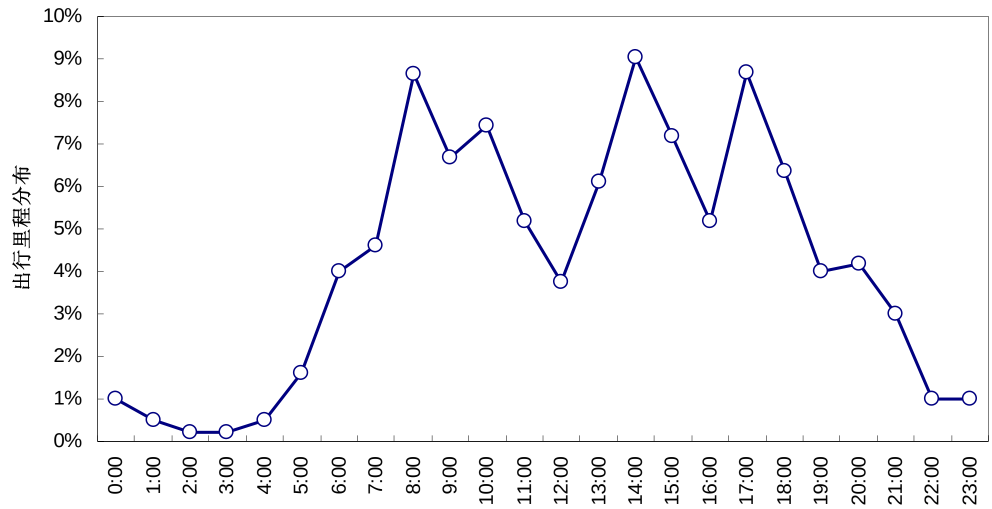


Figure 5-3 The profile of VMT distribution in Shanghai

Table 5-3 Distributions of VMT and start ups in various hours of Shanghai

Time	VMT Distribution	VMT per hour (kilometer)	Start up Distribution	Starts/hour
0:00	1%	508540	1%	93410
1:00	1%	254270	1%	93410
2:00	0%	101708	1%	43112
3:00	0%	101708	1%	43112
4:00	1%	254270	1%	79039
5:00	2%	813664	1%	79039
6:00	4%	2034160	6%	431122
7:00	5%	2344870	6%	431122
8:00	9%	4388201	8%	596385
9:00	7%	3398053	8%	596385
10:00	7%	3779812	6%	416751
11:00	5%	2640770	6%	416751
12:00	4%	1907274	6%	395195
13:00	6%	3111532	6%	395195
14:00	9%	4594583	6%	409566
15:00	7%	3646340	6%	409566
16:00	5%	2639319	7%	524531
17:00	9%	4408833	7%	524531
18:00	6%	3225152	5%	352083
19:00	4%	2034700	5%	352083
20:00	4%	2123541	2%	172449
21:00	3%	1525620	2%	172449
22:00	1%	508540	1%	86224
23:00	1%	508540	1%	86224
Total	100%	50,854,200	100%	7,185,360

3.2 Vehicle Emissions

3.2.1 Distribution of Diurnal Emissions

CO, VOC, NOx and PM emissions of vehicles were calculated by using the IVE model through VMT and start-up profile from on-site surveys conducted during this study.

Figure 5-4 illustrates vehicles' emissions of CO at different hours of the day in Shanghai. The yellow area indicates the emissions while running and the purple area refers to the emissions created during vehicle start-up.

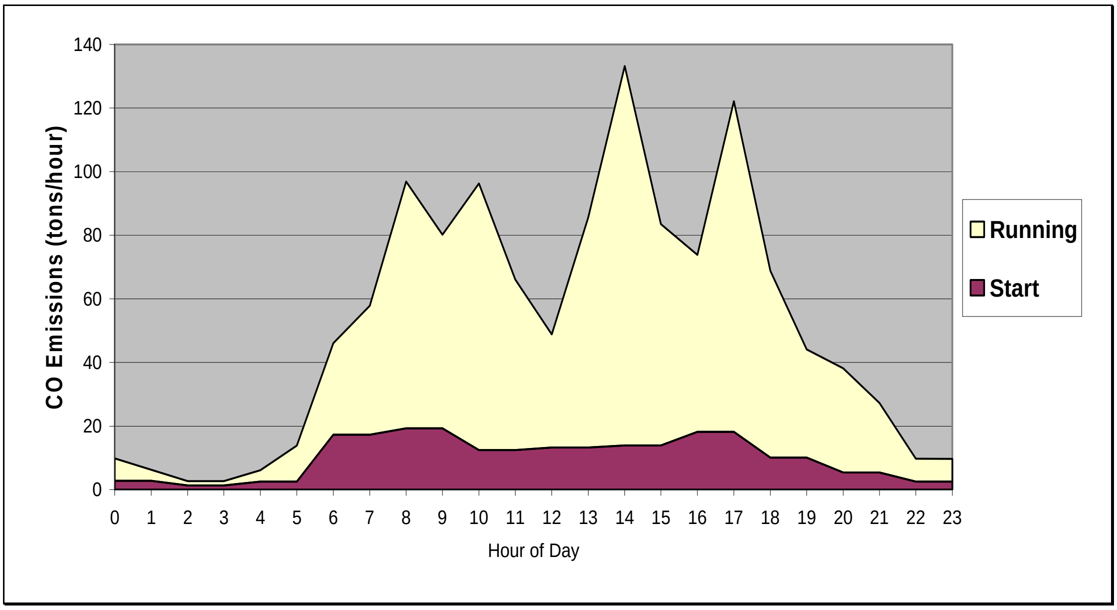


Figure 5-4 The vehicle emission of CO in Shanghai

Vehicle emissions of CO are 1,154 tons per day in Shanghai and the average daily rate of emissions per vehicle (including running and start-up) is 22.6g/km. The figure shows that emissions of CO are strongly influenced by traffic flow and that the highest points for the release of emissions occur at 8:00~9:00, 15:00~1600 and 17:00~18:00, while the valley point appears at 12:00~13:00. Although starting up a vehicle occurs very quickly, it makes a large contribution to CO emissions, especially in the morning. The calculation results indicate that vehicle emissions in the morning represent about 1/3 of total emissions.

Figure 5-5 shows the vehicle emissions of VOC in Shanghai. The evaporative emission of VOC (the blue area) is also considered in this model.

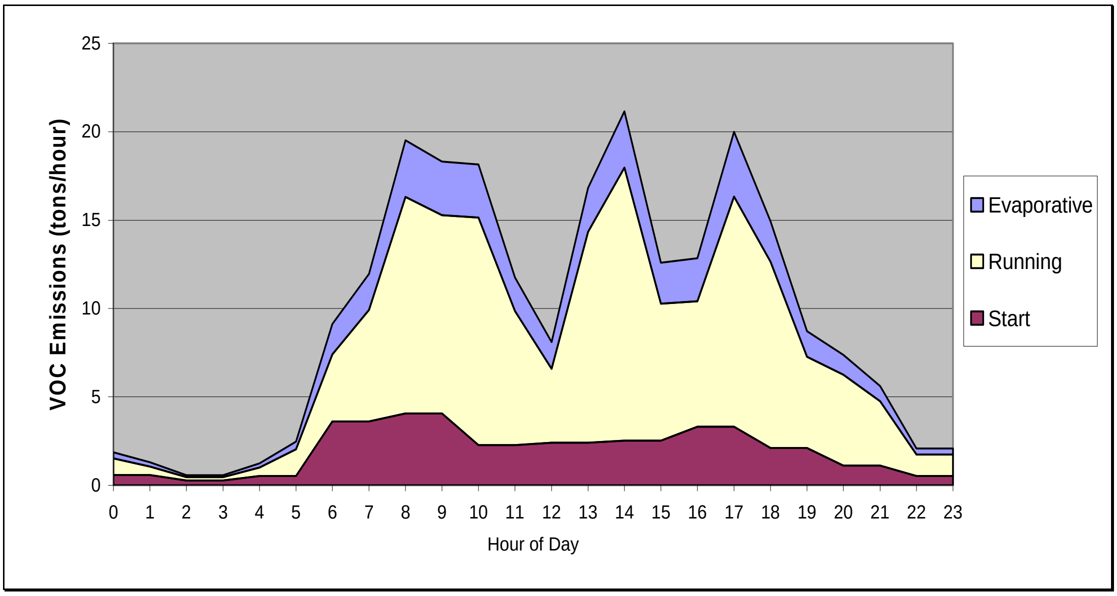


Figure 5-5 Vehicle emissions of VOC in Shanghai

Vehicle emissions of VOC are 176 tons per day in Shanghai and the average daily rate of emissions per vehicle (including running, start-up and evaporation) is 3.46g/km. Figure 5.5 also shows that emissions of VOC are very similar to that of CO emissions and that the highest points for the release of emissions occur at 8:00~9:00, 15:00~1600 and 17:00~18:00, while the valley point appears at 12:00~13:00. Both VOC and CO occur due to incomplete combustion, so the emission released at start up also makes a large contribution to the total VOC emissions. Evaporative emissions also represent a significant proportion of the total.

Figure 5-6 shows the vehicle emissions of NOx as calculated by IVEM in Shanghai. Vehicle emissions of NOx are 182 tons per day in Shanghai and the average daily rate of emissions per vehicle is 3.57g/km. The figure illustrates that emissions created at start up make a much lesser contribution to the total NOx emissions compared to CO and VOC emissions. This is mainly due to the fact that the temperature during a cold start-up of a vehicle is not high enough to produce NOx.

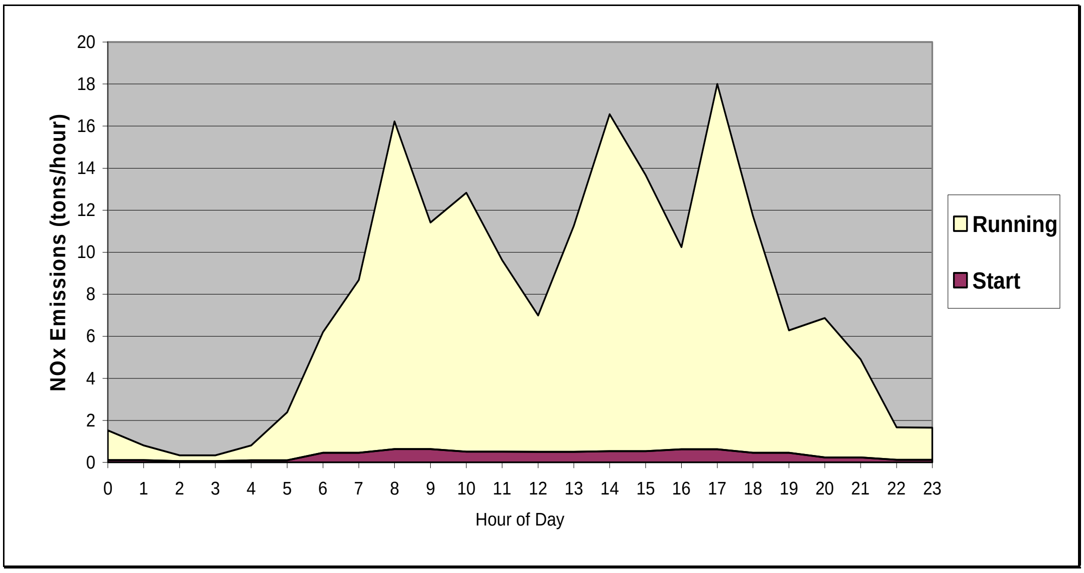


Figure 5-6 Vehicle emissions of NOx in Shanghai

Figure 5-7 shows vehicle emissions of PM in Shanghai. The daily emission is 4.54 tons and the average emission rate per vehicle is 0.089 g/km. PM emissions from vehicles are mainly incomplete combustion matter. This particulate matter usually comes out as black or blue smoke and is particularly harmful to human health.

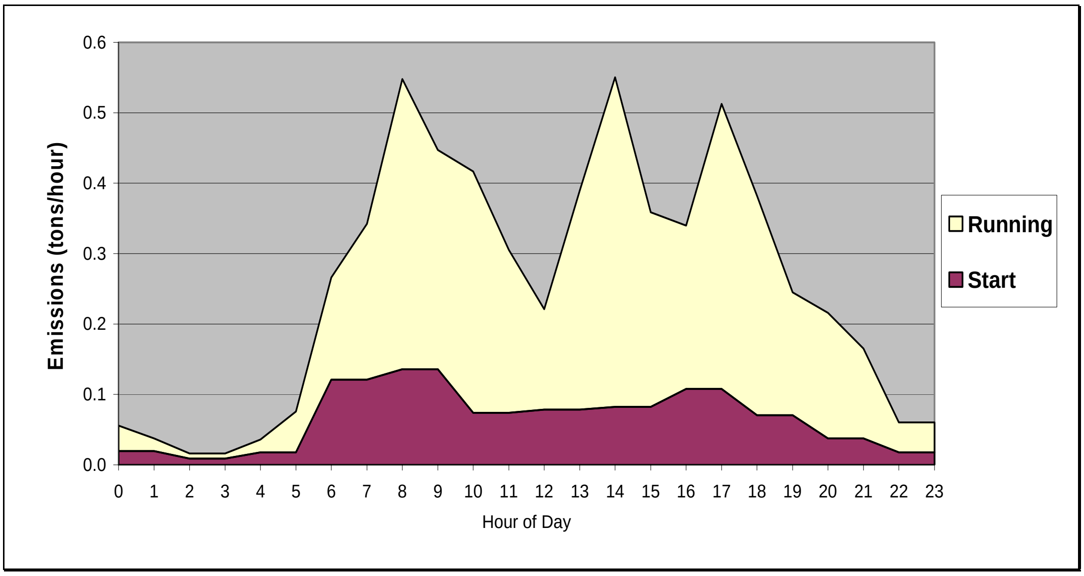


Figure 5-7 Vehicle emissions of PM in Shanghai

3.2.2 Total Emissions

Table 5-4 shows the combined total of vehicle emissions in Shanghai. The vehicles are classified as passenger cars, taxis, trucks, buss, motorcycles and mopeds. From the table, we can see that vehicle emissions of CO, VOC, NOx, PM and CO_2 are respectively 421 thousand tons/year, 64 thousand tons/year, 66 thousand tons/year, 1.7 thousand tons/year and 7.53 million tons/year.

Table 5-4 Total Vehicle Emissions in Shanghai

Fleet	Emission rate										VMT	
	CO		VOC		NOx		PM		CO_2		Population	VMT_{total}
	10^3 ton/a	%	10^3 ton/a	%	10^3 ton/a	%	10^3 ton/a	%	10^3 ton/a	%	10^3	Billion km
Pass. Car	90	21	8	13	11	16	0.008	5	299	40	371	6.635
Taxi	119	28	10	16	9	14	0.05	3	1780	24	47.5	5.201
Dtruck	61	15	5	8	16	24	0.54	32	1020	13	125	0.548
Bus	57	14	6	9	28	43	0.35	21	1500	20	633	2.773
Motorcycle	16	4	4	7	1	1	0.05	3	70	1	32.3	1.533
Moped	77	18	31	48	2	2	0.60	36	180	2	57	1.872
Total	**421**	**100**	**64**	**100**	**66**	**100**	**1.66**	**100**	**7530**	**100**	**1265.8**	**18.562**

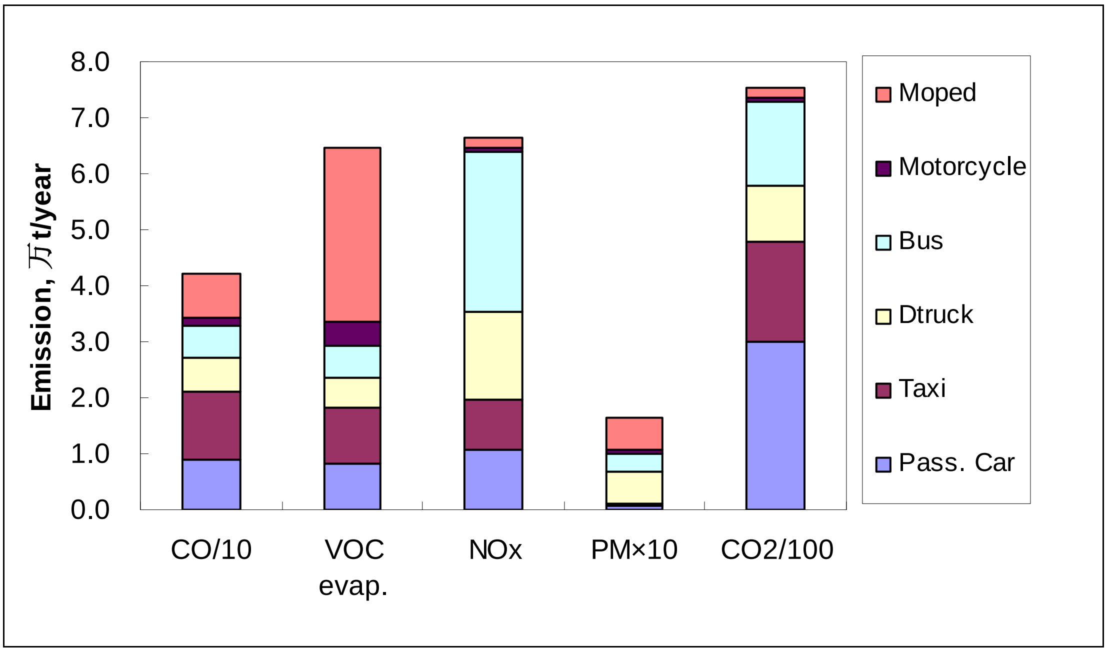


Figure 5-8 of Total vehicle emissions in Shanghai

3.2.3 Emission Contribution of vehicle category

The rate and diversity of emissions varies from vehicles to vehicle. Figure 5-8 shows this variance and which vehicles create which pollutants in Shanghai. From the chart we can see that CO emissions come mainly from light duty vehicles such as passenger cars, taxis and mopeds. Taxis account for 29% of the total emission of CO, passenger cars 21% and mopeds nearly 18%. In 2004, there were still 200 thousand mopeds in Shanghai, which are the main source of VOC, accounting for 48% of total VOC emissions. Passenger cars and taxis occupy 12% and 16% of total VOC emissions respectively. NOx emissions are mainly caused by heavy duty vehicles such as trucks and buses, which account for 42% and 24% respectively. This may seem like a relatively small figure, but it must be remembered that buses and trucks only make up 18.4% of the total vehicles in Shanghai. Thus, the emissions rates of heavy duty vehicles are more serious than that of other type of vehicles. PM emissions from heavy duty buses and trucks account for 21% and 33%. PM emissions from mopeds are also particularly high, accounting for 35% due to poor technology and lack of proper combustion equipment. The main source of CO_2 comes from passenger cars, which account for 40% of total CO_2 emissions. Following passenger cars are taxis and buses which respectively account for 24% and 20% of total CO_2 emissions.

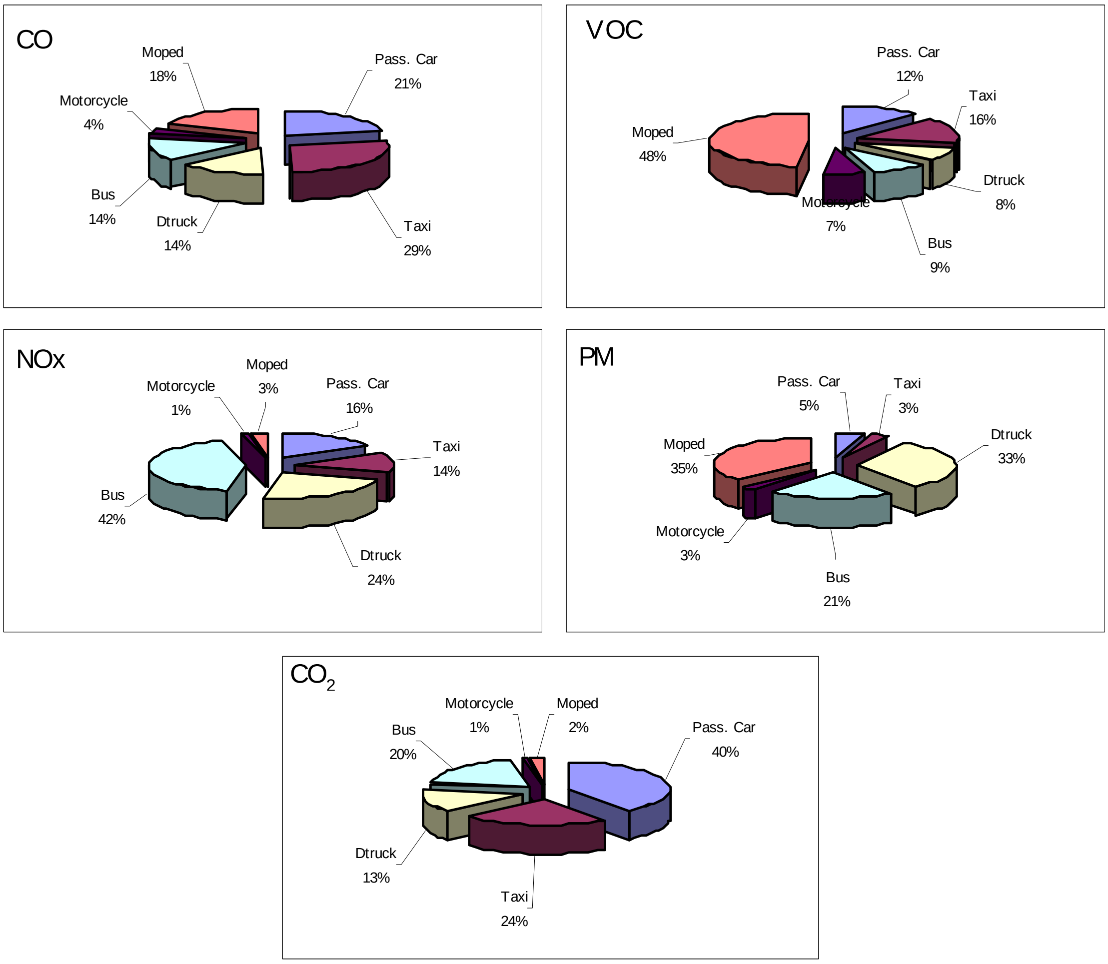


Figure 5-9 Emission shares of vehicles in Shanghai

4. Summary

The IVE model was used to calculate vehicle emission in this chapter. The results can be applied to estimate the vehicle emission situation in Shanghai.

The yearly vehicle emissions of CO, VOC, NOx, PM and CO_2 amount to 421 thousand tons, 64 thousand tons, 66 thousand tons, 1.7 thousand tons and 7.53 million tons respectively, among which 20~30% of CO, VOC and PM occurs during start up of vehicles. Emissions usually peak at 8:00-9:00, 15:00-16:00 and 17:00-18:00. These times correspond to the times when people are starting and finishing work, notably when the traffic flow on the road is at its most congested. The emissions during these periods account for 80~90% of the total emissions.

Figure 5.9 shows that the emission levels of mopeds and heavy duty vehicles (including trucks and buses) are the highest, which respectively account for only 14.9 percent, 8.3 percent, and 10.1 percent of total VMT, but cause 46 percent of total CO emissions, 65 percent of total VOC emissions, 69 percent of total NOx emissions and 89 percent of total PM emissions. They have become the main source of traffic pollution and cause enormous damage to the environment and human health. Light duty vehicles, such as passenger cars, taxis and motorcycles are all relatively new vehicles in Shanghai, and are thus usually equipped with advanced engine and emission control technology. As such, their contribution to air pollution is relatively low.

If sustainable transportation in Shanghai is to be realized, mopeds, essentially "Moving Chimneys", must be phased out and replaced by LPG or electric moped as soon as possible. More strict standards should be applied to heavy-duty vehicles to make them adhere to more environmentally friendly technology. Heavy duty vehicles with high performance and low pollution emissions than can carry heavy loads should also be developed.

Chapter 6. Shanghai Ambient Air Quality Status

1. Distribution of Air Pollution Monitoring Stations

Shanghai's environmental monitoring network includes 21 automatic stations and 23 manual monitoring stations located in both urban and county areas. Currently, there are 21 sub auto monitoring sites and one central station, which compose the auto air quality monitoring system of Shanghai. Among them there are 10 national control sites (including one for background monitoring), 8 urban control sites, 2 supervising sites and 1 comparing site. These sites are located in all 8 districts of Shanghai and try to accurately represent the different land uses in Shanghai; hence they are found in large and medium industrial parks, small industry concentrated regions, urban residential areas, educational areas, commercial and heavy traffic areas, mixed areas and clean areas.

There are 23 monitoring sites for monitoring SO_2, NOx, NO_2 and TSP. The distribution of these monitoring items and sites are shown in Table 6-1.

Table 6-1 Distribution of Ambient Air Quality Monitoring Sites in Shanghai

Monitoring methods	Number of Sampling sites			
	Urban area	Suburban area	Counties	Total
Auto	7	12	2	21
Manual	11	9	3	23
Total	18	21	5	44

2. Frequency and Methods of Air Pollutant Monitoring

The main center of the monitoring network inspects the environmental monitoring data for the 21 ambient air quality auto-monitoring stations via wire-transmission in real-time, thus ensuring not only the authenticity and accuracy of the information but also that it is received in a timely fashion. Everyday these daily air quality reports and forecasts are released via various sources of media.

Monitoring methods are based on the *National Atmospheric Quality Criterion* and the *Air and Waste Gas Monitoring and Analyzing Approaches* compiled by SEPA, as shown in Table 6-2.

Table 6-2　Air Pollution Monitoring Methods

Items	Standard methods	Method Code	Lowest detect limitation or metrical range
CO	NDIR	GB 9801-88	0.3 mg/m^3
NOx	Saltzman	GB/T 15436-1995	0.015 mg/m^3
NO_2	Saltzman	GB/T 15435-1995	(0.015～2.0) mg/m^3
O_3	Indigo disulphonate spectrophotometry	GB/T 15437-1995	(0.030～1.200)mg/m^3
	ultraviolet spectrophotometric method	GB/T 15438-1995	2.14　$\mu g/m^3$
SO_2	Formaldehyde absorbing-pararosaniline spectrophotometry	GB/T 15262-94	0.007 mg/m^3
TSP	Gravimetric method	GB/T 15432-1995	0.001 mg/m^3
PM_{10}	β-radial method	GB 6921-86	1 $\mu g/m^3$
Dust	Gravimetric method	GB/T 15265-94	0.2 $t/km^2 \cdot 30d$

3. Ambient air quality status

As the air pollution monitoring data in the 1990 to 2003 *Shanghai Ambient Air Quality Reports* shows, air pollution from 1990 to 1993 was primarily caused by coal burning and thus the main pollutants were SO_2 and smoke from burning coal. However, from 1994 to 1996, the main type of air pollution was more complex due to both the presence of coal burning as well as construction, meaning the main pollutants were dustfall, TSP and SO_2.

In order to control air pollution in Shanghai, a number of control measures have been implemented taken since the late 1990s such as "Control Total Amount of SO_2 Emission", "Integrated Renovation in Main Polluted Areas", "One Control and Two Compliances", "Trans-Century Green Project", and "Construct Non-Coal–Burning Area". With the implementation of these control measures, pollution from burning coal has been gradually decreasing year after year. The type of air pollution prevalent in Shanghai is thus changing into a more complex kind of pollution which is both coal and petroleum based, with the primary pollutants being NOx, TSP, SO_2 and dust.

As a result of the various measures that have been put into force, there has been a sharp reduction in coal and smoke pollution since 2002. However, this has been furthered strengthened by an increase in vehicle pollution controls. The Euro II emission standard has been in force Since March 1, 2003. The I/M (Inspection/Maintenance) program was implemented for in-use vehicles and a centralized I/M station was set up. Moreover, a petrol-mopeds scrapping program had been conducted. With these control measures in place, the upward trend of vehicle pollution in the city centre has been brought under control. However, due to the rapid increase in the number of vehicles in Shanghai, air pollution caused by vehicle emissions is still as serious problem and is controlled city-wide yet, despite implementation of the Euro II emission standards,. The data in the *Shanghai Environmental Bulletin* shows that the particulate matter (PM) and NOx are the main pollutants in the city at present. The visibility in Shanghai has shown no obvious improvement due to PM pollution.

Table 6-3 shows the annual average concentrations of SO_2, NOx, TSP and PM_{10} from 1990 to 2003.

Table 6-3 Shanghai Annual Average Concentrations of SO_2, NOx, TSP and PM_{10} (Unit：mg/m^3)

	SO_2		NOx		TSP		PM_{10}
	City Avg.	City centre	City Avg.	City centre	City Avg.	City centre	City centre
1990	0.048	0.095	0.040	0.062	0.284	0.358	
1995	0.032	0.053	0.051	0.073	0.237	0.246	
2000	0.022	0.045	0.056	0.090	0.155	0.156	0.100
2003	0.039	0.043	0.070	0.082	0.156	0.140	0.097

3.1 The Annual concentration of NOx and PM_{10}

Figure 6-1 shows the trends of NOx concentration from 1990 to 2003. From the figure we can see, that NOx concentration, both in the whole city and urban areas, increased from the early 1990s to the late 1990s. The situation is even more obvious in the urban area compared with 1990, particularly in the city centre. The city-wide NOx concentration increase of 75 percent in 2003 is closely related to the rapid increase in vehicle numbers. From 1998 to 2003, via adjustment of city functions, energy structure and industry structure, and implementation of strict vehicle emission standards, the increasing trend of NOx concentration in the city centre was prevented. However, increasing urban mobilization as well as the lagged strategies, caused an increase in NOx concentration in suburban areas. Therefore, the average concentration of NOx is increasing city-wide.

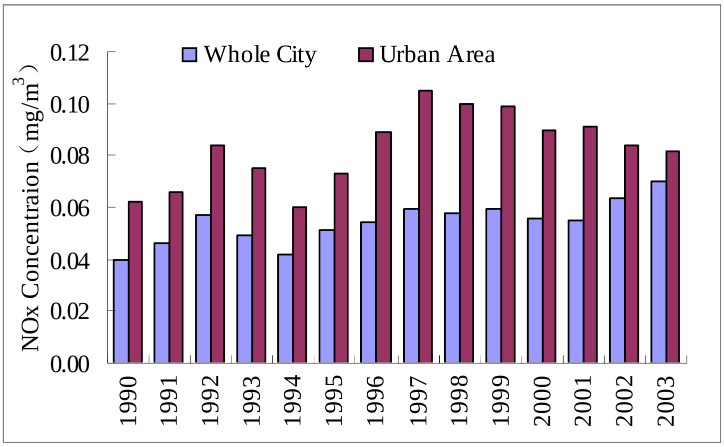


Figure 6-1 NOx Annual Concentrations in Shanghai

From 1990 to 2003, TSP pollution in Shanghai was effectively under control and was actually decreasing. As shown in Figure 6-2, if compared with 1990, the TSP concentration in 2003 decreased 61 percent. However, the PM_{10} annual concentration remained at 0.100 mg/m^3 and the maximum concentration of PM_{10} was 0.108 mg/m^3, as is shown in Figure 6-3.

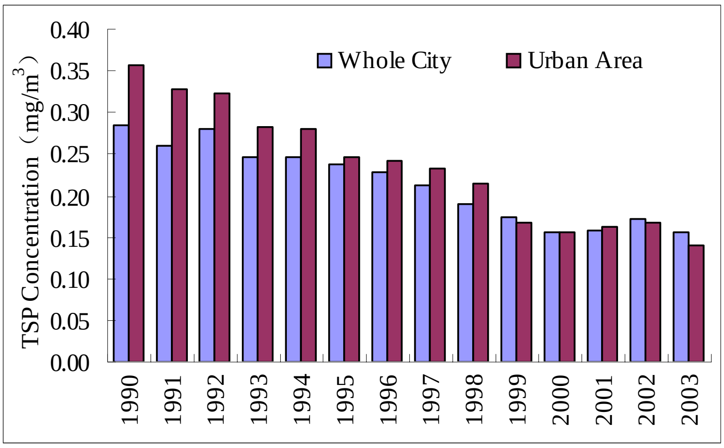


Figure 6-2 TSP Annual Concentration in Shanghai

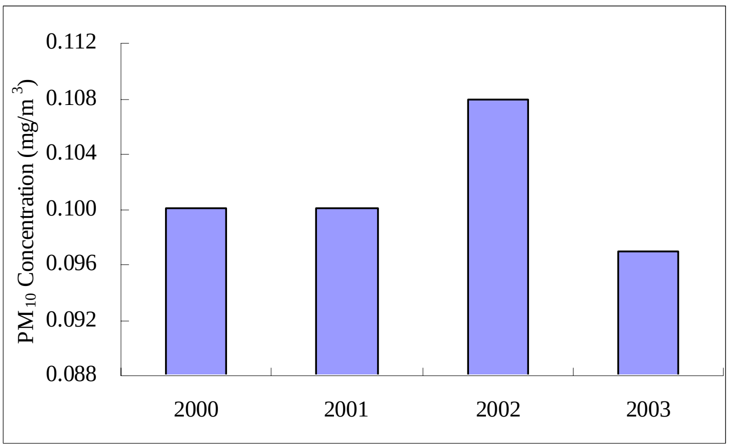


Figure 6-3 PM_{10} Annual Concentration in Shanghai

3.2 The Seasonal Variety of NOx and PM_{10} Pollutions

Figure 6-4 shows the seasonal variety of NOx in the whole city from 1990 to 2002. From the figure we can see that the first quarter includes March, April and May, (the springtime months); while the forth quarter includes December, January, and February (wintertime). It can be seen from the figure that the highest NOx concentration occurred in winter and the lowest in summer. Take 2002 as an example. NOx concentration in the 4th quarter is 0.081 mg/m^3 and 0.056 mg/m^3 in the 2nd quarter. Compared with NOx, the seasonal variety of PM_{10} is a little different as can be see from Figure 6-5. The highest PM_{10} concentration is in spring, which is related with sand storms that appear in Northern China frequently during that time. PM_{10} concentrations in the spring of 2001 and 2002 are 0.126 mg/m^3 and 0.142 mg/m^3 respectively, which are 2.1 and 1.8 times that in autumn of the corresponding years respectively.

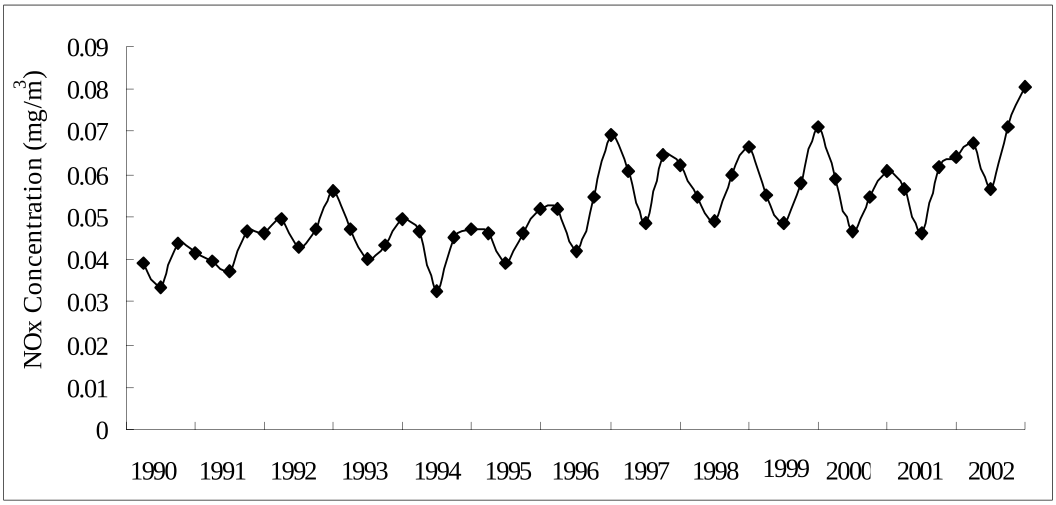


Figure 6-4 The Seasonal Variety of NOx Concentrations in Shanghai

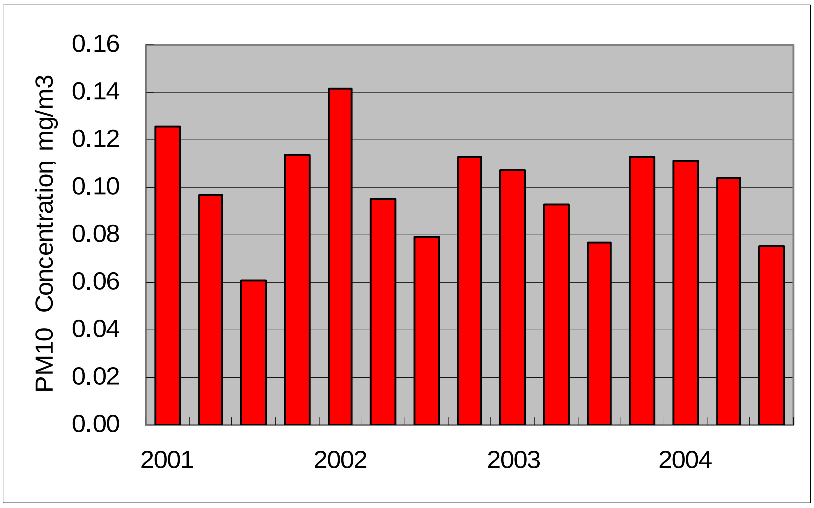


Figure 6-5 The Seasonal Variety of PM_{10} Concentrations in Shanghai

3.3 Regional Distribution of the NOx Pollution

Using data from the Shanghai Environmental Monitoring Center (SEMC), we can see the monthly average NOx concentration in 2002 in urban areas, the suburbs, counties and the the city of Shanghai city as a whole in Figure 6-6. The NOx annual pollution level can be expressed as follows: urban level > suburban level > county level. The concentrations of different districts are respectively 0.084 mg/m^3 for the urban area, 0.049 mg/m^3 for suburbs, 0.034 mg/m^3 for counties and 0.069 mg/m^3 for all of Shanghai.

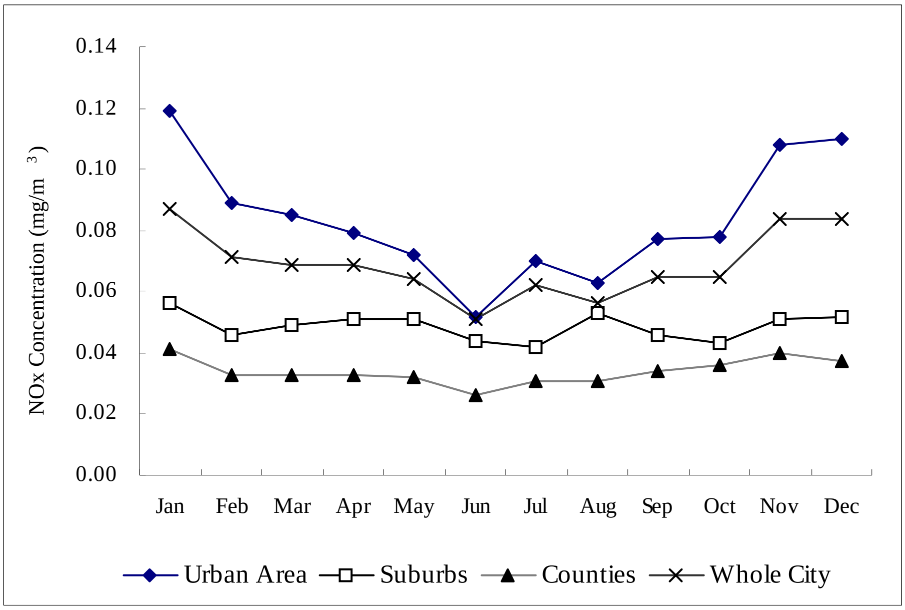


Figure 6-6 NOx Monthly Average Concentrations in Shanghai,2002

3.4 Transportation Air Pollution Status

In order to get a better understanding of air pollution caused by transportation in Shanghai, eighteen monitoring sites were set along the main road. An air quality monitoring program was conducted by SEMC, who contracted out to SAES, from October 9 to November 12, 2004. This data reflects the air pollution caused by traffic during the autumn season. The monitoring results indicated that:

The hourly concentrations of NO fluctuate between 0.004 mg/m^3 (Wai Qing Song Road) and 0.812 mg/m^3 (Shi Ji Dadao). The average hourly concentrations of NO are between 0.017 mg/m^3 (Wai Qing Song Road) and 0.346 mg/m^3 (East Yan'an Road).

The hourly NO_2 concentrations fluctuate between 0.022 mg/m^3 (Wai Qing Song Road) and 0.250 mg/m^3 (Guang Zhong Road) The average hourly concentrations of NO_2 are 0.041 mg/m^3 (Wai Qing Song Road)~0.172 mg/m^3 (Shanghai Stadium Site).

The hourly NOx concentrations fluctuate between 0.026 mg/m^3 (Wai Qing Song Road) and 0.954 mg/m^3 (Shi Ji Dadao). The average hourly concentrations of NOx are 0.059 mg/m^3 (Wai Qing Song Road)~0.469 mg/m^3 (East Yan'an Rd. Site). The average hourly concentrations of NOx at all 18 sites are shown in Figure 6-7, 16 of which display concentrations higher than the *National Atmospheric Quality Second Criterion*. The pollution situation on the main roads is severe to say the least.

The hourly PM_{10} concentrations fluctuate between between 0.005 mg/m^3 (Wai Qing Song Road) and 1.199 mg/m^3 (Hong Mei Road). The average hourly concentrations of PM_{10} are 0.075 mg/m^3 (Yuan Shen Road)~0.326 mg/m^3 (Hong Mei Road). The average hourly concentrations of PM_{10} for all 18 sites are shown in Figure 6-8. PM_{10} concentration on Hong Mei Road is 4.3 times that on Yuan Shen Road.

The hourly CO concentrations fluctuate between 2.172 mg/m^3 (Shanghai Stadium Site) and 12.209 mg/m^3 (East Yan'an Rd.). The average hourly concentrations of CO are 3.023 mg/m^3 (Yuan Shen Road)~5.982 mg/m^3 (East Yan'an Road), which don't exceed the National Criterion.

The hourly THC concentrations fluctuate between 1.896 mg/m^3(Zhong Shan Park Site) and 5.656 mg/m^3 (Jiang Su Road). The average hourly concentrations of THC are 2.371 mg/m^3 (Wai Qing Song Road)~4.108mg/m^3 (Siping Road).

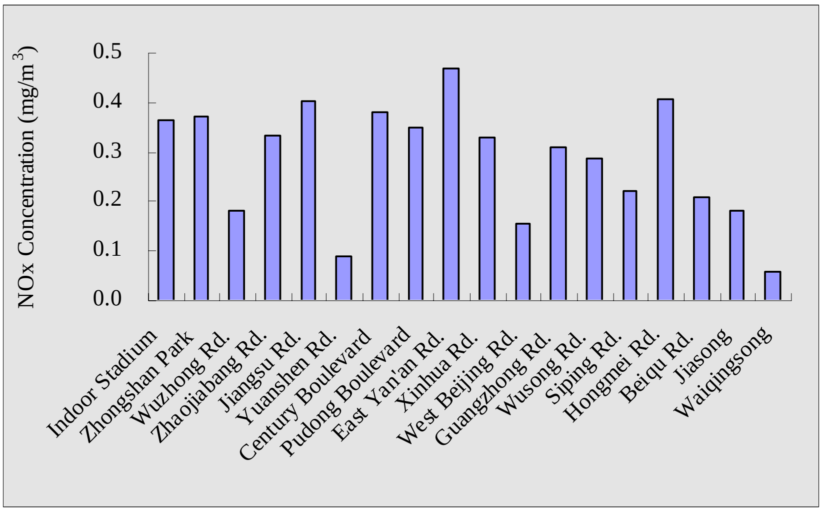


Figure 6-7 Average Hourly Concentrations of NOx on Main Traffic Roads

NOx concentrations monitored at Shi Ji Dadao Site are at the same level with that of the Pudong Dadao Site, while PM_{10} concentrations are much lower in the Shanghai Stadium and Zhong Shan Park sites.

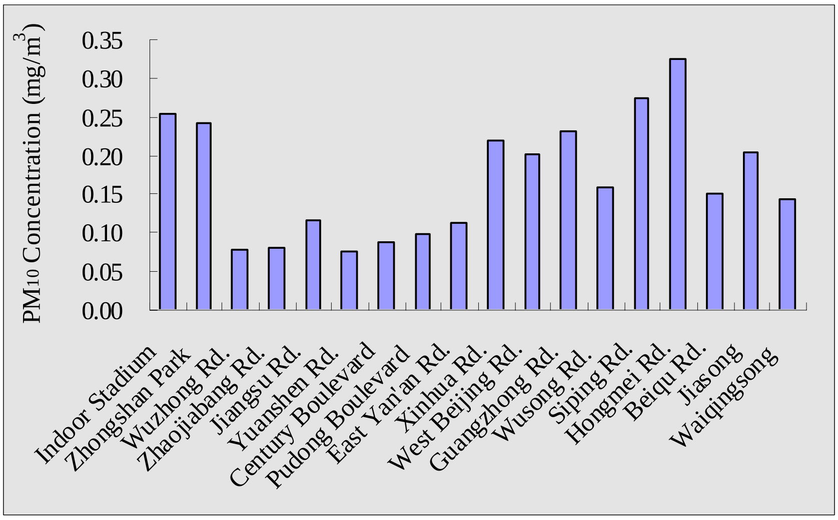


Figure 6-8 Average Hourly Concentrations of PM_{10} on Main Traffic Roads

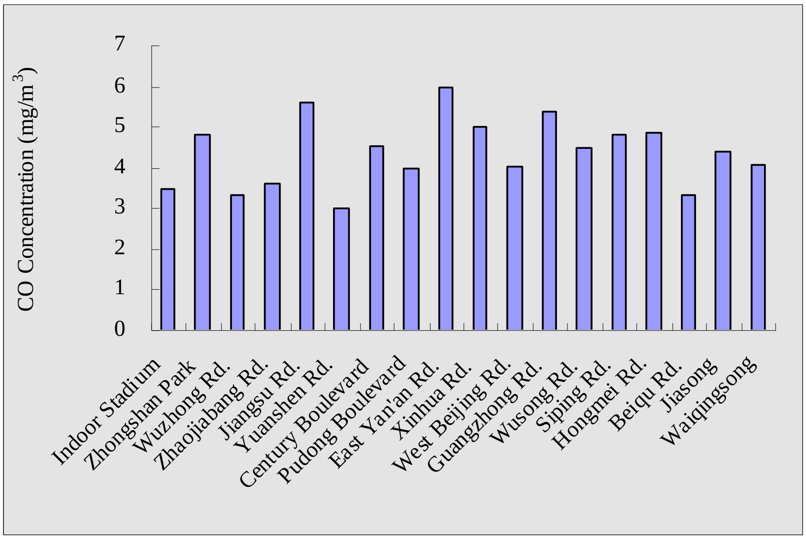


Figure 6-9 Average Hourly Concentrations of CO on Main Traffic Roads

Figures 6-10 and 6-11 show a daily measurement of air pollution caused by vehicles at the monitoring sites. From the figures, we can see that the NOx and CO concentrations at East Yan'an Rd. and Hong Mei Rd. monitoring sites are quite high, with average hourly concentrations of over 0.40 mg/m^3 for NOx, 4.5 mg/m^3 for CO, and over 0.100 mg/m^3 for PM_{10}. As can be seen by the figures, the air pollution around roads is closely related to its traffic flow. At rush hour and other periods with congested transportation, namely 6:00-9:00 in the morning, the concentrations of NOx, CO and PM_{10} rises sharply. In addition, when thermal inversion is formed at night, the air pollutants begin to accumulate near the ground, thus, the pollution caused by vehicle emissions deteriorate. A lowest point for pollution caused by traffic is usually at around 22:00 at night.

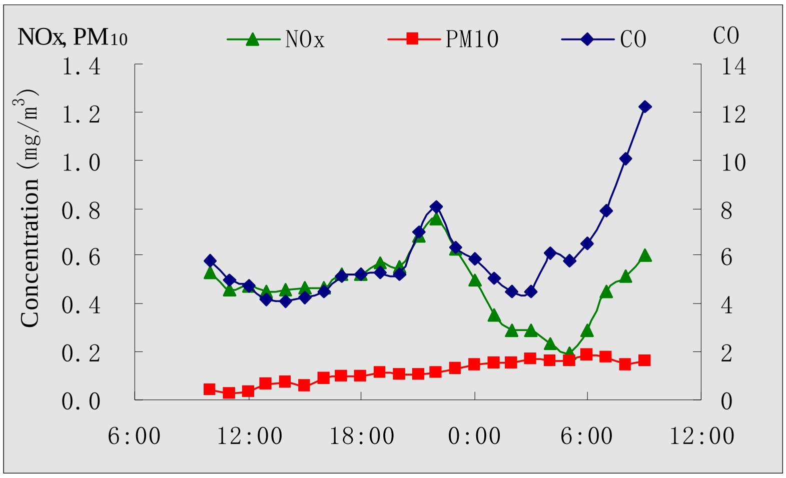


Figure 6-10 Diurnal Change of Pollutants Concentration at East Yan'an Rd. on October 30-31, 2004

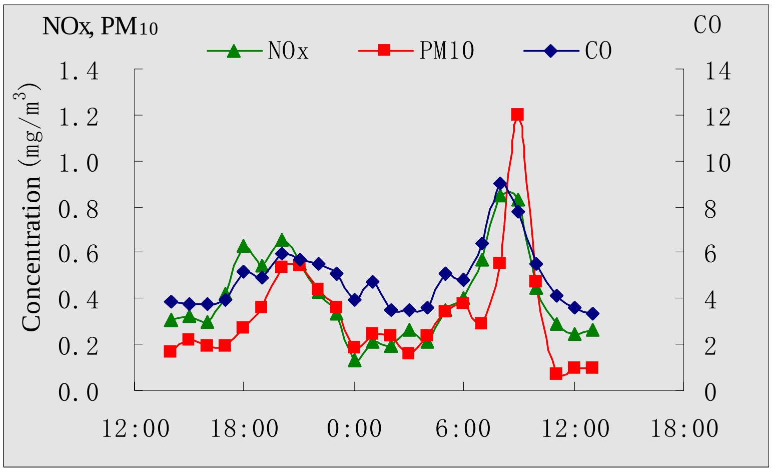


Figure 6-11 Diurnal Change of Pollutants Concentration at Hongmei Rd. on November 7-8, 2004

Table 6-4 shows the *National Atmospheric Quality Second Criterion*. Tables 6-5 through 6-22 show the monitoring results of NO, NO_2, NOx, CO, THC and PM_{10} at 18 monitoring sites, the times of exceeding standards and ratios compared with the National Criterion. The ratios of exceeding standards for the average hourly NO_2 concentration are between 0 and 83 percent. NOx concentrations are between 0 and 100 percent, among which there are 13 sites exceeding the national standard by 70 percent. With respect to hourly concentrations of CO, only East Yan'an Rd exceeds national standard, by roughly 8 percent, while those on other sites are within national standard.

Table 6-4 Secondary Criterion of National Ambient Air Quality (GB3095-1996)

National Secondary Criterion	NO	NO_2	NOx	CO	THC	PM_{10}
Hourly Average (mg/m^3)	N/A	0.12	0.15	10.00	N/A	N/A

Daily Average (mg/m^3)	N/A	0.08	0.10	4.00	N/A	0.15

Table 6-5 Pollution Situation at Stadium Site

Pollutants	NO	NO_2	NOx	CO	THC	PM_{10}
Hourly Max. (mg/m^3)	0.399	0.244	0.614	5.034	3.269	0.331
Hourly Min. (mg/m^3)	0.005	0.086	0.091	2.172	1.950	0.112
Hourly Ave. Value (mg/m^3)	0.194	0.172	0.366	3.462	2.678	0.254
Hourly Max. Exceeding Times	N/A	2.0	4.1	No Exceeding	N/A	N/A
Hourly Values Exceeding Times	N/A	1.4	2.4	No Exceeding	N/A	N/A
Hourly Values Exceeding Percentage	N/A	83%	83%	0%	N/A	N/A

Table 6-6 Pollution Situation at Zhongshan Park Site

Pollutants	NO	NO_2	NOx	CO	THC	PM_{10}
Hourly Max. (mg/m^3)	0.531	0.233	0.646	6.526	3.266	0.373
Hourly Min. (mg/m^3)	0.043	0.113	0.207	3.222	1.896	0.114
Hourly Ave. Value (mg/m^3)	0.230	0.143	0.373	4.839	2.664	0.242
Hourly Max. Exceeding Times	N/A	1.9	4.3	No Exceeding	N/A	N/A
Hourly Ave. Exceeding Times	N/A	1.2	2.5	No Exceeding	N/A	N/A
Hourly Values Exceeding Percentage	N/A	79%	100%	0%	N/A	N/A

Table 6-7 Pollution Situation at Wuzhong Rd. Site

Pollutants	NO	NO_2	NOx	CO	THC	PM_{10}
Hourly Max. (mg/m^3)	0.180	0.106	0.272	5.035	4.157	0.179
Hourly Min. (mg/m^3)	0.035	0.059	0.094	2.709	2.485	0.033
Hourly Ave. Value (mg/m^3)	0.093	0.087	0.180	3.332	2.849	0.079
Hourly Max. Exceeding Times	N/A	No Exceeding	1.8	No Exceeding	N/A	N/A
Hourly Ave. Exceeding Times	N/A	No Exceeding	1.2	No Exceeding	N/A	N/A
Hourly Values Exceeding Percentage	N/A	0%	75%	0%	N/A	N/A

Table 6-8 Pollution Situation at Zhaojiabang Rd. Site

Pollutants	NO	NO_2	NOx	CO	THC	PM_{10}
Hourly Max. (mg/m^3)	0.322	0.126	0.448	4.017	2.886	0.115
Hourly Min. (mg/m^3)	0.117	0.090	0.211	3.071	2.604	0.024
Hourly Ave. Value (mg/m^3)	0.229	0.106	0.334	3.602	2.721	0.081

Hourly Max. Exceeding Times	N/A	1.05	3.0	No Exceeding	N/A	N/A
Hourly Ave. Exceeding Times	N/A	No Exceeding	2.2	No Exceeding	N/A	N/A
Hourly Values Exceeding Percentage	N/A	8%	100%	0%	N/A	N/A

Table 6-9 Pollution Situation at Jiangsu Rd. Site

Pollutants	NO	NO_2	NOx	CO	THC	PM_{10}
Hourly Max. (mg/m^3)	0.655	0.151	0.791	9.862	5.656	0.186
Hourly Min. (mg/m^3)	0.027	0.087	0.114	2.877	2.731	0.078
Hourly Ave. Value (mg/m^3)	0.288	0.116	0.404	5.620	3.936	0.115
Hourly Max. Exceeding Times	N/A	1.3	5.3	No Exceeding	N/A	N/A
Hourly Ave. Exceeding Times	N/A	No Exceeding	2.7	No Exceeding	N/A	N/A
Hourly Values Exceeding Percentage	N/A	38%	71%	0%	N/A	N/A

Table 6-10 Pollution Situation at Yuanshen Rd. Site

Pollutants	NO	NO_2	NOx	CO	THC	PM_{10}
Hourly Max. (mg/m^3)	0.116	0.088	0.194	4.113	2.982	0.140
Hourly Min. (mg/m^3)	0.005	0.041	0.048	2.574	2.511	0.010
Hourly Ave. Value (mg/m^3)	0.034	0.056	0.090	3.023	2.705	0.075
Hourly Max. Exceeding Times	N/A	No Exceeding	1.3	No Exceeding	N/A	N/A
Hourly Ave. Exceeding Times	N/A	No Exceeding	No Exceeding	No Exceeding	N/A	N/A
Hourly Values Exceeding Percentage	N/A	0%	25%	0%	N/A	N/A

Table 6-11 Pollution Situation at Century Boulevard Site

Pollutants	NO	NO_2	NOx	CO	THC	PM_{10}
Hourly Max. (mg/m^3)	0.812	0.145	0.954	6.368	4.766	0.141
Hourly Min. (mg/m^3)	0.120	0.073	0.192	3.194	2.559	0.026
Hourly Ave. Value (mg/m^3)	0.280	0.100	0.380	4.557	3.446	0.088
Hourly Max. Exceeding Times	N/A	1.2	6.4	No Exceeding	N/A	N/A
Hourly Ave. Exceeding Times	N/A	No Exceeding	2.5	No Exceeding	N/A	N/A
Hourly Values Exceeding Percentage	N/A	13%	100%	0%	N/A	N/A

Table 6-12 Pollution Situation at Pudong Boulevard Site

Pollutants	NO	NO_2	NOx	CO	THC	PM_{10}
Hourly Max. (mg/m^3)	0.433	0.132	0.565	5.103	4.347	0.158
Hourly Min. (mg/m^3)	0.026	0.061	0.088	2.983	2.622	0.031

Hourly Ave. Value (mg/m^3)	0.252	0.098	0.350	3.988	3.203	0.097
Hourly Max. Exceeding Times	N/A	1.1	3.8	No Exceeding	N/A	N/A
Hourly Ave. Exceeding Times	N/A	No Exceeding	2.3	No Exceeding	N/A	N/A
Hourly Values Exceeding Percentage	N/A	21%	88%	0%	N/A	N/A

Table 6-13 Pollution Situation at East Yan'an Rd. Site

Pollutants	NO	NO_2	NOx	CO	THC	PM_{10}
Hourly Max. (mg/m^3)	0.601	0.158	0.759	12.209	3.816	0.183
Hourly Min. (mg/m^3)	0.096	0.095	0.191	4.117	2.503	0.028
Hourly Ave. Value (mg/m^3)	0.346	0.124	0.469	5.982	3.180	0.114
Hourly Max. Exceeding Times	N/A	1.3	5.1	1.2	N/A	N/A
Hourly Ave. Exceeding Times	N/A	1.0	3.1	No Exceeding	N/A	N/A
Hourly Values Exceeding Percentage	N/A	54%	100%	8%	N/A	N/A

Table 6-14 Pollution Situation at Xinhua Rd. Site

Pollutants	NO	NO_2	NOx	CO	THC	PM_{10}
Hourly Max. (mg/m^3)	0.345	0.205	0.544	6.858	3.729	0.410
Hourly Min. (mg/m^3)	0.014	0.058	0.075	3.149	2.853	0.098
Hourly Ave. Value (mg/m^3)	0.216	0.114	0.330	5.014	3.175	0.218
Hourly Max. Exceeding Times	N/A	1.7	3.6	No Exceeding	N/A	N/A
Hourly Ave. Exceeding Times	N/A	No Exceeding	2.2	No Exceeding	N/A	N/A
Hourly Values Exceeding Percentage	N/A	29%	83%	0%	N/A	N/A

Table 6-15 Pollution Situation at West Beijing Rd. Site

Pollutants	NO	NO_2	NOx	CO	THC	PM_{10}
Hourly Max. (mg/m^3)	0.183	0.122	0.284	5.350	3.497	0.282
Hourly Min. (mg/m^3)	0.010	0.050	0.068	3.150	2.131	0.081
Hourly Ave. Value (mg/m^3)	0.067	0.090	0.157	4.053	2.944	0.200
Hourly Max. Exceeding Times	N/A	1.0	1.9	No Exceeding	N/A	N/A
Hourly Ave. Exceeding Times	N/A	No Exceeding	1.0	No Exceeding	N/A	N/A
Hourly Values Exceeding Percentage	N/A	4%	46%	0%	N/A	N/A

Table 6-16 Pollution Situation at Guangzhong Rd. Site

Pollutants	NO	NO_2	NOx	CO	THC	PM_{10}
Hourly Max. (mg/m^3)	0.349	0.250	0.599	8.467	5.249	0.311

Hourly Min. (mg/m^3)	0.010	0.098	0.109	3.629	3.180	0.119
Hourly Ave. Value (mg/m^3)	0.150	0.159	0.309	5.383	3.771	0.231
Hourly Max. Exceeding Times	N/A	2.1	4.0	No Exceeding	N/A	N/A
Hourly Ave. Exceeding Times	N/A	1.3	2.1	No Exceeding	N/A	N/A
Hourly Values Exceeding Percentage	N/A	75%	79%	0%	N/A	N/A

Table 6-17 Pollution Situation at Wusong Rd. Site

Pollutants	NO	NO_2	NOx	CO	THC	PM_{10}
Hourly Max. (mg/m^3)	0.306	0.163	0.458	8.138	4.325	0.285
Hourly Min. (mg/m^3)	0.046	0.053	0.099	3.031	2.541	0.103
Hourly Ave. Value (mg/m^3)	0.169	0.117	0.286	4.507	3.218	0.159
Hourly Max. Exceeding Times	N/A	1.4	3.1	No Exceeding	N/A	N/A
Hourly Ave. Exceeding Times	N/A	No Exceeding	1.9	No Exceeding	N/A	N/A
Hourly Values Exceeding Percentage	N/A	58%	83%	0%	N/A	N/A

Table 6-18 Pollution Situation at Siping Rd. Site

Pollutants	NO	NO_2	NOx	CO	THC	PM_{10}
Hourly Max. (mg/m^3)	0.254	0.184	0.389	7.545	4.880	0.628
Hourly Min. (mg/m^3)	0.025	0.051	0.076	3.286	3.582	0.164
Hourly Ave. Value (mg/m^3)	0.123	0.096	0.219	4.820	4.108	0.274
Hourly Max. Exceeding Times	N/A	1.5	2.6	No Exceeding	N/A	N/A
Hourly Ave. Exceeding Times	N/A	No Exceeding	1.5	No Exceeding	N/A	N/A
Hourly Values Exceeding Percentage	N/A	21%	67%	0%	N/A	N/A

Table 6-19 Pollution Situation at Hongmei Rd. Site

Pollutants	NO	NO_2	NOx	CO	THC	PM_{10}
Hourly Max. (mg/m^3)	0.751	0.159	0.851	9.009	4.919	1.199
Hourly Min. (mg/m^3)	0.060	0.072	0.132	3.298	2.439	0.071
Hourly Ave. Value (mg/m^3)	0.293	0.112	0.405	4.848	3.167	0.326
Hourly Max. Exceeding Times	N/A	1.3	5.7	No Exceeding	N/A	N/A
Hourly Ave. Exceeding Times	N/A	No Exceeding	2.7	No Exceeding	N/A	N/A
Hourly Values Exceeding Percentage	N/A	38%	96%	0%	N/A	N/A

Table 6-20 Pollution Situation at Beiqu Rd. Site

Pollutants	NO	NO_2	NOx	CO	THC	PM_{10}

Hourly Max. (mg/m^3)	0.330	0.113	0.443	5.304	3.776	0.345
Hourly Min. (mg/m^3)	0.049	0.066	0.120	2.457	1.952	0.052
Hourly Ave. Value (mg/m^3)	0.122	0.089	0.210	3.350	2.795	0.150
Hourly Max. Exceeding Times	N/A	No Exceeding	3.0	No Exceeding	N/A	N/A
Hourly Ave. Exceeding Times	N/A	No Exceeding	1.4	No Exceeding	N/A	N/A
Hourly Values Exceeding Percentage	N/A	0%	79%	0%	N/A	N/A

Table 6-21 Pollution Situation at Jiasong Rd. Site

Pollutants	NO	NO_2	NOx	CO	THC	PM_{10}
Hourly Max. (mg/m^3)	0.222	0.117	0.319	5.332	4.273	0.484
Hourly Min. (mg/m^3)	0.014	0.062	0.076	3.699	2.372	0.057
Hourly Ave. Value (mg/m^3)	0.098	0.084	0.182	4.407	2.827	0.203
Hourly Max. Exceeding Times	N/A	No Exceeding	2.1	No Exceeding	N/A	N/A
Hourly Ave. Exceeding Times	N/A	No Exceeding	1.2	No Exceeding	N/A	N/A
Hourly Values Exceeding Percentage	N/A	0%	54%	0%	N/A	N/A

Table 6-22 Pollution Situation at Waiqingsong Rd. Site

Pollutants	NO	NO_2	NOx	CO	THC	PM_{10}
Hourly Max. (mg/m^3)	0.044	0.075	0.111	4.869	2.656	0.321
Hourly Min. (mg/m^3)	0.004	0.022	0.026	3.639	2.190	0.005
Hourly Ave. Value (mg/m^3)	0.017	0.041	0.059	4.069	2.371	0.144
Hourly Max. Exceeding Times	N/A	No Exceeding	No Exceeding	No Exceeding	N/A	N/A
Hourly Ave. Exceeding Times	N/A	No Exceeding	No Exceeding	No Exceeding	N/A	N/A
Hourly Values Exceeding Percentage	N/A	0%	0%	0%	N/A	N/A

4. Summary

The air pollution in Shanghai has gradually transformed into something more complex than was previously found, namely a mix of pollutants stemming from coal and petroleum. The ambient air quality situation is not optimistic. Particulate matter and NOx are the main pollutants in the city at present. In 2003, the PM_{10} and NOx concentrations for the urban area were 0.097 mg/m^3 and 0.082 mg/m^3 respectively.

From 1990 to 2003, it can be seen that NOx concentrations in Shanghai as a whole are increasing, due in great part to the increase in the number of vehicles on the road,. The NOx concentration in 2003 was 1.75 times that of 1990. In recent years, this tendency for NOx pollution in the city center to increase has been brought under control with the implementation of various vehicle pollution control strategies. However, NOx pollution in the counties is still increasing. PM pollution, especially fine particle matter pollution, in the air is quite severe.

The NOx concentration has an obvious seasonal variety: the highest concentration of NOx concentration can be found in winter while the lowest concentration occurs in the summer. PM_{10} concentration reaches a peak in spring due to frequent dust storms in North China while the lowest concentration can be found in autumn.

The distribution of NOx annual average concentrations in various districts can be expressed as: urban level > suburban level > county level.

The pollution situation on the 18 main traffic roads is severe. For the most part, the average hourly concentration of NOx exceeds the national standard. 13 of the 18 sites are particularly problematic, exceeding the national standard by more than 70 percent on average. The highest average hourly concentration is 0.469 mg/m^3 at East Yan’an Rd. The average hourly concentration of PM_{10} at the majority of sites is relatively steady, with values between 0.075 mg/m^3 and 0.326 mg/m^3. With respect to the hourly concentration of CO, only East Yan’an Rd exceeds the national standard, by roughly 8 percent, while the concentrations found at other sites are within the national standard.

Chapter 7. Establishment of Exposure-Response Functions of NO_2 and Adverse Health Outcomes

1. Introduction

Combustion of fossil fuels results in the oxidation of nitrogen-containing compounds and the formation of nitrogen oxides. There are at least 7 types of nitrogen oxide compounds: nitric oxide (NO), nitrogen dioxide (NO_2), nitrous oxide (N_2O), nitrogen trioxide (NO_3), dinitrogen trioxide (N_2O_3), dinitrogen tetroxide (N_2O_4), and dinitrogen pentoxide (N_2O_5). These are largely interconvertible, and are therefore referred collectively to as NOx. Nitrogen dioxide is the most abundant in the atmosphere and represents the greatest risk to human health.

Nitrogen dioxide is considered an important air pollutant not only because of potential negative health effects, but also because it is an essential precursor in the formation of tropospheric ozone via photochemical reactions. It also contributes to the formation of atmospheric acids and secondary particles.

Nitrogen dioxide (NO_2) is the most abundant and toxic of the nitrogen oxides formed from combustion of fossil fuels and ambient concentrations are related to traffic density as well as point sources. Indoor NO_2 levels may often exceed those found outdoors. When inhaled, NO_2 tends to remain in the lung periphery for long periods of time because of its relatively low solubility. More than 60% of inhaled NO_2 is deposited in this manner although the fraction deposited increases with exercise. Epidemiological studies have found a strong relationship between both outdoor and indoor NO_2 levels and respiratory illness, decrements in lung function, and exacerbation of asthma, especially in children.

Outdoor NO_2 is also found to be associated with increased mortality. However, these studies are subject to exposure misclassification, and generally fail to consider a possible role of indoor and outdoor particle exposure as a confounding factor. NO2 may represent a marker for exposure to traffic- or combustion-related pollution in these epidemiological studies. Human clinical studies generally fail to show the effects of exposure at concentrations at or below the current NO_2 standard, which supports the concept that NO_2 is a marker of pollution rather than a cause of direct effects at ambient levels.

In the current study, we will use available data, especially that from epidemiological studies, to infer the exposure-response functions between NO2 and adverse health effects in humans.

2. Controlled human clinical studies of NO2

2.1 Pulmonary function and symptoms

Generally, concentrations in excess of 1880 $\mu g/m^3$ (1 ppm) are necessary during acute controlled exposures to induce changes in pulmonary functions in healthy adults[1-3]. Because these concentrations almost never occur in ambient air, concern about the effects of nitrogen dioxide has been focused on people with pre-existing lung problems. There have been numerous studies showing that when people with asthma, chronic obstructive pulmonary disease, or chronic bronchitis are exposed to low levels of nitrogen dioxide it can cause small decrements in forced vital capacity and forced expiratory volume in 1 second (FEV1) or increases in airway resistance. Pulmonary function responses have occurred in studies of asthmatics exposed to 560 μg/m3 (0.30 ppm) while performing mild to moderate exercise. However, these results are not always consistent with other studies of asthmatics exposed to the same or higher levels of nitrogen dioxide concentrations.

The lowest level of nitrogen dioxide exposure reported in more than one laboratory that shows a direct effect on pulmonary functions in asthmatics was a 30-minute exposure, with intermittent exercise, to 560 $\mu g/m^3$ (0.3 ppm) [4-5]. Although similar but statistically non-significant trends have been observed in other controlled human studies performed at lower concentrations [6-7], the small size of the decrements and questions regarding the statistical significance of some of these results together suggest that caution should be exercised in accepting these findings as demonstrating acute effects.

2.2 Airway responsiveness

A significant amount of research has been directed at evaluating the effects of nitrogen dioxide on airway responsiveness to pharmacological, physical (e.g. cold air) or natural (i.e. allergens) bronchoconstrictors. Generally, concentrations higher than 1880 $\mu g/m^3$ (1.0 ppm) are required to increase responsiveness to bronchoconstrictors in healthy adults [1-2]. Of greater interest are the responses of people with pre-existing lung diseases, such as asthmatics who have a markedly elevated baseline responsiveness to bronchoconstrictors.

2.3 Lung lavage and host defences

More recently, investigators have sought to evaluate the effects of nitrogen dioxide on other aspects of human health, not just pulmonary function [1]. Analysis of lung lavage from healthy humans indicated that high levels (5640–7520 $\mu g/m^3$ or 3–4 ppm) reduce the activity of alpha-1-protease inhibitors, a protein that protects the lung from the proteolytic enzyme elastase by inhibiting connective tissue damage. However, 2820 $\mu g/m^3$ (1.5 ppm) had no such effect [1].

In summary, these controlled clinical studies on humans indicate the potential for nitrogen dioxide to affect lung functions, airway responsiveness and antimicrobial host defenses. However, the exposure regimens and endpoints examined are too limited to draw quantitative exposure–response functions about these types of effects in humans.

3. Epidemiological studies of NO_2

There have been a number of epidemiological studies on the relationship between nitrogen dioxide exposure and mortality/morbidity indicators[1-2]. Generally speaking, epidemiological studies attempting to correlate outdoor NO_2 levels and health effects are not as quantitative as indoor studies, but their results tend to be qualitatively similar. One of the difficulties in deriving quantitative estimates of health risks associated specifically with outdoor nitrogen dioxide exposure is in separating its relative contributions from those of other major pollutants (ozone, sulfur dioxide, particulate matter, etc.), which are also often present in urban ambient air mixtures. In such cases, NO_2 might best be considered as just one indicator of polluted ambient air, especially where it is present in traffic-dominated urban areas. Great care is therefore needed in interpreting available outdoor epidemiology studies on NO_2 and its health effects.

Indoor studies have compared groups exposed to nitrogen dioxide emitted from the combustion of gas inside buildings to groups in homes without such sources and hence with lower levels of nitrogen dioxide. The limited studies of adults have tended to show no relationship between the use of gas for cooking and respiratory symptoms or lung functions. Although an epidemiological study of elderly women cooking with gas stoves found an increase in asthma symptoms and shortness of breath [8], there were no significant changes in FEV1 and FVC measurements. Thus, the following discussion will focus on children. In addition, several epidemiological studies have been undertaken in Europe and Japan that look at outdoor NO_2 as a potential indicator for traffic-dominated urban air pollution. The results provide strong evidence to indicate that there is an association between respiratory problems and living near busy roads, presumably in part due to higher exposure to traffic-generated NO_2[9-10].

3.1 Effect of NO2 on daily mortality

APHEA (Air Pollution and Health: a European Approach) is a coordinated study on the short-term effects of air pollution on mortality and hospital admissions using data from 15 European cities, all with a wide range of geographic, socio-demographic, climatic, and air quality patterns. Within the APHEA project, six cities spanning Central and Western Europe provided data on daily deaths and NO2 levels [11]. The data was analyzed by each center separately following a standardized methodology to ensure comparability of results. Poisson autoregressive models allowing for over-dispersion were fitted. Fixed effects models were used to pool the individual regression coefficients when there was no evidence of heterogeneity among the cities and random effects models. Factors possibly correlated with heterogeneity were also investigated. The results indicated significant associations between daily deaths and NO_2. Increases of 50μg /m^3 in NO_2 (1-hour maximum) were associated with a 1.3 percent (95% confidence interval 0.9-1.8) increase in the daily number of deaths. Stratified analysis of NO_2 effects by low and high levels of black smoke or O_3 showed no significant evidence for an interaction within each city. However, there was a tendency for larger effects of NO_2 in cities with higher levels of black smoke. The pooled estimate for the NO_2 effect was almost halved (although it remained significant) when two pollutant models including black smoke were applied.

Moreover, there have been several studies during the past decade that report significant associations between monitored outdoor nitrogen dioxide concentrations (24-hour) and total & cause-specific mortality [12-16]. In each case, however, it is very difficult to separate the relative contributions of nitrogen dioxide from those of simultaneously occurring particulate matter; the latter was more likely to have been the causative agent, given typically much stronger and consistent associations of particulate matter with increased mortality risks in these and other urban areas. For example, Kan and Chen [12] assessed the relationship between air pollution (PM_{10}, SO_2 and NO_2) and daily mortality from June 2000 to December 2001 in Shanghai, China. In the study, a generalized additive model (GAM) was used to allow for highly flexible long-term and seasonable trends, as well as nonlinear weather variables. The results indicate that an increase of 10μg/m^3 of NO_2 corresponds to a 1.015 (95%CI 1.008-1.022) increase in relative risk of non-accidental all-causes mortality. However, the authors also stated that due to high correlation between air pollutants, it was difficult to separate the single effect of one specific pollutant.

Recently, a comprehensive, systematic synthesis was conducted of daily time-series studies of air pollution (including NO_2) and mortality from around the world [17]. Most of the studies incorporated into the analysis were conducted in North America and Europe. Estimates of effect sizes were extracted from 109 studies, both single- and multi-pollutant models, and by cause of death, age, and season. Random effects pooled estimates of excess all-cause mortality (single-pollutant models) associated with a change in pollutant concentration were 2.38percent (95% CI 1.79–2.98%) per 10μg/m^3 NO_2. However, effect sizes were reduced and became insignificantly different from zero in multi-pollutant models for NO_2. Larger effect sizes were observed for respiratory mortality for NO_2.

In summary, the short-term effects of NO_2 on mortality may be confounded by other pollutants. Thus, the issue of independent NO_2 effects requires additional investigation.

3.2 Effect of NO_2 on morbidity

3.2.1 A meta analysis of the effect of NO_2 on the respiratory functions of school-aged children

Many of the epidemiological studies suggest an increase in respiratory morbidity in children from exposure to NO_2, although the effects in the majority of the studies do not reach statistical significance. The following section will look at the consistency of the results across the studies examined. The results of a number of the studies will be pooled together and presented in the analysis below.

3.2.1.1 Health outcomes

The studies in this meta analysis use health outcome measures that provide an indication of the state of respiratory health of various samples of children up to 12 years of age. All the studies utilized standard questionnaires to evaluate lower respiratory health in children. Childhood lower respiratory morbidity is characterized by a group of similar symptoms and diseases that reflect changes located anatomically in the lower respiratory tract.

3.2.1.2 Selection of studies

The requirements for data inclusion were:

(1) The health endpoints measured must be reasonably close to the standard end-point;

(2) Significant exposure differences between subjects must exist and some estimate of exposure must be available;

(3) An odds ratio for a specified exposure gradient must have been calculated or have data presented so that an odds ratio can be calculated.

After a careful review of the published literature, nine studies that met the criteria were selected for inclusion in the quantitative analysis. The NO_2 exposure gradient for the quantitative analysis of relative risks was set at 28.3 μg/m^3 (0.015 ppm) for the purpose of this analysis. This figure is comparable to the reported long-term exposure difference between homes with gas stoves and homes with electric stoves.

3.2.1.3 Brief description of selected studies

Melia et al. (1977) [26] studied 5758 children aged 6 to 11 years in England and Scotland and developed an indicator of the presence of at least one of the following group of symptoms: coughing, chest colds, and bronchitis. The symptom reported most frequently was a chest cold, which was used as an indicator of lower respiratory morbidity. This study did not measure NO_2 exposure, and so the assumption was made that the increase in NO_2 exposure from gas stoves used in England was reasonably similar to that in the other British studies that measured NO_2 (31.1 μg/m3, 0.0165 ppm). The estimated odds ratio was 1.31, with 95% confidence limits of 1.16 and 1.48. After adjusting to a standard increase of 28.3 μg/m^3 (0.015 ppm), the odds ratio became 1.28 with 95% confidence limits of 1.14 and 1.43.

Cross-sectional data reported by Melia et al. (1979) [27] on children aged 5 to 10 years was also employed to estimate an odds ratio, although no exposure estimates were made. The presence or absence of a gas stove was used as a surrogate as in the Melia et al. (1977) study. The estimated odds ratio was 1.24, with 95% confidence limits of 1.09 and 1.42. After adjusting to a standard increase of 28.3 μg/m3 (0.015 ppm), the odds ratio became 1.22 with 95% confidence limits of 1.08 and 1.37.

Melia et al. (1980) [19] studied children aged 6 to 7 years and measured bedroom NO_2 levels for the exposure estimate. This study applied the same combined health end-point as the previous study. The estimated odds ratio for an increase of 28.3 μg/m^3 (0.015 ppm) was 1.49 with 95% confidence limits of 1.04 and 2.14. Melia et al. (1982a,b) [20-21] studied children aged 5 to 6 years and also measured NO_2 exposure in the bedroom and applied the same combined health end-point. The estimated odds ratio for an increase of 0.015 ppm was 1.11, with 95% confidence limits of 0.84 and 1.46. The 10th and the 90th percentiles of the weekly measured concentrations were 0.009 and 0.065 ppm NO_2, respectively, in bedrooms[21].

In the first Harvard Six Cities study cohort, Ware et al. (1984) [25] reported an index of respiratory illnesses. Exposure to NO2 was based on the presence or absence of a gas stove (32.5 μg/m^3, 0.0173 ppm). The estimated odds ratio was 1.08 with 95% confidence limits of 0.97 and 1.19. After adjusting to a standard increase of 28.3 μg/m^3 (0.015 ppm), the odds ratios became 1.07 with 95% confidence limits of 0.98 and 1.17. The second cohort of subjects in the Harvard Six Cities study reported that the 10th and 90th percentiles of the weekly measured concentrations were 0.008 and 0.033 ppm NO_2, respectively, in bedrooms [18]. The estimated odds ratio for an increase in the presence of any respiratory symptom resulting from an increase in exposure of 28.3 μg/m^3 (0.015 ppm) was 1.40, with 95% confidence limits of 1.14 and 1.72.

Ekwo et al. (1983) [24] studied several respiratory illness end-points using a study sample of 1,355 children aged 6 to 12 years old. No exposure measurements were obtained, and the exposure was based on the presence or absence of a gas stove (32.5 μg/m^3, 0.0173 ppm). None of the resulting end-points significantly matched the end-point of interest. The two most similar end-points were hospitalization for chest illness before age 2 and chest congestion and phlegm with colds. The estimated odds ratio for hospitalization was 2.40. The estimated confidence limit for coughing and phlegm with colds was 1.09, with 95% confidence limits of 0.82 and 1.45. This last symptom appears to be most similar to the end-point of interest, and so it was included in the synthesis.

The effect of indoor exposure to nitrogen dioxide on respiratory health was studied by Dijkstra et al. (1990) [22] over a period of 2 years in a population of non-smoking Dutch children 6 to 12 years of age. The data gave an estimated odds ratio of 0.94 for an increase of 28.3 μg/m^3 (0.015 ppm) in NO_2 exposure. The 95% confidence limits were 0.70 and 1.27. The study measured NO2 exposure data, but the meta-analysis did not adjust for covariates because the covariates were not included in the original tables detailing NO2 exposure.

Keller et al. (1979) [23] did not find any statistically significant increases in respiratory disease due to the presence of a gas stove, but the unadjusted estimated odds ratio for lower respiratory illness was 1.10, with 95% confidence limits of 0.74 and 1.54. Assuming that the exposure increase was 32.5 μg/m^3 (0.0173 ppm), the odds ratio was adjusted to an exposure of 28.3 μg/m3 (0.015 ppm). This resulted in an odds ratio of 1.09 with 95% confidence limits of 0.82 and 1.46.

Table 7-1 Summary of odds ratios from studies on the effects of NO_2 increased by 0.015 ppm

Authors	Estimated odds ratio	95% CI
Melia et al. (1977) [26]	1.28	1.14 to 1.43
Melia et al. (1979) [27]	1.22	1.08 to 1.37
Melia et al. (1980) [19]	1.49	1.04 to 2.14
Melia et al. (1982a,b) [20-21]	1.11	0.84 to 1.46

Ware et al. (1984) [25]	1.07	0.98 to 1.17
Neas et al. (1991) [18]	1.40	1.14 to 1.72
Ekwo et al. (1983) [24]	1.09	0.82 to 1.45
Dijkstra et al. (1990) [22]	0.94	0.70 to 1.27
Keller et al. (1979) [23]	1.09	0.82 to 1.46

3.2.1.4 Result of meta-analysis

In the fixed-effects model, the estimated odds ratio is 1.17 and the 95% confidence limits are 1.11 and 1.23. The analysis assumed that the parameters were homogeneous. The chi-square test for homogeneity for the nine studies was 12.32 for 8 degrees of freedom, which has a p value of 0.1375. Thus, there is some evidence that the parameters from each study are not identical.

The estimates for the random-effects model are similar to the estimates for the fixed-effects model, but the confidence limits are slightly broader. The random-effects model is thought to be more appropriate because it does not assume that all studies are estimating the same parameter.

In summary, the conclusion from both models is the same; namely that the odds ratio is estimated to be about 1.2, with 95% confidence intervals ranging from about 1.1 to 1.3.

3.2.2 A meta-analysis of the effect of NO2 on the respiratory disease of young children less than 2 years of age

Various researchers have conducted studies on children under the age of 2. A major difference for this group of studies is that the health outcome measures are less uniform than the studies of older children. For purposes of comparability, a meta-analysis similar to the one for older children was made.

Table 7-2 Summary of odds ratios of the effects of NO2, health outcome and exposure estimates in epidemiological studies on young children (< 2 year)

Reference	Odds ratio	95% CI	Health outcome	NO2 exposure estimate (ppm)	Age	Location and date of study
Melia et al. (1983) [28]	0.63	0.36-1.10	Respiratory illness incidence	0.0165	< 1 year	England (1978)
Ekwo et al. (1983) [24]	2.40	1.06-3.74	Hospitalization for chest illness	0.0173	< 2 years	Iowa, USA
Ware et al. (1984) [25]	1.11	0.97-1.27	Respiratory illness before age 2	0.0173	< 2 years	Six Cities USA (1974-1979)
Ogston et al. (1985) [29]	1.14	0.86-1.50	Respiratory illness incidence	0.0165	< 1 year	Scotland (1980)
Dockery et al. (1989a) [30]	1.15	0.96-1.37	Respiratory illness before age 2	0.0150	< 2 years	Six Cities USA (1983-1986)
Margolis et al. (1992) [31]	1.12	0.63-2.04	Persistent lower respiratory symptoms	0.0105	< 1 year	North Carolina, USA (1986-1988)
Samet et al. (1993) [32]	0.99	0.94-1.04	Lower respiratory illness incidence	0.015	< 18 months	Albuquerque, USA (1988-1990)

Seven studies compared children (under the age of 2) living in homes with gas stoves with those living in homes without gas stoves [24,25,28-32]. The most extensive of these studies involved over 1000 infants aged up to 18 months. It was conducted in Albuquerque, New Mexico, by Samet et al. The 10th and 90th percentiles of the nitrogen dioxide concentrations measured weekly in the children's bedrooms were 9.4 and 94 $\mu g/m^3$ (0.005 and 0.05 ppm), respectively. These bedroom exposures correlated well with short-term exposure of infants in pilot studies. Few of the children remained in the kitchen during cooking, so peak exposures were likely to be rare. The experimental design and exposure assessment were rigorous, but no significant effect was found. Other studies were performed in England, Scotland and other cities of the United States.

As a result, meta-analysis of these seven studies shows a combined odds ratio of 1.09 (for an increase in respiratory disease per increase of 28.3 $\mu g/m^3$) with a 95% confidence interval of 0.95–1.26, indicating that there was no statistically significant increase in respiratory disease.

4. Discussion and Conclusions

In the current analysis, the consistency of NO_2 on mortality and morbidity varies, especially with respect to lower respiratory symptoms and respiratory disease in children aged 5 to 12 years old. Most of the indoor studies showed increased lower respiratory morbidity in children subjected to long-term exposure to NO_2. Several studies showed that the mean weekly NO_2 concentrations in bedrooms reporting NO_2 levels were predominately between 15 and 122 $\mu g/m^3$ (0.008 and 0.065 ppm). Combining the indoor studies as if the end-points were similar gives an estimated odds ratio of 1.2 (95% confidence limits of 1.1 and 1.3) for the effect per 28.3 $\mu g/m^3$ (0.015 ppm) increase of NO_2 on lower respiratory morbidity. This suggests that--subject to assumptions made for the combined analysis--an increase of about 20% in the odds of lower respiratory symptoms and disease corresponded to each increase of 28.3 $\mu g/m^3$ (0.015 ppm) in time periods averaging 2 weeks of NO_2 exposure. Thus, the combined evidence supports the supposition regarding the effects of estimated exposure to NO_2 on lower respiratory symptoms and disease in children aged 5 to 12 years.

In the individual indoor studies of young children (2 years of age or younger), no consistent relationship was found between estimates of NO_2 exposure and respiratory symptoms and disease. Based on the meta-analysis of these indoor infant studies, the combined odds ratio for the increase in respiratory disease per increase of 28.2 $\mu g/m^3$ (0.015 ppm) NO_2 was 1.09 with a 95% confidence interval of 0.95 to 1.26 with cases where the mean NO_2 weekly concentrations in bedrooms were predominately between 9.4 and 94 $\mu g/m^3$ (0.005 and 0.05 ppm) in studies reporting levels. The increase in risk was very small and was not consistently reported in all the studies. We cannot conclude that the evidence suggests an effect on infants comparable to that seen in older children.

Several uncertainties need to be addressed when interpreting the above studies and results of the meta-analysis. Errors in measuring exposure are potentially one of the most important methodological problems in epidemiological studies of NO2. Although there is evidence that symptoms are associated with indicators of NO2 exposure, the quality of these exposure estimates may be inadequate to determine a quantitative relationship between exposure and symptoms with any certainty. Most of the studies that measured NO2 exposure did so only for periods of 1 to 2 weeks and reported the values as averages. Few of the studies attempted to relate the observed effects to pattern of exposures, such as transient peaks. Furthermore, measured NO2 concentrations may not be the biologically relevant dose per se; estimating actual exposure requires knowledge of both pollutant levels and related human activity patterns. However, only very limited activity and aerometric data are available that examine such factors, making any extrapolation regarding possible patterns of ambient exposure difficult. Another problem that arose is that although the level of similarity and common elements between the outcome measures in the NO2 studies do provide some confidence in their use in the quantitative analysis, the symptoms and illnesses combined are to some extent different and could indeed reflect different underlying processes. Thus, caution is necessary in interpreting the meta-analysis results. The fact that a no-effect level for subchronic or chronic NO2 exposure concentrations has not yet been determined should be emphasized.

The relationship between outdoor NO_2 and respiratory health has not been made decisively clear from current research. There is some evidence that the duration of respiratory illness may be increased at higher ambient NO_2 levels. A major difficulty in the analysis of outdoor studies is distinguishing possible effects of NO2 from those of other associated pollutants.

The following conclusions are made according to the assessment above:

(1) Controlled clinical studies on humans indicate that NO2 does have adverse effects on lung functions, airway responsiveness and antimicrobial host defenses. However, quantitative exposure–response functions about these types of effects could not be made using the current studies.

(2) According to the reviewed studies, short-term and long-term NO_2 exposure seems to be significantly associated with respiratory morbidity among children. These associations are rather consistent in studies on children aged 5 to 12 years old.

(3) Among adults, the relationship between short-term and long-term NO_2 exposure and respiratory health has not been as consistently proven as in children. However, some studies have shown significant associations between outdoor NO_2 concentrations and respiratory mortality or morbidity.

(4) In many of the reviewed studies on outdoor air pollution, there was a strong correlation between other co-existing air pollutants (especially particulates), and NO2, thus making it difficult to distinguish the effects of NO_2.

References

1. Air quality criteria for oxides of nitrogen. Research Triangle Park, NC, US Environmental Protection Agency 1993 (EPA Report No. EPA/600/8-91/049aF-cF. 3v).

2. BERGLUND, M. ET AL. Health risk evaluation of nitrogen oxides. Scandinavian journal of work, environment and health, 19 (Suppl. 2) (1993).

3. WAGNER, H. M. Update of a study for establishing criteria (dose/effect relationships) for nitrogen oxides. Luxembourg, Office for Official Publications of the European Communities, 1985 (Report No. EUR 9412 EN).

4. ROGER, L. J. ET AL. Pulmonary function, airway responsiveness, and respiratory symptoms in asthmatics following exercise in NO2. Toxicology and industrial health, 6: 155–171 (1990).

5. BAUER, M.A. Inhalation of 0.30 ppm nitrogen dioxide potentiates exercise-induced bronchospasm in asthmatics. American review of respiratory disease, 134: 1203–1208 (1986).

6. BYLIN, G. ET AL. Effects of short-term exposure to ambient nitrogen dioxide concentrations on human bronchial reactivity and lung function. European journal of respiratory disease, 66: 205–217 (1985).

7. HAZUCHA, M.J. ET AL. Effects of 0.1 ppm nitrogen dioxide on airways of normal and asthmatic subjects. Journal of applied physiology: respiratory, environmental and exercise physiology, 54: 730–739 (1983).

8. JEDRYCHOWSKI, W. ET AL. Effects of domestic gas cooking and passive smoking on chronic respiratory symptoms and asthma in elderly women. International journal of occupational and environmental health, 1: 16–20 (1995).

9. WJST, M. ET AL. Road traffic and adverse effects on respiratory health in children. British medical journal, 307: 596–600 (1993).

10. EDWARDS, J. ET AL. Hospital admissions for asthma in preschool children: relationship to major roads in Birmingham, United Kingdom. Archives of environmental health, 49: 223– 227 (1994).

11. Touloumi G, Katsouyanni K, Zmirou D et al. Short-term effects of ambient oxidant exposure on mortality: a combined analysis within the APHEA project. Air Pollution and Health: a European Approach. Am J Epidemiol. 1997 Jul 15;146(2):177-85.

12. Kan H, Chen B (2003). Air pollution and daily mortality in Shanghai: a time series study. Archives of Environmental Health, 58(6): 360-367.

13. Tsai SS, Huang CH, Goggins WB, Wu TN, Yang CY. Relationship between air pollution and daily mortality in a tropical city: Kaohsiung, Taiwan. J Toxicol Environ Health A. 2003 Jul 25;66(14):1341-9.

14. KINNEY, P.L. & ÖZKAYNAK, H. Associations of daily mortality and air pollution in Los Angeles County. Environmental research, 54: 99–120 (1991).

15. SALDIVA, P.H.N. ET AL. Association between air pollution and mortality due to respiratory diseases in children in São Paulo, Brazil: a preliminary report. Environmental research, 65: 218–225 (1994).

16. ZMIROU, D. ET AL. Short term effects of air pollution on mortality in the city of Lyon, France, 1985-90. Journal of epidemiology and community health, 50 (Suppl. 1): S30–S35 (1996).

17. Stieb DM, Judek S, Burnett RT. Meta-analysis of time-series studies of air pollution and mortality: effects of gases and particles and the influence of cause of death, age, and season. J Air Waste Manag Assoc, 2002; 52(4):470-84.

18. Neas LM, Dockery DW, Ware JH, Spengler JD, Speizer FE, & Ferris BG Jr (1991) Association of indoor nitrogen dioxide with respiratory symptoms and pulmonary function in children. Am J Epidemiol, 134: 204-219.

19. Melia RJW, Florey C du V, Chinn S, Goldstein BD, Brooks AGF, John HH, Clark D, Craighead IB, & Webster X (1980) The relation between indoor air pollution from nitrogen dioxide and respiratory illness in primary schoolchildren. Clin Respir Physiol, 16: 7P-8P.

20. Melia RJW, Florey C du V, Morris RW, Goldstein BD, Clark D, & John HH (1982a) Childhood respiratory illness and the home environment. I. Relations between nitrogen dioxide, temperature and relative humidity. Int J Epidemiol, 11: 155-163.

21. Melia RJW, Florey C du V, Morris RW, Goldstein BD, John HH, Clark D, Craighead IB, & Mackinlay JC (1982b) Childhood respiratory illness and the home environment: II. Association between respiratory illness and nitrogen dioxide, temperature and relative humidity. Int J Epidemiol, 11: 164-169.

22. Dijkstra L, Houthuijs D, Brunekreef B, Akkerman I, & Boleij JSM (1990) Respiratory health effects of the indoor environment in a population of Dutch children. Am Rev Respir Dis, 142: 1172-1178

23. Keller MD, Lanese RR, Mitchell Rl, & Cote RW (1979) Respiratory illness in households using gas and electricity for cooking: II. Symptoms and objective findings. Environ Res, 19: 504-515.

24. Ekwo EE, Weinberger MM, Lachenbruch PA, & Huntley WH (1983) Relationship of parental smoking and gas cooking to respiratory disease in children. Chest, 84: 662-668.

25. Ware JH, Dockery DW, Spiro A III, Speizer FE, & Ferris BG Jr (1984) Passive smoking, gas cooking, and respiratory health of children living in six cities. Am Rev Respir Dis, 129: 366-374.

26. Melia RJW, Florey C du V, Altman DG, & Swan AV (1977) Association between gas cooking and respiratory disease in children. Br Med J, 2: 149-152.

27. Melia RJW, Florey C du V, & Chinn S (1979) The relation between respiratory illness in primary schoolchildren and the use of gas for cooking: I. Results from a national survey. Int J Epidemiol, 8: 333-338.

28. Melia RJW, Florey C, Sittampalam Y, & Watkins C (1983). The relation between

respiratory illness in infants and gas cooking in the UK: a preliminary report. In: Proceedings of the VIth World Congress on Air Quality Paris, Air Pollution Prevention Association, pp 263-269.

29. Ogston SA, Florey C du V, & Walker CHM (1985) The Tayside infant morbidity and mortality study: effect on health of using gas for cooking. Br Med J, 290: 957-960.

30. Dockery DW, Spengler JD, Neas LM, Speizer FE, Ferris BG Jr, Ware JH, & Brunekreef B (1989a) An epidemiologic study of respiratory health status and indicators of indoor air pollution from combustion sources. In: Harper JP ed. Combustion processes and the quality of the indoor environment: transactions of an international specialty conference. Pittsburgh, Pennsylvania, Air and Waste Management Association, pp 262-271 (A&WMA Transactions Series: TR-15).

31. Margolis PA, Greenberg RA, Keyes LL, Lavange LM, Chapman RS, Denny FW, Bauman KE, & Boat BW (1992) Lower respiratory illness in infants and low socioeconomic status. Am J Public Health, 82: 1119-1126.

32. Samet JM, Lambert WE, Skipper BJ, Cushing AH, Hunt WC, Young SA, McLaren LC, Schwab M, & Spengler JD (1993) Health outcomes. In: Nitrogen dioxide and respiratory illness in children, part I. Cambridge, Massachusetts, Institute of Health Effects, pp 1-32 (Research Report No. 58).

Chapter 8. Establishment of Exposure-Response Functions of Air Particulate Matter and Adverse Health Outcomes in China and Abroad

1. Introduction

Numerous epidemiologic studies conducted during the past 10-20 years confirm that exposure to air pollution contributes to higher rates of both mortality and morbidity, both in China and abroad[1]. A large share of the epidemiological studies from the USA report that particulate matter (PM), – measured as either TSP (total suspended particle), PM_{10} (those less than 10 microns), $PM_{2.5}$ (less than 2.5 microns), or black smoke – has the greatest explanatory power in exposure-response functions for several health problems, although other air pollutants may also be associated with the same problems. The evidence of PM playing a central role is especially strong in studies of mortality, for which an association has been reported over a wide range of concentrations, and in a variety of communities with varying climates and mixtures of pollutants.

As evidence of the adverse health effects of air pollution has accumulated, quantification of the impact of air pollution on public health and the subsequent cost-benefit analysis have increasingly become a critical component in policy discussion and priority setting. In fact, numerous studies have been carried out to estimate the health damage due to air particulate matter, both in physical and monetary terms[2].

Exposure-response functions link air quality changes and heath outcomes, thereby providing key information for health impact assessments of air pollution. The composition of air pollution differs significantly between China and most Western states, however, and the exposure-response coefficients found in the Western studies cannot simply be transferred to a Chinese context. Moreover, demographic factors, such as age-distribution and health status, may influence the impact that air pollution has on public health. Previously, we collected various Chinese studies on the topic and did a meta analysis of exposure-response functions of air particulate matter and adverse health outcomes in China[3]. In the present analysis, we tried to make use of available epidemiologic literature both from China and abroad to derive the exposure-response functions and the respective measures of precision (95 percent confidence interval or standard error). With many studies providing information on the same exposure-response associations, a meta-analysis of their results was also conducted to derive a common estimate, which could be further applied to health risk assessments of air particulate matter in China.

2. Materials and Methods

2.1 Data Sources

Using the Chinese Biomedical Literature Database and PubMed, we collected epidemiological literature on particulate air pollution and its adverse health effects published between 1990 and 2002 in China and abroad. Exposure-response coefficients and their 95% confidence intervals (CI) were obtained from this literature.

PM_{10} was selected as the particulate matter indicator because there is much PM_{10} data available for Shanghai and the rest of China. But some studies using TSP and $PM_{2.5}$ for exposure assessment were also included in the analysis. The following formulas were used for converting between different particulate matter indicators:

$PM_{10} = TSP \times 0.65$

$PM_{2.5} = PM_{10} \times 0.65$ [4]

2.2 Literature Selection

Particle-related effects were summed up in a series of health outcomes in different exposure levels, ranging from morbidity to mortality changes. Studies can vary in many ways: for example in their definition of the health outcome, their choice of pollutant metric and their reporting of results. When more than one study has been conducted using the same population, further consideration of the methodology used in the study must be made. They may have been published at different times and may have used different statistical methods. It is also important that study selection is unbiased by knowledge of the result. Hence, guidelines for the study selection are explained below.

(1)The number of estimates available for meta-analysis should not be a determining factor in selecting studies – that is, there should be no compromises made on any of the criteria for study selection in order to raise the number of studies included in the analysis.

(2) Studies conducted in China were preferred. When widely accepted health studies on particulate air pollution were not available from China based sources, e.g., the long-term effect on mortality, the results from international studies were used.

(3) Only one estimate from each city should be used in the meta-analysis. A number of cities have been studied more than once and therefore a mechanism for selecting the appropriate estimate was needed. It was decided to select the latest study published or, if the study participated in a large multi-city study, to use the multi-city study results.

(4) Quantitative exposure-response relationships between particulate matter and health outcomes were established (in the form of either slope or relative risk).

(5) Sub-clinical effects, such as lung function changes, were not included in this assessment, because it is difficult to translate them into long-term health impact & monetary values based on current knowledge.

Based on the above criteria, data was gathered regarding the effect of particulate exposure on the following health outcomes:

- **Long-term mortality**
- **Morbidity**
  - Chronic bronchitis
  - Hospital admission (for respiratory and cardiovascular problems)
  - Outpatient visits (in internal medicine and pediatrics)
  - Other illnesses (acute bronchitis and asthma attacks)

3. Meta-analysis Method

If several studies described exposure-response functions for the same health endpoint, we obtained the mean and 95 percent confidence interval (CI) of the coefficient. This meta-analysis method was based on the variance weighted average across the results of studies with available quantitative effect estimates (coefficients or relative risks): studies with lower standard errors had more weight in the resulting joint estimate.

We used the META command in STATA to perform this process.

4. Results

4.1 Estimates of Long-Term Effects on Mortality

In China, evidence of air pollution having long-term impacts on mortality rates is provided by various cross-sectional studies, but no long-term cohort studies of mortality rates have been carried out. Given that there are no cohort studies available in China, we have to rely on international research.

The exposure-response relationship between ambient particulate matter and long-term mortality was studied in two U.S. cohort studies[5][6]. These cohort studies give the additional number of deaths per person-year which may be directly applied to the per year impact assessment. The most up-to-date results, providing longer follow up and more data on particulate matter, were recently published for the latter study[7]. Thus, the current impact assessment was based on the results these two U.S. studies on the long-term effects on mortality rate in adult populations[5][7].

The American Cancer Society (ACS) study[7] investigated the impact of air pollution exposure in metropolitan areas throughout the United States on the survival of 500,000 people, finding that mortality risk increases 4.0 percent with each increase of 10 $\mu g/m^3$ PM_{10}. The Harvard 6 Cities Cohort study, which followed 8,111 people, found a much higher mortality increase, estimating that mortality risk increases 8.5 percent with each increase of 10 μ g/m^3 PM_{10}[5].

Our meta-analysis yielded a joint estimated relative mortality risk of 1.0430 (95% CI 1.0260, 1.0610）associated with PM_{10} pollution.

4.2 Estimates of Effects on Morbidity

4.2.1 Chronic bronchitis

Two studies conducted in China described the association between chronic bronchitis and long-term exposure to air pollution. Using an ecological cross-sectional design, the Jin, et al. study investigated the effect of ambient air pollution on the number of new cases of chronic bronchitis (incidence) in Benxi, China[8]. A similar study was conducted by Ma, et al. in Shanghai[9]. These studies estimated that the incidence rate of chronic bronchitis increases 3.0 percent in Benxi and 2.9 percent in Shanghai with each increase of 10 μ g/m^3 TSP.

We calculated a joint estimated relative risk of 1.046（1.015, 1.077）per 10 μ g/m^3 PM_{10}.

4.2.2 Hospital admission

The association between air pollution and hospital admission has been confirmed in North American and Europe. There have been no studies on this relationship in China, however. Therefore, we had to rely on international peer-reviewed papers for our analysis.

Hospital admission for respiratory problems. Using three European studies[10-12], we calculated a joint relative risk for hospital admission for respiratory problems of 1.008 (95% CI 1.004-1.012) for each increase of 10 μ g/m^3 PM_{10} . From 8 U.S. and Canadian studies[13-20], a joint relative risk of 1.017 (95% CI 1.013-1.020) for each increase of 10 μ g/m^3 PM_{10} was calculated.

Combining all these European, U.S., and Canadian studies yielded a relative risk of 1.013 (95% CI 1.010-1.015) per 10 μ g/m^3 PM_{10}.

Hospital admissions for cardiovascular problems. Using four European studies[11][12][21][22], we calculated the joint relative risk of hospital admission for cardiovascular problems to be 1.013 (95% CI 1.007-1.019) for each increase of 10 μ g/m^3 PM_{10}. We derived a joint estimated relative risk of 1.008 (95% CI 1.004-1.011) per 10 μ g/m^3 increase in PM_{10} using three U.S. and Canadian studies [20] [23] [24].

All European, U.S., and Canadian studies combined yielded an estimated relative risk of 1.009 (95% CI 1.006-1.013) per 10 μ g/m^3 increase in PM_{10}.

4.2.3 Hospital outpatient visits

To date, there has been only one study in China on the association between air pollution and outpatient visits. The Xu X., et al. study conducted in Beijing reported a 3.4% (95% CI 1.9-4.9%) increase in outpatient visits to internal medicine and a 3.9%（95% CI 1.4-6.4%）increase in outpatient visits to pediatrics departments with each increase of 10 μ g/m^3 PM_{10}[25].

4.2.4 Acute bronchitis

There has been one study conducted in China on the relationship between air pollution and acute bronchitis[8]. That study found that with each increase of 10 μ g/m^3 PM_{10}, the incidence rate of acute bronchitis increases 4.6 percent (95% CI 0.0-9.2%).

4.2.5 Asthma

- Asthma in children（≤15 yrs）

Wei F. et al., investigated the relationship between air pollution and incidence of asthma in children in four Chinese cities, Lanzhou, Guangzhou, Wuhan, and Chongqing. He found that the incidence rate of asthma in children increases 6.95 percent* with each 10 μ g/m^3 increase of PM_{10}[26].

- Asthma in adults （>15 yrs）

Using three European panel studies on adults[27] [28] [29], we calculated a joint relative risk of 1.039 (95% CI 1.019-1.059) per 10 μ g/m^3 increase of PM_{10}. Another estimate from two U.S. panel studies[30] [31] was 1.002 (95% CI 0.998-1.006) per 10 μ g/m^3 increase of PM_{10}. Combining these five studies yields a joint relative risk of asthma among adults of 1.004 (95% CI 1.000-1.008) per 10 μ g/m^3 increase of PM_{10}.

Table 8-1 summarizes the results of the meta-analysis, expressed as relative risk of each health endpoint associated with 10μg/m3 increase of PM10.

Table 8-1. Relative risk of each health endpoint associated with each increase of 10μg/m^3 PM_{10} (mean and 95％CI)

Health endpoints	Population	Relative risk（95％ CI）
Total mortality	adults（≥30 yrs）	1.0430（1.0260，1.0610）
Chronic bronchitis	Total population	1.0460（1.0150，1.0770）
Respiratory hospital admission	Total population	1.0130（1.0010，1.0250）
Cardiovascular hospital admission	Total population	1.0095（1.0060，1.0130）
Outpatient visits (internal medicine)	Total population	1.0034（1.0019，1.0049）
Outpatient visits (pediatrics)	Total population	1.0039（1.0014，1.0064）
Acute bronchitis	Total population	1.0460（1.0000，1.0920）
Asthma	Children（≤15 yrs）	1.070*
Asthma	Adults（≥15 yrs）	1.0040（1.0000，1.0080）

* 95％CI were not provided in the original paper

* 95％CI were not provided in the original paper.

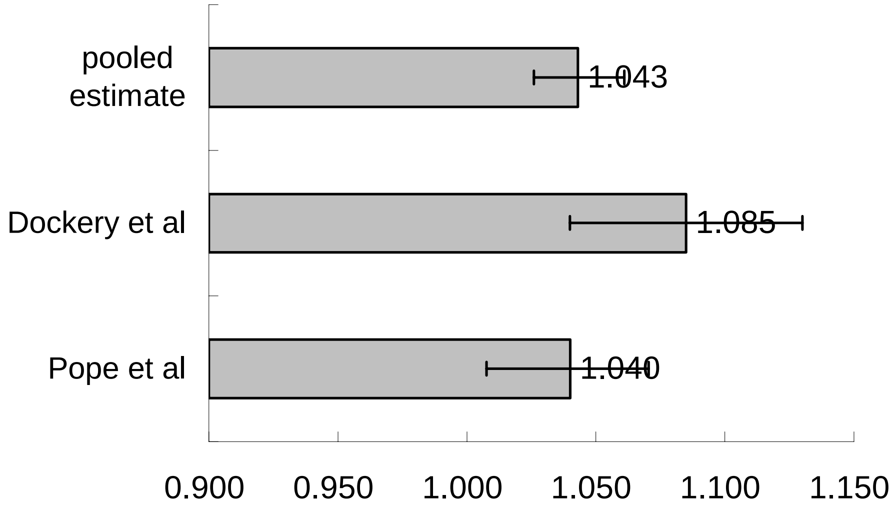


Figure 8-1 Relative risk of total mortality (long-term) with each increase of 10μg/m^3 PM_{10}

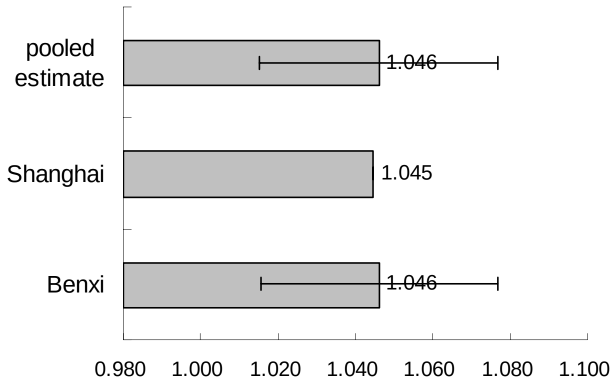


Figure 8-2 Relative risk of chronic bronchitis with each increase of 10μg/m^3 PM_{10}

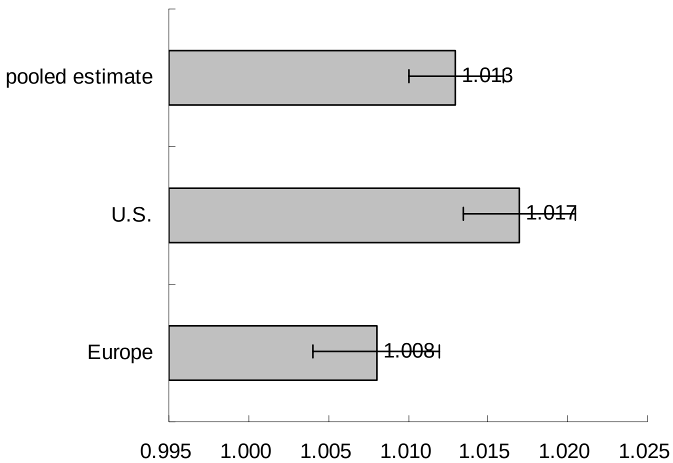


Figure 8-3 Relative risk of respiratory hospital admission with each increase of 10μg/m^3 PM_{10}

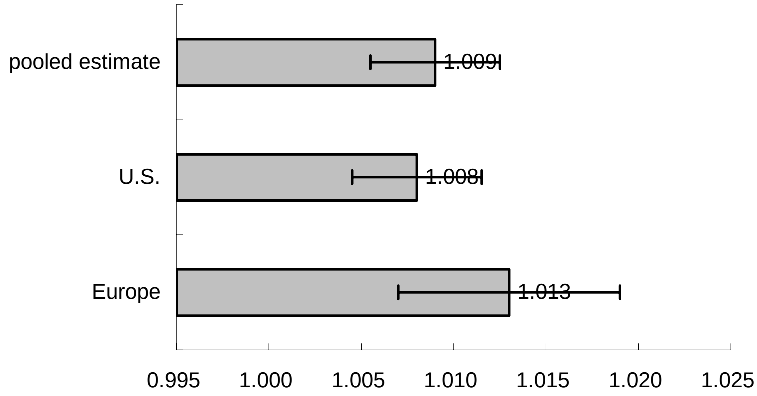


Figure 8-4 Relative risk of cardiovascular hospital admission with each increase of 10μg/m^3 PM_{10}

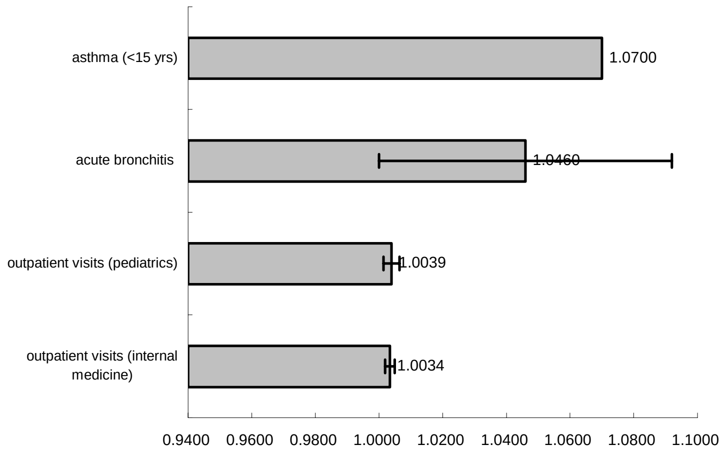


Figure 8-5 Relative risk of outpatient visits (internal medicine, pediatrics), acute bronchitis and asthma (≤15 yrs) with each increase of 10μg/m^3 PM_{10}*（*We didn't conduct meta analysis due to the data limit）

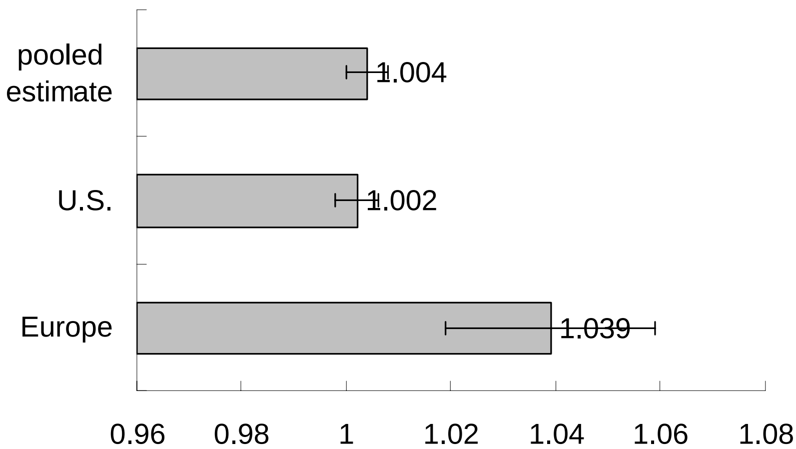


Figure 8-6. Relative risk of asthma (>15 yrs) with each increase of 10μg/m^3 PM_{10}

5. Discussion

Mortality is often considered the most important aspect when studying air particulate exposure. Dozens of epidemiologic studies have measured increases in mortality associated with particulate air pollution. In the short-term, air pollution levels of a given day or short period of days may trigger an increase in deaths within days or weeks. Most of the literature on the short-term effects of air pollution are based on time-series or case-crossover studies. In terms of long-term effects of air pollution on mortality, the cohort studies revealed that long term exposure to of air pollution might lead to a measurable reduction of survival in the population. Generally, the prospective cohort studies report a substantially larger effect for long-term exposure than that reported by daily time-series studies. Since the cohort studies provided a more complete assessment of the impact from exposure to air pollution than that from time-series studies [32], we decided to use cohort-based exposure-response functions in the current analysis. Unfortunately, we had to rely on the results of two U.S. cohort studies, because no such study was available in China.

Some exposure-response functions employed in this analysis are not available in Chinese studies and for this reason it was necessary to rely on international studies, conducted mostly in the U.S. and Western Europe. As an example, we compared the effect of exposure to particulate matter on mortality changes (both short-term and long-term) in China and developed countries. Figure 7 describes the relative risks of total mortality in response to an increase of 10μg/m3 PM10, among which the acute effects of particulate matter was derived from a meta analysis of 109 studies[33] and a pooled estimate of Chinese studies[34]. The chronic effects were estimated from two US cohort studies for developed countries and one cross-sectional study in China. Compared with the studies in the U.S. and Europe, the Chinese studies generally reported lower coefficients for the exposure-response relationships between air pollution and acute/chronic mortality change. Similarly, European studies tended to report lower coefficients than studies in the USA. At least for particulate air pollution and mortality there is evidence from studies in Western countries to suggest the exposure-response relationship may become less steep as ambient concentration levels rise. Our observation that coefficients tend to be lower in China is consistent with this feature.

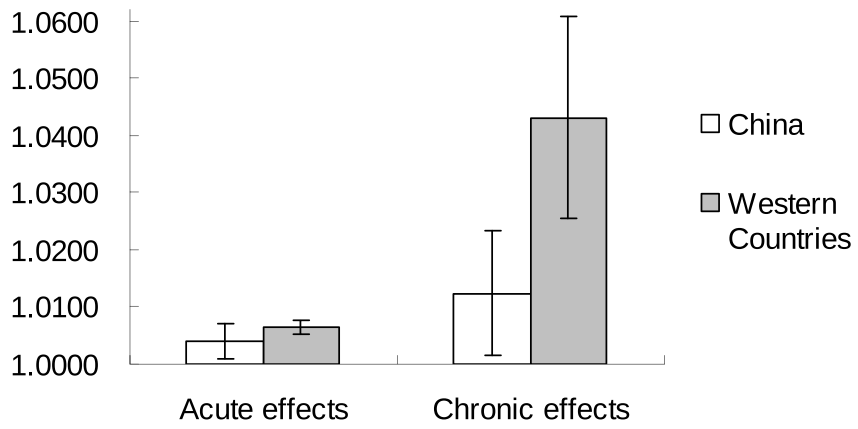


Figure 8-7. Relative risk of mortality in China and Western countries with 10μg/m3 increase of PM_{10}

The probable reasons might include different levels of air pollution, local population sensitivity, age distribution and, most particularly, different air pollutant components. For instance, the composition of motor vehicle emissions in Western Europe and U.S., where most of the epidemiological studies were performed, differs substantially from that in China. This, together with other differences, such as greater usage of coal in China, implies that the air pollution mixture differs substantially between China and the areas where most epidemiologic studies were conducted. Therefore, conceptually, when exposure-response functions from developed countries were applied to other regions, for example China, they should be revised to a certain extent, taking into account local conditions, such as physical (diameter, etc.) and chemical (components) character of particles, socio-economic status of local populations, and so on. According to the WHO, extrapolation of health impacts for particulate matter beyond 150 μg/m3 PM10 must be done with extreme care due to a possible flattening of the curve.

Of course, transferring results from one part of China to another entails uncertainties in itself, for instance due to differences in effect modifying factors. Regarding the impact of air pollution on mortality rates, recent work has suggested that effects on health are not uniformly distributed. Factors such as education and antioxidant vitamin status may be important; thus disadvantaged population groups may be more susceptible to the negative effects of pollution. A possible synergistic effect of air pollution and smoking is also of particular relevance in China, where smoking is extremely common, particularly among men. Moreover, in China indoor air pollution resulting from the use of raw coal for cooking and heating poses large health risks to parts of the population. Generally, women and children are more highly exposed to high levels of indoor air pollution, and thus suffer a disproportional share of the enhanced health risk. More research into the likely distributional features of health damage due to outdoor and indoor air pollution in China is needed.

In summary, the exposure-response coefficients recommended here can be applied to health risk assessment of air particulate matter in China.

References

1. Wilson, R., and Spengler, J. (1996). Particles in our air: concentrations and health effects. Harvard University Press, Boston.

2. Kan, H., Chen, B., Chen, C., Fu, Q., and Chen, M. (2004). An evaluation of public health impact of ambient air pollution under various energy scenarios in Shanghai, China. Atmospheric Environment, 38(1): 95-102.

3. Kan, H., and Chen, B. (2002). Meta analysis of exposure-response functions of air particulate matter and adverse health outcomes in China. Journal of Environment and Health, 19(6): 422-424.

4. Teng, E., Hu, W., and Wu, G. (1999). The composing characteristics of elements in coarse and fine particle in air of the four cities in China. China Environmental Science, 19: 238-242.

5. Dockery, D.W., Pope, C.A., Xu, X., Spengler, J.D., Ware, J.H., Fay, M.E., Ferris, B.G. , Speizer, F.E. (1993). An association between air pollution and mortality in six U.S. Cities. N Eng J Med. 329: 1753-1759.

6. Pope, C.A., Thun, M.J., Namboodiri, M.M., Dockery, D.W., Evans, J.S., Speizer, F.E., and Heath, C.W. (1995). Particulate Air Pollution as a Predictor of Mortality in a Prospective Study of U.S. Adults. Am J Resp Crit Care Med, 151: 669-674.

7. Pope, C.A., Burnett, R.T., Thun, M.J., Calle, E.E., Krewski, D., Ito, K., and Thurston, G.D. (2002). Lung cancer, cardiopulmonary mortality, and long-term exposure to fine particulate air pollution. JAMA, 287 (9): 1132-1141.

8. Jin, L.B., Qin, Y., and Xu, Z. (2000). Relationship between air pollution and acute and chronic respiratory disease in Benxi. Journal of Environment and Health, 17: 268-270.

9. Ma, H.B., and Hong, C.J. (1992) Effects of particulate air pollution on respiratory disease. Chinese Journal of Public Health, 11: 229-232.

10. Spix, C., Anderson, H.R., Schwartz, J., Vigotti, M.A., LeTertre, A., Vonk, J.M., Touloumi, G., Balducci, F., Piekarski, T., Bacharova, L., Tobias, A., Ponka, A., and Katsouyanni, K. (1998). Short-term effects of air pollution on hospital admissions of respiratory diseases in Europe: a quantitative summary of APHEA study results. Air Pollution and Health: a European Approach. Arch Environ Health, 53(1): 54-64.

11. Wordley, J., Walters, S., and Ayres, J.G. (1997). Short term variations in hospital admissions and mortality and particulate air pollution. Occup Environ Med. 54 (2): 108-16.

12. Prescott, G.J., Cohen, G.R., Elton, R.A., Fowkes, F.G., and Agius, R.M. (1998). Urban air pollution and cardiopulmonary ill health: a 14.5 year time series study. Occup Environ Med. 55 (10): 697-704.

13. Thurston, G.D., Ito, K., Hayes, C.G., Bates, D.V., and Lippmann, M. (1994). Respiratory hospital admissions and summertime haze air pollution in Toronto, Ontario: consideration of the role of acid aerosols. Environ Res, 65(2): 271-290.

14. Schwartz, J. (1994a). Air pollution and hospital admissions for the elderly in Detroit, Michigan.

Am J Respir Crit Care Med, 150(3): 648-655.

15. Schwartz, J. (1994b). Air pollution and hospital admissions for the elderly in Birmingham, Alabama. Am J Epidemiol, 139(6): 589-598.

16. Schwartz, J. (1994c). PM10, ozone, and hospital admissions for the elderly in Minneapolis-St. Paul, Minnesota. Arch Environ Health, 49(5): 366-374.

17. Schwartz, J. (1995). Short term fluctuations in air pollution and hospital admissions of the elderly for respiratory disease. Thorax, 50(5): 531-538.

18. Schwartz, J. (1996). Air pollution and hospital admissions for respiratory disease. Epidemiology, 7(1): 20-28.

19. Schwartz, J., Spix, C., Touloumi, G., Bacharova, L., Barumamdzadeh, T., Tertre, A., Piekarksi, T., Ponce, A., Ponka, A., Rossi, G., Saez, M., and Schouten, J.P. (1996). Methodological issues in studies of air pollution and daily counts of deaths or hospital admissions. J Epidemiol Community Health. 50 Suppl 1:S3-11.

20. Burnett, R.T., Cakmak, S., Brook, J.R., and Krewski, D. (1997). The role of particulate size and chemistry in the association between summertime ambient air pollution and hospitalization for cardiorespiratory diseases. Environ Health Perspect. 105 (6): 614-620.

21. Medina, S., Tertre, A., and Dusseux, E. (1997). Evaluation des Risques de la Pollution Urbaine sur la Santé (ERPURS). Analyse des liens à court terme entre pollution atmoshérique et santé. Resultats 1991-1995, Conseil Regional d'Ile de France.

22. Poloniecki, J.D., Atkinson, R.W., Leon, A.P., and Anderson, H.R. (1997). Daily time series for cardiovascular hospital admissions and previous day's air pollution in London, UK. Occup Environ Med, 54(8): 535-540.

23. Schwartz, J., and Morris, R. (1995). Air pollution and hospital admissions for cardiovascular disease in Detroit, Michigan. Am J Epidemiol, 142(1): 23-35.

24. Schwartz, J. (1997). Air pollution and hospital admissions for cardiovascular disease in Tucson. Epidemiology, 8(4): 371-377.

25. Xu, X., Dockery, D.W., Christiani, D.C., Li, B., and Huang, H. (1995). Association of air pollution with hospital outpatient visits in Beijing. Arch Environ Health, 50(3): 214-220.

26. Wei, F., Hu, W., and Teng, E. (2000). Relation analysis of air pollution and children's respiratory system disease prevalence. China Environmental Science, 20(3): 220-224.

27. Dusseldorp, A., Kruize, H., Brunekreef, B., Hofschreuder, P., Meer, G., and Oudvorst, A.B. (1995). Association of PM10 and airborne iron withrespiratory health of adults living near a steel factory. Am J Respir Crit Care Med, 152: 1032-1039.

28. Hiltermann, T.J., Stolk, J., Zee, S.C., Brunekreef, B., Bruijne, C.R., Fischer, P.H., Ameling, C.B., Sterk, P.J., Hiemstra, P.S., and Bree, L. (1998). Asthma severity and susceptibility to air pollution. Eur Respir J, 11: 686-693.

29. Neukirch, F., Segala, C., Moullec, Y., Korobaeff, M., and Aubier, M. (1998). Short-term

effects of low-level winter pollution on respiratory health of asthmatic adults. Arch Environ Health, 53: 320-328.

30. Ostro, B.D., Lipsett, M.J., Wiener, M.B., and Selner, J.C. (1991). Asthmatic responses to airborne acid aerosols. Am J Public Health, 81(6): 694-702.

31. Pope, C.A., Dockery, D.W., Spengler, J.D., and Raizenne, M.E. (1991). Respiratory health and PM10 pollution: A daily time series analysis. Am Rev Respir Dis, 144: 668-674.

32. Kunzli, N., Medina, S., Kaiser, R., Quenel, P., Horak, F., and Studnicka, M. (2001). Assessment of deaths attributable to air pollution: should we use risk estimates based on time series or on cohort studies? Am J Epidemiol, 153(11): 1050-1055.

33. Stieb, D.M., Judek, S., and Burnett, R.T. (2002). Meta-analysis of time-series studies of air pollution and mortality: effects of gases and particles and the influence of cause of death, age, and season. J Air Waste Manag Assoc, 52: 470-484.

Chapter 9. Application of DALYs in Measuring the Health Burden of Ambient Air Pollution: A Case Study in Shanghai, China

1. Introduction

Various epidemiologic research carried out during the past 10-20 years confirms that exposure to air pollution contributes significantly to both mortality and morbidity, both in China and abroad. Health complications resulting from air pollution include respiratory symptoms, reduced lung function, increases in hospital admission, chronic bronchitis, and mortality to name a few. Among air pollutants, particulate matter – measured as either TSP (total suspended particle), PM_{10} (particulate matter less than 10 microns), $PM_{2.5}$ (particulate matter less than 2.5 microns), or black smoke – appears to show the most consistent association with those outcomes.

As evidence of the adverse health effects of air pollution becomes more and more convincing, quantification of the impact of air pollution on public health and the subsequent cost-benefit analysis has increasingly become a critical component of policy discussion. In fact, several studies have closely examined the health damage due to air pollution, both in physical and monetary terms[1] [2].

Disability-adjusted life years (DALYs) are a standard measure of the burden of disease. The concept combines life years lost due to premature death and fraction of years of healthy life lost as a result of illness or disability, thereby providing an aggregate measure to reduce all air pollution-related health effects into one denominator.

In an era moving toward sustainable development and a healthy populace, urban air quality is becoming a serious public health concern. The number of deaths globally every year due to air pollution is estimated at more than 2.7 million people, with cities accounting for approximately 33%[3] of that figure. In Shanghai, the largest city in China, more than 13 millions residents are exposed on a daily basis to particulate matter (PM) levels that greatly exceed the normal population exposure level in western countries. As a case analysis, the present study attempts to express the health burden of ambient air pollution in DALYs.

2. Methods:

2.1 Air pollutant concentrations

In order to study the applicability of the DALY Shanghai transportation project, the air pollutant data, as presented in the *Study on Energy scheme and Health benefits in Shanghai*, has been adopted as the basic foundation. In that study, the MARKAL (MARKet ALlocation) optimization model was used to estimate pollutant emissions in Shanghai in 2000. MARKAL is a dynamic linear programming model that optimizes a technology-rich network representation of an energy system. One MARKAL model is a representation of (part of) the economy of a region. The economy is modeled as a system, represented by processes and physical and monetary flows between these processes. Details on the application of the MARKAL model on energy and environmental policies in Shanghai have also been discussed in other studies[4].

Based on the principle of transfer matrix, a type of quick air quality model was developed, namely the Exposure Level model which links emission scenarios of MARKAL models and air pollutant concentrations.

The fundamental matrix was input by a long-range transport and deposition model (ATMOS model) for SO_2 and PM_{10}. The ATMOS model is a Lagrangian parcel model with three vertical layers. For the Shanghai project, the ATMOS model provided a 4km by 4km resolution of the concentration of SO_2 and PM_{10}. For the purpose of the study, the total area of Greater Shanghai, 6341 km^2, is divided into 487 grids. Two transfer matrices for use in exposure level prediction were produced: a region-to-grid matrix for the area sources and a large point source-to-grid matrix for the elevated point sources. Based on the matrix output of the ATMOS model, the Shanghai Exposure Level model was developed in Excel to link the emission predictions of MARKAL while providing exposure levels for a health impact analysis.

2.2 Human exposure level to air pollution

Ambient air pollution consists of a mix of various pollutants (e.g. ozone, SO_2, NO_2, particles, CO) that are correlated in various ways. In most epidemiologic studies, it is impossible to attribute negative health effects to one specific pollutant. A problem called the “double counting effect” would arise when the health effects associated with several pollutants simultaneously are simply added up for assessment. In the present assessment, PM10 was selected as an indicator of air pollution to estimate relevant health effects, since epidemiologic evidence most strongly points to it among all other air pollutants as being the most closely linked to adverse health effects. In this context, PM_{10} is a useful indicator of several sources of outdoor air pollution, such as fossil-fuel combustion. Our choice of indicator pollutant is also in line with other similar assessments[5].

People living in Greater Shanghai were considered the exposed population in this analysis. An estimate of the number of Shanghai residents in each 4km×4km grid cell was then made for the assessment based on the population data collected from the Shanghai Bureau of Statistics. Of course it is impossible to have accurate data on the number of people in each 4km× 4km cell in Shanghai due to the fact that the borderline of communities is not in a 4km×4km rectangular form. We used a modified approach that approximated the portion of the population of each community lying within a given grid cell by multiplying the population density of that community by the area within the cell it covered and then calculated the total population within a grid by adding up the population of each community lying within it In addition, population growth was assumed to grow at the same rate in all the cells and age distribution was assumed to be identical in each cell.

Combining the PM_{10} level and population numbers of each cell, we estimated the population exposure level to outdoor air pollution in 2000 in Shanghai.

2.3 Estimation on health effects

To develop estimates of the public health impact of air pollution, we relied on published studies on air pollution and health, using concentration-response (C-R) coefficients derived from studies conducted in China and abroad.

Exposure-response functions of PM_{10} for each health endpoint, which were derived from available epidemiologic studies, were used to quantify the health effects of outdoor air pollution under various scenarios. Since most of the epidemiologic studies linking air pollution and health are based on a relative risk model in the form of Poisson regression, the cases at a given concentration C, could be represented by:

$$E = \exp(\beta \times (C - C_0)) \times E_0 \qquad (1)$$

In equation (1), C and C_0 are the PM10 concentration under one specific scenario and baseline scenario, respectively, and E and E_0 are the corresponding health effect cases under the concentration of C and C_0. The health effect (benefit/damage) under the scenario in question with respect to the baseline scenario is the difference between E and E_0. The value could be obtained if the following data components are available: exposure-response functions (β), population exposure levels (C and C_0), and baseline rate (E_0).

Exposure-response functions (β) link air quality changes and heath outcomes. The preference for this analysis was to select C-R functions from Chinese studies whenever they were available. Only when the selected endpoints could not be found in Chinese studies were the results of international peer-reviewed studies used. If there were several studies describing the C-R function for the same health endpoint, we used the pooled estimate to get the mean and 95 percent confidence interval (CI) of the coefficient.

The baseline incidence data (E_0) for various health outcomes were collected from data originating in Shanghai, proxy data from other regions of China or from data compiled at the national level. This data was usually in the form of annual incidence rates.

2.4 Estimation of DALYs lost due to ambient air pollution

In this exercise, we attempt to express the health impact of air pollution in DALYs. The approach we adopted was recommend by the World Bank[6]. For mortality due to air pollution, the approach is straightforward: use of 10 DALYs lost per death; however, converting air pollution-induced morbidity to DALYs is assumed to be a tougher challenge because of the lack of literature relating to morbidity endpoints assess in air pollution dose-response studies to lost DALYs.

3. Results:

3.1 Exposure assessment to PM_{10} of general population in Shanghai

As mentioned above, we calculated the numbers of people exposed to a specific PM_{10} concentration and then pooled it together in each 4km×4km cell. Figures 9-1 describes the percentage of the population exposed to different levels of PM_{10} in 2000 in Shanghai.

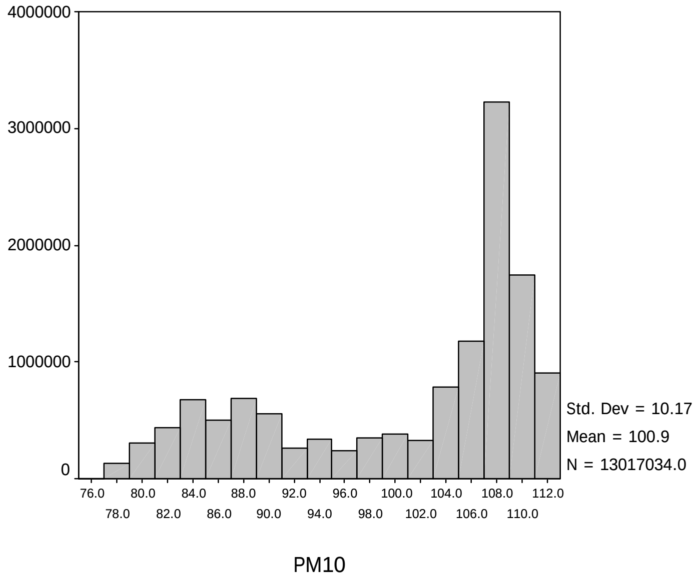


Figure 9-1. Percent of Shanghai residents exposed to different level of PM_{10} in 2000

3.2 Health effects estimation

The PM_{10} exposure-response coefficients (mean and 95% CI) and the incidence rates of selected health outcomes in the analysis have been summarized in previous studies.

Using the exposure-response functions, frequency of the outcomes, exposure concentration and the threshold level, we calculated the attributable number of cases of mortality due to particulate air pollution of Shanghai residents (see Table 9-1).

In total it was found that particulate air pollution caused 8,220 attributable deaths in Shanghai in 2000. It also accounted for: 16,870 new cases of chronic bronchitis, 5,240 respiratory hospital admissions, 2,690 cardiovascular hospital admissions, 386,600 internal medicine visits, 40,040 pediatrics visits, 540,300 episodes of acute bronchitis, and 9,990 asthma attacks.

Table 9-1. Attributable number of cases due to particulate air pollution in urban area of Shanghai in 2000 (mean and 95% CI)

Health outcomes	Mean	95％ CI
Long-term mortality	8,220	5,570-10,870
Chronic bronchitis	16,870	7,650-25,880
Respiratory hospital admission	5,240	540-9,920

Cardiovascular hospital admission	2,690	1,750-3,610
Outpatient visits- internal medicine	386,600	226,300-547,000
Outpatient visits-pediatrics	40,040	14,750-65,320
Acute bronchitis	540,300	0-1080,500
Asthma attack	9,990	8,290-11,680

3.3 DALYs lost due to air pollution

Table 9-2 converts the health outcomes due to air pollution into DALYs. Using the unit values and quantified health effects, we computed the corresponding DALYs lost (table 9-3). The total DALYs lost due to air pollution in Shanghai in 2000 was about 103,064. Among all health outcomes, premature deaths dominated the value of the total DALYs lost, accounting for around 79.6% of the number. In addition, chronic bronchitis also featured very strongly.

Table 9-2. DALYs values per 10,000 cases of health endpoints due to air pollution[6]

Health endpoints	DALYs lost per 10,000 cases
Premature death	100,000
Chronic bronchitis	12,037
Respiratory hospital admission	264
Cardiovascular hospital admission	264
Outpatient visits- internal medicine	3
Outpatient visits-pediatrics	3
Acute bronchitis	4
Asthma attack	4

Table 9-3. DALYs lost due to air pollution in Shanghai in 2000

Health endpoints	DALYs lost (mean and 95%CI)
Premature death	82,200 (55,700-108,700)
Chronic bronchitis	20,306 (9,208-31,152)
Respiratory Hospital admission	138 (14-262)
Cardiovascular Hospital admission	71 (46-95)
Outpatient visits (internal medicine)	116 (68-164)
Outpatient visits (pediatrics)	12 (4-20)
Acute bronchitis	216 (0 –432)
Asthma attack	4 (3-5)
Total	103,064 (65,044-14,0830)

4. Discussion

Evaluation of health effects is becoming a critical component in assessing the social costs of air pollution, for it allows for a cost-benefit analysis of pollution control measures and provides a basis for measuring priority for action. In our analysis, the impact of air pollution on public health is substantial in Shanghai.

To date, a widely used approach to evaluate the health impact of air pollution has been the willingness-to-pay (WTP) and cost-of-illness (COI) techniques to conduct relevant economic assessments. For example, Kan and Chen estimated the total economic cost of health impacts due to particulate air pollution in urban areas of Shanghai in 2001 was about 625.40 millions US dollars, accounting for 1.03% of the gross domestic product (GDP) of the city[2]. However, the studies on the WTP for reducing the health risk of air pollution are mostly conducted in developed countries, e.g., the US and Western Europe, and are extremely rare in China. Since there have been no original valuation studies on the health endpoints associated with air pollution in China before, economic analysis has to estimate values from previous studies of similar changes. This procedure is often termed as benefit transfer or value transfer in economics. Characteristics of the concerned population, e.g. age distribution, income, health status, and culture, may have contextual effects on the valuation results. For example, different social and health insurance systems will greatly influence the risk perception of the local population, subsequently resulting in a different WTP to avoid the risk. Therefore, it might be inappropriate to directly transfer the WTP values in developed countries into case studies concerning developing countries.

To deal with such a problem, the present analysis tries to employ the concept of DALYs in measuring the health impact of air pollution. DALYs are able to reduce all health effects - mortality and various morbidity endpoints - to one denominator. In this it is similar to the economic valuation procedures, but is independent of income. Expression of the health burden of air pollution in DALYs also has the advantage of direct comparison with the overall burden of disease in various countries and cities, as well as with diseases from other major environmental problems (e.g. water-related diseases). This is possible because of the significant amount of work by public health specialists on generating DALYs estimates for various countries. For example, the World Health Organization (WHO) and the World Bank have taken DALYs as a standard measure of the burden of disease in the Global Burden of Disease (GBD) study.

The limitations of our analyses should be noted. Our assessment only focused on the health impact of pollutants from outdoor air. However, indoor air pollution is also a serious threat to people's health, especially considering that people spend most of their time indoors. In addition, outdoor air pollutants can also be a problem indoors when windows are left open. In developing countries, a fairly large portion of the population is dependent on biomass for their energy requirements, which constitutes an important source of indoor air pollution. According to the WHO, indoor air pollution accounts for 4 percent of the global burden of disease. However, in Shanghai, the research site of the current analysis, indoor air pollution from biomass combustion might not be a serious problem due to the wide use of natural gas and liquefied petroleum gas (LPG) for cooking. In the future, we will try to employ DALY to measure the health impact of indoor air pollution in Shanghai, and compare the disease burden of air pollution from different sources.

Recently, burgeoning numbers of epidemiological studies in developed countries have looked closely at the health effects of outdoor air pollution at levels that were previously considered low, some even below established standards (such as the US EPA, NAAQS, and China National Air Quality Standards). In the calculation of the public health impact of ambient air pollution, it is crucial to decide what level of exposure can be considered as the threshold level or “reference exposure”. Threshold level means that below such a concentration, there is no observed adverse health damage. Normally, there are many different recommendations as to where to impose a threshold in air pollution-related health impact assessments, which include: no threshold (or zero threshold), natural background level, the lowest observed level in epidemiological studies and legal/policy established standards. The possible existence of an effect threshold is a very import scientific issue for an air pollution-related health impact assessment. However, currently there is no scientific basis for setting a particular threshold for the effects considered in this analysis.

In conclusion, our analysis emphasizes the need to consider air pollution-related health effects as a widespread cause of impaired health in Shanghai, and reveal the potentially high social cost stemming from the subsequent health problems. An improvement in air quality can lead to great health benefits for all of society. The approaches recommended in this analysis could be further applied to other regions of China for local and nation-wide air pollution-related health risk assessments. Further development of health impact assessment methods is needed, especially in terms of dealing with uncertainty, transference of exposure-response functions, and more common health indicators such as YOLL (years of life lost). These issues are best handled through close collaboration between air pollution modelers, epidemiologists, economists, and policy makers.

References

1. Kan, H., Chen, B., Chen, C., Fu, Q., Chen, M. (2004). An evaluation of public health impact of ambient air pollution under various energy scenarios in Shanghai, China. Atmos Environ, 38(1): 95-102.

2. Kan, H., Chen, B. (2004). Particulate air pollution in urban area of Shanghai, China: health-based economic assessment. Sci Total Environ, 322(1-3): 71-79.

3. WHO, World Health Organization (2004). WHO Guidelines for air quality, Fact sheet No. 187. http://www.who.int/inffs/en/fact187.html, 2004 Oct 14th cited.

4. Gielen, D., Chen, C. (2001). The CO2 emission reduction benefits of Chinese energy policies and environmental policies: A case study for Shanghai, period 1995–2020. Ecol Econ, 39: 257-270.

5. Kunzli, N., Kaiser, R., Medina, S., Studnicka, M., Chanel, O., Filliger, P., Herry, M., Horak, F. Jr, Puybonnieux-Texier, V., Quenel, P., Schneider, J., Seethaler, R., Vergnaud, J.C., Sommer, H. (2000). Public-health impact of outdoor and traffic-related air pollution: a European assessment. Lancet, 356: 795-801.

6. Lvovsky, K., Hughes, G., Maddison, D., Ostro, B. and Pearce, D. (2000). Environmental costs

of fossil fuels: a rapid assessment methods with application to six cities. The World Bank Environment Department Papers, NO. 78. Oct 2000, Washington DC, USA.

Chapter 10. Conclusions and Recommendations

1. After more than 10 years of developing and modernizing urban transportation in Shanghai, traffic indicators, such as the amount of road area per person or vehicle, have been greatly improved. However, the previous method of expanding roads for vehicle usage into non-mobile roads (including sidewalks) only temporarily improves traffic conditions; doing so actually lays the foundation for large-scale traffic congestion in the future. A sound transportation infrastructure includes not only ample road space for vehicles; it also requires non-mobile roads, sidewalks and parking lots. In particular, enough space should be left for non-mobile roads and sidewalks when constructing new roads to reduce interference between vehicles, non-mobile vehicles, and pedestrians.

2. Results from the driving pattern survey and vehicle technology investigation show that traffic conditions greatly vary by location and time of day. However, there is a certain consistency to these variations, particularly with respect to time of day. In all districts, traffic congestion peaks at approximately the same time. Rush hour mainly appears at 8:00-9:00 and 11:00-12:00 in the morning and 15:00-16:00 and 18:00-19:00 in the afternoon, which reflect the times in which people are starting and ending work.

3. Examination of driving patterns on 9 roads in three different types of regions--central Shanghai, a commercial area, and the outskirts of Shanghai--shows that driving cycles in these different regions differ significantly. Traffic conditions in the outskirts of Shanghai are the best while those in the central area are the worst. Differences in driving patterns on different types of roads are also quite obvious. The best driving conditions are found on highways, where the average speed is highest, the idle ratio is lowest, and traffic is the least congested. Second down the list are residential roads. The worst traffic conditions are found on arterial roads.

4. The driving patterns of different types of vehicles are also different. However, the acceleration of most vehicles varies between -0.5 and $0.5m/s^2$. The distribution of speed-acceleration on various roads is obviously different, which determines the emission characteristics of vehicles.

5. The average age of cars in Shanghai is 3.65 years, which is relatively young, particularly in comparison to the rest of China. On average, vehicles in Shanghai travel 49.2 km per day. More than 80 percent of the cars on the road in Shanghai are of a model year after 2000, meaning that most cars in Shanghai meet

Euro-I or Euro-II emissions standards. However, there is little emissions control on heavy-duty vehicles, such as trucks and buses. Therefore, more research should be done on emissions control strategies for heavy-duty vehicles.

6. Vehicle speed-acceleration distributions vary with vehicle types and the roads they are driven on. With respect to vehicle types, light-duty vehicles travel fastest, at an average speed of 23 km/h and a maximum speed of 77.2 km/h. In terms of road types, vehicles drive fastest when on highways, second fastest on arterial roads, and slowest on residential roads. The distributions of idle time, acceleration, and deceleration of various vehicle fleets on different roads reflect traffic conditions.

7. The response of vehicle fuel consumption and air/fuel ratio change to engine power creates different responses to increases in speed and acceleration, thereby influencing vehicles' emissions. The instantaneous concentrations of CO, THC, and NOx vary with vehicle speed according to certain measurable factors. Even when the rate of acceleration is the same, the emission rates of CO, THC, and NOx vary at different speeds. Results show that low speed and frequent acceleration have a negative effect on fuel economy and vehicle emissions. Therefore, strengthening traffic management can not only improve traffic capacity; it can also reduce vehicle emissions.

8. Vehicle emissions of the vehicles tested vary with road type, driving mode, and the size of the load being transported. Results show that empty trucks on integrated roads emit an average of 5.6 g of CO/km, 2.1 g of THC/km, and 6.5 g of NOx/km. When the trucks are fully loaded, they emit 22.5 g of CO/km, 2.4 g of THC/km, and 7.4 g of NOx/km. The average emission of CO by buses on their routine routes is 3.6 g/km; of THC, 2.1 g/km; and of NOx, 4.7 g/km. The average emission of CO by light-duty vehicles is 1.0 g/km; of THC, 0.6 g/km; and of NOx, 4.0 g/km. The above figures essentially represent the current traffic situation found on roads in Shanghai.

9. Yearly vehicle emissions of CO, VOC, NOx, PM and CO_2 amount to 42.1×10^4 tons, 6.4×10^4 tons, 6.6×10^4 tons, 0.17×10^4 tons, and 753×10^4 tons, respectively. It is worth noting that 20-30% of CO, VOC and PM emissions are released when starting up a vehicle. Emissions usually peak at 8:00-9:00, 15:00-16:00, and 17:00-18:00. These times correspond to the times when people are starting and finishing work and when the traffic flow on the road is at its most congested. The emissions during these periods account for 80-90% of the total emissions.

10. The distribution of emissions among vehicles is especially extreme. Mopeds and

heavy duty vehicles (trucks and buses) represent the greatest sources of emissions. They respectively account for only 14.9%, 8.3% and 10.1% of total VMT, but cause a shocking 51% of total CO emissions, 74% of total VOC emissions, 69% of total NOx emissions, and 92% of total PM emissions. They have become the main source of traffic pollution and cause enormous damage to the environment and human health. Light-duty vehicles, such as passenger cars, taxis and motorcycles, are all relatively new vehicles in Shanghai, and are thus usually equipped with advanced engine and emission control technology. As such, their contribution to air pollution is relatively low.

11. Heavy-duty vehicles are one of the major factors that influence air quality in Shanghai. Emissions of NOx and PM10 from heavy-duty vehicles account for 67% and 54%, respectively, of total vehicle emissions. Emissions of NOx and PM10 are by heavy-duty vehicles are 2-4 times those of light-duty diesel vehicles. At bus stops and intersections, emissions are particularly high due to the frequent stopping and starting up of vehicles, as well as high acceleration. This results in emissions levels that are more than 10 times those at normal speeds. This has a huge negative impact on the urban environment.

12. In addition to CO, THC, and NOx, diesel vehicle exhaust also contains PM10, which are fine pollutants harmful to human health. Due to limitations in the equipment and methodology available to us, we were unable to measure emission factors of PM10 from vehicles. Future studies should be able to take this factor into consideration.

13. If sustainable transportation in Shanghai is to be realized, mopeds, essentially “Moving Chimneys”, must be phased out and replaced by LPG or electric mopeds as soon as possible. More strict standards should be applied to heavy-duty vehicles to make them utilize more environmentally-friendly technology. High performance heavy-duty vehicles with low emissions and the ability to carry heavy loads should be developed.

14. Air pollution in Shanghai has recently changed and is now a complex mix of coal, smoke, and petroleum pollution. The situation is not optimistic. Absorbable particle matter and NOx are the main pollutants in the whole city at present. Due to increases in the number of vehicles from 1990 to 2003, average NOx concentration throughout the whole city has steadily increased. The NOx concentration in 2003 was 1.75 times the concentration in 1990. In recent years, with the implementation of vehicle emission control strategies, the trend of increasing NOx concentrations in the city center has been brought under control. However, surrounding counties are still facing dramatically increasing NOx

concentrations. These concentrations are subject to seasonal variation. The highest concentrations of NOx are found in the winter while the lowest concentrations are found in the summer. The annual distribution of NOx concentrations in different districts can be expressed as: urban > suburb > country. The pollution situations on 18 busy roads are mostly severe with 13 sites exceeding national standards by more than 70%. The maximum hourly average concentration is 0.469 mg/m^3 for East Yan'an Rd. Site. The hourly average PM_{10} concentration for most sites is relatively steady, varying between 0.075 mg/m^3 and 0.326 mg/m^3. The hourly CO concentration and hourly average values for all sites do not exceed the national standard except in the case of East Yan'an Rd where the hourly value is 8% over. PM_{10} reaches its peak in spring due to frequent dust storms in North China while it is at its lowest in autumn.

15. During the "Eleventh Five-Year" period, the rate of growth in the number of vehicles exceeded the rate of economic growth, resulting in a remarkable rise in pollution. The implementation of Euro-III emissions standards partly reduces the damage caused by this dramatic increase, but it is still not enough to stem the increasing pollution problem. To improve air quality of Shanghai, we suggest that the Shanghai government implement Euro-IV emission standards in advance, allowing vehicle emissions to be brought firmly under control.

16. Considering the mobility of vehicles and lack of management of those coming into Shanghai from other provinces, the government of Shanghai should cooperate with transportation and environmental protection agencies in Jiangsu and Zhejiang provinces to implement a region-wide vehicle emission control strategy so as to improve air quality all around the Yangzi River.