ENERGY TECHNOLOGY INNOVATION POLICY

A joint project of the Science, Technology and Public Policy Program and the Environment and Natural Resources Program
Belfer Center for Science and International Affairs

HARVARD Kennedy School
JOHN F. KENNEDY SCHOOL OF GOVERNMENT

In-use Vehicle Emissions in China: Beijing Study

HONGYAN H. OLIVER
KELLY SIMS GALLAGHER
MENGLIANG LI
KONGJIAN QIN
JIANWEI ZHANG
HUAN LIU
KEBIN HE

Discussion Paper 2009-05
March 2009

energytechnologypolicy.org

In-use Vehicle Emissions in China: Beijing Study

Hongyan H. Oliver[*] Kelly Sims Gallagher[*]

Mengliang Li[†] Kongjian Qin[†] Jianwei Zhang[†]

Huan Liu[‡] Kebin He[‡]

Discussion Paper 2009-05

May 2009

[*] Energy Technology Innovation Policy (ETIP) research group, Harvard Kennedy School
[†]China Automotive Research and Technology Center
[‡] Department of Environmental Engineering and Science, Tsinghua University

Citation

This paper may be cited as: Oliver, Hongyan H., Kelly Sims Gallagher, Mengliang Li, Kongjian Qin, Jianwei Zhang, Huan Liu and Kebin He, "In-use Vehicle Emissions in China: Beijing Study" Discussion paper 2009-05, Cambridge, Mass.: Belfer Center for Science and International Affairs, May 2009.

For questions or comments regarding the content of this report, please email Hongyan H. Oliver at hongyan_oliver@harvard.edu or hongyan.oliver@gmail.com.

The views expressed within this paper are the authors' and do not necessarily reflect those of the organizations they are affiliated with. This paper is available at www.belfercenter.org/energy.

Acknowledgement

The Beijing Study would not be possible without the support from and collaboration of many institutes and organizations. First, we would like to thank GM China, the William and Flora Hewlett Foundation, and the Energy Foundation for their generous financial support. We would also like to acknowledge the support and cooperation from the Ministry of Environmental Protection China, National Vehicle Emissions Testing Center of China, Beijing Environmental Protection Bureau, and the Beijing Internal Combustion Engine Group.

We appreciate the International Sustainable Systems Research Center for sharing their computer programs for data analysis, their devices for recording vehicle start patterns, and their testing results of heavy-duty diesel vehicle emissions in Beijing.

Finally, we would like to thank the students from the Department of Environmental Science and Engineering at Tsinghua University and the Department of Environmental Engineering at Beijing Technology and Business University who participated in vehicle activity data collection as well as the students from the Automotive Department of Wuhan University of Technology who were involved in our emissions testing on light-duty passenger vehicles in Beijing.

Energy Technology Innovation Policy (ETIP)

The overarching objective of the Energy Technology and Innovation Policy (ETIP) research group is to determine and then seek to promote adoption of effective strategies for developing and deploying cleaner and more efficient energy technologies, primarily in three of the biggest energy-consuming nations in the world: the United States, China and India. These three countries have enormous influence on local, regional, and global environmental conditions through their energy production and consumption.

ETIP researchers seek to identify and promote strategies that these countries can pursue, separately and collaboratively, for accelerating the development and deployment of advanced energy options that can reduce conventional air pollution, minimize future greenhouse-gas emissions, reduce dependence on oil, facilitate poverty alleviation, and promote economic development. ETIP's focus on three crucial countries rather than only one not only multiplies directly our leverage on the world scale and facilitates the pursuit of cooperative efforts, but also allows for the development of new insights from comparisons and contrasts among conditions and strategies in the three cases.

In-use Vehicle Emissions in China — Beijing Study

Hongyan H. Oliver[1], Kelly Sims Gallagher

Energy Technology Innovation Policy (ETIP) research group
Harvard Kennedy School

Mengliang Li, Kongjian Qin, Jianwei Zhang

China Automotive Research and Technology Center

Huan Liu, Kebin He

Department of Environmental Engineering and Science
Tsinghua University

[1] For questions or comments regarding the content of this report, please email Hongyan H. Oliver at hongyan_oliver@harvard.edu or hongyan.oliver@gmail.com.

Acknowledgements

The Beijing Study would not be possible without the support from and collaboration of many institutes and organizations. First, we would like to thank GM China, the William and Flora Hewlett Foundation, and the Energy Foundation for their generous financial support.

We would also like to acknowledge the support and cooperation from the Ministry of Environmental Protection China, National Vehicle Emissions Testing Center of China, Beijing Environmental Protection Bureau, and the Beijing Internal Combustion Engine Group.

We appreciate the International Sustainable Systems Research Center for sharing their computer programs for data analysis, their devices for recording vehicle start patterns, and their testing results of heavy-duty diesel vehicle emissions in Beijing.

Finally, we would like to thank the students from the Department of Environmental Science and Engineering at Tsinghua University and the Department of Environmental Engineering at Beijing Technology and Business University who participated in vehicle activity data collection as well as the students from the Automotive Department of Wuhan University of Technology who were involved in our emissions testing on light-duty passenger vehicles in Beijing.

Project Teams

Energy Technology Innovation Policy research group
John F. Kennedy School of Government, Harvard University
Hongyan He Oliver
Kelly Sims Gallagher

China Automotive Research and Technology Center
Jianwei Zhang (CATARC team leader)
Jidong Gao
Mengliang Li
Kongjian Qin

Department of Environmental Science and Engineering, Tsinghua University
Kebin He (Tsinghua team leader)
Huan Liu
Qidong Wang
Zhiliang Yao
Mingliang Fu (Beijing Technology and Business University)
Lei Shi (Beijing Technology and Business University)

Executive Summary

China's economic boom in the last three decades has spurred increasing demand for transportation services and personal mobility. Consequently, vehicle population has grown rapidly since the early 1990s, especially in megacities such as Beijing, Guangzhou, and Tianjin. As a result, mobile sources have become a more and more conspicuous contributor to urban air pollution in Chinese cities. In spring 2005, the Energy Technology Innovation Policy research group (ETIP) at Harvard Kennedy School initiated a multiyear research effort to investigate in-use vehicle emissions in selected Chinese cities, joined by the China Automotive Research and Technology Center (CATARC), Tsinghua University, and the International Sustainable Systems Research Center (affiliated with University of California, Riverside). Tianjin was our first focus city, and the study there took us about two years to complete.[2] Built upon the experience and partnership generated through the Tianjin study, the research team carried out the Beijing study from fall 2007–fall 2008.

Beijing was chosen to be our second focus city for several reasons: it has the largest local fleet and the highest vehicle popularity among all Chinese cities, and it has suffered from severe air pollution partially due to the ever-growing population of on-road vehicles. According to the Beijing Environmental Protection Bureau (EPB), mobiles sources contribute about two-thirds, one-half, and one-fourth of nitrogen oxides (NOx), total hydrocarbon (THC), and fine particulate matter (PM) emissions, respectively; the municipal government has taken a wide variety of aggressive measures to control mobile emissions since the early 2000s, such as adopting more stringent emission standards for new vehicles at a faster pace than China as whole, requiring clean mobile fuels, retrofitting and/or scrapping old, high emitting vehicles, and instituting a relatively rigorous inspection & maintenance (I/M) program for in-use vehicles. Beijing offered a nice contrasting case to Tianjin,[3] where mobile emissions had not been a high priority issue to the city at the time of our study. Furthermore, we believe that with Beijing's high political salience, the lessons and insights that we have learned from Beijing are very likely to be heeded by other Chinese cities as well.

The overall research methodology that we used in Beijing is similar to that we had used in Tianjin. However, due to resource limitation, we decided to concentrate on collecting the two most critical parts of original data: vehicle activity and on-road emissions. Three of the four original research partners were engaged in the Beijing study, and the division of labor was consistent the different strengths and experience of the three parties. ETIP was responsible for fundraising, overall planning and coordination, overseeing project implementation, preparing emissions data for the International Vehicle Emission (IVE) model, integrating the emission testing and Vehicle Activity (VA) study, and overall report writing. The CATARC team was responsible for all activities

[2] The Tianjin study report can be downloaded from: http://belfercenter.ksg.harvard.edu/publication/18645/.
[3] There will be a subsequent paper to compare the key findings from Beijing and Tianjin studies.

associated with on-road emissions testing, including planning for field work, securing testing apparatus and sample vehicles, and carrying out each test according to a predetermined protocol. Since CATARC has an ongoing working relationship with Beijing EPB, it also assumed the major responsibility of outreach to the bureau. The Tsinghua team was in charge of all activities comprising the VA activity study, including planning for field work, securing necessary devices and vehicles, recruiting local assistants, screening and reformatting data, and data analysis.

We convened a planning meeting and an outreach meeting for the Beijing study in September 2007. On-road emissions tests for fifty-eight light-duty passenger vehicles were carried out in late November and early December 2007. Vehicle activity data were collected in late March and early April 2008. In July 2008, we briefed the Chinese national and Beijing environmental authority on our preliminary findings.

Our study in Beijing rendered the direct key findings on mobile emissions:

Total Mobile Emissions We have estimated that, in early 2008, the total daily mobile emissions from the Beijing fleet were:

- Carbon monoxide (CO): about 1,270 tons (emission factor is 7.6 g/km);
- Volatile organic compounds (VOC): about 180 tons (emission factor is 1.1 g/km);
- NOx: about 270 tons (emission factor is 1.5 g/km);
- PM: about 4.5 tons (emission factor is 0.03 g/km).

Under mild weather conditions, start emissions accounted for 22 percent, 14 percent, and 11 percent of total daily mobile VOC, CO, and PM emissions, but they only accounted for 6 percent of total mobile NOx emissions in Beijing.

Contributions of Vehicle Sub-fleets Passenger vehicles contributed about 73 percent of the total vehicle mileage travelled (VMT) and similar shares (65 percent and 72 percent) of the total mobile CO and VOC emissions. They contributed 41 percent and 23 percent of the total mobile NOx and PM emissions. The taxi fleet contributed 14 percent of VMT, but its contributions to the total mobile CO, VOC, NOx, and PM emissions were much less (5 percent, 4 percent, 10 percent, and 3 percent, respectively). The truck fleet accounted for only 11 percent of VMT, but it accounted for 39 percent and 49 percent of total NOx and PM emissions. The bus fleet contributed 2.2 percent of total distance travelled; however, it accounted for 26 percent and 11 percent of PM and NOx emissions, respectively, as well as 8 percent of CO emissions.

Emissions Trends of Light-duty Passenger Vehicles (LDPV)

- LDPVs are becoming cleaner over time, corresponding to the tightening trend of emission standards for new vehicles.
- The actual average emissions of vehicles (grouped by certified emission standards) are much higher than their certified limits; this observation even stands for low-mileage vehicles.

- For all vehicle emission groups, the effectiveness of emission control devices decreased considerably over time.

Our analysis of on-road emissions data and our results of model runs under various scenarios have lead to the following policy insights:

- Steadily and continuously tightening emission standards for new vehicles have been proven to be a very effective policy in lowering average vehicle emissions over time.
- An effectual I/M program is essential to curbing the overall deterioration of the emission-control-system performance of high-mileage vehicles.
- China needs to enhance the overall effectiveness of emission standards for new vehicles.
- Accelerating the turnover rate of high-use public fleets (taxis and buses) is an effective way to control mobile emissions.
- Carbureted vehicles are gross emitters and replacing them with clean ones will generate considerable emission reduction benefits.
- The immediate effects of clean fuels on mobile emissions are substantial.
- A complete policy package including key components such as limiting the total number of on-road private cars and boosting public transport services seems to be able to achieve the most drastic effects in reducing total mobile emissions.

Our study shows that the fleet size and total VMT in Beijing are 4.4 times those of Tianjin, but total mobile CO, THC, NOx, and PM emissions in Beijing are only 2.1, 2.2, 1.4, and 0.7 times those of Tianjin. It is evident that all vehicle subgroups are much cleaner in Beijing than in Tianjin. We strongly believe that Beijing's aggressive mobile emission control policies have worked well to reduce the average and total emissions of on-road vehicles in its jurisdiction. Nevertheless, there is still much left to be improved upon in Beijing, especially the effectiveness of its I/M program in identifying and repairing gross emitters among the high-mileage vehicles and substitution of rapidly growing private travel with efficient and convenient public transportation. The ongoing initiatives taken by Beijing (e.g., expanding public transit systems, providing subsides for bus and subway riders, and increasing parking fees in the urban center) indicate that the city is moving in a more desirable direction. We hope that other cities will imitate Beijing's successful actions in curbing vehicle emissions while at the same time not letting the vehicle population grow unchecked, since the effects of making every single vehicle cleaner can easily be negated by the total amount of emissions from a large, ever-growing vehicle fleet, not to mention the congestion effects and time lost in traffic jams.

Contents

Acknowledgements i
Project Teams ii
Executive Summary iii
Contents vi
Acronyms and Abbreviations viii
List of Figures x
List of Tables xii

1. Background **1**
1.1 Vehicles and Air Quality in Beijing 1
1.2 Overall Methodology 6
1.3 Research Partnership 13
1.4 Schedule 14

2. Measuring Emissions with Portable Emission Measurement Systems **15**
2.1 Instrument, Driving Route, and Tested Vehicles 15
2.2 Real-time and Normalized Emissions 19
2.3 Emission Trends over Time 22
2.4 Base Emission Correction Factors 27

3. Vehicle Activity Study **32**
3.1 Methodology, Focus Areas, and Data Collection 32
3.2 Vehicle Distribution 36
3.3 Driving and Start Patterns 43

4. Estimating Mobile Emissions with IVE Model **50**
4.1 Emissions with Base Emission Correction Factors 50
4.2 Comparing Emissions w/ and w/o Correction Factors 55
4.3 Emissions by Major IVE Vehicle Classes 57
4.4 Emissions under Various Scenarios 63

5. Conclusions **76**
5.1 Summary of Major Results 76
5.2 Discussion on Policy Implications 79

Appendices **82**
A Limits of Chinese Ambient Air Quality Standards 82
B Four Interfaces of IVE Model 83
C Comparing FTP Cycle with Actual Driving Cycles during On-Road 87

Emission Testing in Beijing
D IVE Vehicle Technology Classification 90

References 91

Acronyms and Abbreviations

ASM	Acceleration Simulation Mode
BECF	Base Emission Correction Factor
BEF	Base Emission Factor
BICEG	Beijing Internal Combustion Engine Group
BJEPB	Beijing Environmental Protection Bureau
BJPTHC	Beijing Public Transportation Holding Company
BJQTSB	Beijing Quality and Technology Supervision Bureau
CATARC	China Automotive Technology and Research Center
CC	Catalytic Converter
CCTWC	Close-Coupled Three-Way Catalytic Converter
CE-CERT	College of Engineering Center for Environmental Research and Technology (University of California, Riverside)
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CVS	Continuous Volume Sampler
EEA	European Environmental Agency
EGR	Exhaust Gas Recirculation
EPB	Environmental Protection Bureau
ETIP	Energy Technology Innovation Policy research group
FTP	Federal Test Procedure
GPS	Global Positioning System
GVWR	Gross Vehicle Weight Rating
HC	Hydrocarbon
HDV	Heavy-duty Vehicles
I/M	Inspection & Maintenance
ISSRC	International Sustainable Systems Research Center
IVE	International Vehicle Emission model
LDPV	Light-duty Passenger Vehicles
LDP	Light-duty vehicles
LPG	Liquefied Petroleum Gas
MOE	Ministry of Environmental Protection (of China)
MPFI	Multi-Point Fuel Injection
MPV	Multi-Purpose Vehicles
NO_2	Nitric Dioxide
NOx	Nitrogen Oxides
OBS	On-Board System
PC	Passenger Cars
PCArt	Passenger Cars Driven on Arterial Roads
PCHwy	Passenger Cars Driven on Highways
PCRes	Passenger Cars Driven on Residential Roads
PEMS	Portable Emission Measurement System
PM	Particulate Matter
PPM	Parts Per Million

RPM	Revolutions per Minute
RSD	Remote Sensing Device
SEPA	State Environmental Protection Administration (of China)
SO_2	Sulfur Dioxide
SOx	Sulfur Oxides
SULEV	Super Ultra Low Emission Vehicle
THC	Total Hydrocarbons
TSP	Total Suspended Particles
TWC	Three-Way Catalytic Converter
USEPA	United States Environmental Protection Agency
UTC	Universal Time Coordinated
VA	Vehicle Activity
VMT or VKT	Vehicle Miles/Kilometers Travelled
VOC	Volatile Organic Compounds
VOCE	Vehicle Occupancy Count Enumerator
VSP	Vehicle Specific Power

List of Figures

Figure 1-1	Vehicle Population Growth in China and Beijing	1
Figure 1-2	Average Annual Concentrations of Major Air Pollutants in Beijing	3
Figure 1-3	Emission Standards for Light-duty Vehicles ($HC+NO_x$)	4
Figure 1-4	Structure of International Vehicle Emissions Model	8
Figure 1-5-a	Emission vs. Power Bin for Closed-loop, Catalyst-equipped Gasoline Vehicles	12
Figure 1-5-b	Emission vs. Power Bin for Carbureted, No-catalyst Gasoline Vehicles	12
Figure 1-5-c	Emission vs. Power Bin for Diesel Vehicles	12
Figure 1-6	Combining Driving Pattern Distribution with Emission-VSP Curve	13
Figure 2-1	Illustration of OBS-2200 System	16
Figure 2-2	Driving Route for On-road Emissions Testing in Beijing	17
Figure 2-3-a	Comparing Real-time and FTP Cycle CO Emissions	20
Figure 2-3-b	Comparing Real-time and FTP Cycle NO_2 Emissions	20
Figure 2-3-c	Comparing Real-time and FTP Cycle THC Emissions	21
Figure 2-3-d	Comparing Real-time and FTP Cycle CO_2 Emissions	21
Figure 2-4-a	Actual CO Emissions and Certified Limits of Tested Vehicles	24
Figure 2-4-b	Actual $THC+NO_2$ Emissions and Certified Limits of Tested Vehicles	25
Figure 2-5	Average Emissions by Certified Standard and Mileage	26
Figure 3-1	Three VA Focus Areas in Beijing	33
Figure 3-2	Driving Routes and Video-recording Sites in Three Focus Areas	33
Figure 3-3	Bus Routes Included in Beijing VA Study	34
Figure 3-4	Number of New Passenger Vehicles in Beijing	39
Figure 3-5	Mileage Accumulation by Passenger Vehicles over Time	40
Figure 3-6	Distance Travelled by Different Sub-fleets throughout a Day	44
Figure 3-7	Average Speed of Sub-fleets in Beijing	45
Figure 3-8-a	Power Bin Distribution on PC Highways	46
Figure 3-8-b	Power Bin Distribution on PC Arterial Roads	46
Figure 3-8-c	Power Bin Distribution on PC Residential Roads	47
Figure 3-8-d	Power Bin Distribution of Beijing Taxi	47
Figure 3-9	Illustration of Start Pattern Based on Engine Soak Time	48
Figure 3-10	Overall Start Pattern of Beijing Vehicle Fleet	49
Figure 4-1-a	Beijing Total Mobile CO Emissions throughout a Day	51
Figure 4-1-b	Beijing Total Mobile VOC Emissions throughout a Day	52
Figure 4-1-c	Beijing Total Mobile NO_x Emissions throughout a Day	52
Figure 4-1-d	Beijing Total Mobile PM Emissions throughout a Day	53
Figure 4-2	Contributions to Emissions and Travel by Sub-fleet	54
Figure 4-3-a	Changes of Emission Estimations after Applying BECF	55
Figure 4-3-b	Percentage Changes of Emissions after Applying BEFC	56

Figure 4-4-a	Emission Contributions by Major IVE Passenger Vehicle Classes	62
Figure 4-4-b	Emission Contributions by Major IVE Truck and Bus Classes	62
Figure 4-5-a	Hourly Temperature Variation in Different Seasons	64
Figure 4-5-b	Hourly Humidity Variation in Different Seasons	64
Figure 4-6-a	Daily Mobile Emissions in Different Seasons	65
Figure 4-6-b	Differences of Sub-fleet Daily Emissions in Summer and Spring	65
Figure 4-6-c	Daily Running and Start Emissions in Different Seasons	66
Figure 4-7-a	Emission Reductions under Clean-Fuel Scenario	67
Figure 4-7-b	Start and Running Emissions under Different Fuel Scenarios	67
Figure 4-8-a	Emission Reductions under Clean Fuels & I/M Scenario	71
Figure 4-8-b	Start and Running Emissions with/without I/M Program	71
Figure 4-9	Emission Reductions Resulting from Improved Daytime Traffic on Arterial and Residential Roads	72
Figure 4-10-a	Emission Reductions under Traffic Control Scenario	74
Figure 4-10-b	Actual Start and Running Emissions vs. Projected Emissions under Traffic Control Scenario	74

List of Tables

Table 1-1	VSP Bins and Stress Modes	11
Table 1-2	Schedule of Beijing In-use Vehicle Emissions Study	14
Table 2-1	Technology Distribution of Tested Vehicles	18
Table 2-2	IVE Classification of 53 Tested Vehicles	19
Table 2-3	Emissions of Vehicle Groups by Certified Standards	23
Table 2-4	90% Confidence Intervals for Average Values of Tested Vehicle Groups	23
Table 2-5	90% Confidence Intervals of the Average Values of 9 Vehicle Subgroups	27
Table 2-6	Running Emissions based on Emission Testing (g/km)	29
Table 2-7	Running Emissions Projected by IVE Model (g/km)	29
Table 2-8	Correction Factors for Running Emissions	30
Table 2-9	Running Emissions Comparison and Correction Factors	30
Table 2-10	Potential Base Emission Adjustment Values for Heavy-duty Diesel Vehicles in Beijing	31
Table 3-1	Vehicle Activity Data Collection in Beijing	35
Table 3-2	Observed On-road Fleet Composition in Beijing	37
Table 3-3-a	General Characteristics of Surveyed Passenger Vehicles in Beijing	38
Table 3-3-b	Size and Usage of Surveyed Passenger Vehicles in Beijing	38
Table 3-3-c	IVE Technology Fractions of Passenger Vehicles in Beijing	39
Table 3-4	Engine Size and Usage of Surveyed Taxis in Beijing	41
Table 3-5-a	Weight and Usage of Surveyed Trucks in Beijing	41
Table 3-5-b	Technologies and Emission Standards of Trucks in Beijing	42
Table 3-6-a	Weight and Usage of Buses in Beijing	42
Table 3-6-b	Fuel Type and Emission Standards of Buses in Beijing	42
Table 3-7	Fleet Composition, Vehicle Use, and Start in Beijing	43
Table 4-1	Emissions and Emission Factors of Beijing Sub-fleets	54
Table 4-2	Emission Contributions by 92 IVE Vehicle Technology Classes in Beijing	58
Table 4-3	Key Property Requirements for Mobile Gasoline	67
Table 4-4	Emission Reductions under Clean Fuel Scenario	69
Table 4-5	Emission Reduction under Clean Fuel, I/M Scenario	71

1. Background [4]

1.1 Vehicles and Air Quality in Beijing

Beijing, the capital of China, is not only the national political center, but it is also an important national economic and cultural center. With only 1.2 percent of China's population, Beijing produces about 3.7 percent of China's national Gross Domestic Product (GDP) (National Bureau of Statistics of China 2007). The disposal income of its urban residents is 1.7 times the national level, ranking number 2 among all thirty-one province-level entities and following Shanghai[5]. Just like what has happened in more advanced economies, growing wealth has led to increasing demand for mobility and comfort in China as well. As shown in Figure 1-1, vehicle population has grown very rapidly both nationwide and in Beijing since the early 1990s; the speed of growth was particularly fast in Beijing. Since Beijing has no policies restraining automobile ownership (in contrast to Shanghai's policy on a limited annual quota for new vehicle licenses), the penetration of automobile ownership in Beijing was highest among all the Chinese cities (18.1 per hundred households in 2006).[6] As of February 2009, there were about 3.6 million motor vehicles officially registered in Beijing.

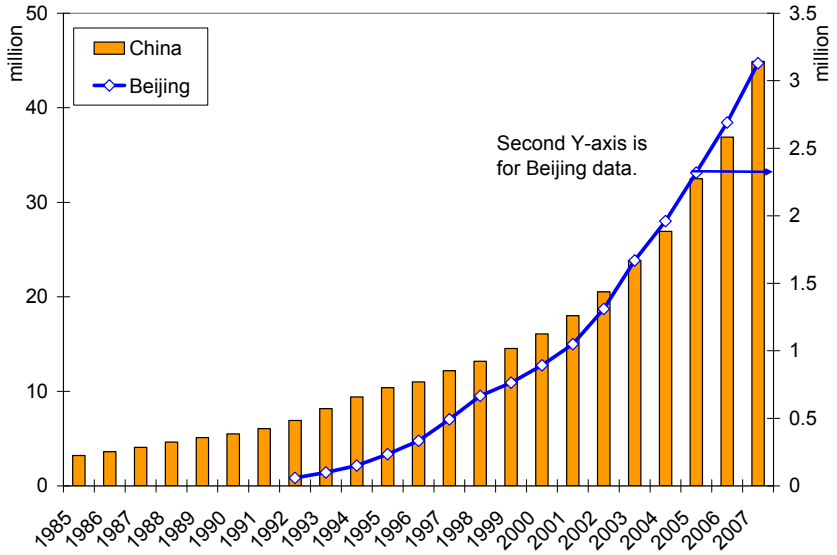

Figure 1-1 Vehicle Population Growth in China and Beijing

[4] Please refer to the first chapter of the report on Tianjin study for a comprehensive review of the overall rationale and goals of the in-use vehicle emissions project in China.

[5] There are thirty-one province-level administrative entities in China: twenty-seven provinces plus four metropolitan areas (Beijing, Chongqing, Tianjin, and Shanghai).

[6] In contrast, the popularity of automobile ownership was only 4.1 per one hundred households in Shanghai in 2006.

One of the common complications of a rapidly growing vehicle population is urban air pollution. Beijing was considered to be among the most polluted cities in China even at the beginning of its vehicle boom because of its reliance on burning coal and polluting industries. Its dependence on coal for spacing heating in the winter further exacerbated the situation. For instance, during the winter seasons in the late 1990s, the average daily Total Suspended Particles (TSP), sulfur dioxide (SO_2), nitrogen oxides (NOx), and carbon monoxide (CO) concentrations in Beijing were as high as 0.431, 0.252, 0.201, and 4.4 mg/m^3, all significantly higher than the Chinese National Ambient Air Quality Standards (National Environmental Protection Agency of China 1996)(please refer to Appendix A for the limits of Chinese standards). Emissions from vehicles (most of them had no pollution control technologies at that time) led to particularly high NOx and CO concentrations in the central districts of the city (Beijing Environmental Protection Bureau 1998–2007).

Since the mid 1990s, Beijing has taken various measures to reduce air pollution. However, pollution control only became one of the top priorities of the municipal government in late 1998, when the government promulgated its first order on "Urgent Measures to Control Air Pollution in Beijing" (Beijing Municipal Government 1998). Beijing's aspiration to win the 2008 Olympic Games bid and later its promise to host a "green" Olympic Games further strengthened its resolution to reduce air pollution. During the last ten years, Beijing has issued fifteen orders to control air pollution. Each of these orders included a very detailed near-term emissions control plan, targeted entities, deadlines for actions, and supervising government agencies (Beijing Municipal Government 1998). The anti-pollution measures fell into four general categories: replacing dirty coal with natural gas and low-sulfur coal; compelling polluting industries to relocate or install emission-removing devices; controlling fugitive dust from construction sites and roads; and controlling mobile emissions. These measures have produced very impressive results. As shown in Figure 1-2, average annual concentrations of all major air pollutants have dropped considerably in the past decade: SO_2, by 61 percent; CO, 39 percent; PM_{10}[7], 21 percent; and NOx, 11 percent. With the exception of PM_{10}, the average annual concentrations of the three other pollutants have all been in compliance with the Chinese National Ambient Air Quality Standards (level II) in recent years.[8]

[7] They are particulate matter with aerodynamic diameters of less than 10 micrometers.

[8] The Chinese authority believes that the Chinese national standards (level II) are sufficient to protect human beings from negative health impacts. However, the levels recommended by the World Health Organization (World Health Organization 2006) are much more stringent: 0.02 mg/m3 for annual PM_{10} concentration and 0.04 mg/m^3 for annual NO_2 concentration.

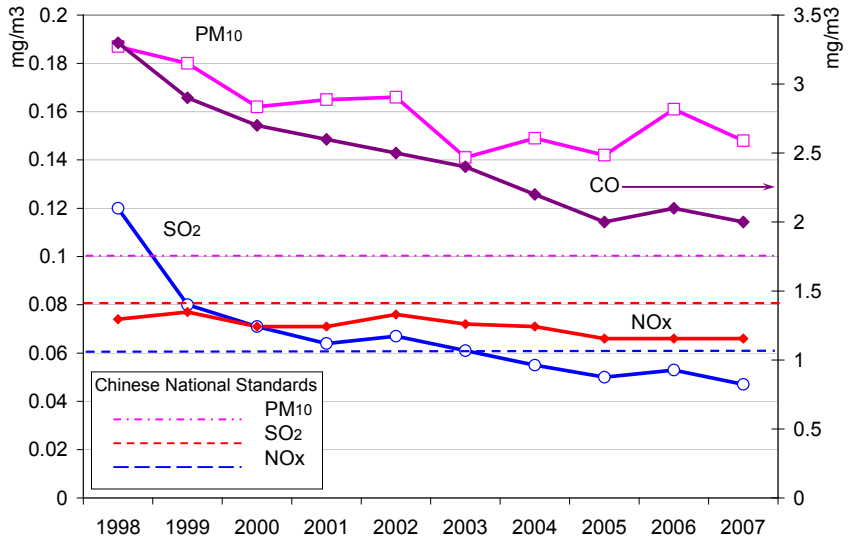

Figure 1-2 Average Annual Concentrations of Major Air Pollutants in Beijing

Despite the overall historical trend of air quality improvement, a second look at the chart shows that the ambient concentrations of PM_{10}, NOx, and CO in Beijing have not changed much since the mid-2000s. Furthermore, $PM_{2.5}$, the group of very fine particles with aerodynamic diameters of less than 2.5 micrometers (they can be inhaled deeply into lungs, and some can even enter blood stream; they aggravate heart and lung diseases) and ground-level ozone are not officially measured and reported in Beijing.[9] Publications by atmospheric scientists on this subject indicate that the annual concentration of $PM_{2.5}$ in Beijing ranges from 0.1 mg/m^3 to 0.15 mg/m^3 (He *et al.* 2001, Duan *et al.* 2006, Dan *et al.* 2004, Wang *et al.* 2005), ten to fifteen times the level recommended in the most recent guideline of the World Health Organization (World Health Organization 2006). The hourly ozone concentrations in Beijing during the summer season also frequently violate China's own standards (Wang *et al.* 2008b). Air pollution problems in Beijing have become more complex and difficult to resolve. The major challenge for the city has been to reduce total mobile emissions while still allowing vehicle population to continue to grow rapidly.

Beijing's efforts to control mobile emissions have accelerated since the late 1990s. Such efforts include the following: implementing increasingly stringent emissions standards for new vehicles; improving mobile fuel quality; enhancing its I/M programs; and, retrofitting, scraping, and replacing old polluting vehicles, especially high-use public vehicles such as buses and taxis.

Beijing adopted the Chinese National Emissions Standards for Light-duty Vehicles (Phase I) in 1999, one year ahead of the national implementation schedule. Since then, the city has always been about two years ahead of the whole nation in actuating newer phases of emissions standards for new vehicles (see Figure 1-3),

[9] China does not have standards for $PM_{2.5}$. It has standards for ground-level ozone, but most cities do not have the capacity to monitor ground-level ozone systematically.

including the standards for heavy-duty vehicles. The stringency of current standards in Beijing (which took effect in March 2008) is equivalent to that of Euro IV standards, while these standards will not enter into force nationwide until the end of 2009.

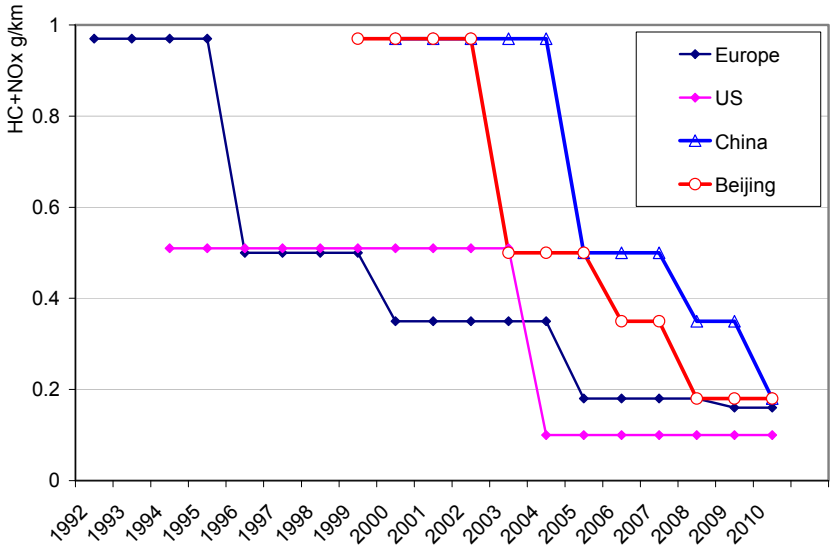

Figure 1-3 Emission Standards for Light-duty Vehicles (HC+NOx)

Note: There are only combined limits for hydrocarbons and NOx in Euro I and II emission standards. It is also worth noting that U.S. has the most stringent emission standards in the world.

Advanced emissions control technologies require clean and high quality fuels to maintain their performance over time.[10] Driven by the high political salience to provide clean air for the 2008 Olympic Games and with strong support from the central government, Beijing was able to negotiate with a couple of oil refineries located in its vicinity to overhaul their refining facilities so that these refineries could provide cleaner fuel. Beijing had made mobile fuel suppliers reduce the sulfur content[11] of their gasoline below 500 ppm by October 1, 2004, below 150 ppm by July 1, 2005, and below 50 ppm by January 1, 2008 (for emission control technologies that would satisfy the Chinese Phase II, III, and IV emissions standards). The limit for sulfur content in diesel fuel in Beijing has also been strengthened significantly: it was 500 ppm by October 1, 2004, 350 ppm by July 1, 2005, and 50 ppm by January 1, 2008. In contrast, nationwide, refineries do not have to provide gasoline with sulfur content less than 150 ppm until 2010.[12]

[10] Lead has immediate "poisoning" effects on the catalysts (i.e., precious metals such as platinum and rhodium) in the three-way catalytic converters, so it must be eliminated from gasoline for catalytic converters to work. China phased out leaded gasoline in the late 1990s.

[11] Sulfur in mobile fuels is a big concern because it also "poisons" catalysts, but at a slower pace than lead.

[12] At the national level, the promulgation of fuel quality standards has not been able to keep pace with the issuance of more stringent emissions standards. Despite that the Chinese Phase III emissions standards for new light-duty gasoline vehicles took effect in July 2007, the refineries had insisted that they could not provide gasoline with sulfur level less than 150 ppm until the end of 2009.

Beijing first started its I/M program for in-use vehicles with two-speed idle tests in the mid-1990s, but then later switched to the method of Acceleration Simulation Mode (ASM) in 2003 because the latter method is closer to real-world driving conditions and can capture NOx emissions as well as CO and HC emissions. As of 2008, over 200 ASM devices had been installed at about forty vehicle inspection stations. Vehicles are required to pass the ASM emission test to have their registrations renewed each year. One average, about 7.3 percent of all vehicles failed to pass the smog check on their first attempt. However, some vehicle models have significantly high (greater than 40 percent) failure rates (Chang 2006).

Beijing launched a large-scale retrofit program during 1998–2000, which required 190,000 carbureted light-duty vehicles registered after January 1, 1995, to each be installed with an electrical air supplement system and a three-way catalytic converter (TWC). The emission reduction effects of the retrofit were obvious at the beginning, but most of the systems failed to perform after two or three years. In the early 2000s, about 22,000 taxis were retrofitted to run on both Liquefied Petroleum Gases (LPG) and gasoline. The effort was also proven to be ineffective since the retrofitted taxis ended up running on gasoline only because LPG delivered less power and did not render better environmental performance (Hao, Hu & Fu 2006; Zhou, Fu, & Cheng 2007). Recently, the city has focused on old diesel vehicles for retrofitting.

Earlier studies on mobile emission inventories in China have used the following four models: the MOBILE5 model developed by the United States Environmental Protection Agency (USEPA) (Hao, Hu, & Fu 2006; Hao *et al.* 2000), the COPERTIII model developed by the European Environmental Agency (EEA) (Cai, Xie 2007; Xie, Song 2006), the CMEM and the International Vehicle Emissions (IVE) models developed by the College of Engineering Center for Environmental Research and Technology (CERT) at University of California, Riverside (He, Wang 2006; Liu *et al.* 2007; *Wang et al*. 2008a). Each of these models has its own advantages and disadvantages when applied in the Chinese context because of the different model assumptions, data demand, and local adaptability.

Generally speaking, an accurate estimation of mobile emissions of an interest area requires two sets of data: local fleet composition and traffic information and vehicle emission factors. Direct application of a sophisticated mobile emission model originally developed in an industrial country in the developing world often leads to considerable errors because many of the default data values such as traffic conditions and emission factors are often very different for different regions. Localizing such models requires a significant amount of original data and technical expertise, which are often lacking at most environmental entities in China.

In contrast, the IVE model was developed with the special circumstances of developing countries (lack of basic data) in the model developers' mind. For a coarse estimation of total mobile emissions, a user only needs to collect and put in basic local fleet and traffic information through a vehicle activity (VA) study. For a more accurate

estimation, a user can make corrections to the default emission factors in the model based on the results of local emissions testing. Thus, we chose to use the IVE model to generate the Beijing mobile emission inventory in 2008. A similar study was carried out in Beijing in 2004, which was summarized in the paper by Liu *et al.* (2007). However, given the rapid development of Beijing's vehicle population and its traffic network, we strongly believed that it was essential to collect up-to-date fleet and traffic information. Furthermore, the earlier study had used the default emission factors that had been built into the model, which had been based on the testing results of U.S. vehicles. The default values may not represent the emission factors of Chinese vehicles since the popular technologies and maintenance status of U.S. vehicles and Chinese ones are likely to be rather different. Therefore, we decided to conduct real-time vehicle emissions testing in Beijing in order to generate base emission correction factors. Finally, the testing results provided information of great value to the Chinese environmental authority, such as the different environmental performance of light-duty vehicles of different model years and manufacturers.

1.2 Overall Methodology

We employed the same methodology in the Beijing study as in the Tianjin study (please refer to Section 1.3 of the Tianjin report for details). The only difference is that we did not use remote sensing devices (RSD) to collect on-road vehicle emissions and did not investigate fuel quality in Beijing ourselves. Thus, our collection of original data in Beijing was comprised of two parts: the VA study and on-road vehicle emissions testing with a portable emission measurement system (PEMS). Chapters 2 and 3 provide detailed explanation of data collection methods and procedures as well as the analyses of vehicle emission and activity data.

We decided not to survey vehicle emissions with RSD and not to examine the quality of mobile fuels in the Beijing market ourselves in part because we had obtained fewer financial resources for the Beijing study than we had for the Tianjin study and in part because Beijing has monitored vehicle emissions with RSD and routinely surveyed mobile fuel quality on its own in recent years. As of February 2008, the Beijing Environmental Protection Bureau (EPB) had purchased nineteen sets of RSDs to monitor real-time emissions from on-road vehicles. Chinese researchers have analyzed some of these RSD data.[13] The Beijing Quality Technology Supervision Bureau (BJQTSB) has been testing about a couple of hundred of mobile fuel samples in each quarter since 2005.[14] Their analyses have shown that almost all fuel samples (greater than 95 percent) were in compliance with the standards that were in effect at the sampling time. We rely

[13] Using RSD data collected in Beijing in spring 2004, Zhou, Fu, and Cheng (2007) have analyzed the emission characteristics of in-use, light-duty gasoline vehicles in Beijing. Similar to what we saw in Tianjin, they found that the average emissions of vehicles (by age group) had declined significantly from 1999 to 2004, consistent with the overall trend of more stringent new-vehicle emission standards.

[14] The quarterly testing results of fuel quality (in Chinese) are posted at the Bureau's website: http://www.bjtsb.gov.cn/index.asp?KindID=8&ClassID=61.

on these official testing results to determine the inputs of fuel quality when estimating total mobile emissions in Beijing.

IVE Model

We used the International Vehicle Emissions (IVE) model (version 2.0) to estimate total mobile emissions in Beijing. The model was jointly developed by researchers at the CE-CERT of University of California, Riverside, Global Sustainable Systems Research (GSSR), and the International Sustainable Systems Research Center (ISSRC). It has the ability to estimate conventional air pollutants, greenhouse gases, and toxic pollutants from various mobile sources of a study area during different time periods.

The fundamental principle of calculating total mobile emissions is the multiplication of emission factors by vehicle activities. A very simple example is that if we know a car on average emits 200 grams of carbon dioxide (CO_2) per kilometer and is driven about 100 kilometers per day, then we can calculate the total amount of CO_2 emissions of that car is 7.3 tons per year. However, in reality, vehicle emissions are affected by vehicle operating conditions by different orders of magnitude, and thus any versatile emissions model must consider factors affecting emissions. Emissions from vehicle starts are affected by the deployed technologies such as fuel injection and catalyst types, as well as the air temperature, engine temperature, and catalyst temperature at the time of start-up. Running emissions are effected by vehicle technologies and a complex variety of parameters, such as vehicle speed, acceleration, pervious driving conditions, and variations in engine load due to road grade and air conditioning use.

The IVE model incorporates various factors influencing vehicle emissions, such as fuel injection and emission control technology, driving and engine conditions, fuel quality, ambient temperature, engine start type, *etc*. Figure 1-4 illustrates the architecture of the IVE model.[15] The basis of the emission prediction process of the model begins with base emission rates [which in the model were derived from several sources: MOBILE6, EMFAC2007, COPERT IV (for vehicles certified to meet European Union (EU) emission standards), extensive measurements made at CE-CERT, and some international data sources][16] and a series of correction factors (which reflect the special situations of the localities under study) that are applied to estimate the amount of pollution from a range of vehicle categories.

[15] This part heavily relies on the IVE user manual, which can be downloaded from www.issrc.org/ive.

[16] MOBILE is the model recommended by USEPA for estimating mobile emissions on air quality of a locality. EMFAC is the model used by the California Air Resource Board to estimate on-road mobile emissions. COPERT is the model recommended by the European Environmental Agency for estimating mobile emissions.

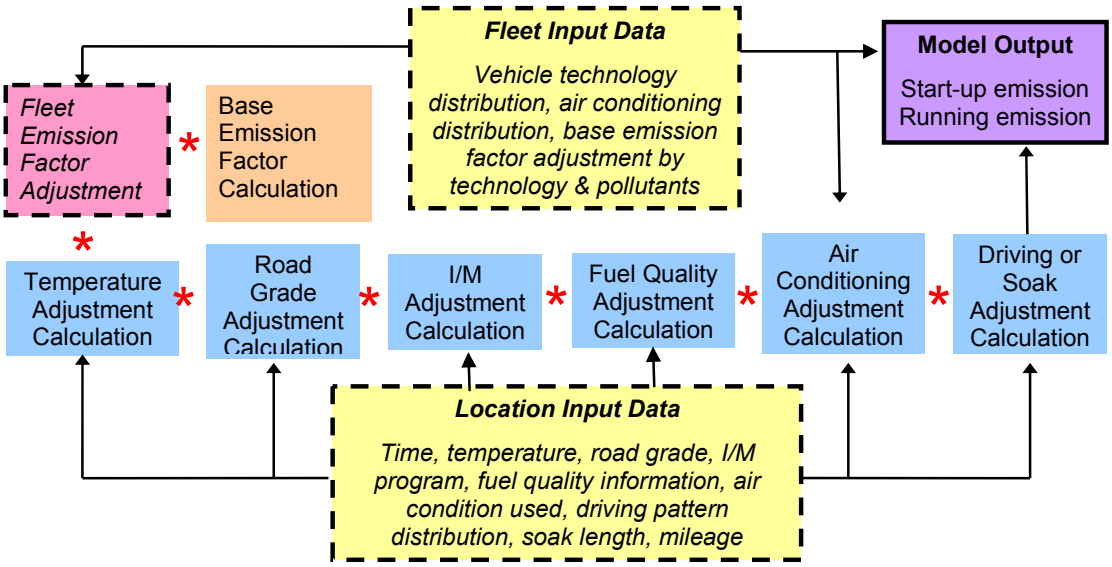

Figure 1-4 Structure of International Vehicle Emissions Model

First, the corrected emission rate of a vehicle technology category is obtained by multiplying the base emission rate for that category by each of the correction factors (defined for each vehicle technology category), as shown in equation 1.

$$\mathbf{Q_{[t]} = B_{[t]} * K_{(1)[t]} * K_{(2)[t]} * \ldots K_{(x)[t]}} \qquad \mathbf{(1)}$$

$Q_{[t]}$: corrected base emission rate of a vehicle technology category (g/km or g/m)
$B_{[t]}$: base emission rate
$K_{(1)[t]}, K_{(2)[t]} \ldots K_{(x)[t]}$: correction factor $_{1, 2, \ldots x}$
(x: temperature, humidity, fuel, I/M program, altitude, etc.)

The total amount of running/start emissions of a certain vehicle technology category can then be calculated by multiplying the corrected emission rate with total distance travelled, while incorporating the distribution of various driving/starting conditions during a certain period of time, as shown in equation (2) and (3):

$$\mathbf{Q_{[t,running]} = [\bar{U}_{FTP} * (D / \bar{U}_C)] * \{Q_{[t]} * \Sigma_d [f_{[dt]} * K_{[dt]}]\}} \qquad \mathbf{(2)}$$

$$\mathbf{Q_{[t, start]} = Q_{[t]} * \Sigma_d [f_{[dt]} * K_{[dt]}]} \qquad \mathbf{(3)}$$

$Q_{[t, running]}$: running emission of one vehicle technology category (kg/hr or ton/day)
$Q_{[t,start]}$: start emission of a vehicle technology category (kg/hr or ton/day)
$\bar{U}_{FTP}$: average velocity of the Federal Test Procedure (FTP) cycle[17]
D: distance travelled by that vehicle category
$\bar{U}_C$: average velocity in a particular location

[17] Refer to the following USEPA website for details on the Federal Test Procedure (FTP) cycle: http://www.epa.gov/otaq/sftp.htm.

$\bar{U}_{FTP}$ *(D / $\bar{U}_C$): unit conversion factor (from g/km to g/second)
$f_{[t]}$:fraction of travel by that vehicle category
$f_{[dt]}$:fraction of each type of driving or start
$K_{[dt]}$: correction factor of driving and soaking style

In the above equations, $B_{[t]}$, $K_{(x)[t]}$, and $K_{[dt]}$ are all built into the model. The needed inputs from a model user are: correction factors for base emission rates (the default values are 1), the total distance travelled by the local fleet, the fraction of distance travelled by every major vehicle category, the average velocity of a particular location, the distribution of the driving pattern, and the distribution of the soaking pattern for each type of vehicle category. As we will show in the next two chapters, by investigating the emissions of a sample of vehicles under different driving conditions, one can build local correction factors for base emission rates; by collecting and analyzing vehicle activities data, one can obtain other travel and driving-related inputs.

There are four user interfaces of the IVE model (see Appendix A). The model needs three sets of critical inputs: vehicle activity (the "Location" interface), vehicle fleet distribution (the "Fleet" interface), and correction for base emission factors ("Base Adjustment" interface). Results from vehicle activity study provide the inputs for the Location and the Fleet interfaces, and results from emissions testing provide the inputs for the Base Adjustment to the model. The model outputs are presented to users in the Calculation interface.

Emissions and Power Bins

In recent years, the concept of Vehicle Specific Power (VSP, kW/ton) has been developed and used to describe the instantaneous power per unit mass of a vehicle. The instantaneous power generated by an engine is used to overcome a vehicle's rolling resistance and aerodynamic drag and to increase the kinetic and potential energies of the vehicle.[18] It is well accepted by mobile emission experts that VSP is more capable of explaining vehicle emission variations than speed or acceleration alone. VSP can be calculated with the formula below (Jimenez 1999):[19]

$$VSP = v \cdot (1.1 \cdot a + 9.81 \cdot \sin(a \tan(grade)) + 0.132) + 0.000302 \cdot (v + v_w)^2 \cdot v \qquad \textbf{(4)}$$

v, v_w: speed (m/s)
a: acceleration (m/s^2)
$grade = (h_{t=-1} - h_{t=0})/v_{(\text{average between t=-1 and t=0})}$
h: altitude (m)

[18] The Motor Vehicle Emission Simulator (MOVE), which in the next generation mobile emissions model currently underdevelopment of the USEPA, will incorporate both on-road and off-road vehicle emissions and are also built upon the concept of VSP (United States Environmental Protection Agency 2002).
[19] Different researchers have developed slightly different formulas to calculate VSP, but the results of different formulas are quite similar.

When the value of *grade* is very small (less than 10 percent), *grade* can be used to replace sin*(a* tan*(grade))*, and [1+*a* tan(*grade*)]^2 is then close to one. The above equation can then be simplified as below:

$$VSP = v \cdot (1.1 \cdot a + 9.81 \cdot grade + 0.132) + 0.000302 \cdot v^3 \qquad \textbf{(5)}$$

After using various statistical methods to analyze a large pool of on-road and dynamometer emission data[20] collected at a minimum frequency of 1 Hz, researchers at CE-CERT and ISSRC drew the conclusion that VSP is the single most important parameter for determining vehicle emissions. It can explain about 65 percent of emissions. However, the researchers also found that emission estimates based on VSP perform best for CO_2, but are not completely satisfactory for other emissions such as CO, HC, NOx, and NH_3. A second dimension, a parameter called engine stress, was then introduced by these researchers to the matrix binning approach. They have demonstrated that engine stress correlates best to vehicle power load requirements over the past twenty seconds of operation and implied engine revolutions per minute (RPM, see equation below). [21]

Engine Stress (unitless) = RPMIndex + (0.08 ton/kW) × PreaveragePower (6)

$$\text{PreaveragePower} = \text{Average}(\text{VSP}_{t=-5\text{sec to } -25\text{ sec}})\ (\text{kW/ton})$$
$$\text{RPMIndex} = \text{Velocity}_{t=0}/\text{SpeedDivider (unitless)}$$
$$\text{Minimum RPMIndex} = 0.9$$

The driving pattern of any vehicle (or any road) during a certain period of time thus can be divided into sixty power bins based on the calculation of instantaneous VSP and engine stress (twenty groups for VSP and three modes for engine stress). Table 1-1 shows the demarcation of VSP bins and stress modes. Bin 1-11 corresponds to the driving condition of deceleration or going down an incline, Bin 12 corresponds to idling, while Bin 13 and above correspond to driving under a constant speed, acceleration, or, going up an incline.

[20] This pool of data is from four sources:

- National Cooperative Highway Research Program data set of over 100 non-catalyst and catalyst light duty vehicles driven on the MEC, FTP, and US06 cycles on the dynamometer (CE-CERT 1998)
- On-road PEMS data collected on several Tier 1 LDVs (EPA 2002)
- On-road, track, and dynamometer data collected from ULEV and SULEV LDVs (CRC 2003), and
- On-road, heavy duty diesel vehicle data from a set of several vehicles collected (Cocker 2003).

[21] Source: ISSRC (2008), IVE Model User Manual. Appendix C. Available at: www.issrc.org/ive.

Table 1-1 VSP Bins and Stress Modes *

Low stress -1.6-3 .1	*Bin*	*0*	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*
	VSP cut point	-80	-44	-39.9	-35.8	-31.7	-27.6	-23.4	-19.3	-15.2	-11.1
	Bin	*10*	*11*	*12*	*13*	*14*	*15*	*16*	*17*	*18*	*19*
	VSP cut point	-7.0	-2.9	1.2	5.3	9.4	13.6	17.7	21.8	25.9	30 1000

Medium stress 3.1-7.8	*Bin*	*20*	*21*	*22*	*23*	*24*	*25*	*26*	*27*	*28*	*29*
	VSP cut point	-80	-44	-39.9	-35.8	-31.7	-27.6	-23.4	-19.3	-15.2	-11.1
	Bin	*30*	*31*	*32*	*33*	*34*	*35*	*36*	*37*	*38*	*39*
	VSP cut point	-7.0	-2.9	1.2	5.3	9.4	13.6	17.7	21.8	25.9	30 1000

High stress 7.8-12.6	*Bin*	*40*	*41*	*42*	*43*	*44*	*45*	*46*	*47*	*48*	*49*
	VSP cut point	-80	-44	-39.9	-35.8	-31.7	-27.6	-23.4	-19.3	-15.2	-11.1
	Bin	*50*	*51*	*52*	*53*	*54*	*55*	*56*	*57*	*58*	*59*
	VSP cut point	-7.0	-2.9	1.2	5.3	9.4	13.6	17.7	21.8	25.9	30 1000

* Source: ISSRC (2008), IVE Model User Manual. Appendix C. Available at: www.issrc.org/ive.

Figure 1-5-a and 1-5-b illustrate the relations of normalized emission rate versus power bin for closed-loop, catalyst-equipped and carbureted, and no-catalyst gasoline vehicles, respectively.[22] (Vehicles with these technologies are most commonly seen in the Chinese passenger fleet). For each stress mode, with the increase of VSP value, CO emissions increase dramatically, and HC emissions increase somewhat; NOx emissions increase first and then level off or even decrease somewhat. CO and HC emissions of vehicles with catalysts seem to be influenced by VSP to a greater extent than vehicles without catalysts, especially at high VSP values. While NOx emissions of vehicles with catalysts do not seem to be influenced by increasing VSP value as much as vehicles without catalysts.

Figure 1-5-c shows the correlation of normalized emission rate versus power bin for diesel vehicles. Similar to gasoline vehicles, emission rates of diesel vehicles increase concurrently with VSP value. However, the emission rates of diesel vehicles rise with VSP at a lesser order of magnitude. It is clear that gasoline and diesel vehicles generate very different emissions even for the same power bins.

[22] Source: ISSRC (2008), IVE Model User Manual. Appendix C. Available at: www.issrc.org/ive.

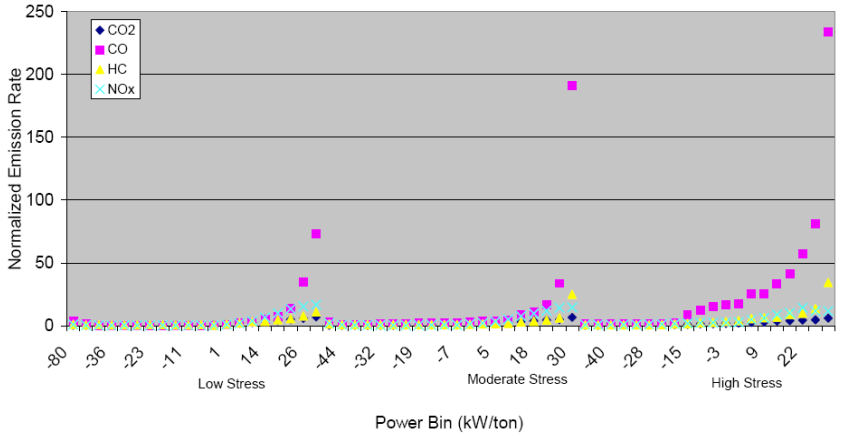

Figure 1-5-a Emission vs. Power Bin for Closed-loop, Catalyst-equipped Gasoline Vehicles

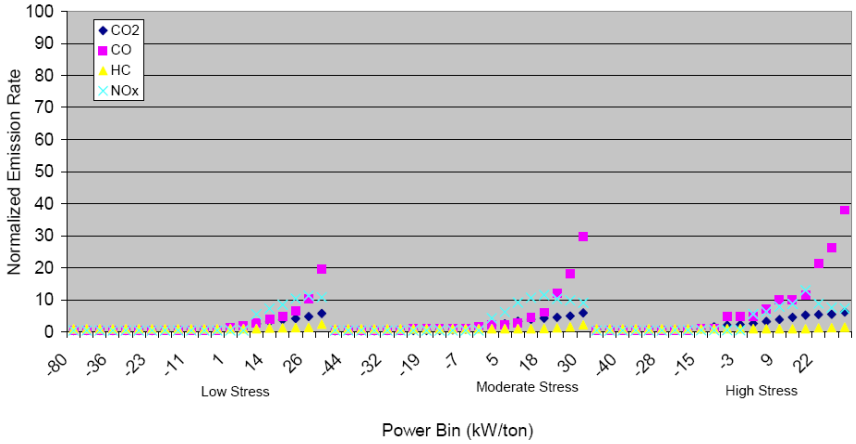

Figure 1-5-b Emission vs. Power Bin for Carbureted, No-catalyst Gasoline Vehicles

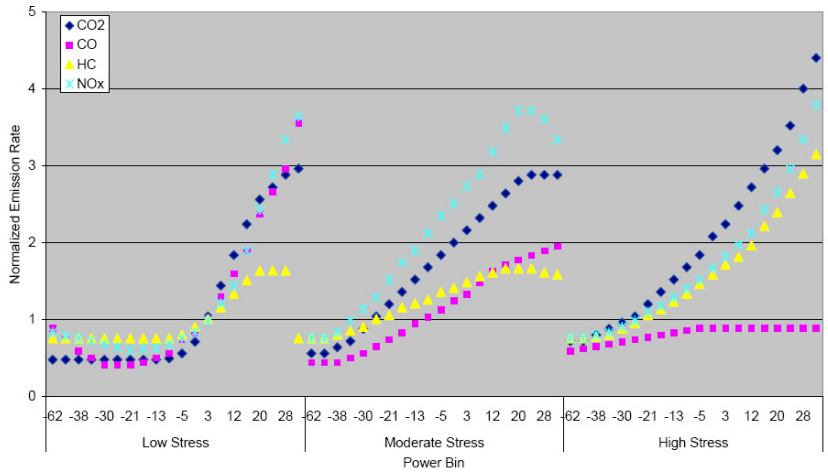

Figure 1-5-c Emission vs. Power Bin for Diesel Vehicles

Once we have established the relationship between emission rate and power bin, vehicle emissions estimates can be calculated by referencing the observed power bin distribution on a second-by-second basis (a specific driving cycle) to the emissions rates calculated from the model development data within the bins, as illustrated in Figure 1-6. The VA study part of this study generated the local driving pattern (as time distribution of different power bins) while the results of PEMS emission testing determined the amount of needed adjustment to the normalized emission-VSP curve in order to reflect the unique characteristics of local fleet emissions.

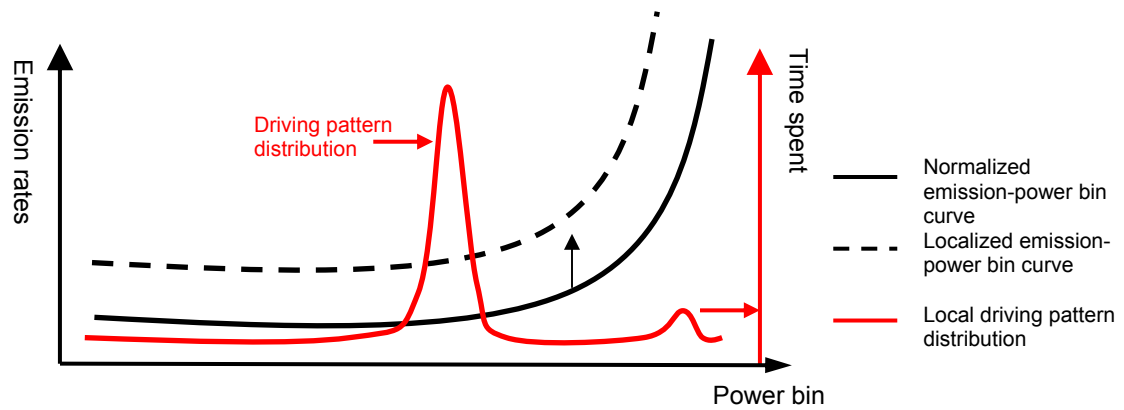

Figure 1-6 Combining Driving Pattern Distribution with Emission-VSP Curve

1.3 Research Partnership

Three parties comprised the research team for the Beijing study: the Energy Technology Innovation Policy (ETIP) research group at the Harvard Kennedy School, the Institute for Vehicle Testing at the China Automotive Research and Technology Center (CATARC), and the Department of Environmental Engineering and Sciences at Tsinghua University. In addition, about ten students from the Beijing Technology and Business University (Department of Environmental Engineering) participated in the field work of VA data collection.

The division of labor was consistent with the different strengths and experience of the three parties. ETIP was responsible for fundraising, overall planning and coordination, overseeing project implementation, preparing emissions data for IVE model, integrating the emission testing and VA study, and overall report writing. The CATARC team was responsible for all activities associated with emissions testing with PEMS, including planning the field work, securing vehicles to be tested, securing PEMS and span gases, and carrying out each test according to a predetermined protocol. Since CATARC has an ongoing working relationship with Beijing EPB, it also assumed the lead responsibility for outreach to the bureau. The Tsinghua team was in charge of all activities comprising the VA activity study, including planning the field work, securing necessary devices and vehicles, recruiting local assistants, screening and reformatting data, and data analysis.

1.4 Schedule

With much experience gained through the Tianjin study, the research team carried out the Beijing study at a much faster pace. Excluding the early preparation stage, it took about fifteen months from preparation of the field work to completion of the Beijing report. Table 1-2 summarizes the major activities and the time line.

Table 1-2 Schedule of Beijing In-use Vehicle Emissions Study

Time period	*Major activity*
January–June 2007	Tianjin study review meeting Outreach to Beijing EPB Fundraising and budgeting
July–September2007	Formulation of Beijing Implementation Plan Regroup of research team
October 2007	Preparation for on-road emission testing with PEMS - Securing a local base - Securing PEMS and span gases - Developing testing protocol - Organizing a team for data collection - Determining driving route
November–December 2007	Data collection with PEMS - 12 days of data collection, 58 vehicles were tested - On-site data screening and evaluation
January–March 2008	Preparation of field work report for on-road emission testing Analysis of vehicle emissions based on original testing data
February–March 2008	Preparation for VA data collection - Developing data collection protocol - Securing video camera, GPS, and VOCEs - Organizing and training a team for data collection - Securing vehicles and drivers for driving pattern study
April 2008	VA Data collection - 9 days of VA data collection - Everyday data screening and evaluation
May–June 2008	Data cleaning, processing and analysis (for both VA and emission testing data)
July 2008	Data corroboration and integration Generation of preliminary results Beijing study review meeting
August–September 2008	Refinement of analysis
November–December 2008	Report writing

2. Testing Emissions with Portable Emission Measurement Systems

We have perceived three purposes for conducting on-road emission tests on selected vehicles in a study locality with PEMS: 1) to correct the default base emission factors in the IVE model so that the model estimations will be more accurate; 2) to provide information on the overall emission characteristics of vehicles from different model years and by different manufacturers; 3) to generate insights on the relationship between mobile emissions and driving conditions in the locality. The first purpose is highly relevant for producing an accurate mobile emission inventory and for improving the IVE model. The latter two are of great interest to the local environmental protection authority because such information will enable the local environmental authority to target specific models and manufacturers and to launch a meaningful dialogue with the local traffic management authority in order to streamline the most congested and polluting road sections.

2.1 Instrument, Driving Route, and Tested Vehicles

Instrument

We used a set of OBS-2200 system manufactured by Horiba[23] to continuously measure real-time emissions from a moving vehicle. The OBS-2200 system is a real-world analytical emissions system designed for on-board measurement. It records the concentrations of raw exhaust gases and simultaneously collects data on the driving environment (humidity, temperature, and atmospheric pressure) and driving conditions (speed and acceleration derived from global positioning system (GPS) information such as altitude, latitude, and longitude data). It takes second-by-second measurements of the exhaust flow rate, the concentrations of CO, CO_2, THC, and NOx, and air/fuel ratio of a moving vehicle. Based on such information, the central control computer simultaneously calculates the mass emissions of the exhaust gases and the fuel consumption per unit of distance travelled. Figure 2-1 illustrates the composition of the system as instrumented on a car.

In our Tianjin study, we have proven that the OBS-2200 system performs satisfactorily in measuring vehicle emissions. We accomplished this by comparing the emission measurements taken by OBS-2200 with those simultaneously taken by a constant volume sampler (CVS)[24] emission measurement system of the same vehicle running on a dynamometer roller. Emission measurement and correlation charts of those experiments are included in the Tianjin report (Section 3.1).

---

[23] Product information can be found at: http://www.ats.horiba.com/obs2000.html.

[24] CVS systems, which have been used for almost forty years to sample gases from automobiles tested in emissions laboratories, utilize a sampling technique based on a constant diluted full flow and a variable dilution ratio. The CVS systems are considered as very accurate in measuring vehicle emissions (with the exception of extremely low emissions).

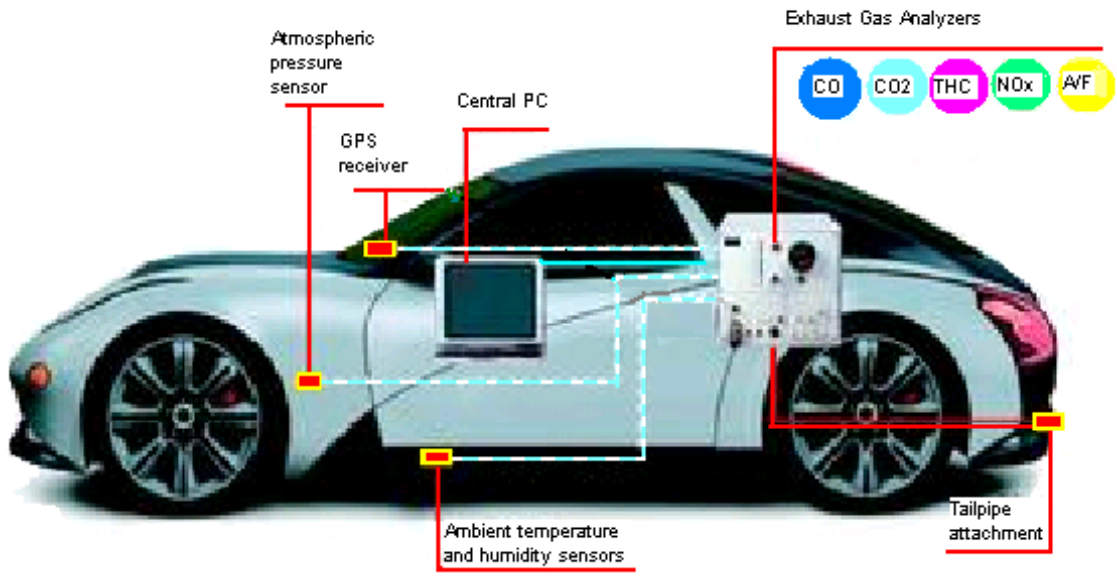

Figure 2-1 Illustration of OBS-2200 System[25]

Driving Route

In the procedure of correcting base emission factors in the IVE model, a key step is to simulate the relationship between vehicle emissions and power bins in the study area (refer to Section 1.2). To achieve this, the driver in the testing experiment must operate a tested vehicle under a wide variety of driving conditions to include as many power bins as possible while the PEMS is taking emission measurements.

The following criteria were used to determine the driving route in Beijing:

1) The route should include various roads (residential, arterial, and expressway) and different traffic conditions;

2) It must start and end at the same site where the PEMS would be dismounted from a tested vehicle and mounted onto the next one (in this case, a building on the campus of Beijing Internal Combustion Engine Group (BICEG) served as the temporary office and vehicle preparation site); and

3) There should be some turning-around points so that the driver could make a shortcut and drive the tested vehicle back to the installation site in a timely fashion in the case of extremely bad traffic congestion.

As illustrated in Figure 2-2, the route starts and ends at the Technology Center of BICEG. The route is about twenty-two kilometers long and is comprised of three types of

[25] The figure is cited from Horiba's website: http://www.ats.horiba.com/obs2000.html.

roads: about 6 kilometers of residential roads (such roads often have many intersections and are characterized by low-speed and stop-and-go driving), about 9.6 kilometers of arterial roads (they have fewer intersections and traffic speed is moderate), and about 5.4 kilometers of urban expressways (these roads have no intersections and allow free-speed traffic most of the time). It took thirty-five to fifty-five minutes to finish the route, depending on the traffic condition at the time of the test.

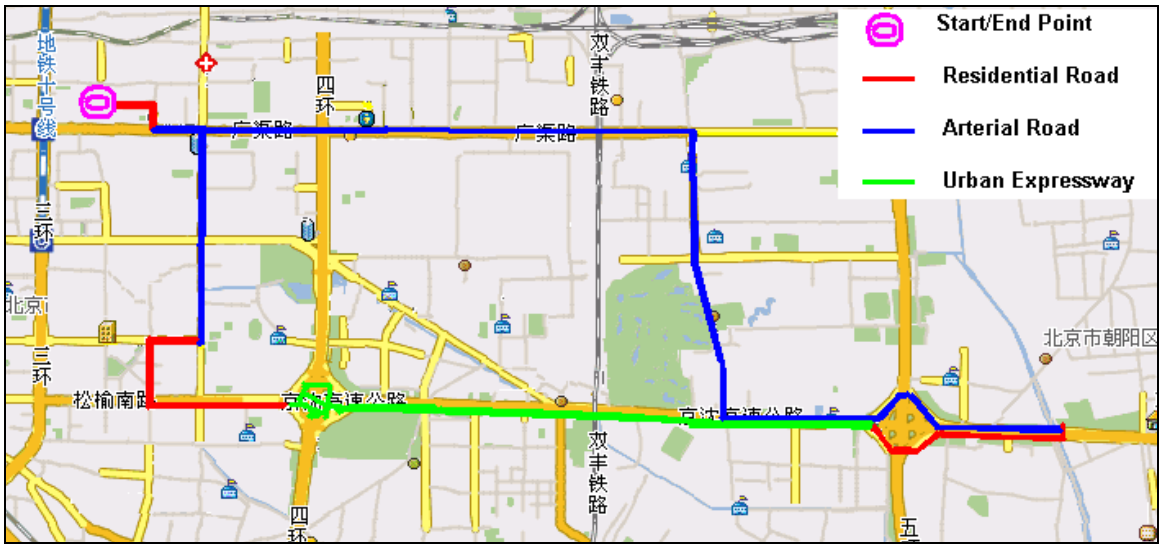

Figure 2-2 Driving Route for On-road Vehicle Emissions Testing in Beijing

Tested Vehicles

During a ten-day period in late November and early December 2007, the CATARC team tested on-road emissions of fifty-eight light-duty gasoline vehicles. Five tests turned out to be invalid due to temporary operation problems with the testing instrument or the tested vehicles. Among the fifty-three vehicles that yielded valid data, eighteen of them had been used as taxis, ten had been owned by individuals, and the rest belonged to the BICEG and had been used as company vehicles.

Table 2-1 gives the detailed technology distribution of the fifty-three vehicles. Among these fifty-three vehicles, three had been purchased before Beijing adopted the Euro I[26] emissions standards for new LDVs. They were equipped with carburetors and later retrofitted with electric fuel injection systems and catalytic converters. Eleven vehicles were made to meet Euro I emissions standards, among which, three were carbureted vehicles with three-way catalytic converters (TWC) while the rest were

[26] As explained in Section 1.1, Figure 1-3, the Chinese vehicle emission standard series mirror the European series. For simplicity, we use Euro 0, I, II, and III to represent the emission standards before Chinese national phase I took effect, phase I, II, and III emission standards for new light-duty gasoline vehicles.

equipped with multi-point fuel injection (MPFI) systems and TWC. Twenty-five vehicles had been certified to meet Euro II emission standards when they had been originally purchased, and all of these vehicles were equipped with MPFI and TWC. Fourteen tested vehicles had been certified to meet Euro III emission standards when they had been originally purchased, and all of them were equipped with MPFI and TWC (these TWCs probably have higher pollutant removal efficiency than those TWCs used for vehicles certified to Euro II emissions standards).[27]

Among all the tested vehicles, fifteen vehicles had been driven for less than 80,000 kilometers, twenty had accumulated mileage between 80,000 and 160,000 kilometers, and the remaining seventeen vehicles had been driven for more than 160,000 kilometers. Forty-nine of these vehicles had an engine displacement (size) of between 1.5 and 3.0 liters (according to the IVE model classification, they are "medium-sized" passenger vehicles) and only four of them had an engine displacement of less than 1.5 liters (small vehicles). Among the forty-nine medium-sized LDVs, thirty-two vehicles had an engine displacement of between 1.5 and 2.0 liters; fifteen of them have an engine displacement of between 2.0 and 2.5 liters; and only two vehicles have an engine displacement of greater than 2.5 liters.

Table 2-1 Technology Distribution of Tested Vehicles

Emission standards	*Num of cars*	*Engine size*	*Num of cars*	*Mileage accumulated*	*Num of cars*
Pre-Euro I	3	≤1.5 L	0		
		1.5-3.0L	3	> 160K km	3
		>3.0 L	0		
Euro I	11	≤1.5 L	2	> 160K km	2
		1.5-3.0L	9	80K – 160K km	6
				> 160K km	3
		>3.0 L	0		
Euro II	25	≤1.5 L	2	≤ 80K km	1
				80K – 160K km	1
		1.5-3.0L	23	≤ 80K km	5
				80K – 160K km	13
				> 160K km	7
		>3.0 L	0		
Euro III	14	≤1.5 L	0		
		1.5-3.0L	14	≤ 80K km	10
				80K – 160K km	2
				> 160K km	2
		>3.0 L	0		
Subtotal	*53*		*53*		*53*

[27] As we found out in Tianjin, it is also possible that some of the vehicles certified for Euro III emission standards may have been equipped with close-coupled TWC. There are two separate parts, the first TWC is small but very close to the outlet of the engine so it can warm up very quickly and remove a significant amount of start-up emissions while the main TWC is warming up.

2.2 Real-time and Normalized Emissions[28]

Despite that we had chosen a fixed driving route for on-road vehicle emission testing, the driving conditions during different tests still varied considerably depending on the traffic conditions at the time of each test. To minimize the impact of driving conditions on vehicle emissions (especially vehicles equipped with similar technologies), emissions of each tested vehicle were normalized to a hypothetic Federal Test Procedure (FTP) driving cycle. This is achieved by the following three steps:

1) Real-time emissions and driving condition information collected during an on-road test were put into the sixty power bins on a second-by-second basis (refer to methodology in Section 1.2);

2) The linear fitting method was used to create the emission-power bin curve for each vehicle (when there were not enough data for some power bins, the default curve shape was used to make up for those sections); and

3) The power bin distribution of the FTP cycle was referred to the emission-power bin curve for each vehicle (developed in step 2) to calculate the emissions of that vehicle on a hypothetic FTP cycle.

We categorized the fifty-three tested vehicles into twelve groups, based on their respective certified emission standard, engine size, and accumulated mileage. Table 2-2 summarizes the categorization. The results of real-time emissions and normalized FTP cycle emissions of the twelve groups are illustrated in Figure 2-3-a, b, c, and d.

Table 2-2 IVE Classification of the 53 Tested Vehicles

IVE Class	*Description*	*Number of vehicles*
5	Pre Euro, medium-sized engine, high mileage	3
173	Euro I, small-sized engine, high mileage	2
175	Euro I, medium-sized engine, medium mileage	7
176	Euro I, medium-sized engine, high mileage	2
180	Euro II, small-sized engine, low mileage	1
181	Euro II, small-sized engine, medium mileage	1
183	Euro II, medium-sized engine, low mileage	5
184	Euro II, medium-sized engine, medium mileage	11
185	Euro II, medium-sized engine, high mileage	7
192	Euro III, medium-sized engine, low mileage	10
193	Euro III, medium-sized engine, medium mileage	2
194	Euro III, medium-sized engine, high mileage	2

[28] Please refer to the Tianjin study report (Section 3.3) for detailed explanation of each step that we took to clean and process the vehicle emissions data.

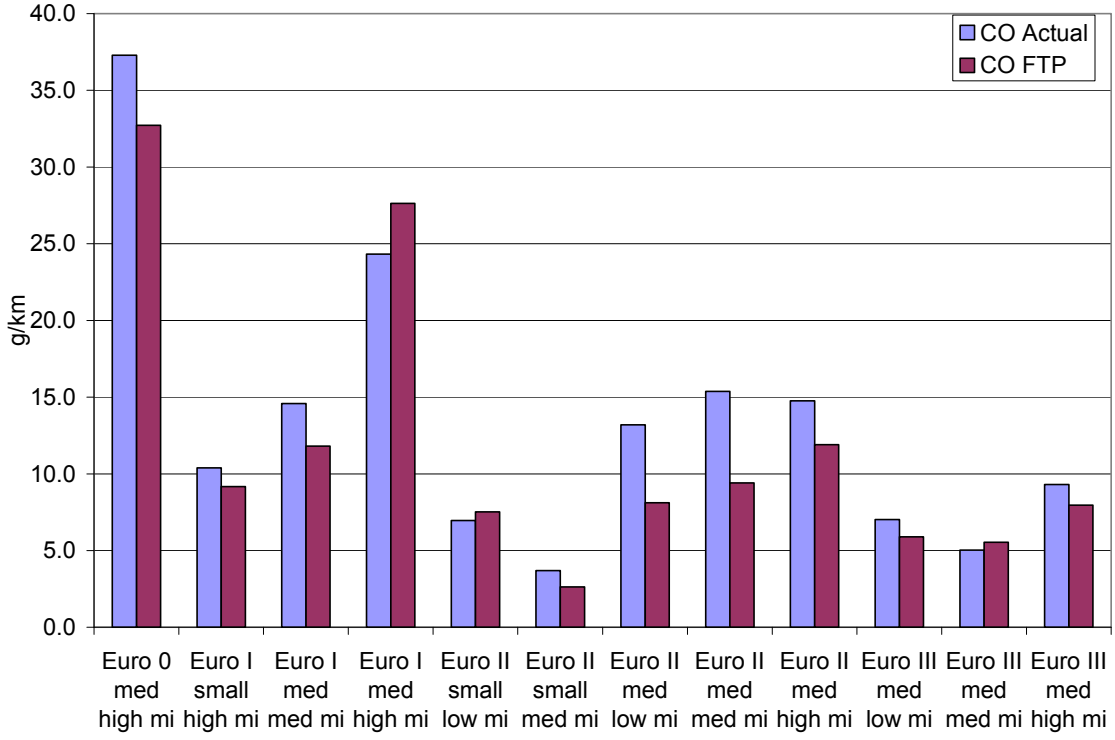

Figure 2-3-a Comparing Real-time and FTP Cycle CO Emissions

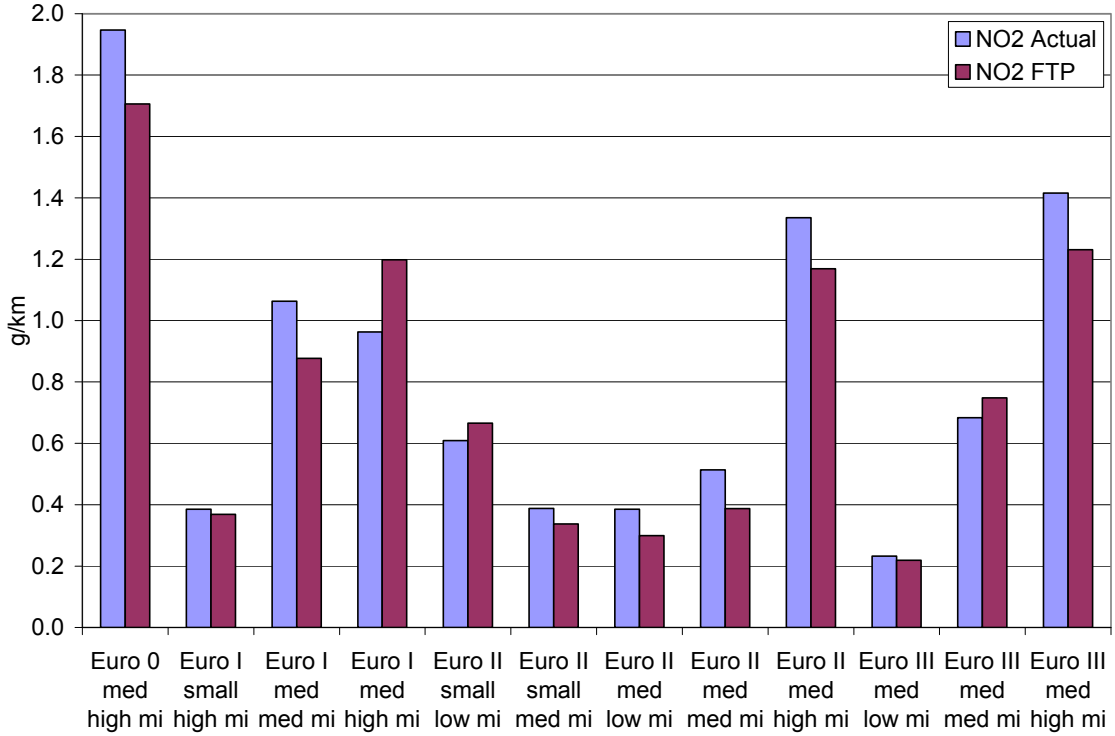

Figure 2-3-b Comparing Real-time and FTP Cycle NO_2 Emissions

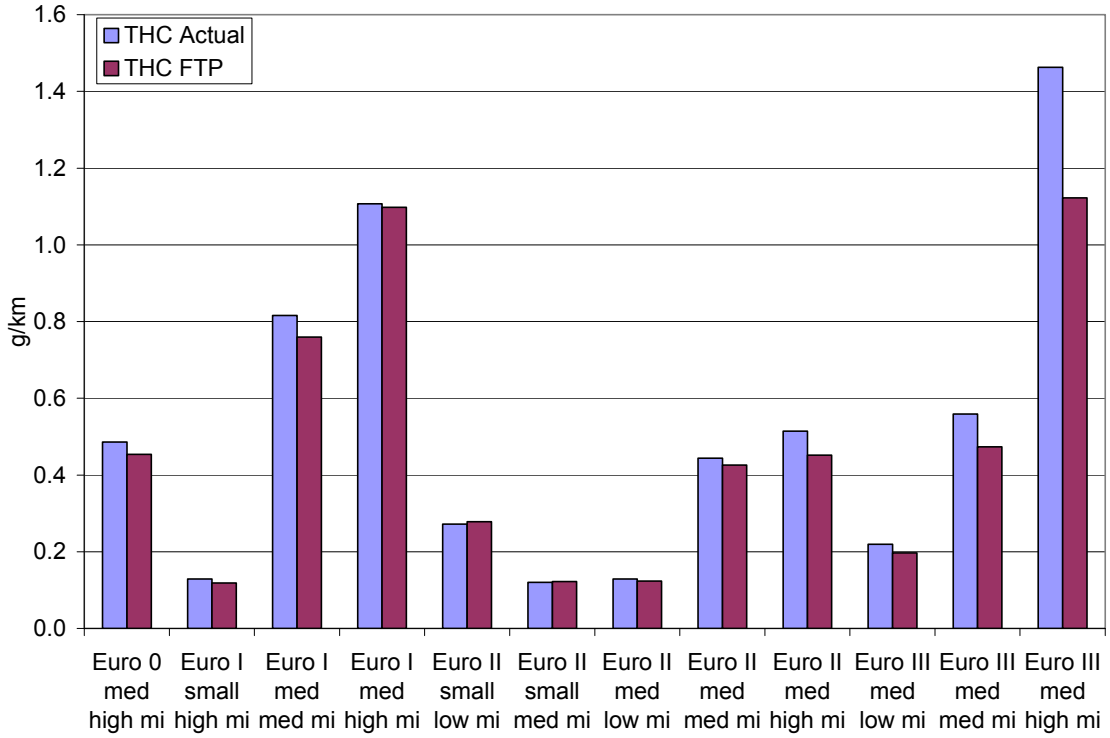

Figure 2-3-c Comparing Real-time and FTP Cycle THC Emissions

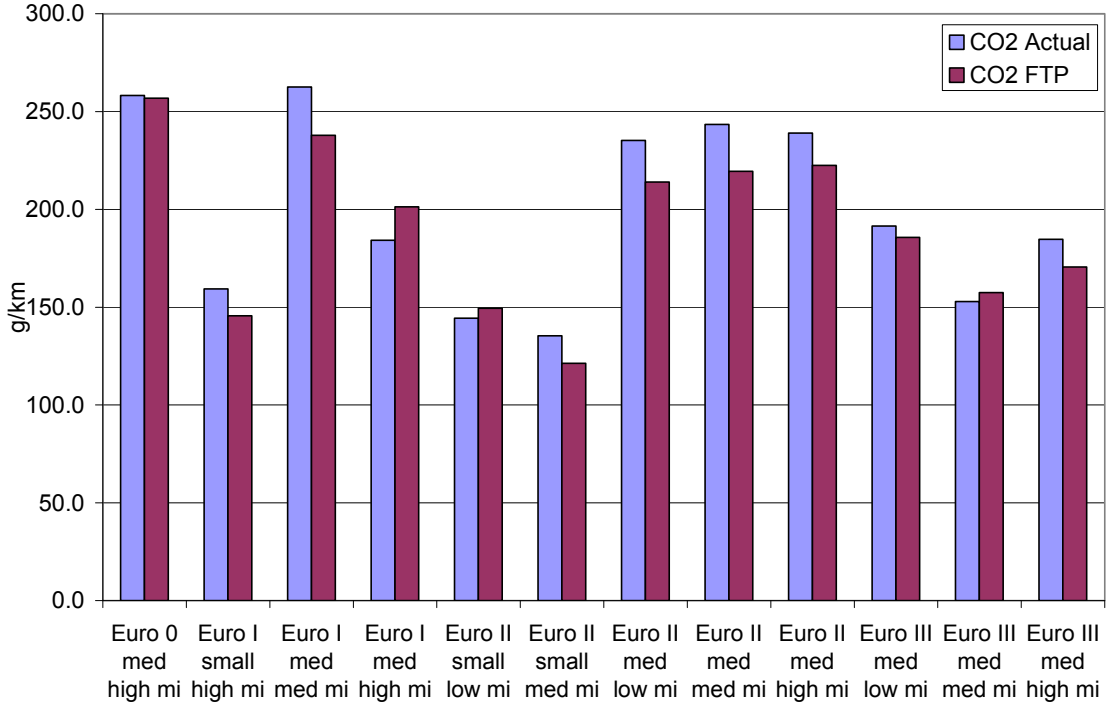

Figure 2-3-d Comparing Real-time and FTP Cycle CO_2 Emissions

For most of the vehicle groups, their average emissions during the tests are somewhat higher than their average emissions on a hypothetic FTP driving cycle. This is consistent with our anticipation because the FTP cycle is generally considered to be a rather mild driving condition while the real-world driving situation is usually more aggressive. Since emission rates of high power bins are often tens of times higher than emission rates of low power bins, total emissions during an aggressive driving cycle are typically much higher than total emissions of a mild driving cycle.

Nevertheless, the above figures also show that there were a few exceptions: vehicle group 176 (Euro I, medium-sized, and high-mileage vehicles), vehicle group 180 (Euro II, small-size, and low-mileage vehicles), and vehicle group 193 (Euro III, medium-sized, and medium-mileage vehicles). Our analysis of the power bin distribution of the FTP cycle and those of the driving cycles during the Beijing tests showed that a few tests were comprised of slightly milder driving conditions than those of the FTP cycle (i.e., less time was spent in higher power bin during these on-road tests than in the FTP cycle). Consequently, the emissions of these few on-road tests were lower than those of a hypothetic FTP cycle. Appendix B provides examples of such comparison.

For the twelve vehicle groups, the difference between the average CO emissions during the on-road tests and those of a hypothetic FTP cycle ranges from minus 14 percent to 30 percent; the difference between the average NO_2 emissions during the on-road tests and those of a hypothetic FTP cycle ranges from minus 22 percent to 24 percent; for THC, the variation is from minus 2 percent to 23 percent; while for CO2, it is minus 9 percent to 10 percent. To eliminate the impacts of driving conditions on the emissions of tested vehicles, emissions of a hypothetic FTP cycle are used for analyses in the sections below.

2.3 Emission Trends over Time

Vehicles Certified to Different Emission Standards

We put the fifty-three tested vehicles into four groups based on the emission standards that these vehicles were required to meet at the time of their original sales. Table 2-3 shows the average CO, THC, NO_2, and CO_2 emissions of these four groups. It is obvious that the average emissions of vehicles certified to more recent, stricter emission standards are much lower than those of vehicles certified to earlier, looser emission standards. For example, vehicles made before Euro I standards took effect on average emit about thirty-three grams of CO per kilometer, while vehicles certified to Euro III standards on average emit only six grams of CO per km, a difference of 450 percent. The average NO_2 emission per kilometer from vehicles certified to Euro III emission standards was 300 percent less than that from vehicles made prior to Euro I standards took effect. In contrast, the decrease of average THC emissions is much more limited. *There is no doubt that passenger vehicles are getting much cleaner over time as the result of more stringent emission standards for new vehicles.*

The table shows that average CO_2 emissions of the four vehicle groups also decreased. However, we do not think that our data from this particular study allows us to draw the conclusion that vehicles are becoming more fuel-efficient over time.[29] In fact, the distribution of the engine size of the fifty-three tested vehicles was such that the newer vehicles happened to have smaller engine displacement. Thus, it is not surprising that on average the newer vehicles use less fuel and emit less CO_2 than the older vehicles when they are compared on the same driving cycle.

Table 2-3 Emissions of Vehicle Groups by Certified Standards

Number of Tested Vehicles	*Description*	*Normalized Emissions (g/km)*			
		CO	*THC*	*NO_2*	*CO_2*
3	Pre Euro	32.7	0.5	1.7	256.7
11	Euro I	14.2	0.7	0.8	214.4
25	Euro II	9.5	0.4	0.6	212.5
14	Euro III	6.1	0.4	0.4	179.5
53	*Total*	*10.9*	*0.4*	*0.7*	*206.7*

Table 2-4 shows that confidence intervals for the average values of the four tested vehicle groups. It is self-evident that a larger sample size increases the result confidence. Thus, we feel more confident about the average emission values of tested Euro II vehicles than those of the tested pre-Euro vehicles. For example, we are 90 percent confident that the CO emission of any vehicle certified to Euro II emission standards are within the range of 7.94–12.1 g/km (a rather narrow range), but for any vehicle manufactured prior to the implementation of any emission standards, we are 90 percent confident that its CO emission may fall anywhere within the range of 3.27–62.1 g/km (a very broad range).

Table 2-4 90% Confidence Intervals for Average Values of Tested Vehicle Groups

Number of Vehicles	*Description*	*90% Confidence Interval*			
		CO	*CO_2*	*NO_2*	*THC*
3	Pre Euro	90%	26%	9%	80%
11	Euro I	44%	16%	28%	86%
25	Euro II	27%	11%	39%	37%
14	Euro III	29%	10%	47%	47%
53	*Total*	*24%*	*7%*	*22%*	*34%*

[29] In a separate study, Oliver *et al.* (2009) investigated the impacts of Chinese fuel economy standards, and they did find that Chinese light-duty vehicles have become about 10% more efficient from 2002 to 2006.

Figure 2-4-a and -b compare the average emissions of the four vehicle groups with the limits of their respective certified standards. [30] (One may also compare the values in Table 2-3 and those in footnote 29.) Again, the reduced height of the lightly colored bars over time (blue in the color version of this report) shows that *newer vehicles certified to stricter emission standards emit fewer pollutants per kilometer than older ones certified to looser standards*. However, the drastic differences between the lightly colored bars (blue in the color version) and the darker bars (maroon in the color version) indicate that *the average emissions of these vehicle groups are very much higher than the limits of their certified standards*. For CO, the actual average emissions of tested Euro I, II, and III vehicles are 5.2, 4.3, and 2.7 times the corresponding requirements of their certified standards. For THC and NO_2 (combined concentration), the actual average emissions of tested Euro I, II, and III vehicles are 1.6, 1.9, and 2.3 times the corresponding requirements of their certified standards.

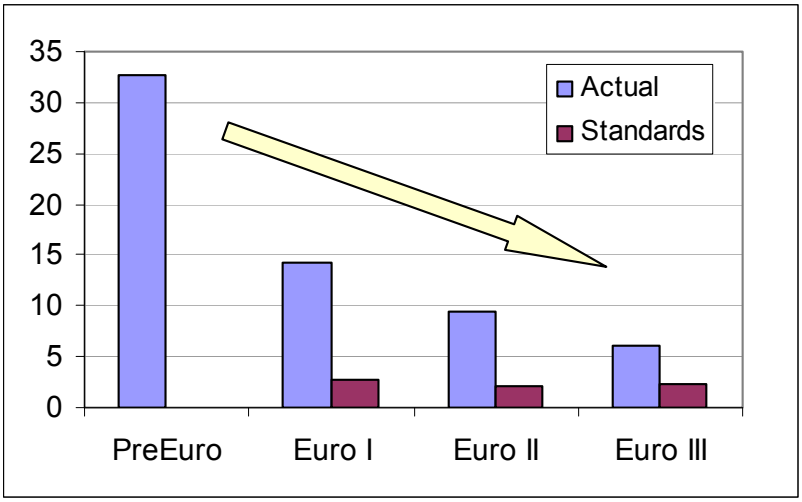

Figure 2-4-a Actual CO Emissions and Certified Limits of Tested Vehicles

[30] Limits for Euro I, II, III, and IV emission standards are listed in the table below. The requirements for THC and NO_2 emissions are combined concentrations in Euro I and Euro II standards, while the requirements are separate in Euro III and IV standards.

	CO (g/km)	*HC (g/km)*	*NOx (g/km)*
Euro I	2.72	0.97	
Euro II	2.2	0.5	
Euro III	2.3	0.2	0.15
Euro IV	1	0.1	0.08

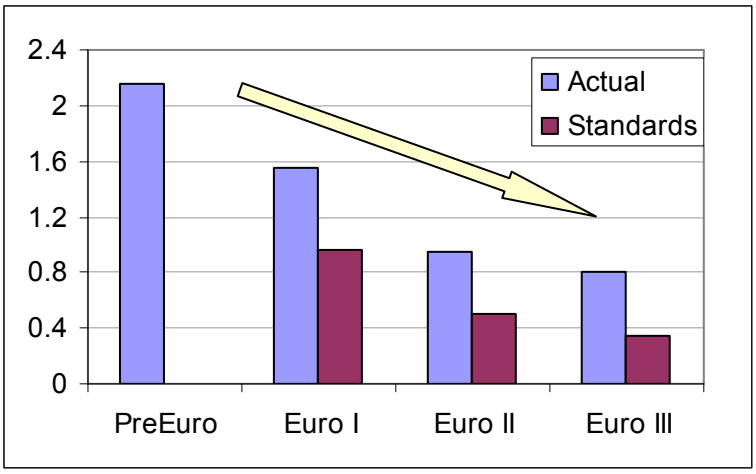

Figure 2-4-b Actual THC+NO_2 Emissions and Certified Limits of Tested Vehicles

Emissions and Accumulated Mileage

We further divided medium-sized vehicles (forty-nine in total) in each emission group into three subgroups, based on the amount of accumulated mileage. Our purpose in doing this is to examine whether the performance of vehicle emission control devices deteriorate over time (indicated by the accumulation of mileage) and to examine whether low mileage vehicles are in compliance with their certified emission standards.

Figure 2-5 shows that, clearly, *for all vehicle emission groups, the effectiveness of emission control devices decreased considerably over time*. For example, it appears that high-mileage vehicles on average emit about the same amounts of NOx and THC, without regard to which level of emission standards they had been certified. Among the tested Euro III vehicles, average aggregated NOx and THC emissions of the high-mileage subgroup were 4.7 times higher than those of low-mileage subgroup. We speculate three plausible explanations for the deterioration of emission control performance:

1) Certain parts used in some vehicle models in China (e.g., oxygen sensors, catalysts, and air-fuel ratio control devices) had poor durability;
2) The quality of the fuel available commercially could not guarantee continuous performance of three-way catalytic convertors; and,
3) Vehicle owners did not have their vehicles maintained according to manufacturers' recommendation as their vehicles aged.

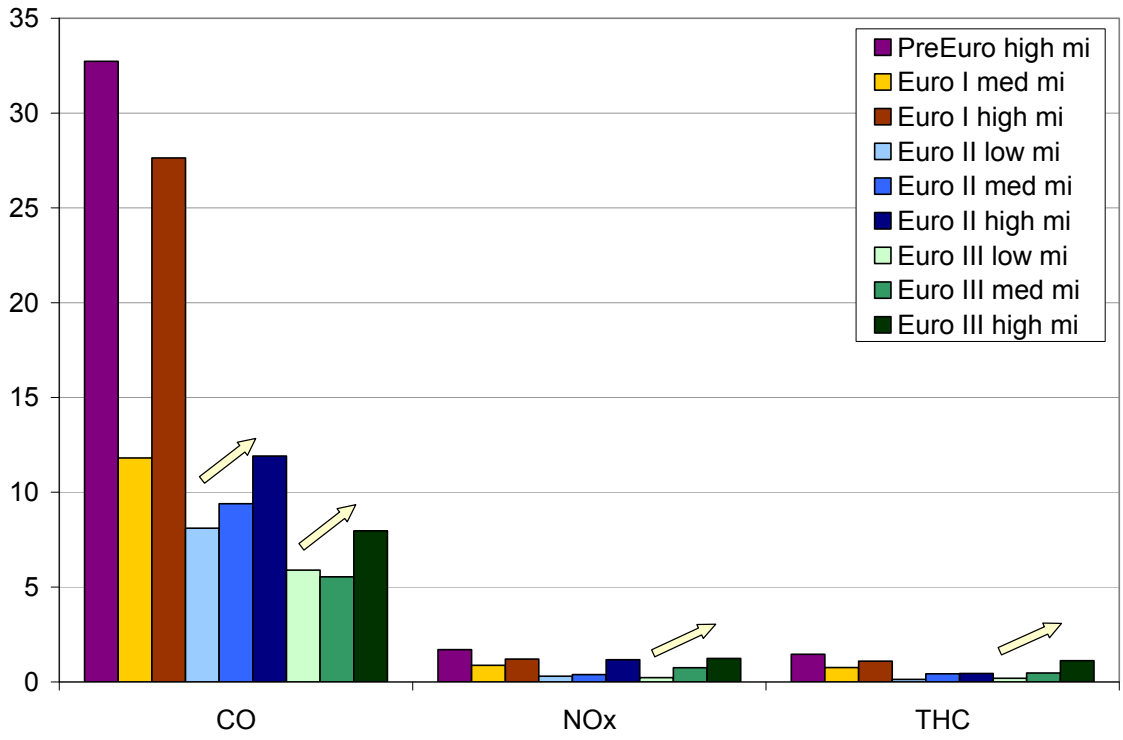

Figure 2-5 Average Emissions by Certified Standard and Mileage

It seems that the CO emission control effectiveness of the Euro I vehicle group deteriorates more dramatically than those of the Euro II and Euro III vehicle groups; while the NOx and THC emission control effectiveness of the Euro II and III vehicle groups deteriorates more rapidly than those of the Euro I vehicle group. Comparing the emission limits in Euro I, II, and III standards, one can see that the CO emission limit for new vehicles was only tightened by less than one-fifth (from 2.7 g/km to 2.2 g/km to 2.3 g/km), while the aggregated NOx and THC emission limit was tightened by almost two-thirds (from 0.97 g/km to 0.5 g/km to 0.35 g/km). It is possible that CO control technology employed in vehicles sold in China has achieved better durability over time, while the durability of NOx and THC control technologies are yet to be improved.

Since the average emissions of the low-mileage Euro III subgroup were lower than those of low-mileage Euro II subgroup, we are confident that *tightening emission standards did have an obvious impact on the emission levels of new vehicles*. However, a comparison of actual emissions of low-mileage subgroups with the limits of their corresponding certified standards illustrates that *even the low-mileage vehicle subgroups were not in compliance with any of their certified emission requirements*. We hypothesize three possible explanations:[31]

[31] Our data collected in this study does not allow us to verify which reason and to which extent a possible cause can explain the observed phenomenon.

1) Some of the new vehicles did not meet the standards they were supposed to meet. (This implies that the implementation of the Chinese emission certification need to be enhanced); and
2) Emissions of vehicles are higher in the real-world situation than their certified limits because the fuel used for certification tests is much cleaner than the fuel available on the market. (This implies that the quality of fuels used in certification and of those sold commercially need to be harmonized.)
3) The FTP driving cycle to which we normalized real-time emissions was more aggressive than the driving cycle used for vehicle emission certification in China. Thus, a vehicle emits more when driving on the FTP cycle than on the certification cycle. However, the real-world driving conditions are usually more aggressive than those of the FTP cycle, which means that real-world vehicle emissions are even higher than their certified limits. (This implies the driving cycle used for certification in China needs to be modified to reflect the real-world driving conditions).

Nevertheless, the above observations need to be treated with caution because when we divide a limited number of tested vehicles into many categories, there are only a very few vehicles left in each of the subgroups. With a small sample size for each subgroup, the representativeness of the tested vehicles in each subgroup became an issue. Table 2-5 shows the 90 percent confidence intervals of the average emission values for these nine subgroups.

Table 2-5 90% Confidence Intervals of the Average Values of 9 Vehicle Subgroups

IVE Class	*# Tested*	*CO*	*CO_2*	*NO_2*	*THC*
5	3	90%	26%	9%	80%
175	7	45%	19%	31%	124%
176	2	108%	1%	65%	63%
183	5	67%	22%	33%	58%
184	11	34%	17%	48%	54%
185	7	58%	20%	59%	62%
192	10	39%	13%	53%	34%
193	2	41%	18%	10%	108%
194	2	85%	16%	67%	47%

2.4 Base Emission Correction Factors

As explained in Section 1.2, the IVE model estimates the emissions of a certain vehicle (or a certain vehicle technology group) by referencing the driving time

distribution in various VSP bins of a driving cycle to the base emission rates of each of the VSP bins. The default base emission rates in the model are developed from dynamometer testing on a specific cycle at standard conditions. Most of these default values are derived from studies carried out in the United States and some are from study results in the European Union (for vehicles certified to meet the European series of emissions standards). It is necessary to modify the default base emission rates in order to reflect the unique emission characteristics of vehicle technologies in a developing country.

Because the road and traffic conditions in Beijing did not allow us to obtain the driving conditions of high power bins (i.e., high engine stress and high vehicle specific power) during our on-road emissions tests and because we only tested a very limited number of vehicles in major technology classes, our ability to construct completely new curves representing the relationships between emission rates and power bins for various vehicle technology classes in Beijing is very limited. However, we have established in Section 1.2 that for the same vehicle technology class, curves representing the relationships between normalized emission rates and power bins assume the same shape. What we aimed to achieve in this study was to determine the extent to which we must adjust the positions of default emissions-power bin curves based on the information we had obtained through on-road emission tests. The adjustment factors can be determined through the following five steps:

1) Estimate the second-by-second emission rates of tested vehicles, corresponding to power bins calculated from speed and acceleration data. Original testing data must be processed, time-aligned, and error free. Refer to our Tianjin report Section 3.3 for the data processing steps;

2) Calculate the total emissions of each of the tested vehicles on a hypothetic FTP cycle, using the emission-power bin relations established in step 1);

3) Estimate the total emissions of each of the tested vehicles on a hypothetic FTP cycle, using the emission-power bin relations built in the IVE model;

4) Compare results from Step 2) and Step 3) to obtain the emission correction factors for each vehicle; and

5) Combine and rationalize results from Step 4 to generate emission correction factors for major vehicle classes. Good judgment based on relevant research experience is necessary to make sense of sometimes seemly contradictory data from Step 4.

Correction Factors for Light-Duty Passenger Vehicles

Through this study, we obtained base emission correction factors only for light-duty passenger vehicles since our limited financial resources only allowed us to conduct

emissions tests on light-duty passenger vehicles. We followed the five steps described in the previous subsection. Step 2) produced the data in Table 2-6, and Step 3) generated the data in Table 2-7.

Table 2-6 Running Emissions based on Emission Testing (g/km)

IVE class	*# of Tested*	*CO*	*CO_2*	*NO_2*	*THC*
5	3	32.7	256.7	1.7	0.5
173	2	9.2	145.6	0.4	0.1
175	7	11.8	237.8	0.9	0.8
176	2	27.6	201.3	1.2	1.1
180	1	7.5	149.5	0.7	0.3
181	1	2.6	121.3	0.3	0.1
183	5	8.1	214.0	0.3	0.1
184	11	9.4	219.5	0.4	0.4
185	7	11.9	222.4	1.2	0.5
192	10	5.9	185.7	0.2	0.2
193	2	5.5	157.4	0.7	0.5
194	2	8.0	170.5	1.2	1.1

Table 2-7 Running Emissions Projected by IVE Model (g/km)

IVE class	*# of Tested*	*CO*	*CO_2*	*NO_2*	*THC*
5	3	34.2	262.0	2.2	5.2
173	2	19.4	178.8	0.6	1.4
175	7	14.0	232.3	0.8	1.1
176	2	30.6	222.1	1.0	2.2
180	1	2.9	188.1	0.2	0.1
181	1	4.4	186.6	0.2	0.4
183	5	2.1	239.0	0.3	0.1
184	11	9.8	232.3	0.4	0.5
185	7	21.4	222.1	0.4	1.0
192	10	1.2	239.0	0.2	0.1
193	2	5.9	232.3	0.2	0.3
194	2	12.9	222.1	0.3	0.7

Table 2-8 summarizes the final results of running emission correction factors (Step 5). The table shows that IVE model estimations of CO_2 emissions for all LDPV groups are the most consistent, about 10 percent higher than the actual emissions. This result is reasonable because Chinese LDPVs in general have smaller engines than their western counterparts (so the Chinese ones have higher fuel efficiency and emit less CO_2). For LDPVs manufactured before Euro I emission standards took effect in China, their NO_2 and THC emission rates are on average about 20 percent and 70 percent less than the defaults values in the model. For medium- and high-mileage LDPVs compliant with Euro I emission standards, their CO and THC emissions are on average 10 percent and 30

percent less, but their NO_2 emissions are 20 percent higher than the default values in the model. Interestingly, we saw that for LDPVs compliant with Euro II and III emission standards, CO emissions of low-mileage vehicles are significantly higher than the default values in the model, but CO emissions of high-mileage vehicles are 40 percent less than the default values. This indicates that over time, CO removal efficiency of the TWCs used in Chinese LDPVs does not decrease as much as the model assumes. In contrast, the NO_2 and THC removal efficiency of TWCs in Chinese LDPVs (with the exception of high-mileage LDPVs certified to meet Euro II emission standards) declines more severely than the model assumes. This is consistent with what we have seen in Figure 2-5.

Table 2-8 Correction Factors for Running Emissions

Standards	*Mileage*	*IVE class*	*CO*	*CO_2*	*NO_2*	*THC*
Pre Euro	>160K	5	1.0	0.9	0.8	0.3
Euro I	>80K	173, 175, 176	0.9	0.9	1.2	0.7
Euro II	< 80K	180, 183	3.9	0.9	1.0	0.9
	80-160K	181, 184	1.0	0.9	1.1	0.9
	>160K	185	0.6	0.9	2.7	0.6
Euro III	< 80K	192	4.0	0.9	1.2	1.9
	80-160K	193	1.0	0.9	3.5	1.5
	>160K	194	0.6	0.9	4.8	1.5

Table 2-9 shows cold start emissions of carbureted and fuel injection vehicles and the corresponding correction factors for base emissions.[32] It appears that the IVE model overestimates all start emissions from carbureted vehicles significantly and somewhat overestimated CO and CO_2 start emissions from fuel injection vehicles considerably. This is generally consistent with our findings in Tianjin.

Table 2-9 Start Emissions Comparison and Correction Factors

Pollutant	*Technology*	*Measured Cold Start*	*IVE Cold Start*	*IVE CF*	*Model Input CF*
CO	Carbureted	135	445	0.3	*0.3*
	Fuel Injection	26	72	0.4	*0.4*
CO_2	Carbureted	-26	194	-0.1	*0.01*
	Fuel Injection	35	169	0.2	*0.2*
NO_2	Carbureted	-1.9	9.5	-0.2	*0.01*
	Fuel Injection	0.9	1.0	1.0	*1.0*
THC	Carbureted	6.9	31.2	0.2	*0.2*
	Fuel Injection	6.2	6.7	0.9	*0.9*

[32] The method by which mobile fuel was introduced to an engine is the most critical factor in determining cold start emissions. Therefore, vehicles were only put into two large categories (carbureted or electric fuel injection) for correcting cold start emission factors.

Correction Factors for Light Heavy-Duty Diesel Trucks

In summer 2007, researchers from ISSRC and Tsinghua jointly carried out on-road emission testing of thirty-three heavy-duty diesel vehicles in Beijing with financial support from the Energy Foundation China Sustainable Energy Program.[33] Among these vehicles, twenty-four were light heavy-duty trucks, three were medium heavy-duty trucks, and six were buses. The distribution of these thirty-three tested vehicles by emission standard is below: three had been manufactured before any emission standards had been implemented in China, seven had been certified to Euro I standards, seventeen had been certified to Euro II standards, and six had been certified to Euro III standards.

The study recommends that the following emission rate adjustment factors (as listed in Table 2-10) may be used to for the heavy-duty diesel vehicle fleet in Beijing:

Table 2-10 Potential Base Emission Adjustment Values for Heavy-duty Diesel Vehicles in Beijing

Vehicle Categories	*CO*	*VOC ratio*	*NO_2 ratio*	*PM ratio*	*CO_2 ratio*
Pre Euro	0.22	0.13	0.23	0.38	0.85
Euro I	3.56	4.58	1.83	0.71	1.32
Euro II	3.72	4.80	1.79	1.66	1.39
Euro III	2.11	4.25	1.95	0.54	1.34
Overall	1.84	3.00	1.45	1.00	1.29
Recommendation	**1.59**	**2.40**	**1.32**	**1.0**	**1.0**

We used these recommended values to correct the base emission factors for heavy-duty diesel vehicles in Beijing when we estimated the total emissions from these vehicles in Chapter 4.

[33] We are deeply grateful to ISSRC, Tsinghua University, and the Energy Foundation China Sustainable Energy Program for permitting us to use the results (i.e., the base emission correction factors for heavy-duty diesel vehicles) of their study "A Study of the Emissions from Diesel Vehicles Operating in Beijing, China" in our analysis. The report the this study may be accessed at: http://www.efchina.org/FReports.do?act=detail&id=241.

3. Vehicle Activity Study

3.1 Methodology, Focus Areas, and Data Collection

Information on fleet composition and driving patterns is critical for calculating vehicle emission inventories, as explained earlier in Section 1.2. Detailed information on the number and share of various vehicles on the road, the average velocity of a particular location, the fraction of travel by each vehicle category, and the fraction of each type of driving all needed to be collected locally.

Driving and Start Pattern

Since the driving conditions of vehicles greatly influence their emissions, researchers need to understand which kind of driving and start (and how much of a particular kind of driving and start) occurs in a studied location. We carried out two different data collection activities in Beijing to obtain local driving patterns:

1) Collection of speed and acceleration distribution on different local roads with GPS devices.

A number of GPS devices were installed on four different types of vehicles (i.e., passenger car, taxi, bus, and truck) to collect their driving patterns in Beijing. To obtain the general driving pattern of passenger cars, we first selected three districts with different economic activities (i.e., a high-tech district, a central business district, and a district with mixed commercial and residential functions, see Figure 3-1). Next, in each of the three districts, a representative driving route (including a section of urban expressway, a section of multilane arterial road, and a section of residential road) was selected (see Figure 3-2). It took on average 45–60 minutes to completely travel each route. On each route, an experienced driver drove a car equipped with a GPS device continuously, following the traffic flow. To obtain driving patterns of taxis and trucks, a taxi and a truck were both instrumented with a GPS device first, and then their drivers drove these two vehicles for everyday use while the GPS devices recorded the driving patterns automatically. To obtain the driving pattern of buses, seven students were hired in Beijing. Each of them carried a GPS device and rode buses for six days (the routes were predetermined by the VA study coordinator). The GPS devices automatically recorded the driving patterns of various bus routes those students had taken. (Figure 3-3 illustrates the bus routes included in this study).

The GPS data was later screened and processed to generate second-by-second speed and acceleration profiles of the four different types of vehicles during different times of day. The amounts of time spent in each of the sixty power bins were then calculated (refer to section 1.2 for detailed description of the bin method in the IVE model). Finally, the driving pattern distributions were then matched with the emissions–power bin curves to generate local emissions inventories (refer to Figure 1-6).

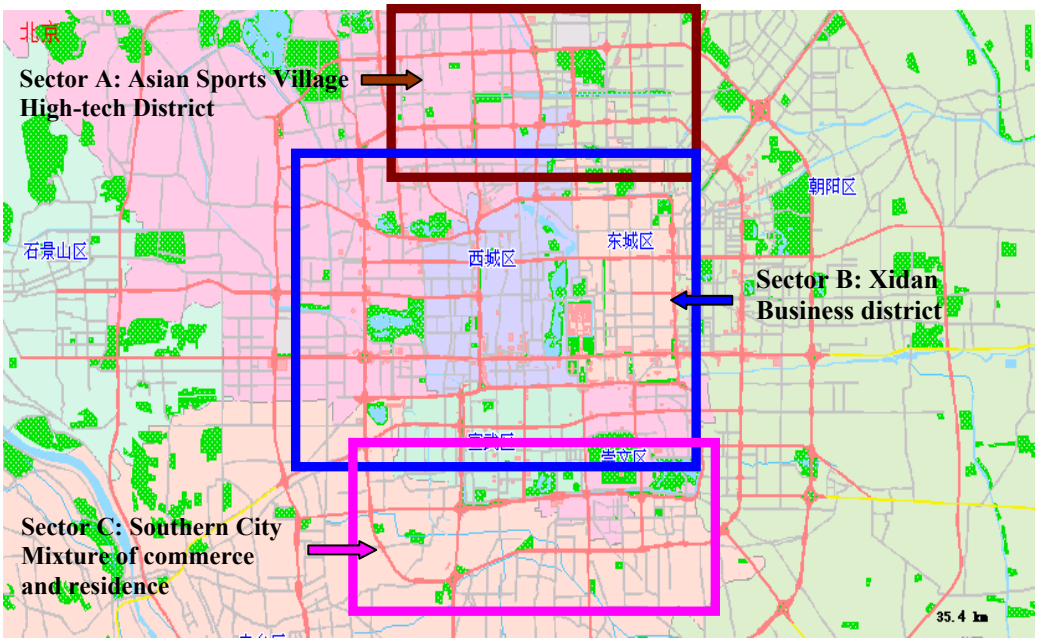

Figure 3-1 Three VA Focus Areas in Beijing

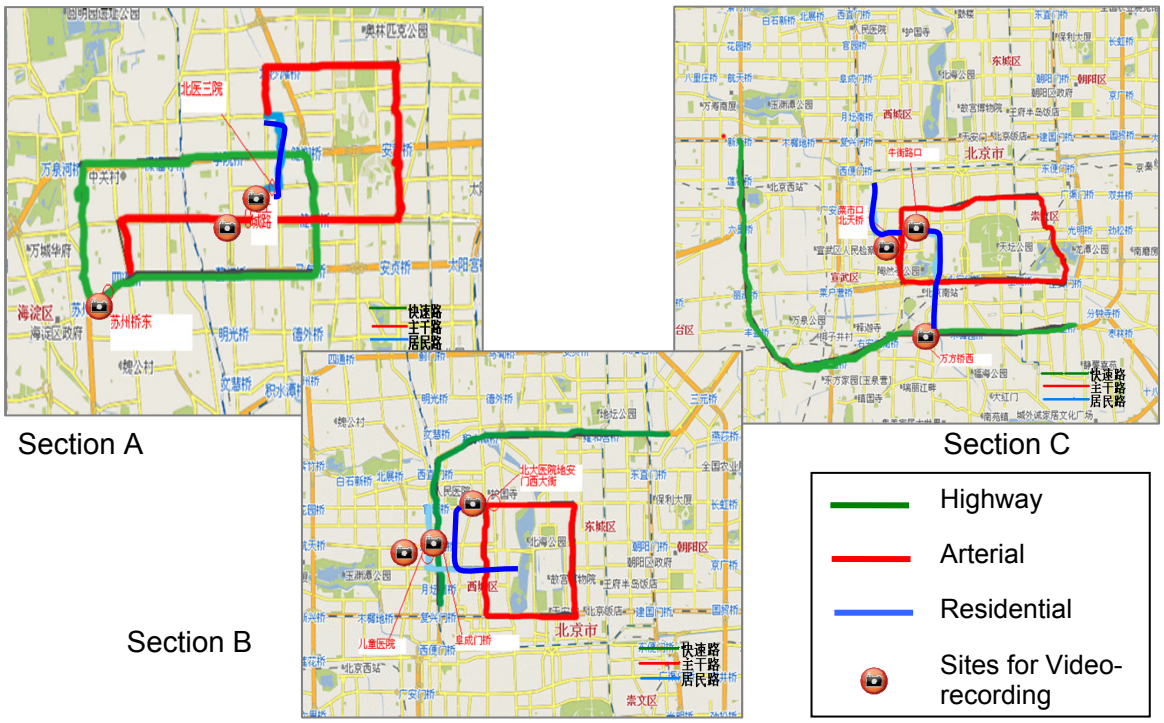

Figure 3-2 Driving Routes and Video-recording Sites in Three Focused Areas

Figure 3-3 Bus Routes Included in Beijing VA Study

2) Collection of the amount and distribution of engine starts.

The vehicle activity (VA) team used devices called vehicle occupancy count enumerators (VOCEs) to record the start patterns of private cars, taxis, and trucks. The VOCE records the voltage variation when an engine turns on and off and the time of each variation. The start pattern of each survey vehicle was recorded continuously for a period of five to seven days. A special piece of software developed by ISSRC was later used to categorize starts into different types (based on the interval timing of two adjacent starts).

Fleet Composition

The composition of on-road fleets under real-world conditions is often not the same as what is revealed by vehicle registration or I/M data because some types of vehicles are driven more than others. In Beijing, we used two methods to generate an accurate description of the real-world local fleet profile:

1) Videotaping traffic on various roadways to collect the proportion of various types of on-road vehicles (see Figure 3-2 for the videotaping sites). We recorded the traffic flow from the sides of nine urban roads during daytime hours (6:00 to 20:00). These nine roads represent three types of roads (i.e., urban expressways, arteries, and residential roads) in three urban districts with different economic activities and social strata. The fleet mix observed on these nine roads was then extrapolated throughout the city, following the distribution of various urban road types.

2) Surveying vehicles at parking lots, vehicle service centers, bus terminals, taxi stops, and truck rest areas to determine the distribution of specific vehicle technologies (e.g., age, mileage accumulated, emission control technology, engine size and technology, and use of air conditioning, *etc*.) of personal cars, taxis, buses, and trucks. Surveys were conducted at selected parking lots in different urban districts.

Statistics of Collected VA Data

The VA team, comprised of a dozen students from the Department of Environmental Science and Engineering at Tsinghua University and the Department of Environmental Engineering at Beijing Technology and Business University, collected original vehicle activity data in Beijing from March 31 to April 8, 2008. Table 3-1 summarizes the types of data collected during the nine-day period, the devices used to collect these data, and the numbers of valid data points obtained in Beijing.

Using twelve GPS units, the VA team collected velocity, acceleration, altitude, longitude, and latitude data from three passenger cars, one taxi, a number of buses (seven students carrying GPS devices rode with various buses for six days), and one truck. Data for generating general fleet composition were collected with three video cameras, concurrently with the driving pattern study. Traffic flow at the nine sites was recorded with these three cameras during daytime hours for three days (from 6:00 to 20:00, twenty minutes of each hour). Data on specific vehicle technology were collected through a survey of 2,500 cars, 120 trucks, and 60 taxis. The specific technology distribution of buses was retrieved based on relevant information from the Beijing Pubic Transport Holdings company.

Table 3-1 Vehicle Activity Data Collection in Beijing

VA activity item	*Device used*	*Type of data collected*	*Valid data points*
Driving pattern	GPS	Second-by-second velocity, UTC (universal time coordinated), altitude, longitude, latitude, number of satellite	PC expressway: 100,604 seconds PC arteries: 109,835 seconds PC residential: 96,543 seconds Taxi: 648,000 seconds Truck: 36,000 seconds Bus: 117,258 seconds
Start pattern	VOCE	Starting and stopping time	132 days (vehicle day)
On-road fleet composition	Video camera	Vehicle, license plate, load	42 sections, about 20 minutes in each section
Specific technology	none	License number, model year, fuel, engine size, automaker, age, mileage, AC, transmission, TWC, fuel injection, maintenance	Passenger cars: 2,500 Trucks: 120 Taxis: 60

3.2 Vehicle Distribution

On-road Fleet Composition

Our analysis of the forty-two sections of recorded traffic flow in the three focus areas led to the results in Table 3-2. The composition of on-road fleet varied on different roads of the city at different times. Overall, from 6:00 to 20:00, passenger vehicles and taxis were responsible for about 87 percent of road use in the urban center of Beijing, buses of all different sizes together contributed about 12 percent of road use, and small- and medium-sized trucks accounted for less than 1 percent of road use. During daytime hours, very few motorcycles were observed on the urban roads of Beijing, and big trucks did not appear on the videotapes at all. This is because heavy trucks were not allowed to enter the urban area (within fifth-ring road) from 6:00 to 23:00, and motorcycle ownership is generally restrained in Beijing's urban districts.

One must be cautious when extrapolating the fleet composition observed during daytime in the urban areas of Beijing to the whole metropolitan area. It is very likely that in the suburban districts of Beijing, trucks and motorcycles account for a higher share of road use while taxis account for a much lower share of road use. Also, since heavy trucks can only enter the urban areas of the city at night, they contribute to the majority of the road use in urban areas at night, which was not captured by our video cameras. Thus, when estimating the total daily distance travelled of taxi, bus, and truck fleets, we did not use their relative share of road use in comparison to passenger cars (which was revealed by recorded traffic flow). Instead, as shown later in this section, we used direct results from parking lot surveys, and the average daily travel by a single vehicle.

Table 3-2 Observed On-road Fleet Composition in Beijing

Focus Area	*Time*	*Passenger Vehicles*	*Taxi*	*Small Truck*	*Medium Truck*	*Large Truck*	*Small Bus*	*Medium Bus*	*Large Bus*	*Motor-cycles*	*Total*	*Average Vehicles / Hr*
A	06:00-13:00	57.3%	30.5%	0.3%	0.1%	0.0%	6.9%	1.3%	3.4%	0.2%	100.0%	1097
A	13:00-20:00	62.7%	24.9%	0.5%	0.0%	0.0%	6.3%	1.3%	3.7%	0.5%	100.0%	1066
B	06:00-13:00	58.5%	25.6%	0.8%	0.2%	0.0%	9.0%	0.7%	4.3%	0.8%	100.0%	1669
B	13:00-20:00	61.5%	24.9%	0.8%	0.1%	0.0%	6.0%	0.7%	5.1%	0.8%	100.0%	1354
C	06:00-13:00	58.0%	21.8%	1.1%	0.4%	0.0%	11.8%	1.1%	4.7%	1.1%	100.0%	1293
C	13:00-20:00	57.0%	25.2%	0.5%	0.3%	0.0%	11.3%	0.5%	4.3%	0.9%	100.0%	1235
Subtotal	06:00-13:00	57.8%	28.6%	0.5%	0.1%	0.0%	7.7%	1.1%	3.8%	0.5%	100.0%	1267
Subtotal	13:00-20:00	62.3%	24.9%	0.6%	0.0%	0.0%	6.2%	1.1%	4.2%	0.6%	100.0%	1165
Total	All Day	60.0%	26.9%	0.6%	0.1%	0.0%	7.0%	1.1%	4.0%	0.5%	100.0%	1216

Specific Technology Distribution

Passenger Vehicles

The VA team surveyed about 500 passenger vehicles in selected parking lots and 2,000 vehicles in various vehicle service centers.[34] Table 3-3-a, -b, and -c summarize the distributions of the surveyed vehicles based on their main technical features. Our survey shows that nearly all passenger vehicles in Beijing use gasoline and are equipped with air conditioning systems and catalytic converters (CC). About 56 percent of the surveyed passenger vehicles are equipped with mechanical (standard) transmission systems, and the rest have automatic transmission systems.

Table 3-3-a General Characteristics of Surveyed Passenger Vehicles in Beijing

*Type of Fuel**	*Air Conditioning System*	*Type of Transmission*	*Catalytic Converter (CC)*
100% gasoline	99.7% with A/C	55.7% mechanical transmission	0% without CC
0% diesel	0.3% without A/C	44.3% automatic transmission	100% with CC

About 14 percent of these surveyed vehicles have engine displacements smaller than 1.5 liters, 53 percent of them have engine displacements ranging between 1.5 and 3.0 liters, and a third of them have engine displacements larger than 3.0 liters. About 61 percent of the surveyed vehicles had been driven for less than 80,000 kilometers, 28 percent had accumulated mileage ranging between 80,000 and 160,000 kilometers, while the rest had been driven for more than 160,000 kilometers (see Table 3-3-b).

Table 3-3-b Size and Usage of Surveyed Passenger Vehicles in Beijing

Engine Size	*61.2% Low Use (<80 K km)*	*28.4% Medium Use (80-161 K km)*	*10.4% High Use (>161 K km)*
13.7% Small (<1.5 liters)	11.04%	1.19%	1.49%
53.1% Medium (1.5-3.0 liters)	28.66%	18.21%	6.27%
33.2% Large (>3.0 liters)	21.50%	8.96%	2.69%

[34] Passenger vehicle fleet is relatively new in China, and most of the vehicles have electronic dashboards. To obtain odometer readings during a survey, vehicle owners had to be present, and the engine had to be turned on. This has made parking lot surveys very time consuming and difficult to execute. Under such circumstances, we turned to service centers to collect vehicle information. We realized that sampling vehicles at service centers is likely to incur certain bias. We then compared the results of this survey with those from a similar study in Beijing in 2004 and those from our VA study in Tianjin in 2006 as well as Beijing vehicle sales data from recent years. To our delight, the comparison indicates that the survey results appear to be quite reasonable.

According to information from the Beijing Environmental Protection Bureau (BJEPB), we estimated that at the beginning of 2008, about 8 percent of passenger vehicles in Beijing had been manufactured before the Euro I emission standards took effect in Beijing.[35] In the late 1990s, the Beijing municipal government ordered these vehicles to be retrofitted with two-way catalysts to reduce their emissions.[36] About 17 percent, 42 percent, and 30 percent of passenger vehicles were certified to meet Euro I, II, and III emission standards, respectively. Only 4 percent of passenger vehicles in use were certified to Euro IV emission standards (see Table 3-3-c).

Table 3-3-c IVE Technology Fractions of Passenger Vehicles in Beijing

Technology Description	*Emission Standards*	*Fraction*
Gasoline, 4-stroke, Carburetor, 2-way Catalyst		8.2%
Gasoline, 4-stroke, MPFI, TWC	Euro I	17.4%
	Euro II	41.7%
	Euro III	30.0%
	Euro IV	3.7%

Our survey of 2,500 passenger vehicles shows that the average age of Beijing passenger vehicle fleet was about 4.7 years old (the number is slightly higher, but close to the findings in our 2006 Tianjin study and the 2004 Beijing VA study). Figure 3-4 illustrates the age distribution of the passenger vehicles in Beijing, based on vehicle sales and turnover information.

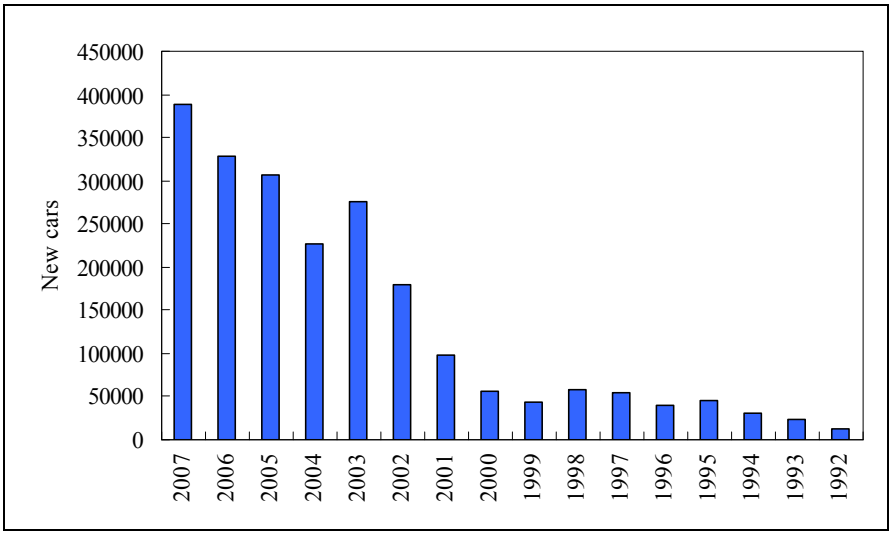

Figure 3-4 Number of New Passenger Vehicles in Beijing

[35] Over the past ten years, the Beijing municipal government has ordered the scrapping of most carbureted vehicles, and it intended to phase out all carbureted vehicles in the coming year.

[36] However, our own emissions testing and other people's studies (Zhou, Fu, & Cheng 2007) all indicate that the retrofitting program was not very effective.

A polynomial regression of average accumulated mileage versus vehicle age led to the equation showing in Figure 3-5. [37] The second derivative of the equation is negative, indicating that unlike the common trend in developed countries, the average mileage driven by passenger cars in Beijing does not reduce with the aging of these vehicles. In other words, the high mileage vehicles are used as much as newer vehicles, while the former vehicles usually generate many more pollutants per kilometer driven because of less effective pollution control. This may be caused by dated engine and emission control technologies or deterioration of these technologies over time.

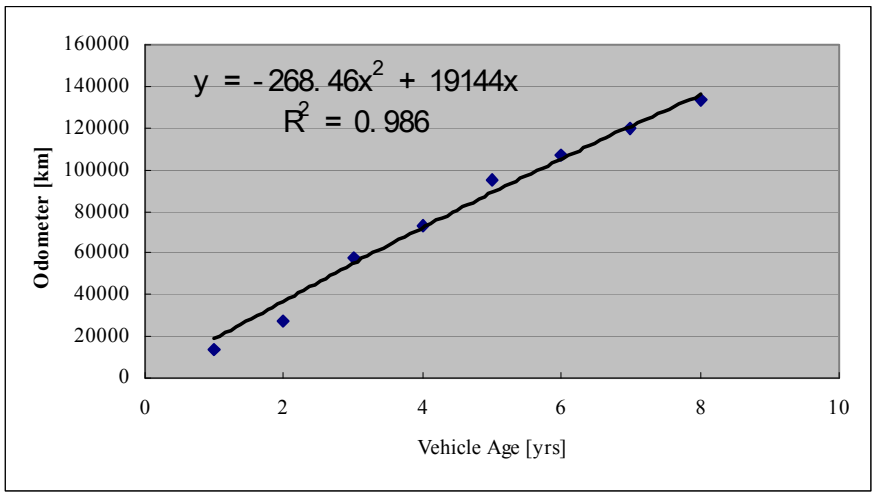

Figure 3-5 Mileage Accumulation by Passenger Vehicles over Time

From Figure 3-5, we estimated that passenger vehicles in Beijing were driven for about fifty kilometers per day. There were about 2.42 million passenger vehicles registered in Beijing at the end of 2007; thus, the total mileage driven by the Beijing passenger fleet per day was about 121 million kilometers.

Taxis

Our surveys of sixty taxis show that 96 percent of them had an engine displacement of greater than 1.5 liters but less than 3.0 liters, and only 4 percent of all taxis had an engine displacement of less than 1.5 liters. Two thirds of the surveyed taxis had already accumulated high mileage (greater than 160,000 kilometers), while only 10 percent had been driven less than 80,000 kilometers (see Table 3-4). The majority of the taxis (82 percent) met Euro III emission standards, and the rest met Euro II standards.

[37] We were not able to collect sufficient mileage information through parking lot surveys this time, so we combined information collected during this survey with the information collected in the 2004 Beijing VA study to generate the chart and equation.

Table 3-4 Engine Size and Usage of Surveyed Taxis in Beijing

Engine Size	*10% Low Use (<80 K km)*	*22% Medium Use (80-160 K km)*	*68% High Use (>160 K km)*
4% Small (<1.5 liters)	0.00%	0.00%	4.00%
96% Medium (1.5–3.0 liters)	10.00%	22.00%	64.00%

Data collected by the GPS device show that a typical Beijing taxi is driven for about 360 kilometers during an eighteen-hour working schedule per day. There were about 66,000 taxis in Beijing at the beginning of 2008. Thus, the Beijing taxi fleet drove for nearly 23.8 million kilometers per day in total in early 2008.

Trucks

Our surveys of 120 trucks indicate that 56.5 percent of trucks registered in Beijing were medium-sized trucks [their gross vehicle weight ratings (GVWR)[38] are between 14,000 to 33,000 pounds], 30 percent were heavy trucks (their GVWRs are greater than 33,000 pounds), and only 13.5 percent were light trucks (their GVWRs are between 9,000 and 14,000 pounds). About two-thirds of these vehicles were relatively new, with accumulated mileage that was less than 80,000 kilometers, 19 percent had accumulated mileage between 80,000 to 160,000 kilometers, and 14 percent had been driven for more than 160,000 kilometers (see Table 3-5-a).

Table 3-5-a Weight and Usage of Surveyed Trucks in Beijing

Vehicle Weight	*67.3 % Low Use (<80 K km)*	*18.6% Medium Use (80-160 K km)*	*14.1% High Use (>160 K km)*
13.5% Light (9 K to 14 K lbs GVWR)*	4.7%	6.0%	2.8%
56.5% Medium (14 K to 33 K lbs GVWR)	38.9%	9.1%	8.5%
30% Heavy (>33 K lbs GVWR)	23.7%	3.5%	2.8%

Nearly 83 percent of all surveyed trucks ran on diesel fuel, and the rest ran on gasoline. Less than 1 percent of these trucks were certified only to Euro I emission standards, 22 percent of them were supposed to meet Euro II standards, and the majority, 77 percent, were certified to Euro III standards (see Table 5-6-b).

[38] Gross Vehicle Weight Rating (GVWR) indicates how much weight a vehicle is designed to carry. The GVWR includes the net weight of the vehicle, plus the weight of passengers, fuel, cargo, and any additional accessories. The GVWR is a safety standard used to prevent overloading.

Table 3-5-b Technologies and Emission Standards of Surveyed Trucks in Beijing

Fuel	*Air/Fuel Control*	*Certified Standards*	*Fraction*
Petrol	Fuel Injection	Euro I	0.4%
	Fuel Injection	Euro II	3.0%
	Fuel Injection	Euro III	13.7%
Diesel	Fuel Injection	Euro I	0.4%
	Fuel Injection	Euro II	19.2%
	Fuel Injection	Euro III	63.3%

Beijing trucks on average travelled about 100 kilometers per day, and there were about 184,000 trucks registered in Beijing at the end of 2007. Thus, the total distance travelled by the Beijing truck fleet was about 18.4 million kilometers per day.

Buses

The VA team was not able to obtain all needed information on specific technology distribution of the Beijing bus fleet for 2008. To compensate for the missing information, we decided to borrow the weight distribution of the Beijing bus fleet from the 2004 Beijing VA study (Liu *et al.* 2005). However, the mileage and emission performance data of the 2004 study were obviously outdated. To prepare for the 2008 Beijing Olympic Games, the municipality had replaced a large number of its old buses with new and cleaner ones (including both lower emission diesel buses and natural gas buses). We estimated the distribution of the accumulated mileage and emission performance of Beijing buses in 2008 based on relevant information from the Beijing Public Transportation Holding Company (BJPTHC), such as the numbers and the types of new buses put in use each year and average daily distance driven by public buses. The results are shown in Table 3-6-a and 3-6-b.

Table 3-6-a Weight and Usage of Buses in Beijing

Vehicle Weight	*37.2% Low Use (<80 K km)*	*22.1% Medium Use (80-160 K km)*	*40.7% High Use (>160 K km)*
76.2% Medium (14 K – 33 K lbs GVWR)	23.2%	18.6%	34.3%
23.8% Heavy (>33 K lbs GVWR)	13.9%	3.5%	6.4%

Table 3-6-b Fuel Type and Emission Standards of Buses in Beijing

Fuel	*Emission Standard*	*Fraction*
Natural Gas, carbureted or FI, no TWC or EGR		22.0%
Diesel	Euro II	6.0%
	Euro III	49.8%
	Euro IV	22.2%

Our analysis indicated that the majority of Beijing buses (about 76 percent) were considered to be medium-sized buses and the rest were heavy buses. About 37 percent had not been driven more than 80,000 kilometers, about 41 percent had accumulated mileage of more than 160,000 kilometers, and the rest had accumulated mileage between 80,000 and 160,000 kilometers. About 22 percent of Beijing buses ran on natural gas, and the rest used diesel fuel. Among the diesel buses, nearly two thirds were compliant with Euro III emission standards, 28 percent were certified to Euro IV emission standards, and about 6 percent could only meet Euro II emission standards.

Information from BJPTHC shows that Beijing public buses ran about 185 kilometers per day, and there were about 20,000 public buses in Beijing. Therefore, we estimated that the Beijing bus fleet travelled about 3.7 million kilometers per day in total.

3.3 Driving and Start Patterns

The overall use and starts of the four major vehicle sub-fleets are summarized in Table 3-7. According to official statistics, there were about 2.7 million registered vehicles (including passenger vehicles, taxis, buses, and trucks) in Beijing as the end of 2007, among which, 90 percent were passenger vehicles. We estimate that the Beijing fleet travelled about 167 million kilometers per day in total: 121 million kilometers were attributed to passenger vehicles, about 23.8 million kilometers to taxis, about 18.4 million kilometers to trucks, and about 3.7 million kilometers to buses. On a per vehicle basis, taxis had the most daily average travel, at 360 kilometers per day, buses had the second highest daily travel, at 185 kilometers per day, trucks travelled on average about 100 kilometers per day, and passenger vehicles, about 50 kilometers.

Table 3-7 Fleet Composition, Vehicle Use, and Start in Beijing

Category	*Passenger Vehicle*	*Taxi*	*Bus*	*Truck*	*All*
Number of Vehicles	2,420,000	66,000	20,000	184,000	*2,690,000*
Vehicle Use (km/veh/day)	50	360	185	100	--
Starts (#/veh/day)	6.7	9	9	9	--
Overall Starts (#/day)	16,214,000	594,000	180,000	1,656,000	*18,644,000*
Overall Travel (km/day)	121,000,000	23,760,000	3,700,000	18,400,000	*166,860,000*

Driving Pattern

Daily Distance Travelled by Sub-fleets

The driving pattern of passenger vehicles was analyzed for the three different types of roads: highways, residential, and arterial roads. They are abbreviated as PCHwy,

PCRes, and PCArt in the sections and charts below. Figure 3-6 shows total distance travelled by six major vehicle sub-fleets in Tianjin. The total distance travelled by all vehicles in Beijing was about 167 million kilometers per day in early 2008. Passenger vehicles accounted for about 72 percent of total distance travelled (the lower three blocks in each column in the figure). Of all passenger-vehicle distance travelled, about 42 percent occurred on urban residential roads, 30 percent on urban expressways, and the rest on arterial roads. Taxis and buses accounted for about 14.2 percent and 2.2 percent of total travel, respectively. Trucks accounted for only about 11 percent of travel in Beijing. In terms of distribution of total travel over time, it was evident that total vehicle activity increased in the early morning after 5:00 and reached the first peak during the morning rush hour (7:00 to 9:00). Another traffic peak occurred around late afternoon and early evening during the evening rush hour (16:00 to 19:00). Yet, traffic in Beijing was heavy in general during the daytime. Interestingly, traffic picked up somewhat before 24;00 and lasted until 3:00, largely due to concentrated heavy truck activities.

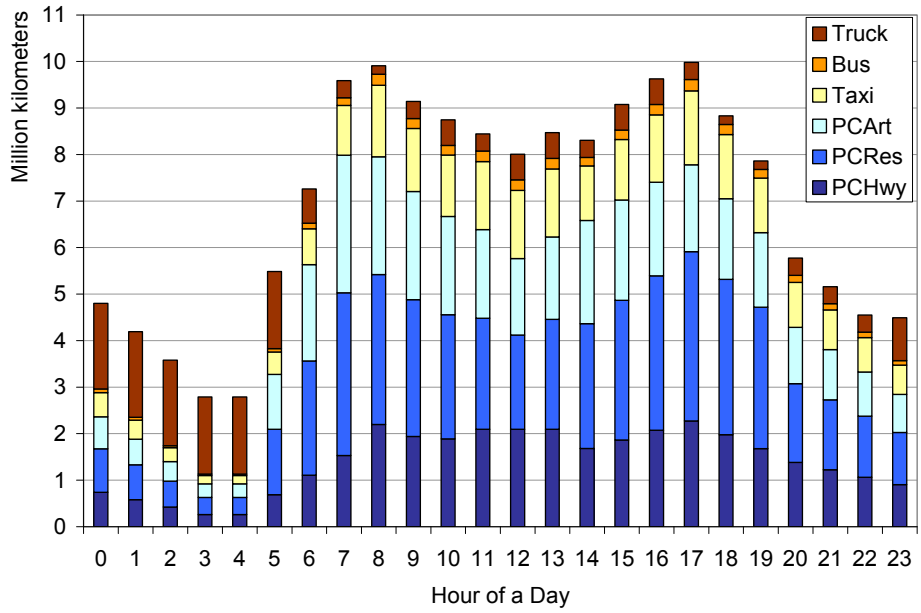

Figure 3-6 Distance Travelled by Different Sub-fleets throughout a Day

Speed

Figure 3-7 depicts the average hourly speeds of different types of vehicles throughout the day. It is obvious that for almost all vehicles and on all kinds of road, speeds during morning and evening rush hours were the lowest during the day, just somewhere between 10 to 15 kilometers per hour. The highest speed was achieved on urban highway in late evening and at night, at about 45 km/hr. The average daily speed on urban highway was about 35 km/hr, although during rush hour the hourly speed on highways were sometimes as low as 24 km/hr. Average daily speeds on arterial roads and residential roads were quite similar, and both were around 20 km/hr. Among all the sub-

fleets, buses had the lowest average speed of less than 17 km/hr, trucks were the next slowest, with an average daily speed of 19 km/hr, and the taxis did slightly better at an average daily speed of 21 km/hr.

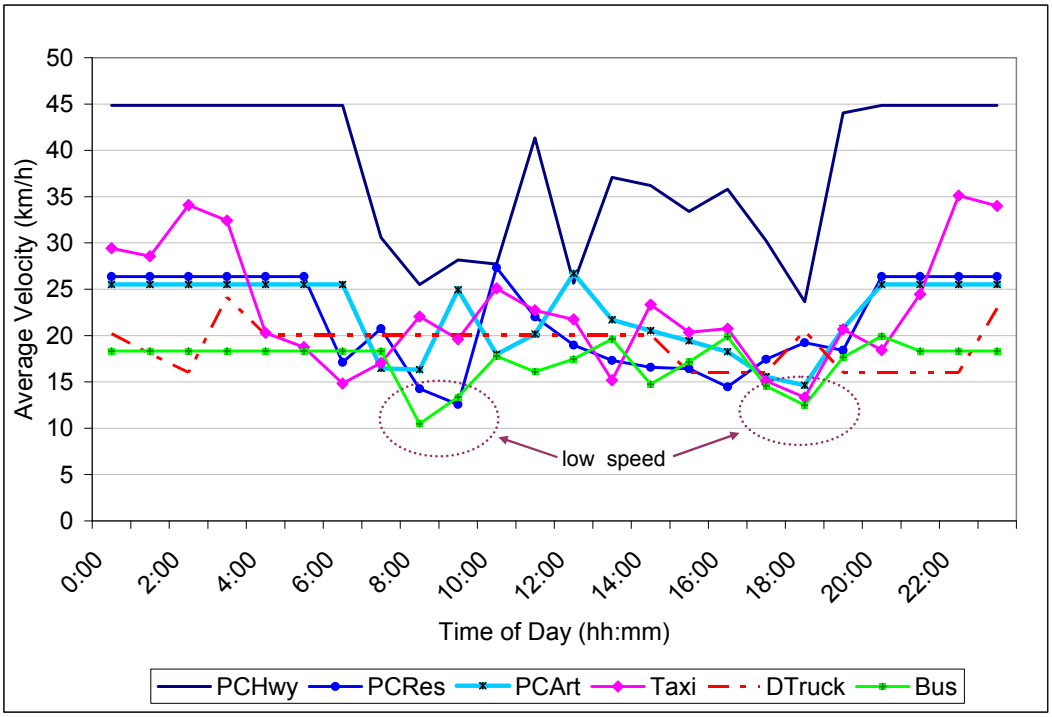

Figure 3-7 Average Speed of Sub-fleets in Beijing

Note: original speed data are lacking for some hours. For instance, the passenger cars and buses were not used at night, while the heavy trucks were rarely used in the morning and early afternoon. Their speed data for those hours were extrapolated from the closest available data points.

Power Bin Distribution

One purpose of the VA study is to create the local driving pattern curves for major sub-fleets for different hours of the day. (Recall from Section 1.2 that local driving pattern distribution is one of the two key components for calculating mobile emissions.) Using a program developed by ISSRC, the second-by-second speed, altitude, longitude, and latitude data recorded by GPS devices (which were mounted onto three passenger vehicles, a taxi, a number of buses, and a truck) were converted into second-by-second VSP and engine stress data, and then power bin distributions of the different driving cycles (expressed as the percentage of time spent by a vehicle in different power bins during one hour) were created. Figure 3-8-a, -b and -c illustrate the typical power bin distributions of passenger vehicles on highways, residential roads, and arterial roads at 9:00, 12:00, and 2:00. Figure 3-9-d illustrates the typical power bin distributions of taxis at 9:00, 12:00, and 2:00.

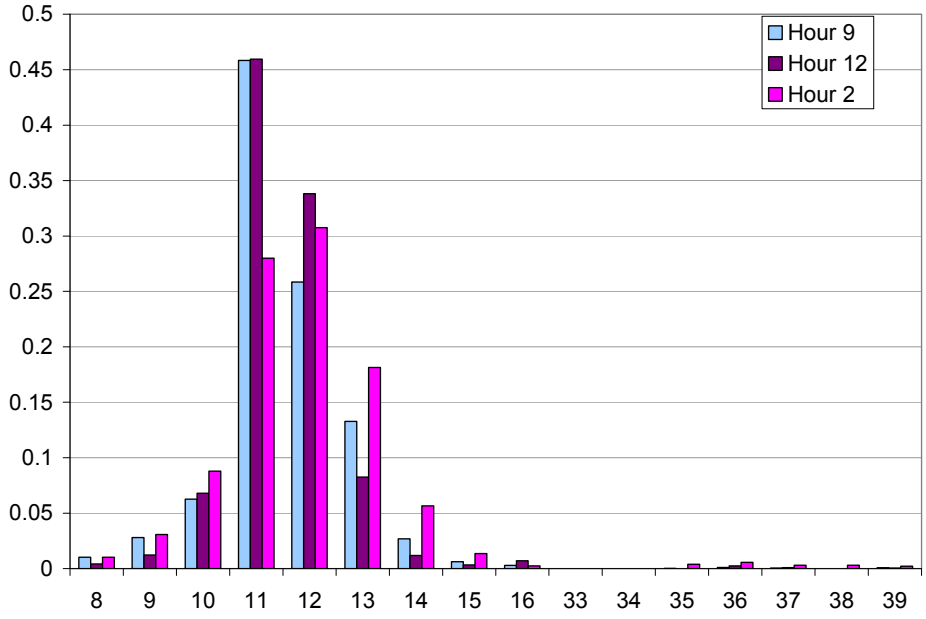

Figure 3-8-a Power Bin Distribution on PC Highways

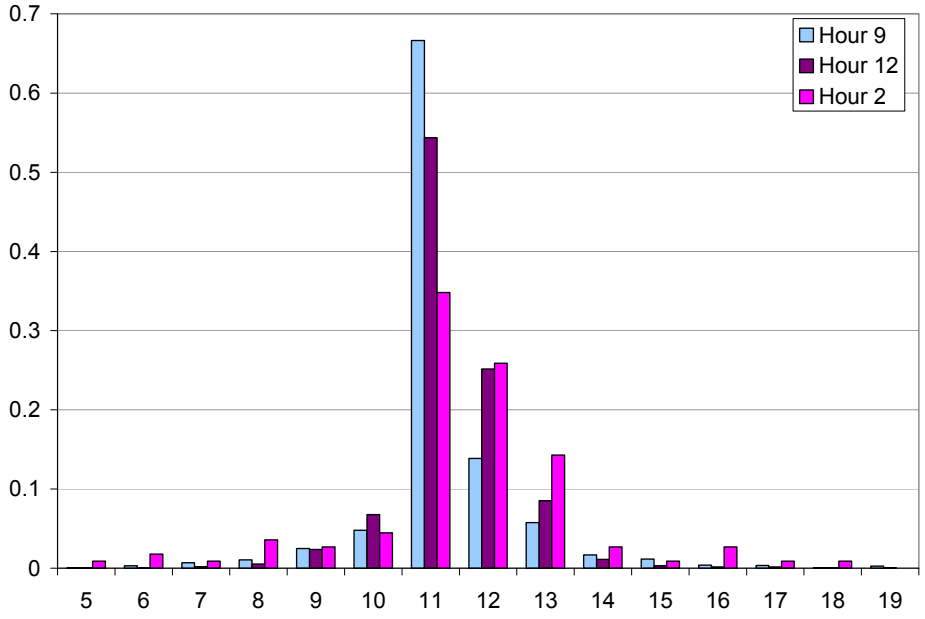

Figure 3-8-b Power Bin Distribution on PC Residential Roads

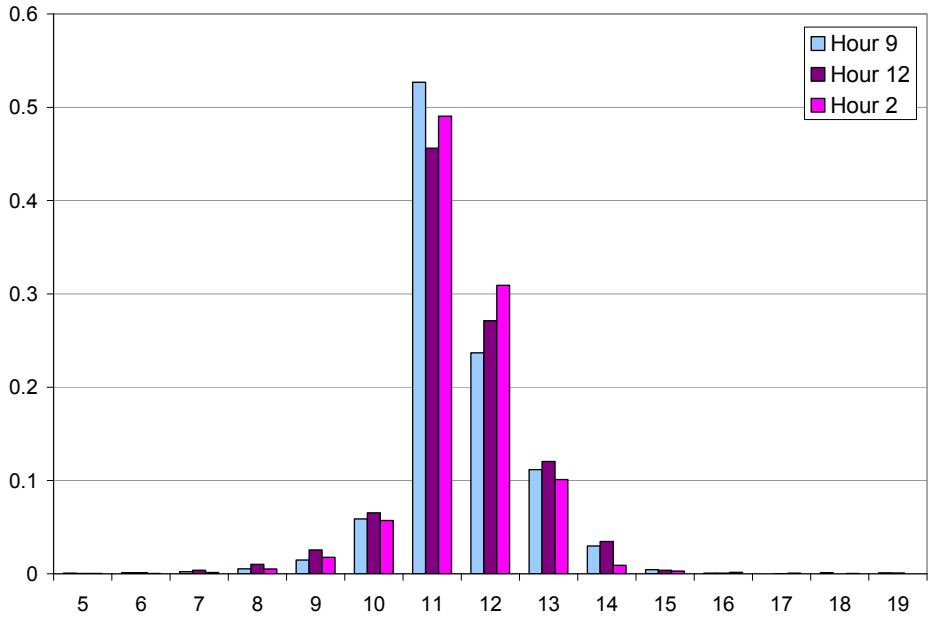

Figure 3-8-c Power Bin Distribution on PC Arterial Roads

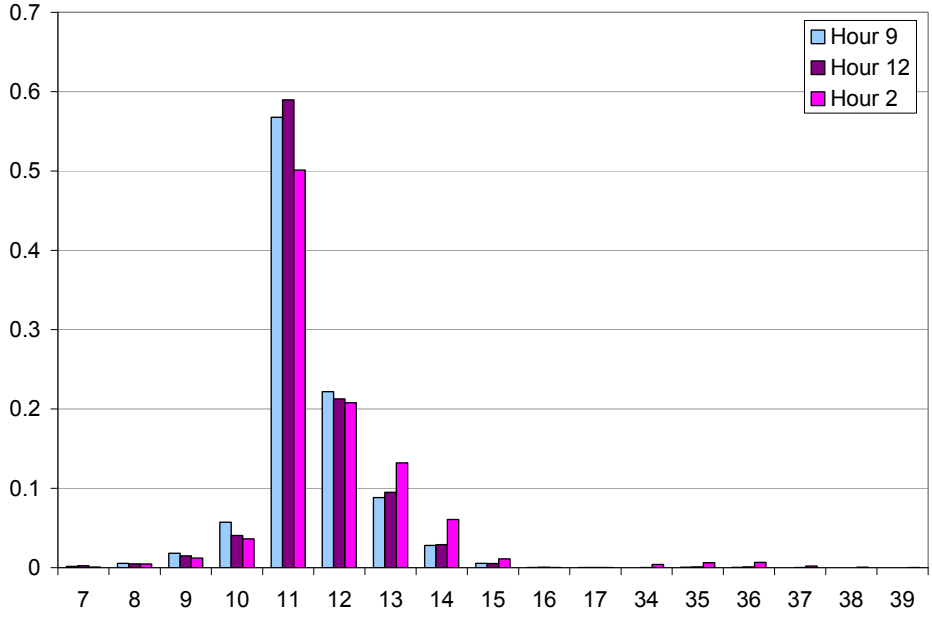

Figure 3-8-d Power Bin Distribution of Beijing Taxi

These charts show that in general passenger vehicles were driven more aggressively on highways and at a higher speed in the early morning (2:00) (i.e., more time on highways and during early morning was spent in higher power bins). Traffic was the worst during morning rush hour, especially on residential roads, on which about two-thirds of all driving time was spent under idling and very low-speed driving conditions.

Start Pattern

Vehicle emissions are influenced by the temperature and status of their engines and three-way catalysts. Engines and catalysts only work at their best efficiency when their temperature reaches certain levels. Therefore, it is important to include the impacts of engine starts when estimating mobile emissions, especially for cold climate. We used Vehicle Occupancy Count Enumerators (VOCEs), devices made by researchers at ISSRC, to record the number of starts and soak time. Soak time of a vehicle engine operation log is defined as the duration of time in which the vehicle's engine is not operating and that precedes a successful vehicle start, as illustrated in Figure 3-9. Start pattern is determined by the length of soak time. The longer the soak time, the more likely a start is to be categorized as a cold start.

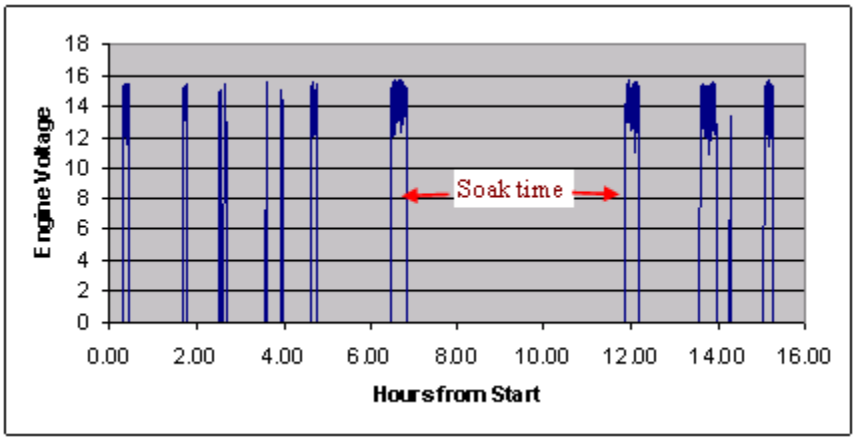

Figure 3-9 Illustration of Start Pattern Based on Engine Soak Time

Figure 3-10 describes the start distribution (number of starts and start pattern) of the Beijing fleet throughout the day. Our study has shown that passenger vehicles on average had 6.7 starts and other vehicles had about nine starts per day. The total number of starts of Beijing fleet totaled about 18.6 million per day, of which, passenger vehicles accounted for 87 percent. Starts with soak time of no less than six hours (cold starts) accounted for about 23 percent of all starts, and most of them occurred during early morning and late afternoon. Since engines and catalysts do not work at their best efficiency during cold starts, start emissions are likely to account for a considerable share of total emissions during early morning and late afternoons. This will be shown in Chapter 4. Starts with a soak time of no longer than fifteen minutes account for about one third of all starts, and their distribution was rather even throughout the day. Such starts are usually considered as "hot" and do not generate many start emissions.

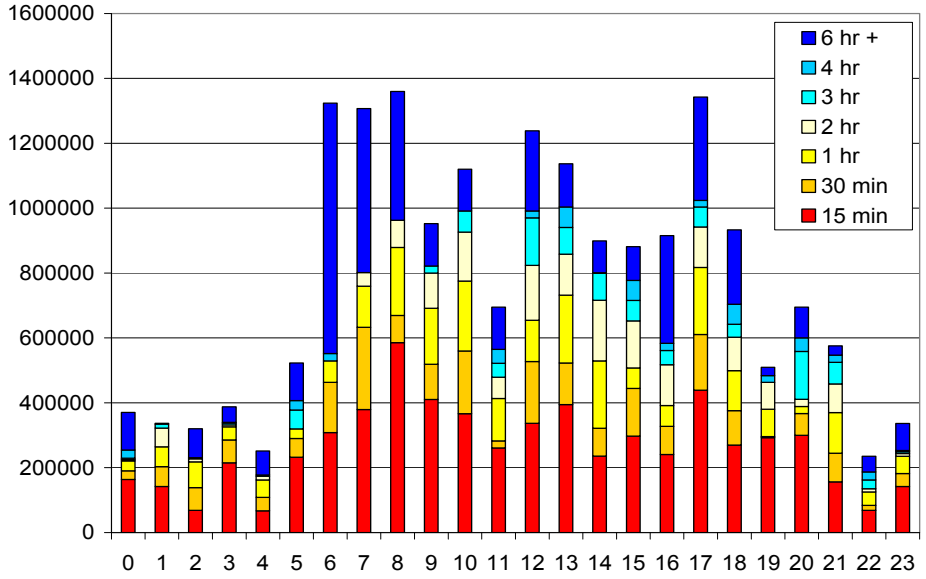

Figure 3-10 Overall Start Pattern of Beijing Vehicle Fleet

4. Estimating Mobile Emissions with IVE Model

In previous chapters, we have explained and examined the essential information for estimating emission inventory with the IVE model, i.e., local fleet composition, vehicle specific technology distribution, driving and start patterns, and base emission correction factors (BECF). The original data collected in the field were cleaned, processed, and converted into a number of files in certain formats that can be read by the IVE model. After the model has read and imported critical information contained in those files, users can interact with the model through four interfaces, as illustrated in Appendix B.

In this chapter, we first estimate the total amount of mobile emissions of the Beijing fleet, incorporating the base emission correction factors generated in Chapter 2. Next, we compare estimated emissions with base emission correction factors and those without base emission correction factors. We then examine emissions by major sub-fleets and every vehicle technology group to scrutinize relative emission contributions by different vehicle groups. Lastly, we analyze emissions under several different scenarios to investigate how certain inputs, such as daily temperature, fuel quality, effectiveness of I/M program, and traffic management, may influence total mobile emissions.

4.1 Emissions with Base Emissions Correction Factors

When we run the IVE model, it takes information from the Beijing fleet files (including information on specific technology distributions for passenger cars, taxis, trucks, and buses), location files (including information such as distance travelled by different types of vehicles, VSP distribution of different types of roads during different hours of the day, and number and distribution of engine starts) and the BECF file (base emission correction factors for Beijing light-duty passenger vehicles and light and medium heavy-duty diesel vehicles are listed in Section 2.4.). We also entered additional necessary inputs manually: for local climate information, we used hourly weather conditions (temperature and relative humidity) of April 1, 2008.[39] On that particular day, the hourly temperature ranged between 8ºC to 14ºC and the hourly humidity varied from 33 percent to 81 percent. We chose the option that the quality of mobile fuels is moderate (the sulfur and benzene contents in gasoline are around 300 ppm and 1.5 percent; while sulfur content in diesel fuel is around 500 ppm). We also assumed that about two-thirds of all the trucks' activities (distance travelled and engine starts) occurred between 23:00 and 6:00 when heavy trucks were allowed to enter the city.

Using the IVE model, we estimated that the total daily mobile emissions from the Beijing fleet are the following:

- CO: about 1,270 tons (emission factor is 7.6 g/km);
- VOC: about 180 tons (emission factor is 1.1 g/km);

[39] The weather data were obtained from www.wunderground.com.

- NOx: about 270 tons (emission factor is 1.5 g/km); and,
- PM: 4.5 tons (emission factor is 0.03 g/km).

Figure 4-1-a, -b, -c, and -d portray hourly variations of total CO, VOC, NOx, and PM emissions. CO and VOC emissions have two peaks, at morning and evening rush hours. There are also small peaks of CO and VOC emissions around 12:00. These peaks are related to high vehicle activities during these time periods (refer to Figure 3-6 for the hourly total distance travelled). Hourly trends of NOx and PM emissions are quite similar to each other. Interestingly, in addition to the peaks during morning and evening rush hours, emissions of these two pollutants also peak around 2:00.[40] Since the truck fleet is a major contributor to both NOx and PM emissions in Beijing, the activity pattern of trucks (night driving) to a large extent determines the emission patterns of NOx and PM.

Start emissions (the darker parts in the figures below) account for 22 percent, 14 percent and 11 percent of total daily VOC, CO, and PM emissions, but only account for 6 percent of total NOx emissions.[41] The overall hourly trends of start emissions are consistent with the vehicle start pattern illustrated in Figure 3-10. In other words, total start emissions peak during morning and evening hours when a high percentage of total engine starts are cold starts.

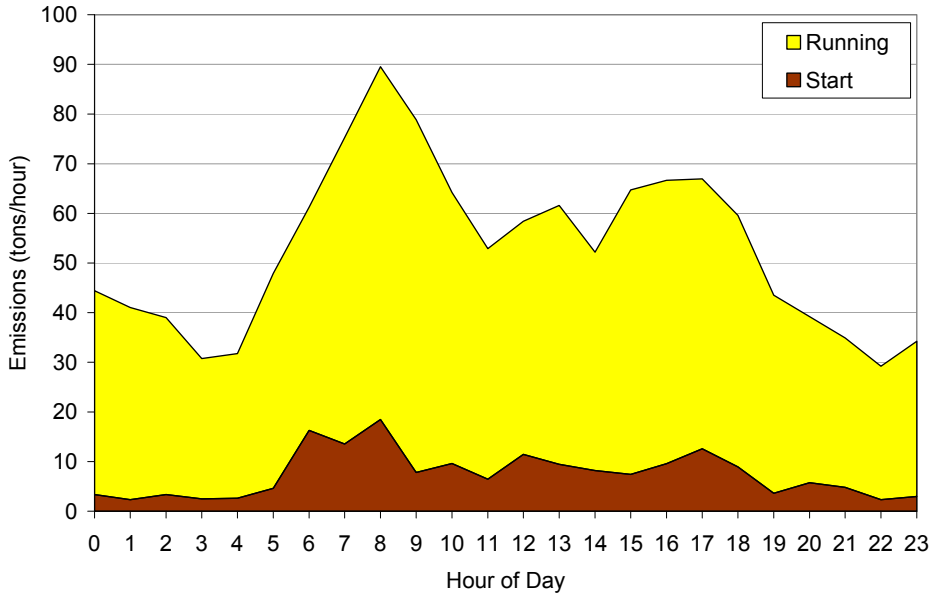

Figure 4-1-a Beijing Total Mobile CO Emissions throughout a Day

[40] Westerdahl *etc.* (2009) measured black carbon, surface area, and ultra fine particles number concentrations near a major urban highway in Beijing. They also found that the concentrations of these pollutants started increasing at about 23:00 and fell back around 6:00.
[41] This is reasonable since the formation of NOx is often associated with high engine temperature.

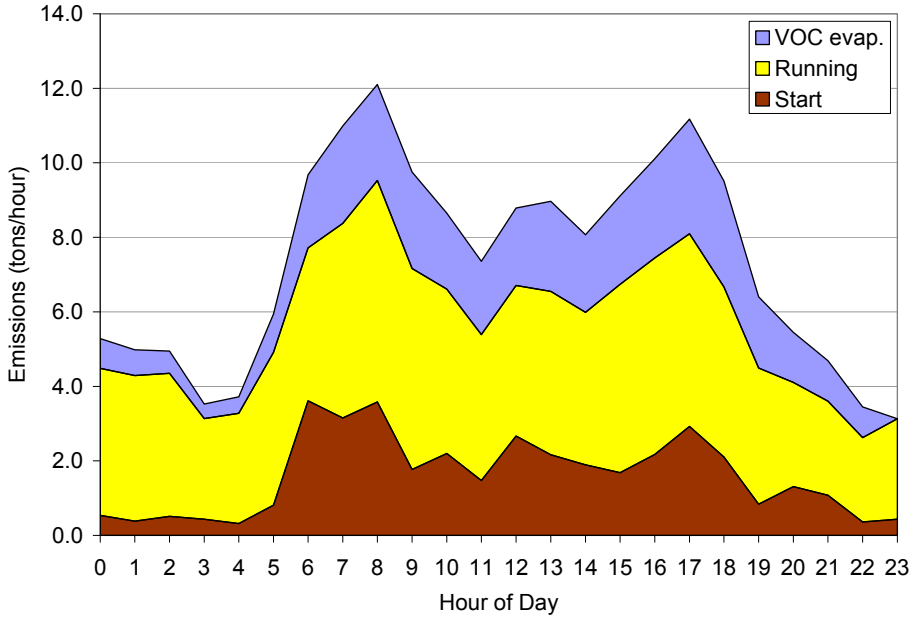

Figure 4-1-b Beijing Total Mobile VOC Emissions throughout a Day

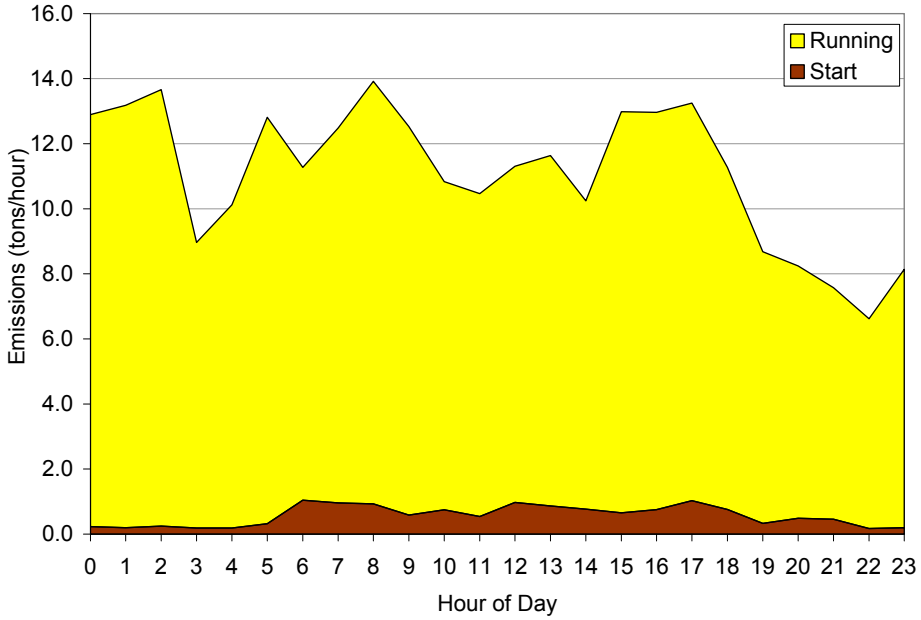

Figure 4-1-c Beijing Total Mobile NOx Emissions throughout a Day

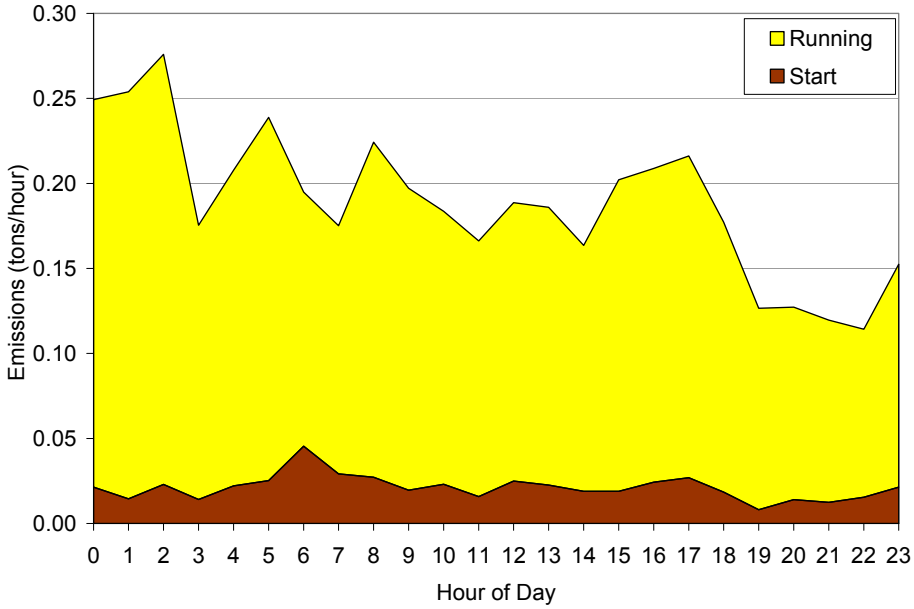

Figure 4-1-d Beijing Total Mobile PM Emissions throughout a Day

Figure 4-2 illustrates the contributions to total emissions and vehicle mileage travelled (VMT) by four major sub-fleets. Passenger vehicles contribute about 73 percent of the total VMT and similar shares (65 percent and 72 percent) of the total mobile CO and VOC emissions, but they only contribute 41 percent and 23 percent of the total mobile NOx and PM emissions. The taxi fleet contributes 14 percent of VMT, but its contributions to the total mobile CO, VOC, NOx, and PM emissions are much less. In other words, the taxi fleet emits fewer pollutants per kilometer travelled than the passenger fleet. This indicates that the taxi fleet on the whole is cleaner than the passenger fleet.

The truck fleet accounts for only 11 percent of VMT, but it accounts for several times more of its percentages of NOx and PM emissions (39 percent and 49 percent, respectively), and it also contributes about one-fifth of CO and VOC emissions. The bus fleet contributes 2.2 percent of total distance travelled; however, it accounts for 26 percent and 11 percent of PM and NOx emissions, as well as 8 percent of CO emissions.

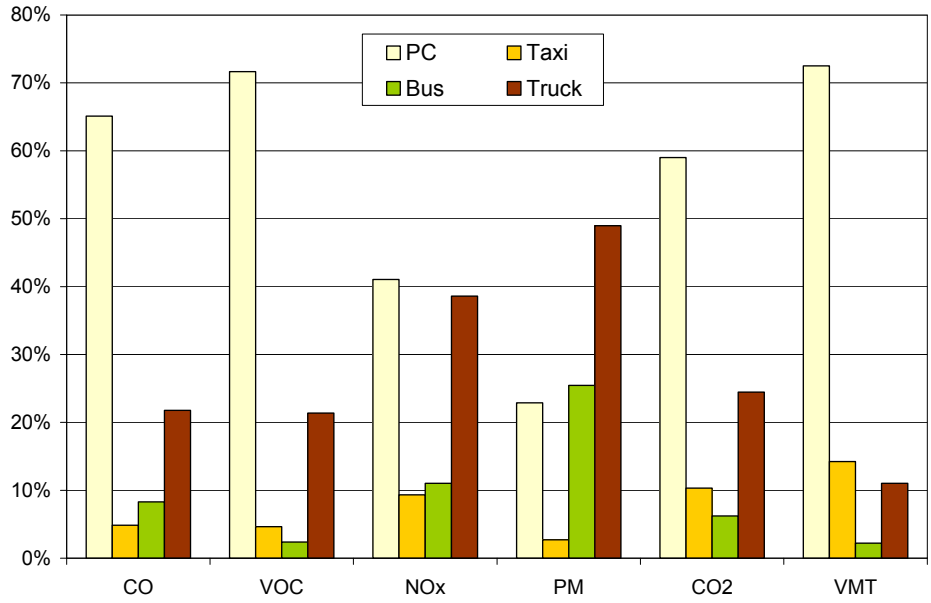

Figure 4-2 Contributions to Emissions and Travel by Sub-fleet

Table 4-1 summarizes the total emissions and emission factors of major sub-fleets in Beijing. If we use emission factors as the basis for comparison, the taxi fleet is the cleanest sub-fleet (it has the lowest emissions per kilometer driven with exception of NOx), and passenger vehicles on highways were the second least polluting sub-fleet. Passenger vehicles on residential roads emit at least twice the amounts of pollutants per kilometer as passenger vehicles on highways (due to start emissions and traffic conditions). The truck fleet had the highest emission factors for PM and VOC, and the bus fleet had the highest emission factors for CO and NOx. The variations in emission factors among different sub-fleets are partially due to the differences in their vehicle and emission technologies and partially due to the difference in their driving patterns.

Table 4-1 Emissions and Emission Factors of Beijing Sub-fleets

	CO		***VOC w/evap.***		***NOx***		***PM***	
	Tons/day	***g/km***	***Tons/day***	***g/km***	***Tons/day***	***g/km***	***Tons/day***	***g/km***
Overall	1268.0	7.6	176.5	1.1	266.1	1.6	4.5	0.03
PCHighway	155.8	4.6	17.3	0.5	21.0	0.6	0.2	0.005
PCResidential	419.4	8.3	63.0	1.2	55.9	1.1	0.5	0.010
PCArterial	250.6	6.9	42.0	1.2	32.3	0.9	0.3	0.009
Taxi	61.4	2.6	19.5	0.8	24.8	1.0	0.1	0.005
Bus	105.0	28.4	3.7	1.0	29.3	7.9	1.2	0.311
Truck	275.9	15.0	31.1	1.7	102.7	5.6	2.2	0.120

4.2 Comparing Emissions w/ and w/o Correction Factors

To understand the extent to which the correction of default base emission factors influences emission estimations, we calculated the total mobile emissions of the Beijing fleet using the default base emission factors in the IVE model and then compared these emission estimations with the emission estimations obtained in Section 4.1.

It appears that without correcting base emission factors, the model overestimates the overall CO, VOC, and CO_2 emissions and underestimates the overall NOx emissions. Figure 4-3-a and -b illustrate the emission differences in absolute and relative terms. The overall actual daily emissions of CO, VOC, and CO_2 of the Beijing fleet are about 200, 20, and 2,800 tons less than the model's estimations if the base emission factors were not corrected (the relative discrepancies are 14 percent, 10 percent, and 5 percent); and the overall actual daily NOx emission is forty-nine tons more than the model's default estimation (a 23 percent difference).

(PM is not included in the discussion of this section because our on-road emission testing on gasoline light-duty passenger vehicles did not monitor PM emissions for this type of vehicles and because the ISSRC and Tsinghua study on heavy-duty diesel vehicles concluded that it is not necessary to correct the default emission factors for heavy-duty diesel vehicles.)

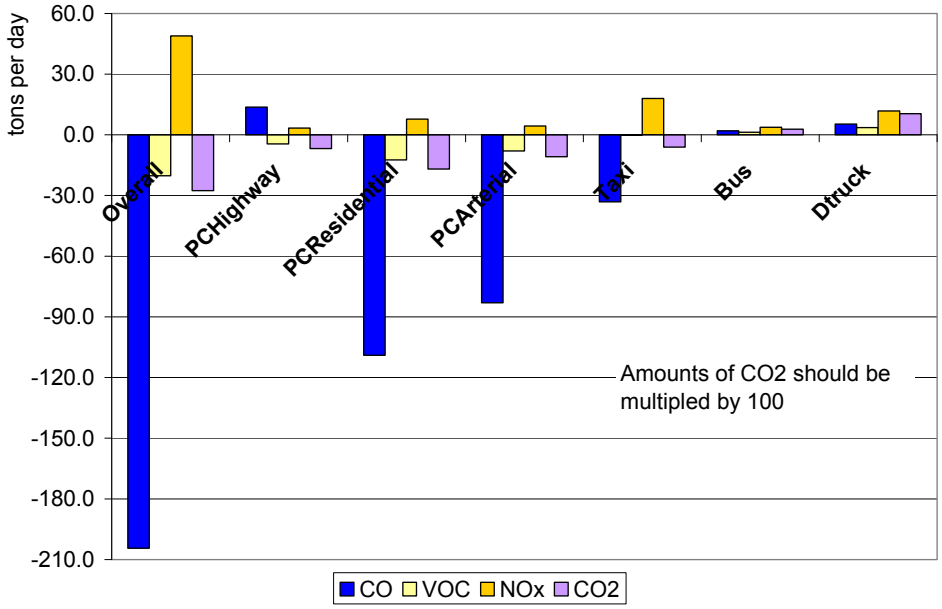

Figure 4-3-a Changes of Emission Estimations after Applying BECF

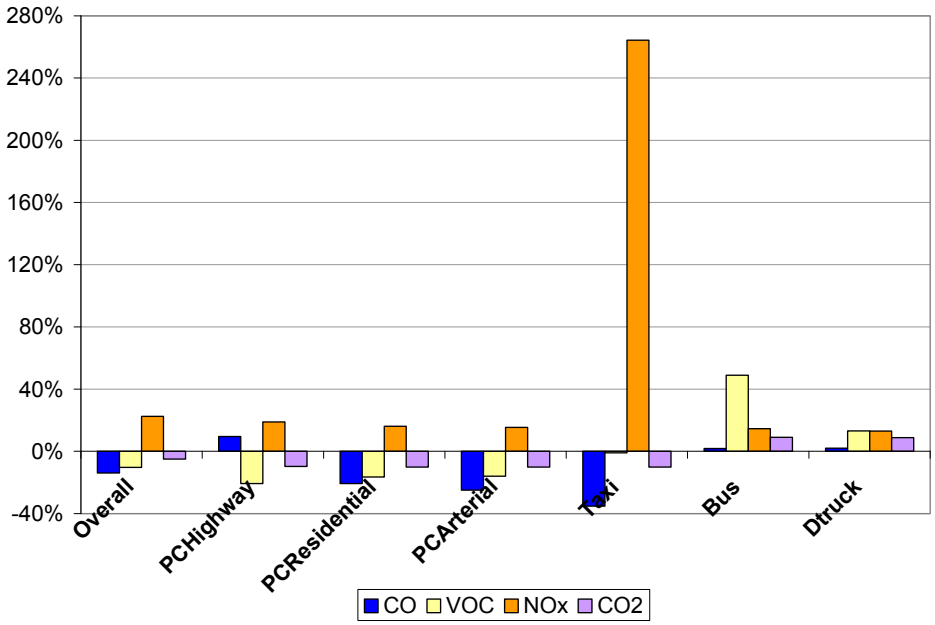

Figure 4-3-b Percentage Changes of Emissions after Applying BEFC

The two figures show that with the application of the BECFs, the overall trends of changes in estimated emissions from the three passenger vehicle sub-fleets (and the taxi fleet) are rather similar. Except the slight increase in CO emissions from the PC Highway sub-fleet, the CO, VOC, and CO_2 emissions from all four sub-fleets became slightly less while NOx emissions from these sub-fleets increased. The increase of the total NOx emission from the taxi sub-fleet is particularly noticeable (a 250 percent increase). This perceived abnormity of the taxi fleet is consistent with our early findings:

a) We have established in Section 3.2 (page 37) that most taxis (68 percent) have accumulated high mileage (greater than160,000 kilometers) and were certified to meet Euro III emissions standards; and

b) We have found in Section 2.4 that the average NOx emission rate of high-mileage light-duty passenger vehicles which were certified to Euro III standards is several times higher than the default emission rate in the model.

Thus, it is very possible that the taxi fleet has very high NOx emission factors.

With the application of the BECFs, emissions of all four pollutants from both the bus and truck sub-fleets are higher than the model's default projections. The biggest difference is total VOC emissions (a 50 percent difference for the bus fleet and 15 percent for the truck fleet), while the differences in NOx emissions are also considerable (a 15 percent difference for both the bus and truck fleets).

4.3 Emissions by Major IVE Vehicle Classes

The IVE model includes 1,328 vehicle classes based on fuel type, engine technology, emission control technology, engine/vehicle size, and use (i.e., mileage driven).[42] Appendix D explains the classification of these vehicle classes. Following this approach of vehicle categorization, our vehicle survey in Beijing generated ninety-two vehicle classes. Among these vehicle classes, thirty-five classes are light-duty gasoline passenger vehicles (six are carbureted vehicles with retrofitted two-way catalysts, and the remaining twenty-nine classes are equipped with MPFI and three-way catalysts. Among the twenty-nine classes, nine were certified to meet Euro I emission standards; nine to Euro II emission standards; eight to Euro III emission standards; and three to Euro IV emission standards). Twenty-seven classes were light-duty diesel trucks, eight were gasoline trucks, six were natural gas buses, and the remaining sixteen classes were heavy-duty diesel trucks or buses.

Table 4-2 lists each of these ninety-two vehicle classes and their respective contributions to total daily mobile emissions in Beijing (columns 1 to 6). There are fourteen vehicle classes whose contributions to at least one of the major pollutant emissions (mobile sources) are higher than 5 percent. The table also groups the ninety-two vehicle classes into fourteen larger groups, based on their fuel type and the emission standards that they are supposed to meet. These fourteen groups are:

1. Gasoline LDPVs with carburetors and two-way catalysts;
2. Gasoline LDPVs with MPFI and certified to Euro I standards;
3. Gasoline LDPVs with MPFI and certified to Euro II standards;
4. Gasoline LDPVs with MPFI and certified to Euro III standards;
5. Gasoline LDPVs with MPFI and certified to Euro IV standards;
6. Diesel, light-duty trucks certified to Euro I standards;
7. Diesel, light-duty trucks certified to Euro II standards;
8. Diesel, light-duty trucks certified to Euro III standards;
9. Gasoline, heavy-duty trucks/buses certified to Euro I and II standards;
10. Gasoline, heavy-duty trucks/buses certified to Euro III standards;
11. Natural gas, heavy-duty buses;
12. Diesel, heavy-duty trucks/buses certified to Euro II standards;
13. Diesel, heavy-duty trucks/buses certified to Euro III standards;
14. Diesel, heavy-duty trucks/buses certified to Euro IV standards;

The accumulated emission contributions of these fourteen groups are listed in columns 7 to 11 in the table.

[42] The model also allows a user to define forty-five additional vehicle classes. However, a user must also create other related files (base emission rates and various correction factors) if he/she desires to add additional classes.

Table 4-2 Emission Contributions by 92 IVE Vehicle Technology Classes in Beijing

IVE Vehicle Technology Class	*CO*	*VOC*	*NOx*	*PM*	*CO_2*	*CO*	*VOC*	*NOx*	*PM*	*CO_2*
10 Pt: Auto/SmTk : Lt : Carb : 2Wy : PCV : 80-161K km	0.3%	0.2%	0.2%	0.0%	0.2%	18.0%	20.4%	16.2%	5.3%	6.8%
11 Pt: Auto/SmTk : Lt : Carb : 2Wy : PCV : >161K km	3.7%	3.8%	3.8%	0.5%	1.2%					
13 Pt: Auto/SmTk : Med : Carb : 2Wy : PCV : 80-161K km	1.5%	1.7%	1.6%	0.1%	0.8%					
14 Pt: Auto/SmTk : Med : Carb : 2Wy : PCV : >161K km	9.1%	10.6%	7.4%	1.2%	2.9%					
16 Pt: Auto/SmTk : Hv : Carb : 2Wy : PCV : 80-161K km	0.8%	0.9%	0.9%	0.1%	0.5%					
17 Pt: Auto/SmTk : Hv : Carb : 2Wy : PCV : >161K km	2.7%	3.3%	2.2%	3.4%	1.2%					
171 Pt: Auto/SmTk : Lt : MPFI: EuroI : PCV/Tank : <79K km	0.0%	0.0%	0.0%	0.0%	0.0%	22.2%	23.9%	9.4%	6.8%	9.5%
172 Pt: Auto/SmTk : Lt : MPFI: EuroI : PCV/Tank : 80-161K km	1.2%	1.9%	0.6%	0.3%	0.8%					
173 Pt: Auto/SmTk : Lt : MPFI: EuroI : PCV/Tank : >161K km	0.7%	0.7%	0.2%	0.1%	0.2%					
174 Pt: Auto/SmTk : Med : MPFI: EuroI : PCV/Tank : <79K km	0.2%	0.1%	0.1%	0.0%	0.1%					
175 Pt: Auto/SmTk : Med : MPFI: EuroI : PCV/Tank : 80-161K km	8.0%	8.4%	3.8%	1.0%	3.8%					
176 Pt: Auto/SmTk : Med : MPFI: EuroI : PCV/Tank : >161K km	3.7%	3.5%	1.0%	0.7%	0.8%					
177 Pt: Auto/SmTk : Hv : MPFI: EuroI : PCV/Tank : <79K km	0.1%	0.1%	0.1%	0.0%	0.1%					
178 Pt: Auto/SmTk : Hv : MPFI: EuroI : PCV/Tank : 80-161K km	5.8%	6.4%	2.9%	0.6%	3.1%					
179 Pt: Auto/SmTk : Hv : MPFI: EuroI : PCV/Tank : >161K km	2.6%	2.7%	0.8%	4.0%	0.7%					
180 Pt: Auto/SmTk : Lt : MPFI: EuroII : PCV/Tank : <79K km	1.2%	0.8%	0.4%	0.5%	1.5%	19.2%	22.7%	13.6%	10.2%	25.2%
181 Pt: Auto/SmTk : Lt : MPFI: EuroII : PCV/Tank : 80-161K km	0.5%	1.0%	0.3%	0.3%	0.8%					
182 Pt: Auto/SmTk : Lt : MPFI: EuroII : PCV/Tank : >161K km	0.3%	0.8%	0.5%	0.3%	0.4%					
183 Pt: Auto/SmTk : Med : MPFI: EuroII : PCV/Tank : <79K km	4.6%	3.7%	2.7%	1.7%	6.5%					
184 Pt: Auto/SmTk : Med : MPFI: EuroII : PCV/Tank : 80-161K km	4.1%	5.2%	2.5%	1.3%	4.6%					
185 Pt: Auto/SmTk : Med : MPFI: EuroII : PCV/Tank : >161K km	1.7%	3.4%	2.7%	1.4%	2.0%					
186 Pt: Auto/SmTk : Hv : MPFI: EuroII : PCV/Tank : <79K km	4.0%	3.8%	2.5%	1.3%	6.2%					
187 Pt: Auto/SmTk : Hv : MPFI: EuroII : PCV/Tank : 80-161K km	2.2%	3.0%	1.4%	0.6%	2.8%					
188 Pt: Auto/SmTk : Hv : MPFI: EuroII : PCV/Tank : >161K km	0.5%	1.0%	0.7%	3.0%	0.5%					
189 Pt: Auto/SmTk : Lt : MPFI: EuroIII : PCV/Tank : <79K km	0.9%	0.3%	0.3%	0.2%	1.9%	10.3%	12.9%	10.9%	3.2%	26.0%
190 Pt: Auto/SmTk : Lt : MPFI: EuroIII : PCV/Tank : 80-161K km	0.0%	0.0%	0.0%	0.0%	0.0%					
191 Pt: Auto/SmTk : Lt : MPFI: EuroIII : PCV/Tank : >161K km	0.1%	0.4%	0.2%	0.1%	0.3%					

IVE Vehicle Technology Class	*CO*	*VOC*	*NOx*	*PM*	*CO_2*	*CO*	*VOC*	*NOx*	*PM*	*CO_2*
192 Pt: Auto/SmTk : Med : MPFI: EuroIII : PCV/Tank : <79K km	3.4%	2.1%	1.9%	0.9%	9.1%					
193 Pt: Auto/SmTk : Med : MPFI: EuroIII : PCV/Tank : 80-161K km	0.9%	1.0%	1.5%	0.2%	2.4%					
194 Pt: Auto/SmTk : Med : MPFI: EuroIII : PCV/Tank : >161K km	2.5%	6.9%	5.6%	1.3%	5.4%					
195 Pt: Auto/SmTk : Hv : MPFI: EuroIII : PCV/Tank : <79K km	2.5%	2.1%	1.4%	0.5%	6.9%					
196 Pt: Auto/SmTk : Hv : MPFI: EuroIII : PCV/Tank : 80-161K km	0.0%	0.0%	0.0%	0.0%	0.1%					
198 Pt: Auto/SmTk : Lt : MPFI: EuroIV : PCV/Tank : <79K km	0.0%	0.0%	0.0%	0.0%	0.2%					
201 Pt: Auto/SmTk : Med : MPFI: EuroIV : PCV/Tank : <79K km	0.1%	0.1%	0.1%	0.1%	0.9%	0.1%	0.3%	0.2%	0.1%	1.8%
204 Pt: Auto/SmTk : Hv : MPFI: EuroIV : PCV/Tank : <79K km	0.0%	0.2%	0.1%	0.0%	0.7%					
783 Ds: Auto/SmTk : Lt : FI : EuroI : None : <79K km	0.0%	0.0%	0.0%	0.0%	0.0%					
784 Ds: Auto/SmTk : Lt : FI : EuroI : None : 80-161K km	0.0%	0.0%	0.0%	0.0%	0.0%					
785 Ds: Auto/SmTk : Lt : FI : EuroI : None : >161K km	0.0%	0.0%	0.0%	0.1%	0.0%					
786 Ds: Auto/SmTk : Med : FI : EuroI : None : <79K km	0.0%	0.0%	0.0%	0.0%	0.0%					
787 Ds: Auto/SmTk : Med : FI : EuroI : None : 80-161K km	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	0.5%	0.1%
788 Ds: Auto/SmTk : Med : FI : EuroI : None : >161K km	0.0%	0.0%	0.0%	0.1%	0.0%					
789 Ds: Auto/SmTk : Hv : FI : EuroI : None : <79K km	0.0%	0.0%	0.0%	0.0%	0.0%					
790 Ds: Auto/SmTk : Hv : FI : EuroI : None : 80-161K km	0.0%	0.0%	0.0%	0.0%	0.0%					
791 Ds: Auto/SmTk : Hv : FI : EuroI : None : >161K km	0.0%	0.0%	0.0%	0.1%	0.0%					
792 Ds: Auto/SmTk : Lt : FI : EuroII : None : <79K km	0.0%	0.0%	0.0%	0.2%	0.1%					
793 Ds: Auto/SmTk : Lt : FI : EuroII : None : 80-161K km	0.0%	0.0%	0.1%	0.2%	0.1%					
794 Ds: Auto/SmTk : Lt : FI : EuroII : None : >161K km	0.0%	0.0%	0.1%	0.5%	0.1%					
795 Ds: Auto/SmTk : Med : FI : EuroII : None : <79K km	0.0%	0.0%	0.0%	0.2%	0.1%					
796 Ds: Auto/SmTk : Med : FI : EuroII : None : 80-161K km	0.0%	0.0%	0.1%	0.2%	0.1%	0.1%	0.1%	0.5%	2.7%	0.7%
797 Ds: Auto/SmTk : Med : FI : EuroII : None : >161K km	0.0%	0.0%	0.1%	0.6%	0.1%					
798 Ds: Auto/SmTk : Hv : FI : EuroII : None : <79K km	0.0%	0.0%	0.0%	0.2%	0.1%					
799 Ds: Auto/SmTk : Hv : FI : EuroII : None : 80-161K km	0.0%	0.0%	0.0%	0.2%	0.1%					
800 Ds: Auto/SmTk : Hv : FI : EuroII : None : >161K km	0.0%	0.0%	0.1%	0.5%	0.1%					
801 Ds: Auto/SmTk : Lt : FI : EuroIII : None : <79K km	0.0%	0.0%	0.2%	0.6%	0.3%					
802 Ds: Auto/SmTk : Lt : FI : EuroIII : None : 80-161K km	0.0%	0.0%	0.2%	0.8%	0.3%	0.1%	0.3%	2.1%	9.2%	3.4%
803 Ds: Auto/SmTk : Lt : FI : EuroIII : None : >161K km	0.0%	0.1%	0.3%	1.5%	0.3%					

IVE Vehicle Technology Class	*CO*	*VOC*	*NOx*	*PM*	*CO_2*	*CO*	*VOC*	*NOx*	*PM*	*CO_2*
804 Ds: Auto/SmTk : Med : FI : EuroIII : None : <79K km	0.0%	0.0%	0.2%	0.6%	0.4%					
805 Ds: Auto/SmTk : Med : FI : EuroIII : None : 80-161K km	0.0%	0.0%	0.2%	0.8%	0.4%					
806 Ds: Auto/SmTk : Med : FI : EuroIII : None : >161K km	0.0%	0.1%	0.3%	1.8%	0.4%					
807 Ds: Auto/SmTk : Hv : FI : EuroIII : None : <79K km	0.0%	0.0%	0.2%	0.6%	0.5%					
808 Ds: Auto/SmTk : Hv : FI : EuroIII : None : 80-161K km	0.0%	0.0%	0.2%	0.7%	0.5%					
809 Ds: Auto/SmTk : Hv : FI : EuroIII : None : >161K km	0.0%	0.0%	0.2%	1.8%	0.5%					
919 Pt: Tk/Bus : Lt : FI : EuroI : PCV : 80-161K km	0.6%	0.3%	0.2%	0.1%	0.1%					
927 Pt: Tk/Bus : Lt : FI : EuroII : PCV : <79K km	0.9%	0.6%	0.3%	0.2%	0.2%	4.5%	2.7%	1.3%	0.6%	1.0%
928 Pt: Tk/Bus : Lt : FI : EuroII : PCV : 80-161K km	0.6%	0.3%	0.1%	0.1%	0.1%					
930 Pt: Tk/Bus : Med : FI : EuroII : PCV : <79K km	2.4%	1.5%	0.7%	0.3%	0.5%					
937 Pt: Tk/Bus : Lt : FI : EuroIII : PCV : 80-161K km	0.4%	0.2%	0.1%	0.1%	0.1%					
939 Pt: Tk/Bus : Med : FI : EuroIII : PCV : <79K km	6.3%	4.2%	2.1%	0.8%	2.2%	15.2%	9.7%	4.3%	2.4%	4.1%
940 Pt: Tk/Bus : Med : FI : EuroIII : PCV : 80-161K km	3.4%	2.1%	0.9%	0.4%	0.9%					
941 Pt: Tk/Bus : Med : FI : EuroIII : PCV : >161K km	5.1%	3.2%	1.2%	1.1%	0.9%					
966 NG: Tk/Bus : Med : Carb/Mx : None : PCV : <79K km	1.1%	0.1%	0.3%	0.0%	0.2%					
967 NG: Tk/Bus : Med : Carb/Mx : None : PCV : 80-161K km	1.3%	0.1%	0.3%	0.0%	0.2%					
968 NG: Tk/Bus : Med : Carb/Mx : None : PCV : >161K km	3.5%	0.3%	0.6%	0.0%	0.3%	7.7%	0.7%	1.6%	0.1%	0.9%
969 NG: Tk/Bus : Hv : Carb/Mx : None : PCV : <79K km	1.2%	0.1%	0.3%	0.0%	0.2%					
970 NG: Tk/Bus : Hv : Carb/Mx : None : PCV : 80-161K km	0.3%	0.0%	0.1%	0.0%	0.0%					
971 NG: Tk/Bus : Hv : Carb/Mx : None : PCV : >161K km	0.4%	0.0%	0.1%	0.0%	0.0%					
1125 Ds: Tk/Bus : Lt : FI : EuroII : None : <79K km	0.0%	0.1%	0.3%	0.3%	0.1%					
1126 Ds: Tk/Bus : Lt : FI : EuroII : None : 80-161K km	0.0%	0.1%	0.6%	1.1%	0.2%					
1128 Ds: Tk/Bus : Med : FI : EuroII : None : <79K km	0.2%	0.9%	5.2%	4.0%	2.1%	0.4%	1.6%	9.0%	13.1%	3.5%
1129 Ds: Tk/Bus : Med : FI : EuroII : None : 80-161K km	0.1%	0.2%	1.3%	2.0%	0.5%					
1130 Ds: Tk/Bus : Med : FI : EuroII : None : >161K km	0.1%	0.2%	1.2%	3.4%	0.5%					
1133 Ds: Tk/Bus : Hv : FI : EuroII : None : >161K km	0.0%	0.0%	0.3%	2.3%	0.1%					
1137 Ds: Tk/Bus : Med : FI : EuroIII : None : <79K km	0.7%	2.0%	9.7%	10.4%	5.2%					
1138 Ds: Tk/Bus : Med : FI : EuroIII : None : 80-161K km	0.2%	0.4%	2.1%	4.3%	1.1%	1.9%	4.6%	29.4%	45.2%	15.6%
1139 Ds: Tk/Bus : Med : FI : EuroIII : None : >161K km	0.1%	0.4%	1.8%	7.1%	0.9%					

IVE Vehicle Technology Class	*CO*	*VOC*	*NOx*	*PM*	*CO_2*	*CO*	*VOC*	*NOx*	*PM*	*CO_2*
1140 Ds: Tk/Bus : Hv : FI : EuroIII : None : <79K km	0.8%	1.6%	14.0%	15.2%	7.4%					
1141 Ds: Tk/Bus : Hv : FI : EuroIII : None : 80-161K km	0.1%	0.1%	1.2%	2.6%	0.6%					
1142 Ds: Tk/Bus : Hv : FI : EuroIII : None : >161K km	0.0%	0.1%	0.5%	5.7%	0.3%					
1146 Ds: Tk/Bus : Med : FI : EuroIV : None : <79K km	0.0%	0.0%	1.0%	0.4%	0.9%					
1147 Ds: Tk/Bus : Med : FI : EuroIV : None : 80-161K km	0.0%	0.0%	0.2%	0.1%	0.1%	0.0%	0.0%	1.4%	0.7%	1.3%
1149 Ds: Tk/Bus : Hv : FI : EuroIV : None : <79K km	0.0%	0.0%	0.2%	0.1%	0.2%					
1150 Ds: Tk/Bus : Hv : FI : EuroIV : None : 80-161K km	0.0%	0.0%	0.0%	0.0%	0.0%					
Total	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%

Figure 4-4-a illustrates the emission and VMT contributions of four major groups of light-duty gasoline passenger vehicles (groups 1 to 4 on page 57). These four groups include thirty-five IVE vehicle classes which are grouped based on their certified emission standards. Figure 4-4-b illustrates the emission and VMT contributions of six major groups of trucks and buses (groups 9 to 14 on page 57). These six groups also include thirty-five IVE vehicle classes which are grouped based on fuel type and certified emission standards. The nine groups of vehicles all together contribute more than 95 percent of all mobile emissions.

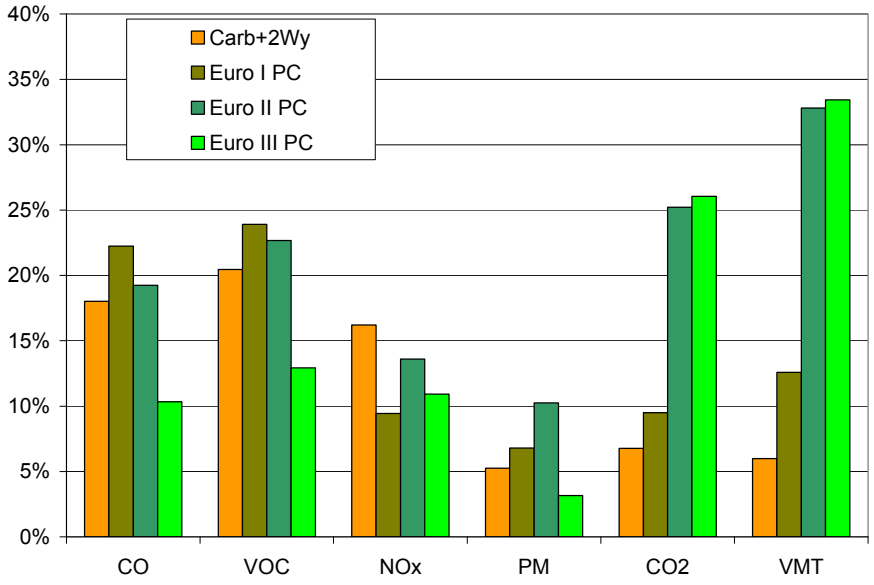

Figure 4-4-a Emission Contributions by Major IVE Passenger Vehicle Classes

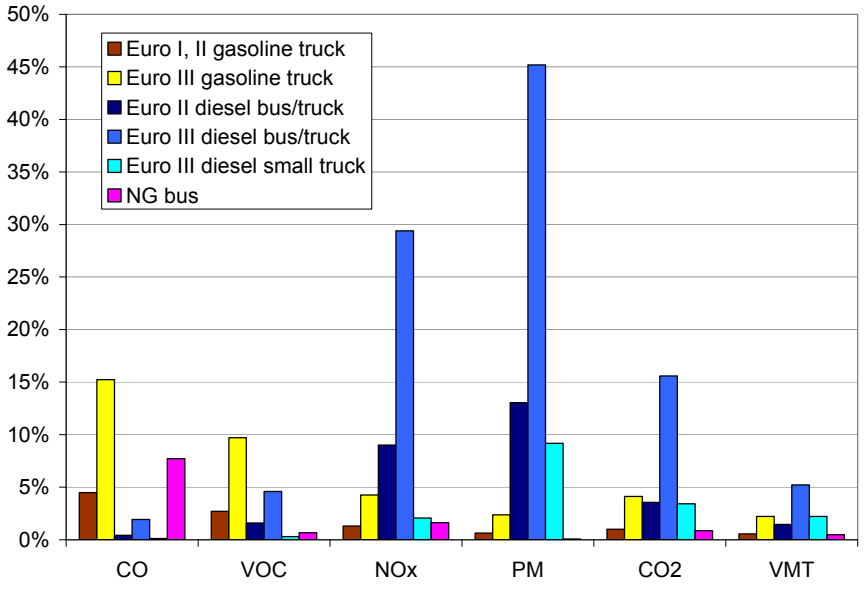

Figure 4-4-b Emission Contributions by Major IVE Truck and Bus Classes

As shown in the above figures, gasoline vehicles (both gasoline-powered passenger cars and trucks) are the dominant contributors to mobile CO and VOC emissions. They together account for 88 percent of total mileage travelled, 90 percent and 92 percent of total mobile CO and VOC emissions, 56 percent of NOx emissions, and 29 percent of PM emissions. Diesel vehicles accounted for 9 percent of total distance travelled but 67 percent and 40 percent of total PM and NOx emissions. Natural gas buses[43] account for only about 0.5 percent of total distance travelled but almost 8 percent of CO emissions.

A close examination of the emission contributions of light-duty passenger vehicles (Figure 4-4-a) reveals that older vehicles with no or less efficient emission control technology emit more per unit of distance travelled than newer vehicles. For instance, carbureted passenger vehicles account for only 6 percent of total distance travelled, but contribute 18 percent, 20 percent, and 16 percent of CO, VOC, and NOx emissions, respectively. Vehicles certified to meet Euro I emission standards account for 15 percent of total distance travelled and 22 percent, 24 percent, and 9 percent of CO, VOC, and NOx emissions, respectively. In contrast, vehicles certified to meet Euro III emission standards account for one-third of total distance travelled, but only 10 percent, 13 percent, and 11 percent of CO, VOC, and NOx emissions, respectively. In other words, on average, an in-use passenger vehicle certified to Euro III emissions standards is eight to nine times cleaner than a retrofitted, carbureted passenger vehicle in Beijing.

4.4 Emissions under Various Scenarios

Seasonal Variation

Ambient temperature and humidity impact the working status of automobile engines and the catalysts, and thus, mobile emissions, especially start emissions. We picked a typical day in spring, summer, and winter, respectively to examine the extent to which the hourly variations of atmospheric temperature and humidity influence the mobile emissions in different seasons. Figures 4-5-a and 4-5-b summarize the hourly ambient temperature and humidity values in Beijing on a typical winter, spring, and summer day. On a moderately cold winter day (January 1, 2008), the high ambient temperature was about 2ºC while the low was about -5ºC; the relative humidity ranged between 11 to 24 percent. On a warm spring day (April 1, 2008), the hourly temperature varied from 8ºC to 14ºC while the relative humidity varied from 33 to 71 percent. On a hot summer day (July 13, 2008), the hourly temperature reached 36 ºC in the afternoon and only dropped to 24 ºC in the early morning; the humidity ranged between 34 to 100 percent.

[43] We assumed that all the natural gas buses in Beijing are without any emission control. It is possible that the newest natural gas buses in China actually have emission control systems. In that case, the emissions of natural gas buses would be much lower.

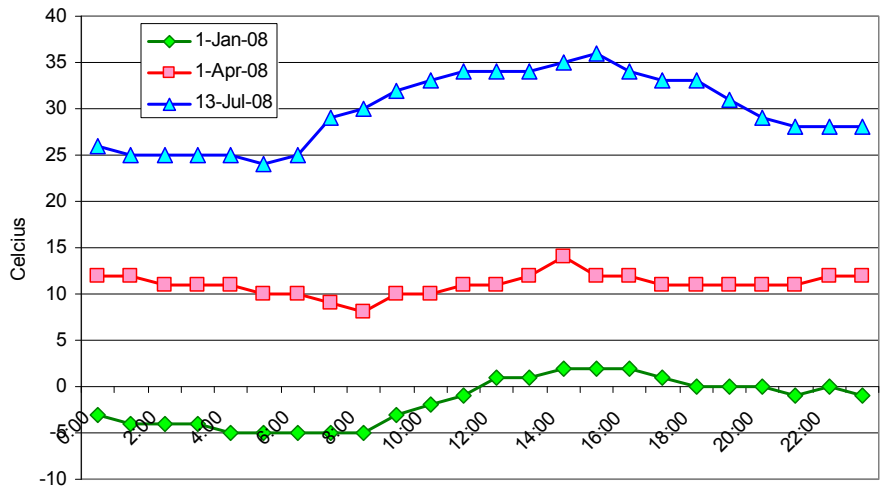

Figure 4-5-a Hourly Temperature Variation in Different Seasons

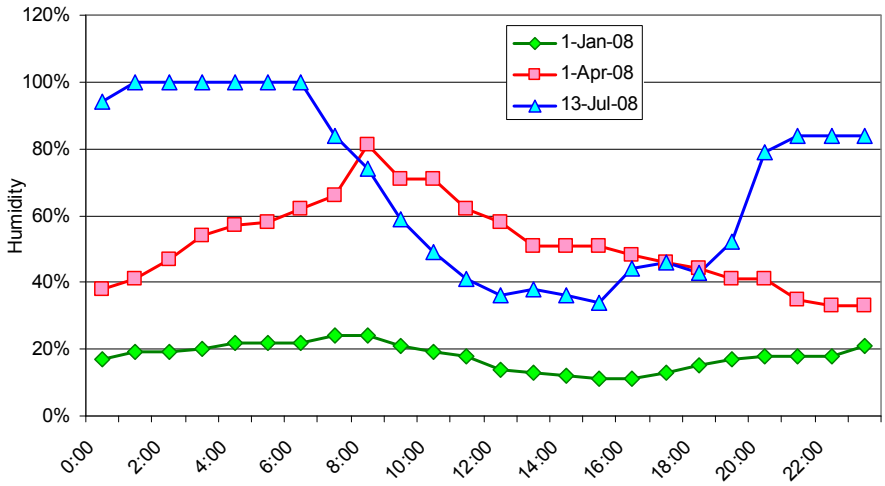

Figure 4-5-b Hourly Humidity Variation in Different Seasons

The results of our model run for the three different seasons are shown in Figures 4-6-a, b, and c. The total daily mobile emissions of CO, VOC, PM, and CO_2 are highest on a hot summer day and the lowest on a cold winter day, while the total daily NOx emission is the highest on a cold winter day (Figure 4-6-a). The biggest difference is between summer and spring daily CO emissions (the former is about one-third higher than the latter), and the next biggest difference is between summer and spring VOC emissions (11 percent). Most of the daily mobile emissions in winter and spring are rather close (with no more than a 3 percent difference), with the exception of NOx (an 8 percent difference).

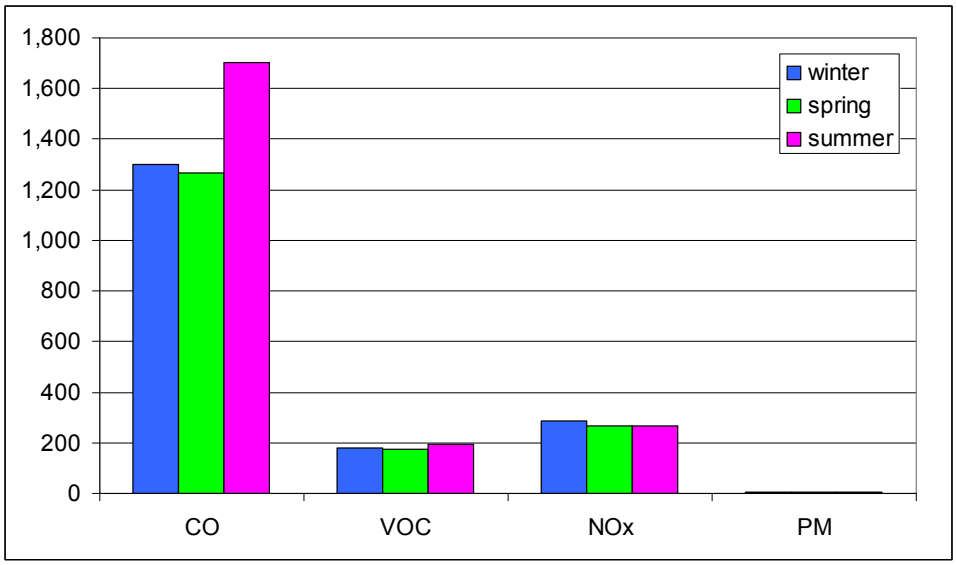

Figure 4-6-a Daily Mobile Emissions in Different Seasons

A further comparison of total daily emissions from different sub-fleets on the aforementioned summer and spring days shows that, in absolute terms, both CO and VOC emissions from passenger vehicles on residential roads (named as "PCResidential" in Figure 4-6-b) increased the most (170 tons and 6.3 tons respectively, accounting for 41 percent and 10 percent of the total changes). However, in relative terms, increases of the total daily CO and VOC emissions from passenger vehicles on highways are the most significant (62 percent and 26 percent increase in the summer). Interestingly, projected daily NOx emissions from the Beijing taxi fleet in the summer are considerably higher than in the spring despite that daily NOx emissions from other light-duty passenger vehicle sub-fleets are slightly less in the summer than in the spring.

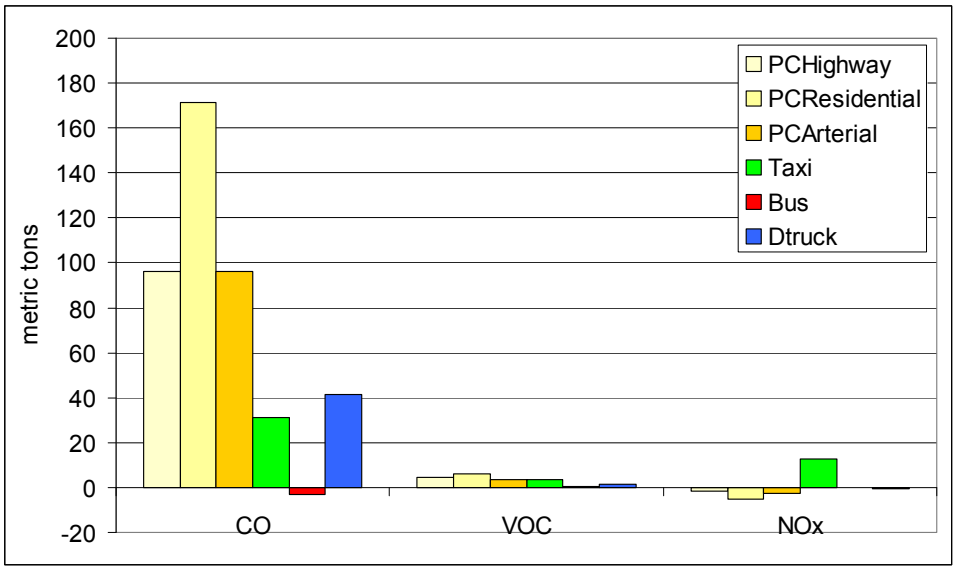

Figure 4-6-b Differences of Sub-fleet Daily Emissions in Summer and Spring

Figure 4-6-c shows both total daily running and start emissions in different seasons. Daily start emissions are generally higher in winter than the other two seasons because it takes a longer time to warm up engines and TWCs in cold weather. In contrast, daily CO and VOC running emissions in the winter are much lower than in the summer. This is likely to be caused by use of air conditioners in the summer. Daily NOx running emissions in the winter are somewhat higher than in the summer. The combined results are thus consistent with Figure 4-6-a.

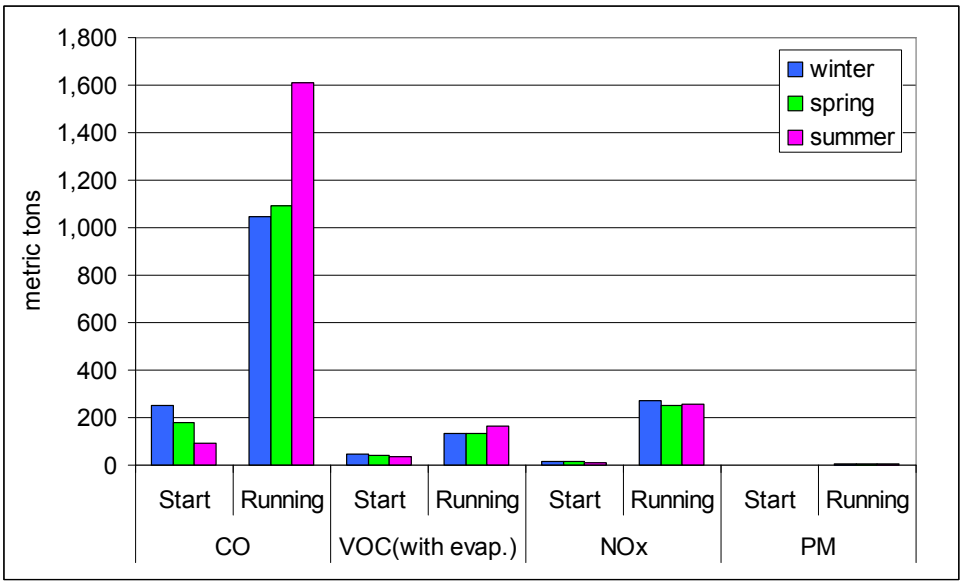

Figure 4-6-c Daily Running and Start Emissions in Different Seasons

Fuel Quality

Besides vehicle technology itself, fuel quality is the other key factor influencing engine performance and emissions. Often, advanced engine technologies and emission control devices need clean-burning fuels to ensure their best performance. For instance, lead of any amount in gasoline will render catalysts ineffective. Therefore, lead content will affect CO, VOC, NOx, 1,3-butadiene, benzene, formaldehyde, acetaldehyde, and benzene emissions for catalytic vehicles. Sulfur also interferes with the performance of catalysts and adversely affects heated exhaust gas oxygen sensors. High sulfur content has similar impacts on emissions as lead, but to a lesser extent, and the deterioration of catalysts occurs over a much longer period of time. The octane number indicates gasoline's ability to resist anti-ignition and thus influences engine performance. Olefins can boost octane number, but they can also lead to gum formation and deposits in the intake system. Their combustion products form toxic dienes. Aromatics are linked to the formation of combustion chamber deposits, which can increase tailpipe emissions such as hydrocarbon (HC) and NOx. The combustion of aromatics can lead to the formation of carcinogenic

benzene. Metal containing additives, such as lead and manganese-based compounds, can irreversibly affect the operation of catalysts and other components (e.g., oxygen sensors). Oxygenates help increase the octane number and induce a lean shift in engine stoichiometry to reduce CO and VOC emissions, especially during cold operation and rapid acceleration.

To ensure the consistent performance of their products, major automobile and engine manufacturer associations have been promoting the harmonization of fuel quality over the world. Their recommendations for mobile fuel properties suitable for various levels of emission standards have been summarized in the series of World-wide Fuel Charters (ACEA, Alliance, EMA, and JAMA 2006). China had also realized fuel quality must be consistent with engine and catalyst technologies. The State Council issued an order to prohibit leaded gasoline in 1998, requiring that only unleaded gasoline be supplied nationwide. One year later, the State Environmental Protection Administration (SEPA) issued a set of standards (GWKB001-1999/8/30) to limit the amounts of hazardous chemicals in gasoline.

However, it has been difficult for the Chinese central government to push its oil industry to provide cleaner fuels which would be consistent with China's own schedule for vehicle emission standards.[44] When the Euro III emission standards took effect nationwide in China in July 2007, most refineries could not provide gasoline with a sulfur content of less than 150 ppm, which is the level considered appropriate even in China's own gasoline quality standards (GB17930-2006). Nevertheless, as we have revealed in Section 1.1, Beijing, with the central government's backing and with its high political salience associated with sponsoring the 2008 Olympic Games, was able to negotiate with a few refineries located in its vicinity to provide mobile fuels consistent with Beijing's own schedule for emission standards. Table 4-3 summarizes the schedules and the requirements for key gasoline properties in Beijing and China.

Table 4-3 Key Property Requirements for Mobile Gasoline

Properties	***Unit***	***Beijing***			***China***		
		Phase 1	***Phase 2***	***Phase 3***	***Phase 1***	***Phase 2***	***Phase 3***
Standard code		DB11/238-2004		DB11/238 -2007	GWKB001 -1999/8/30	GB 17930-2006	
Effective from		Oct. 1, 2004	July 1, 2005	Jan. 1, 2008	July 1, 2000	Dec. 6, 2006	Dec. 31, 2009
Sulfur	% m/m	≤ 0.05	≤ 0.015	≤ 0.005	≤ 0.08	≤ 0.05	≤ 0.015
Benzene	% v/v	≤ 2.5	≤ 1	≤ 1.0	≤ 2.5	≤ 2.5	≤ 1.0
Olefins	% v/v	≤ 30	≤ 18	≤ 25	≤ 35	≤ 35	≤ 30
Aromatics	% v/v	≤ 40	≤ 42	≤ 60 – [Olefins]*	≤ 40	≤ 40	≤ 40
Methanol	% m/m	--	--	≤ 0.3	--	≤ 0.3	≤ 0.3
Lead	g/L	≤ 0.005	≤ 0.005	≤ 0.005	≤ 0.013	≤ 0.005	≤ 0.005
Iron	g/L	≤ 0.01	≤ 0.01	≤ 0.01	≤ 0.005	≤ 0.01	≤ 0.01
Manganese	g/L	-- **	-- **	≤ 0.006	≤ 0.018	≤ 0.018	≤ 0.016

[44] Gallagher and Oliver (2005) discussed the policy options for China to promote clean fuels in their paper.

Note: * 60 is the combined upper limit for olefins and aromatics contents.
** Mobile fuel suppliers for Beijing must comply with the biding national requirement (0.018 g/L) at that time.

Beijing also adopted its own diesel fuel standards. Using the Chinese national standard (GB242-2000) as the foundation, Beijing gradually tightened its requirement for sulfur and added limits for aromatics. The national requirement for sulfur has been 2000 ppm while the current requirement in Beijing is 50 ppm. There is no national limit for aromatics while the Beijing limit is 11 percent.

According to the testing results of gasoline and diesel fuel samples provided by the Beijing Quality and Technology Supervision Bureau (BJQTSB), almost all the gasoline samples and most of the diesel fuel sampled have been in compliance with Beijing's mobile fuel quality requirements.[45] To investigate the impacts of fuel quality on mobile emissions in Beijing, we assumed two scenarios: [46]

a) Moderate fuels. Gasoline: sulfur content is about 300 ppm, no detectable lead additive, benzene content is about 1.5 percent, and oxygenate content is about 0 percent. Diesel fuel: sulfur content is about 500 ppm.
b) Clean fuels. Gasoline: sulfur content is about 50 ppm, no detectable lead addictive, benzene content is about 1.5 percent, and oxygenate content is about 2.5 percent. Diesel fuel: sulfur content is about 50 ppm.

Figure 4-7-a shows that clean mobile fuels will lead to emission reductions in all major pollutants, with the exception of CO_2 (which remains the same). In absolute terms, the greatest reductions are seen in daily mobile CO emissions. Reductions of daily VOC emissions are next. Total daily CO and VOC emissions will be reduced by 230 and 22 tons, respectively. Total daily NOx, SOx, and PM emissions will be 12, 5, and 0.1 tons less. Among different sub-fleets, passenger vehicles on residential roads ("PCResidential" in Figure 4-7-a) will have the greatest absolute amounts of CO, VOC, NOx, and SOx reductions. The truck fleet will achieve the greatest PM emission reduction.

[45] The bureau website is: http://www.bjtsb.gov.cn/ (only in Chinese). During the inspection in spring 2008, 104 gasoline samples were tested, and all of them were in compliance with quality requirements. Ninety-six diesel samples were tested but only 88 percent were in compliance. Most of the inferior samples had sulfur contents higher than the requirement.

[46] These assumptions are based on the input intervals that are preset in the IVE model. The correction factors of fuel properties in the IVE model are based on the USEPA MOBILE6 inputs. We used the temperature and humidity readings of April 1, 2008, to run these two scenarios.

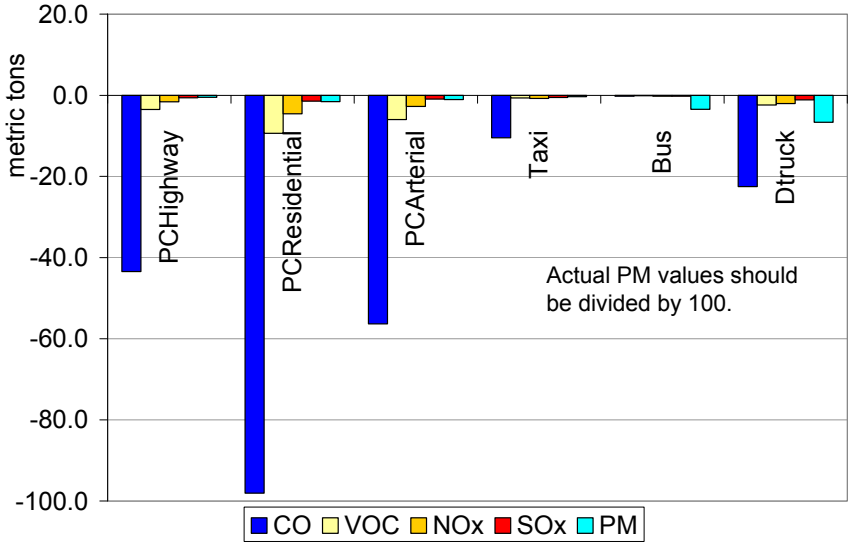

Figure 4-7-a Emission Reductions under Clean-Fuel Scenario

In relative terms, the reduction of the total daily mobile SOx emissions under the clean-fuel scenario is the most significant—84%, while the reductions of CO and VOC emissions are also noticeable, at 18 percent and 16 percent respectively (see Table 4-4). NOx and PM reductions are less, at 4 percent and 3 percent. The bus fleet will attain the highest percentage of SOx reduction (89 percent). Passenger vehicles on highway ("PCHighway" in the table) will have the highest percentages of CO and VOC reductions (28 percent and 27 percent), and passenger vehicles on arterial roads ("PCArterial" in the table) will achieve the highest percentages of NOx reduction (9 percent).

Table 4-4 Emission Reductions under Clean Fuel Scenario

	CO	*VOC*	*SOx*	*NOx*	*PM*
Overall	-18%	-16%	-84%	-4%	-3%
PCHighway	-28%	-27%	-83%	-8%	-3%
PCResidential	-23%	-19%	-83%	-8%	-3%
PCArterial	-22%	-18%	-83%	-9%	-3%
Taxi	-17%	-11%	-83%	-3%	-3%
Bus	0%	-2%	-89%	-1%	-3%
Truck	-8%	-8%	-88%	-2%	-3%

Figure 4-7-b shows that in absolute terms, clean fuels have larger impacts on running emissions than on start emissions. In relative terms, this statement also stands for CO and VOC emissions. Total running emissions of CO and VOC are 20 percent less under the clean-fuel scenario than under the moderate-fuel scenario, but total start emissions of CO and VOC under the clean-fuel scenario are only 7 percent less than those of the moderate-fuel scenario. However, for the two different scenarios, relative

reduction of NOx start emissions is higher than that of its running emissions (12 percent vs. 4 percent). The relative impacts on SOx running and start emissions are about the same (84 percent).

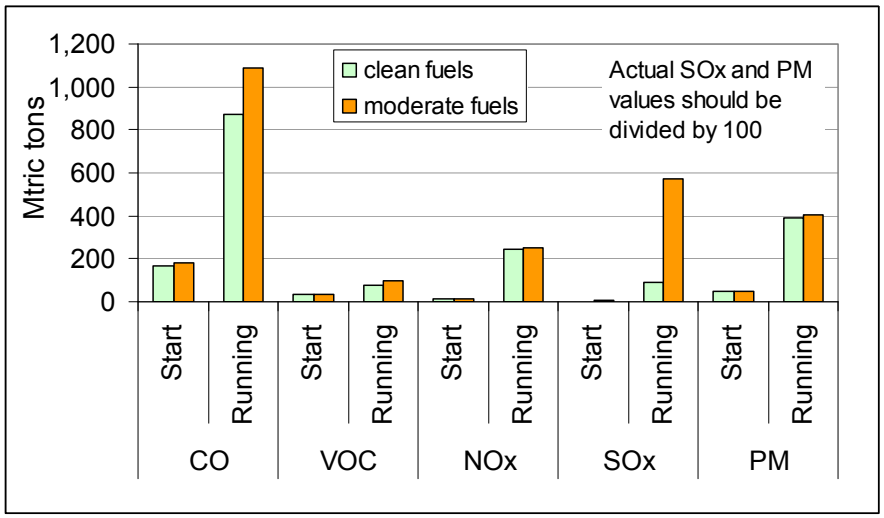

Figure 4-7-b Start and Running Emissions under Different Fuel Scenarios

Inspection and Maintenance Program

Vehicles that are poorly maintained or that have malfunctioning emission control devices often exceed the emission standards which they were certified to meet. Even minor malfunctions can increase emissions considerably while major malfunctions can cause emissions to skyrocket. It is commonly observed that an average car on the road is emitting several times more pollution than standards allow for new cars. Inspection and Maintenance (I/M) is a way to check whether the emission control system on a vehicle is working correctly. Under an I/M system, in-use vehicles that have failed to pass smog tests must be repaired before they can renew their registrations.

Beijing started its I/M program for in-use vehicles initially with two-speed idle tests in mid-1990s, but switched to the method of Acceleration Simulation Mode (ASM) in 2003 because the latter is closer to real-world driving conditions and can capture NOx emissions (two-speed idle tests cannot). To date, over 200 ASM devices have been installed at about forty vehicle inspection stations. Vehicles are required to pass the ASM emission test in order to have their registrations renewed annually, but vehicles owners are free to choose which inspection station to use. Under the Beijing I/M program, inspection stations in general do not perform repair services.

The IVE model allows a user to change the input options concerning I/M programs.[47] Since Beijing is now using the ASM method and requires all vehicles to be inspected annually, we decided to run two scenarios for the impacts of an I/M program on emissions.

a) No I/M program at all;

b) Loaded, centralized I/M program for all vehicles.

Two other input assumptions are clean fuels and mild weather conditions (we used hourly temperature and humidity data on April 1, 2008).

Figures 4-8-a and -b illustrate the likely emission reduction effects of a loaded, centralized I/M program. In comparison with no I/M program at all, the implementation of such a program will lead to decreased CO, VOC, NOx, and PM emissions. The daily emissions of these four pollutants will be reduced by about 120, 10, 16, and 0.3 tons per day respectively, i.e., 12 percent, 7 percent, 6 percent, and 8 percent lower than the emissions under no I/M program scenario. In absolute terms, passenger vehicles on residential roads ("PCResidential" in Figure 4-8-a) will have the greatest CO, VOC, and NOx emission reductions. Truck and bus fleets will achieve the greatest PM emission reductions.

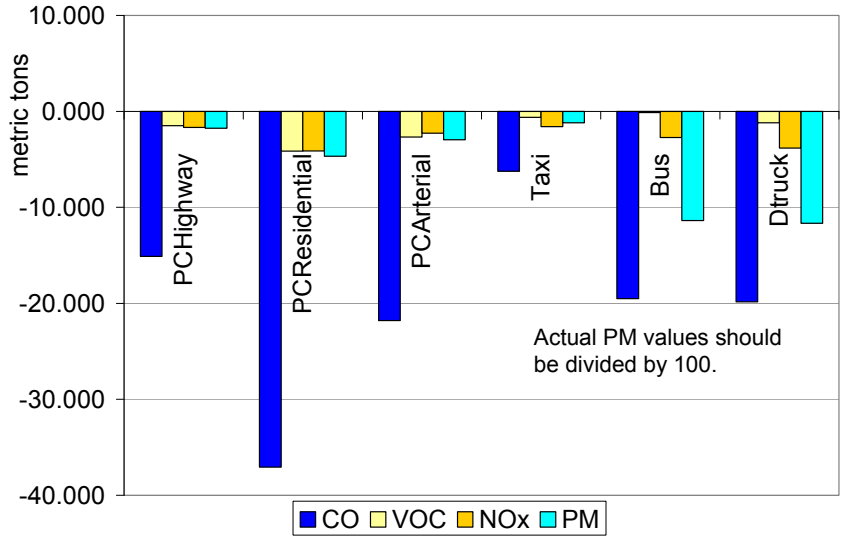

Figure 4-8-a Emission Reductions under Clean Fuels & I/M Scenario

Figure 4-8-b shows that an effective I/M program will reduce both start and running emissions of the four major pollutants. Its impacts on running emissions are more significant than on start emissions.

[47] The correction factors for I/M program in the IVE model are based on the U.S. data. Since we do not have enough information about the effect of the Beijing I/M program, we used the default values of I/M correction factors.

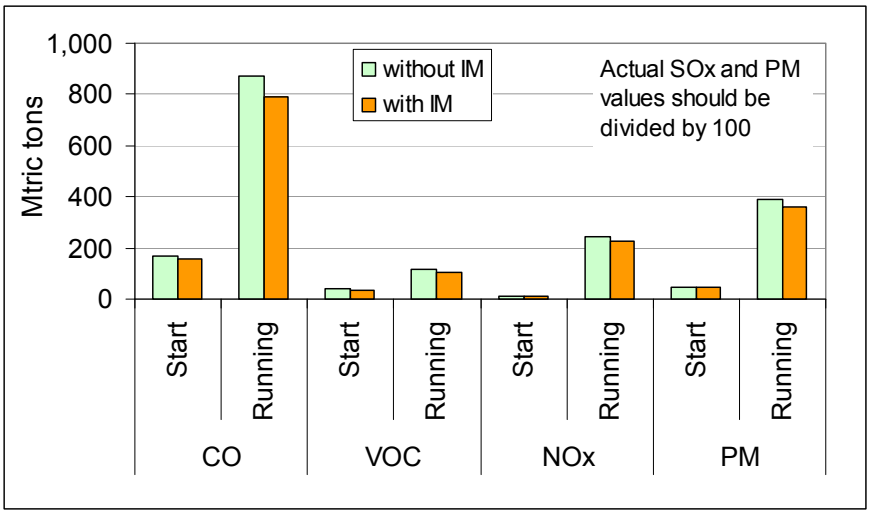

Figure 4-8-b Start and Running Emissions with/without IM Program

In relative terms, under the effective I/M program scenario, the bus fleet will have the highest percentage of decreases in CO and NOx emissions, while the passenger vehicles on the highway will have the most relative reductions in VOC and PM emissions (see Table 4-5).

Table 4-5 Emission Reductions under Clean-Fuel, I/M Scenario

	CO	*VOC*	*NOx*	*PM*
Overall	-11.5%	-6.6%	-6.4%	-7.7%
PCHighway	-13.5%	-10.7%	-8.6%	-10.6%
PCResidential	-11.5%	-7.7%	-8.0%	-9.2%
PCArterial	-11.2%	-7.4%	-7.7%	-9.0%
Taxi	-12.2%	-3.3%	-6.6%	-9.9%
Bus	-18.6%	-3.2%	-9.4%	-10.2%
	-8%	-8%	-2%	-3%

Traffic Management

Driving Pattern

To examine how traffic conditions may impact vehicle emissions, we ran the IVE model with the following two assumptions[48] (under the conditions of spring weather and moderate fuel quality):

a) Adjust the driving patterns of PC arterial roads and PC residential roads in the daytime to be the same as the driving patterns when they achieve the second highest hourly speed. On PC arterial roads, we chose the driving pattern from 11:00–12:00 (average speed 20.03 km/hr) as the assumed typical daytime driving pattern. On PC residential roads, we chose the driving pattern from 9:00 to 10:00 (average speed 24.95 km/hr) as the assumed typical daytime driving pattern.
b) Keep the driving patterns of buses, trucks, taxis, and PC highway the same (thus, the emissions from the bus, truck, taxi, and PCHighway sub-fleets will not change).

The results are illustrated in Figure 4-9. Improved daytime traffic conditions on arterial and residential roads will reduce total mobile CO, VOC, NOx, SOx, PM, and CO_2 emissions by 15, 6, 8, 0.4, 0.7, and 3,200 tons per day, only 1 percent, 4 percent, 2 percent, 6 percent, 1 percent, and 6 percent fewer emissions. Thus, improving traffic conditions on certain roads alone are not as effective as adopting clean fuels or implementing an I/M program to reduce total mobile emissions.

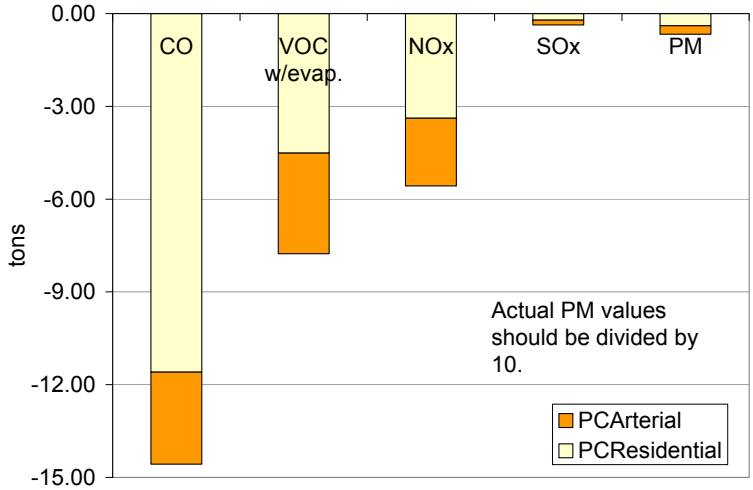

Figure 4-9 Emission Reductions Resulting from Improved Daytime Traffic on Arterial and Residential Roads

[48] We acknowledge that such assumptions are oversimplified. During both rush hours, most roads in Beijing are fully saturated. Thus, improved driving conditions on arterial and residential roads are likely to induce a redistribution of vehicles on various roads at different hours. Unfortunately, the scope of this study does not allow us to include a traffic model to predict the new balance of road use and traffic conditions under different traffic assumptions.

Between the PCResidential and PCArterial sub-fleets, the former will achieve greater amounts of emission reductions. It is partially because the RCResidential sub-fleet accounts for a higher share of road use and partially because the extent of traffic improvement occurring on residential roads is also higher under our assumption.

Vehicle Population

During the 2008 Beijing Olympic Games, policies to control mobile emissions include restraining the total number of passenger vehicles on the road and prohibiting use of highly polluting cars (those failed to meet Euro I emission standards). We ran the IVE model with the following assumptions to examine the possible emission reductions induced by such policies:[49]

a) Scrap all the carbureted passenger cars and replace them with cars certified to meet Euro IV emission standards;
b) Only permit half of all passenger vehicles to be driven on any day (depending on whether a license number ends with an odd or even number);
c) Double the number of buses. The added new buses are certified to meet Euro IV emissions standards; three quarters of which are medium-sized, and the remaining ones are large-sized (the same as the weight distribution of existing buses). And,
d) Improve traffic conditions during the daytime significantly (the same assumptions regarding traffic patterns on residential and arterial roads in the previous subsection).

The above assumptions have changed the composition of the passenger vehicle fleet and bus fleet, as well as the location files of passenger vehicles on residential roads and arterial roads. With these changed inputs, the IVE model predicts that the total amounts of mobile CO, VOC, NOx, PM, and CO_2 emissions will be reduced by about 520, 80, 60, 0.5, and 14,300 tons per day, respectively. The corresponding relative emission reductions will be 41 percent, 60 percent, 22 percent, 12 percent, and 27 percent, respectively. Figure 4-10-a illustrates emission reductions by the various sub-fleets.

[49] An ideal study would require real VA data during the Olympic Games. However, we were not collecting Beijing VA data during the Olympic Games due to resource constraints and logistical difficulty.

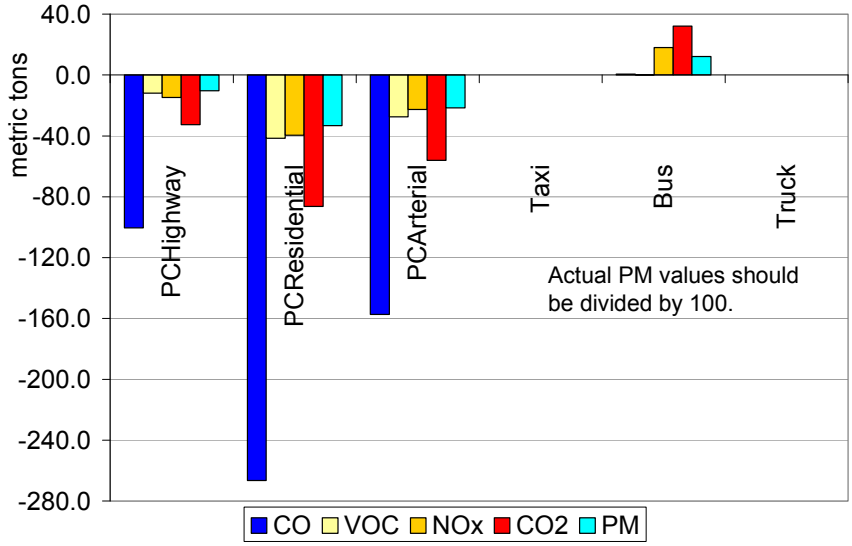

Figure 4-10-a Emission Reductions under Traffic Control Scenario

Since most of the measures target passenger vehicles, emissions from the passenger vehicle sub-fleets are projected to be cut back drastically (more than 50 percent). VOC emissions from these three sub-fleets will be reduced by 80–90 percent and CO, NOx, and PM emissions will be reduced by 60–70 percent. In absolute terms, the PCResidential sub-fleet will achieve the highest amounts of reductions of all pollutants.

Figure 4-10-b compares the actual running and start emissions and those under this hypothetic traffic control scenario. In absolute terms, the reductions of start emissions are less than the reductions of running emissions. However, in relative terms, the opposite is true.

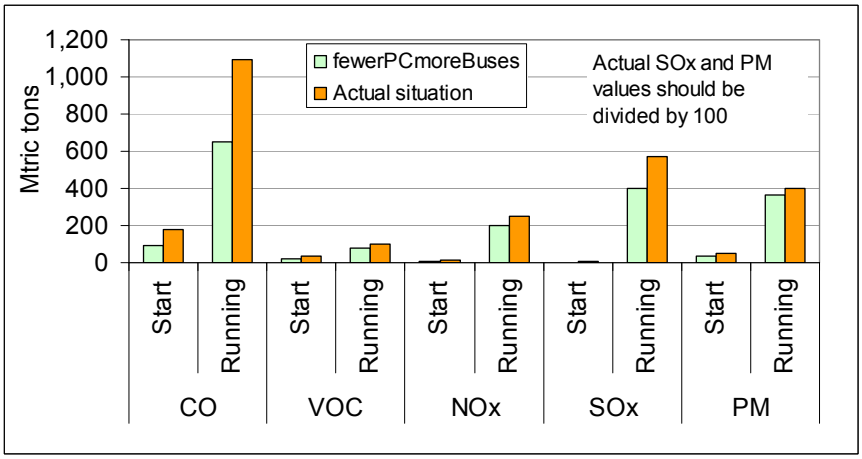

Figure 4-10-b Actual Start and Running Emissions vs. Projected Emissions under Traffic Control Scenario

5. Conclusions

5.1 Summary of Major Results

Our study on in-use vehicle emissions in Beijing led to the following four major accomplishments:

1) We collected original data on on-road emissions of light-duty passenger vehicle (LDPV) under various driving conditions, pattern of vehicle use, vehicle technology distribution, and driving conditions in Beijing.

Our data collection in the field in Beijing consisted of two major parts: testing of vehicle emissions on the road and collection of vehicle activity information. Each part of the field work was carried out intensely during a two-week period of time.

Second-by-second emission and driving condition data of fifty-eight preselected light-duty gasoline vehicles were collected on a fixed driving route, which is about 22 kilometers long and comprised of sections of urban expressway, arterial roads, and residential roads. We eventually obtained valid testing results of fifty-three vehicles. These vehicles were certified to different emission standards (from no standards to Euro III standards), of various engine sizes (from 1.0 to 2.7 liters), and accumulated mileages (from less than 15,000 to 400,000 kilometers).

During the 2008 Beijing VA study, we collected driving patterns on various roads (velocity, acceleration, altitude, longitude, and latitude data) for three days from three passenger cars, one taxi, a number of buses, and one truck with GPS devices. Concurrently with the driving pattern study, we also collected data for producing real-time on-road fleet composition with three video cameras. Traffic flow at the nine sites was recorded with these three cameras for three days (6:00 to 20:00, twenty minutes of each hour). Data on specific vehicle technology were collected through a survey of 2,500 cars, 120 trucks, and 60 taxis. The specific technology distribution of buses was generated based on relevant information from the Beijing Pubic Transport Holdings company.

2) Our on-road testing of LDPVs emissions led us to detect the overall trends of emission characteristics of LDPVs in Beijing.

Our analysis of emissions testing data has revealed three big trends of Beijing LDPV's emission performance:

Light-duty passenger vehicles are becoming cleaner over time, corresponding to tightening trend of emission standards for new vehicles.

It is obvious that the average emissions of vehicles certified to more recent, stricter emission standards are much lower than those of vehicles certified to earlier,

looser emission standards. For example, vehicles made prior to Euro I standards on average emit about thirty-three grams of CO per kilometer, while vehicles certified to Euro III standards on average emit only six grams of CO per kilometer, a difference of 450 percent. Similarly, the average NO_2 emission per kilometer from vehicles made prior to Euro I standards is about 300 percent higher than those from vehicles certified to Euro III emission standards.

However, *the actual average emissions of vehicles (grouped by certified emission standards) are much higher than their certified limits; this observation even stands for low-mileage vehicles.*

For CO, the actual average emissions of tested vehicles that had been certified to meet Euro I, II, and III standards are 5.2, 4.3, and 2.7 times the corresponding requirements of their certified standards. For THC and NO_2 (combined concentration), the actual average emissions of tested vehicles that had been certified to meet Euro I, II, and III vehicles are 1.6, 1.9, and 2.3 times the corresponding requirements of their certified standards.

For all vehicle emission groups, the effectiveness of emission control devices decreased considerably over time.

It appears that all high-mileage vehicles emit about the same amounts of NOx and THC, without regard to which levels of emission standards they were certified. The deterioration of emission control systems of high-mileage vehicles that were certified to more stringent standards seems to be very dramatic. For example, among the fourteen tested Euro III vehicles, the average combined NOx and THC emissions of high-mileage vehicles were 4.7 times higher than those of low-mileage vehicles.

3) <u>Identification of road use pattern, vehicle technology distribution, driving and start patterns of various vehicle types in Beijing.</u>

Our analysis of traffic videos at the nine sample sites has shown that from 6:00 to 20:00, passenger vehicles and taxis take up about 87 percent of road use, buses of all different sizes together contribute about 12 percent of road use, and small- and medium-sized trucks account for less than 1 percent of road use in the urban areas of Beijing. During daytime hours, very few motorcycles were observed on the urban roads of Beijing, and heavy trucks did not appear on the videotapes at all.

We estimated that in early 2008, about 8 percent of passenger vehicles were made before Euro I emission standards took effect. About 17 percent, 42 percent, 30 percent, and 4 percent of passenger vehicles had been certified to meet Euro I, II, III, and IV emission standards, respectively. Passenger vehicles in Beijing were about 4.7 years old and were driven for about fifty kilometers per day. The total distance driven by the Beijing passenger fleet was about 121 million kilometers per day in early 2008.

Our surveys of sixty taxis showed that two thirds of Beijing taxis had accumulated high mileage (greater than 160,000 kilometers), while only 10 percent had been driven less than 80,000 kilometers. Most of Beijing taxis (82 percent) had been certified to Euro III emission standards and 18 percent to Euro II standards. Taxis on average were driven for about 360 kilometers per day, and the total distance driven by Beijing taxi fleet was about 23.8 million kilometers in early 2008.

Beijing's truck fleet was quite new. Eighty-three percent of all 120 surveyed trucks ran on diesel fuel, and the rest ran on gasoline. More than three-quarters of the trucks were certified to Euro III standards, and the rest were almost all certified to Euro II standards. Beijing trucks on average travelled about 100 kilometers per day, and the overall daily distance travelled totaled 18.4 million kilometers.

About three quarters of Beijing buses were medium-sized buses, and the rest were heavy buses. About 22 percent of Beijing's buses ran on natural gas, and the rest used diesel fuel. Among the diesel buses, nearly two-thirds were made to meet Euro III emission standards, 28 percent were certified to Euro IV emission standards, and about 6 percent could only meet Euro II emission standards. Buses on average ran 185 kilometers per day, and total daily distance travelled by Beijing's bus fleet was about 3.7 million kilometers.

4) <u>We generated daily mobile emission inventories for Beijing and estimated the relative contributions of different vehicle technology groups to total mobile emission and road use.</u>

Using corrected base emission factors and local inputs of vehicle activities, climate conditions, and fuel quality, we estimated that the total daily mobile emissions from the Beijing fleet were the following in early 2008:

- CO: about 1,270 tons (emission factor is 7.6 g/km);
- VOC: about 180 tons (emission factor is 1.1 g/km);
- NOx: about 270 tons (emission factor is 1.5 g/km);
- PM: about 4.5 tons (emission factor is 0.03 g/km).

Under mild weather conditions, start emissions accounted for 22 percent, 14 percent, and 11 percent of total daily VOC, CO, and PM emissions but only account for 6 percent of total NOx emissions in Beijing.

Passenger vehicles contributed about 73 percent of the total vehicle mileage travelled (VMT) and similar shares (65 percent and 72 percent) of the total mobile CO and VOC emissions, respectively. They contributed 41 percent and 23 percent of the total mobile NOx and PM emissions, respectively. The taxi fleet contributed 14 percent of VMT, but its contributions to the total mobile CO, VOC, NOx, and PM emissions were much less (5 percent, 4 percent, 10 percent, and 3 percent, respectively). The truck fleet accounted for only 11 percent of VMT, but it accounted for 39 percent and 49 percent of total NOx and PM emissions, respectively. The bus fleet contributed 2.2 percent of total distance travelled; however, it accounted for 26 percent and 11 percent of PM and NOx emissions, respectively, as well as 8 percent of CO emissions.

We also estimated emissions from ninety-two different vehicle technology classes in Beijing. Gasoline vehicles all together (including both gasoline passenger cars and trucks) were the dominant contributors to mobile CO and VOC emissions. Together, they accounted for 88 percent of total mileage travelled; 90 percent and 92 percent of total mobile CO and VOC emissions, respectively; 56 percent of NOx emissions; and 29 percent of PM emissions. Diesel vehicles were major contributors to total PM and NOx emissions. They accounted for 9 percent of total distance travelled and 67 percent and 40 percent of PM and NOx emissions, respectively.

Our model, which was run with three sets of different climate conditions, showed that total mobile emissions in Beijing have quite noticeable seasonal variations. The biggest difference is between summer and spring. Daily CO emissions on a hot summer day can be 30 percent higher than on a mild spring day, and the VOC emissions can be 10 percent higher.

5.2 Discussion on Policy Implications

The abovementioned technical findings of our Beijing vehicle emissions study have provided us with a sound basis for policy insights to mobile emission control in the Chinese context. Some insights are directly from the discerned trends of emission performance of different LDPV groups, as revealed by our on-road testing; some rely on the emission estimations of IVE model using real local inputs; and some are derived from the emission reduction results of our hypothetic policy scenarios.

1) <u>Steadily and continuously tightening emission standards for new vehicles has been proven to be a very effective policy in lowering average vehicle emissions over time.</u>

The undisputable evidence from our emission testing in Beijing (and Tianjin) shows that light-duty passenger vehicles are becoming cleaner over time, corresponding to the stringency steps and implementation schedules of emission standards for new vehicles.

2) <u>An effective I/M program is essential to curb the overall deterioration of emission-control-system performance of high-mileage vehicles.</u>

Both our on-road emission testing and IVE model results show that for all vehicle groups (classified by their emission standards), the average emissions increase considerably with the accumulation of mileage. This indicates a rapid deterioration of emission control systems over time. To make sure that high-mileage vehicles maintain minimal environmental performance, reasonably strict standards for in-use vehicles must be established and an effective I/M program has to be in place to enforce such standards.

3) China needs to enhance the effectiveness of emission standards for new vehicles.

We were surprised to find the even low-mileage vehicles on average emit much more pollution than the maximum limits in their certified standards. This scope of this study does not allow us to investigate the actual causes, but our educated guess is that the phenomenon is the result of a combination of several factors: the fuel used for certification process has much superior quality than what is available commercially; many of the emission control devices have very poor durability; and some new vehicle models simply can not meet the standards, but obtained certification anyway.

4) Acceleration of the turnover rate of high-use public fleets (taxis and buses) is an effective way to control mobile emissions.

In comparison with our findings in Tianjin, we were delighted to see that that Beijing taxis are much cleaner than Tianjin taxis, and the latter was identified in our Tianjin study as gross emitter overall. Beijing taxis on average are even much cleaner than Beijing passenger vehicles, while the opposite was true in Tianjin. A typical Beijing taxi emits only 2.6, 0.8, and 1.0 grams of CO, VOC, and NOx per kilometer driven while a typical Tianjin taxi emits 21.6, 3.7, and 1.5 grams of CO, VOC, and NOx per kilometer driven. Beijing's buses on average are also much cleaner than Tianjin buses. A typical Beijing bus emits 7.9 and 0.3 grams of NOx and PM per kilometer driven while a typical Tianjin bus emits 21.7 and 0.8 grams of NOx and PM per kilometer driven. Since the daily use of such public vehicles is generally very high, local policies that make sure these public vehicles are clean have significant impacts on mobile emissions and public health.

5) Carbureted vehicles are gross emitters and replacing them will generate considerable emission reduction benefits.

Carbureted passenger vehicles account for 6 percent of total distance travelled, but they contribute 18 percent, 20 percent, and 16 percent of total mobile CO, VOC, and NOx emissions, respectively. The emission factors of these carbureted vehicles are twenty to fifty times higher than the corresponding requirements in the Euro IV standards. Most of these vehicles have accrued high mileage and are at the end of their lifetime. Thus, replacing these vehicles with vehicles that can meet Euro IV standards would reduce total mobile CO, VOC, and NOx emissions considerably. Similarly, there are also a considerable number of trucks that cannot meet Euro I emission standards according to Beijing EPB. We strongly believe that replacing these trucks will also lead to significant emission reductions. As a matter of fact, at the end of 2008, Beijing's government announced that all the vehicles that cannot meet Euro I emission standards must be scrapped before 2010, and the government will provide a certain amount of subsidies for these owners to replace their vehicles.

6) The immediate effects of clean fuels on mobile emissions are substantial.

Our scenario analysis shows that reducing the sulfur content of both gasoline and diesel fuel will lead to considerable emission reductions. Lowering the sulfur content in gasoline from the current 500 ppm to 50 ppm and lowering the sulfur content in diesel fuel from 500 ppm to 50 ppm will lead to 84 percent, 18 percent, and 16 percent reductions of total mobile SOx, CO, and THC emissions, respectively. Emission reductions in NOx and PM are less impressive due to improved fuel quality (only a few percent). However, it is mainly because the emission control technologies currently employed by the Beijing diesel fleet are largely meant to meet Euro II and III standards, which do not have particularly high requirements for sulfur content in diesel fuel. With China moving to Euro IV emission standards nationwide, low sulfur diesel fuel will become a prerequisite for Euro IV emission control technology to function well.

7) A complete policy package including key components such as limiting the total number of on-road private cars and boosting public transport service seems to be able to achieve the most drastic effects in reducing total mobile emissions.

Our conservative estimation shows that limiting 50 percent of light-duty passenger vehicles and doubling the number of buses will lead to at least 41 percent, 60 percent, 22 percent, and 12 percent reductions in total mobile CO, THC, NOx, and PM emissions, respectively. There is no doubt that the drastic traffic control measures taken by Beijing during the 2008 Olympic Games contributed to the much improved air quality during the Olympic Games. However, we also acknowledge that the public (especially the existing vehicle owners) can only accept such drastic measures during a dramatic event and for a very short period of time. The city should consider restraining vehicle population growth in the long term and focusing on providing expedient and convenient public transportation service as an alternative. There is plenty of positive experience that Beijing can learn from highly dense and yet efficient cities like Tokyo and Singapore.

Appendices

A. Limits of Chinese Ambient Air Quality Standards

Pollutants	*Unit*	*Average time*	*Limits **		
			Level I	*Level II*	*Level III*
SO_2	mg/m^3 (standard condition)	Annual	0.02	0.06	0.10
		Daily	0.05	0.15	0.25
		Hourly	0.15	0.50	0.70
TSP		Annual	0.08	0.20	0.30
		Daily	0.12	0.30	0.50
PM_{10}		Annual	0.04	0.10	0.15
		Daily	0.05	0.15	0.25
NO_2		Annual	0.04	0.08	0.08
		Daily	0.08	0.12	0.12
		Hourly	0.12	0.24	0.24
CO		Daily	4.00	4.00	6.00
		Hourly	10.00	10.00	20.00
O_3		Hourly	0.16	0.20	0.20
Pb	ug/m^3 (standard condition)	Quarterly		1.50	
		Annual		2.00	
B(a)P		Daily		0.01	
F		Daily		7 **	
		Hourly		20 **	
	ug/decimeter^2 per day	Monthly	1.8 ***	3.0 ****	
		Growth season	1.2 ***	2.0 ****	

Source: Ambient Air Quality Standards of China (National Environmental Protection Agency of China 1996) and its 1998 amendment. The 1998 amendments cancelled the limits for NOx and relaxed limits for NO_2 (Class II) and O_3 (Class I and II).

Note: * Level I limits are for natural conservation and special landscape areas; Level II limits are for residential areas (both urban and rural), commercial and common industrial areas; and, Level III limits are for special industrial areas.

** These limits are for urban area.

*** These limits are for pasture land and agricultural areas specialized in growing mulberry tress (for silkworms).

**** These limits are for agricultural and forest area.

B. Four Interfaces of IVE Model

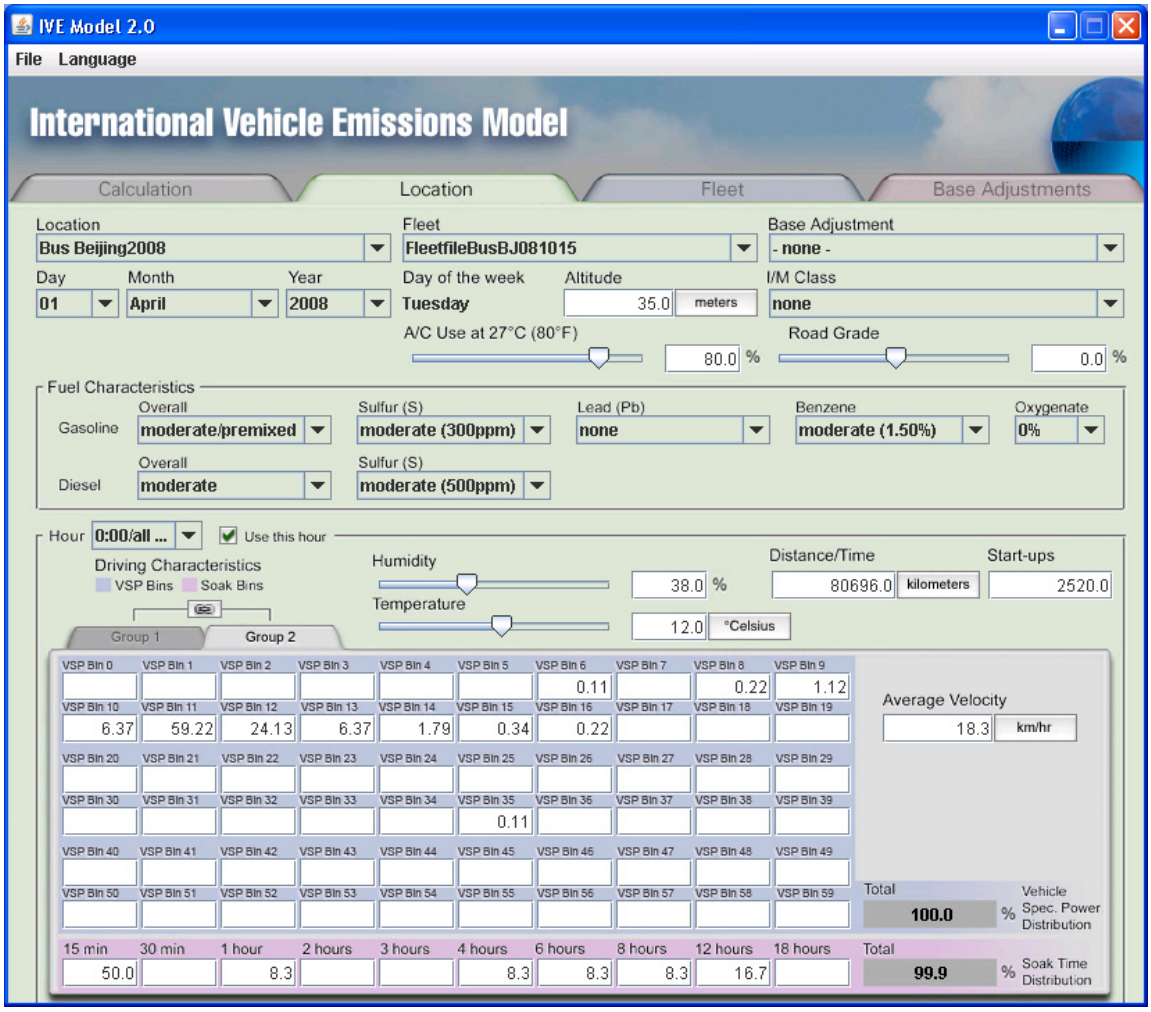

Figure B-a Interface of the Location File in the IVE Model

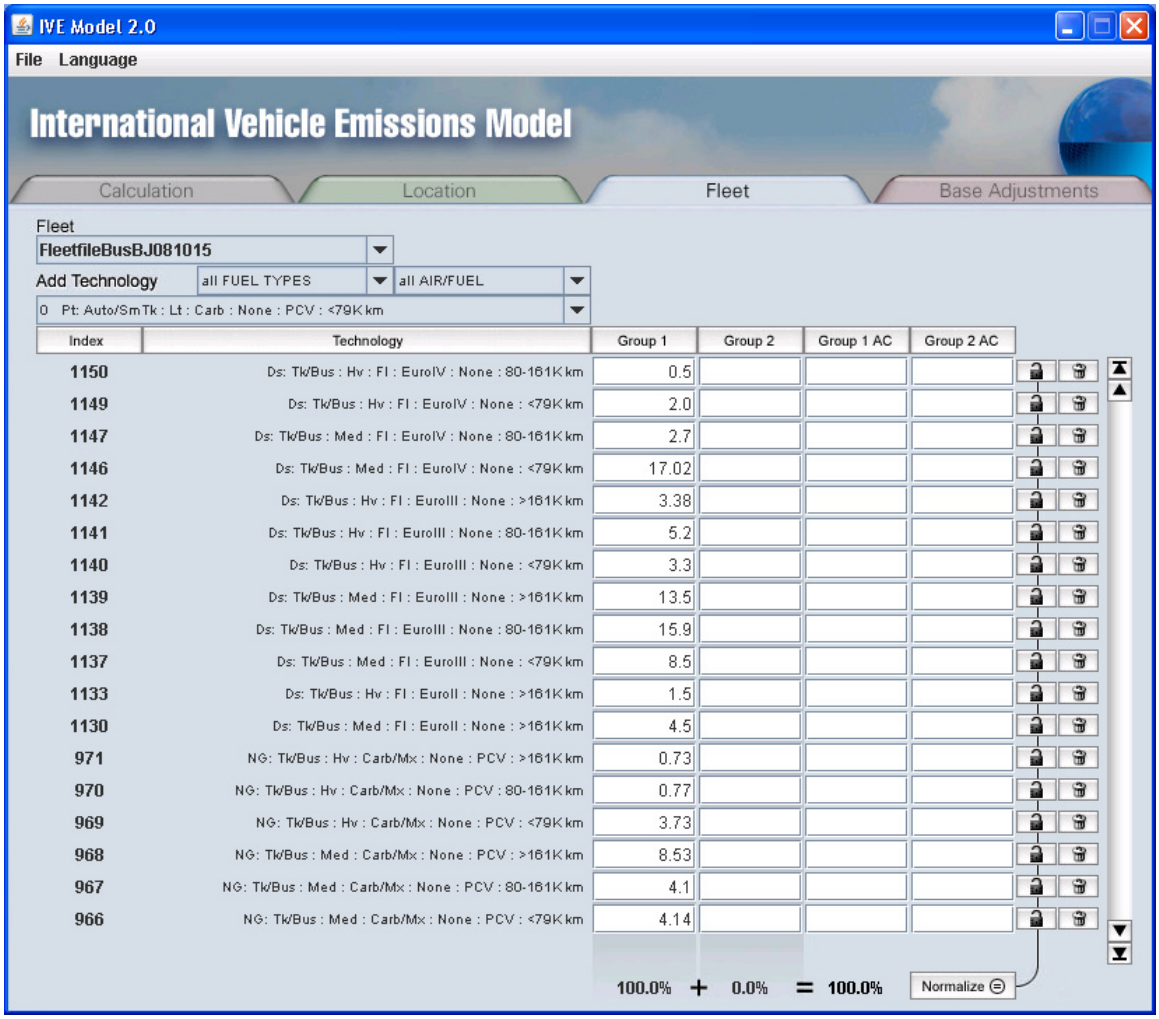

Figure B-b Interface of the Fleet File in the IVE Model

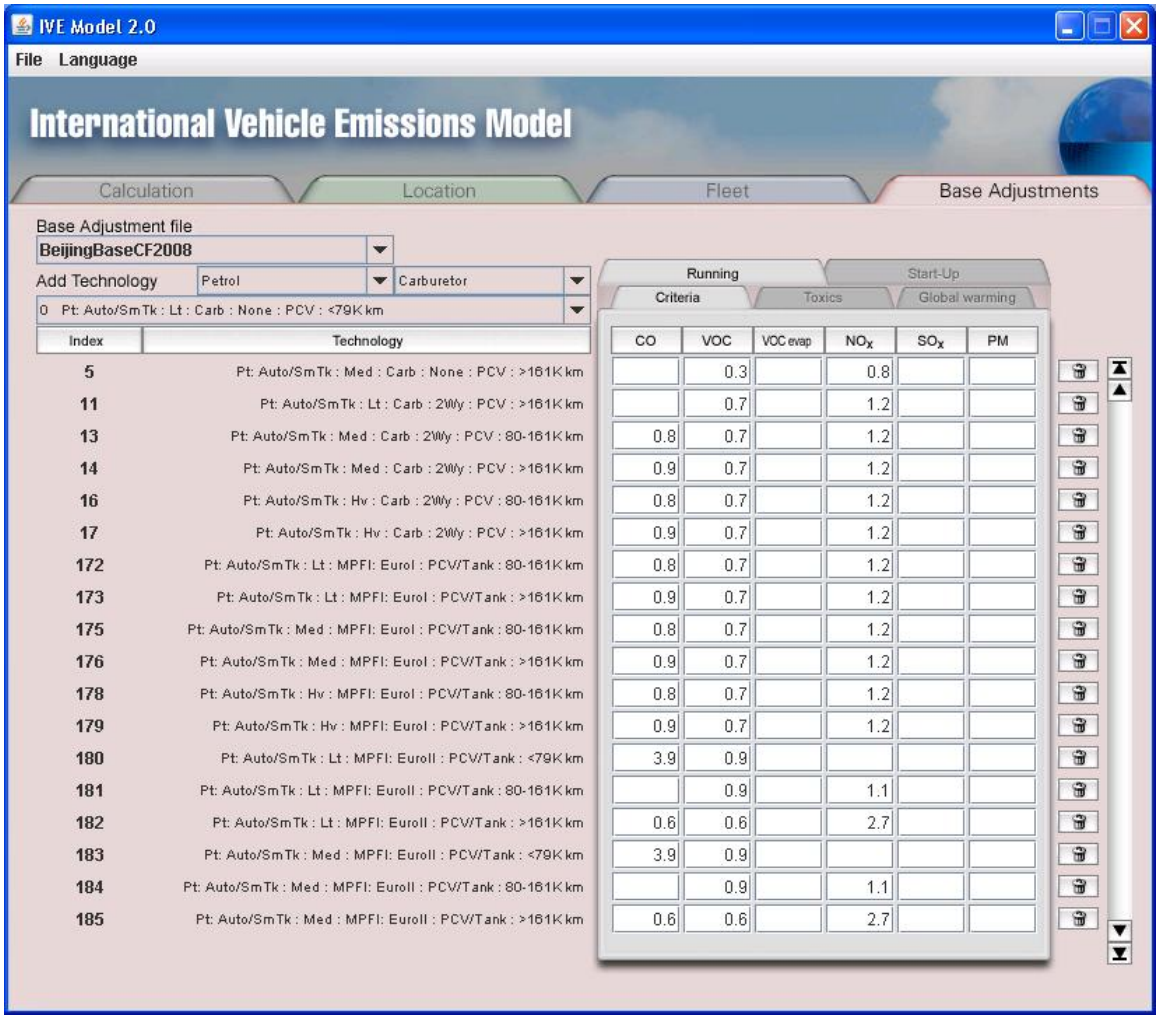

Figure B-c Interface of Base Emission Adjustment Factors in the IVE Model

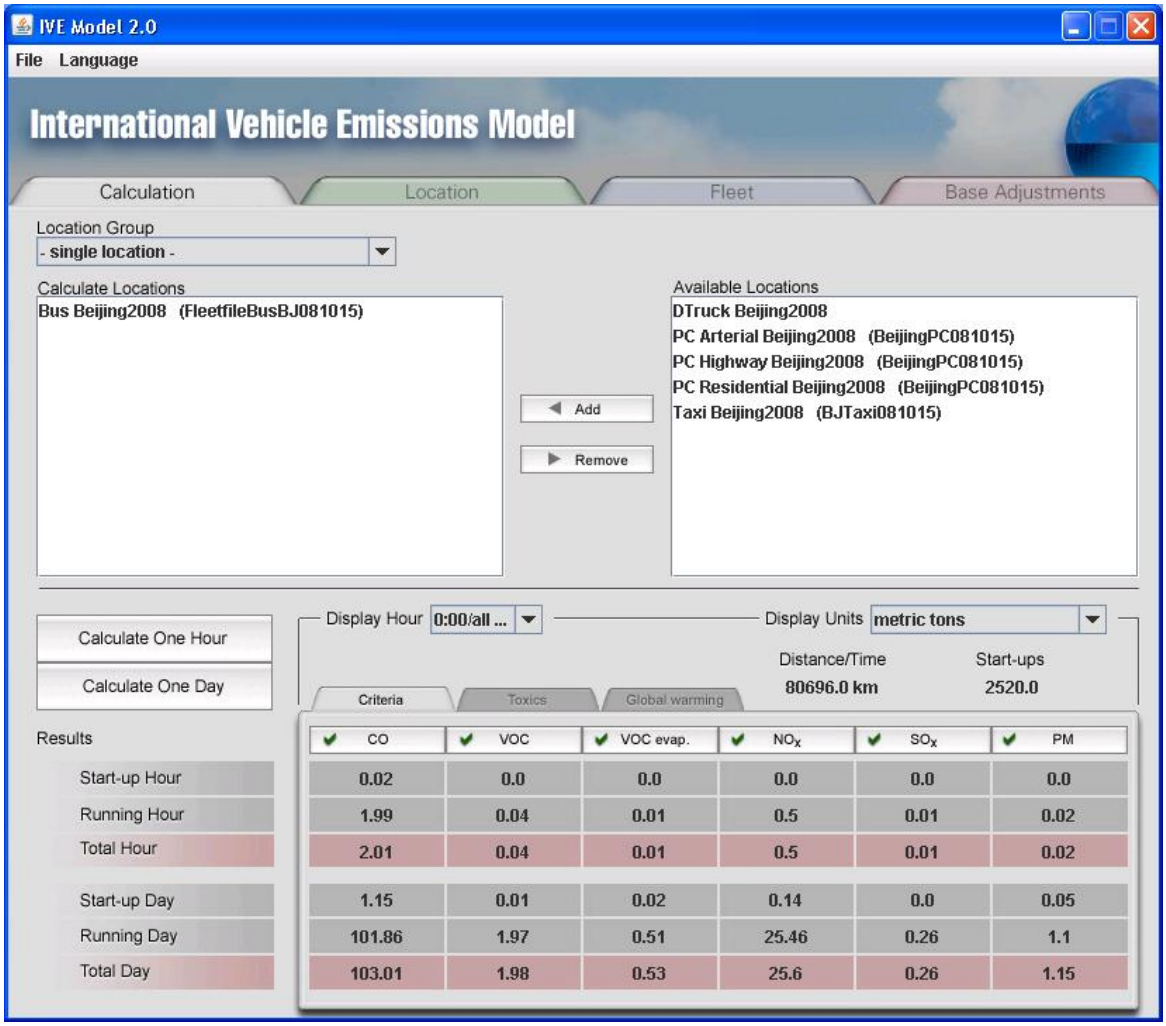

Figure B-d Interface of Calculation Results in the IVE Model

C. *Comparing FTP Cycle with Actual Driving Cycles during On-Road Emission Testing in Beijing*

Emissions from a vehicle under aggressive driving conditions are often higher than those from the same vehicle under less aggressive driving conditions. To compare emissions from different vehicles, we normalized emissions during on-road tests to a FTP cycle. Charts below illustrate the speed traces of FTP cycles and two on-road tests. Test 54 is less aggressive while test 38 is slightly more aggressive than the FTP cycle.

C.1. FTP cycle

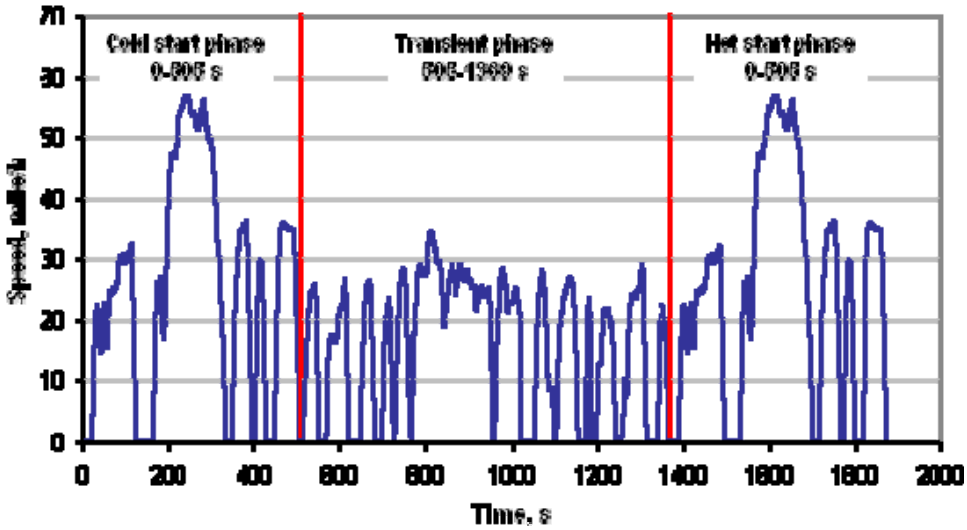

Figure C-a Speed Trace of FTP-75 cycle

- Distance travelled: 11.04 miles (17.77 km)
- Duration: 1874s
- Average speed: 21.2 mph (34.1 km/h).

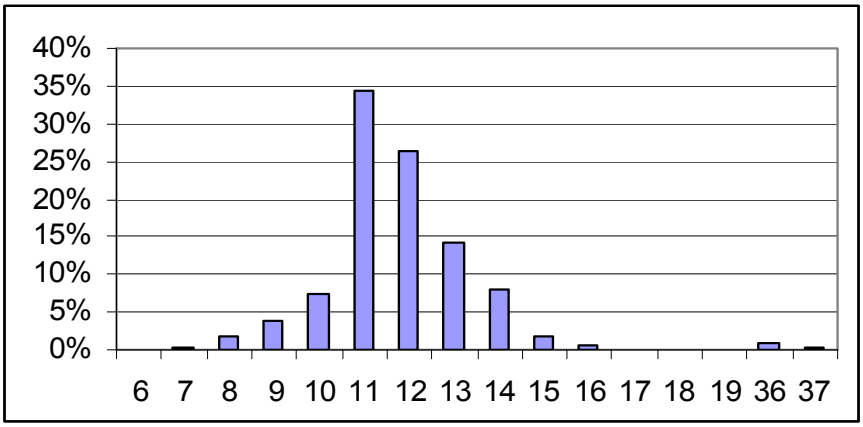

Figure C-b Power Bin Distribution of the FTP Cycle

C.2. Test 54

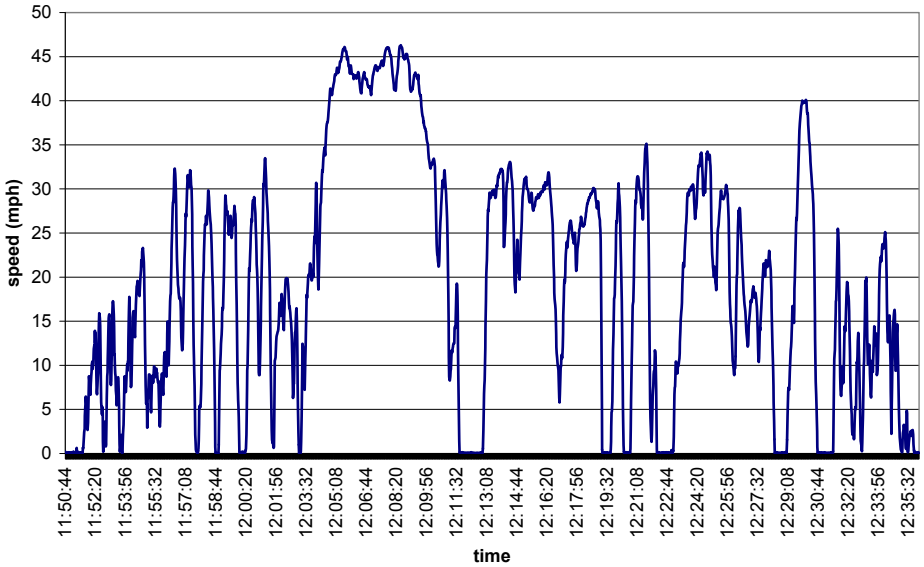

Figure C-c Speed Trace during Test 54 in Beijing

- Distance travelled: 14.6 miles (23.34 km)
- Duration: 2372 seconds
- Average speed: 19.3 mph (30.9 km/h).

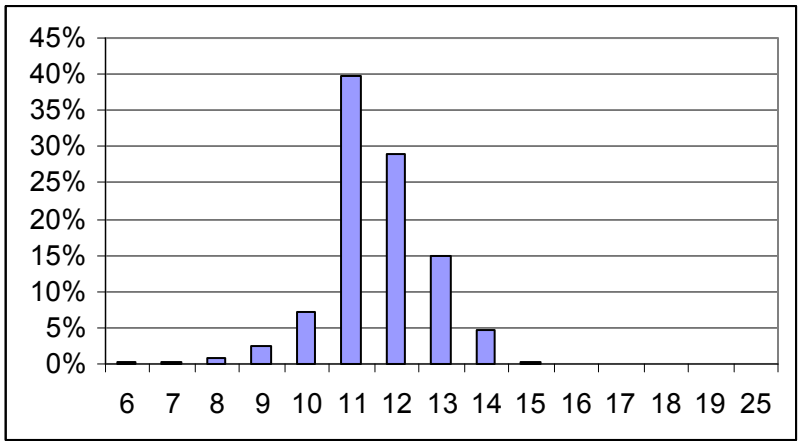

Figure C-d Power Bin Distribution of Test 54

Test 54 is less aggressive than the FTP cycle. The power bin distribution chart shows there was no time spent in any power bin higher than 16. Consequently, the normalized emissions are higher than the actual emissions monitored during the on-road test.

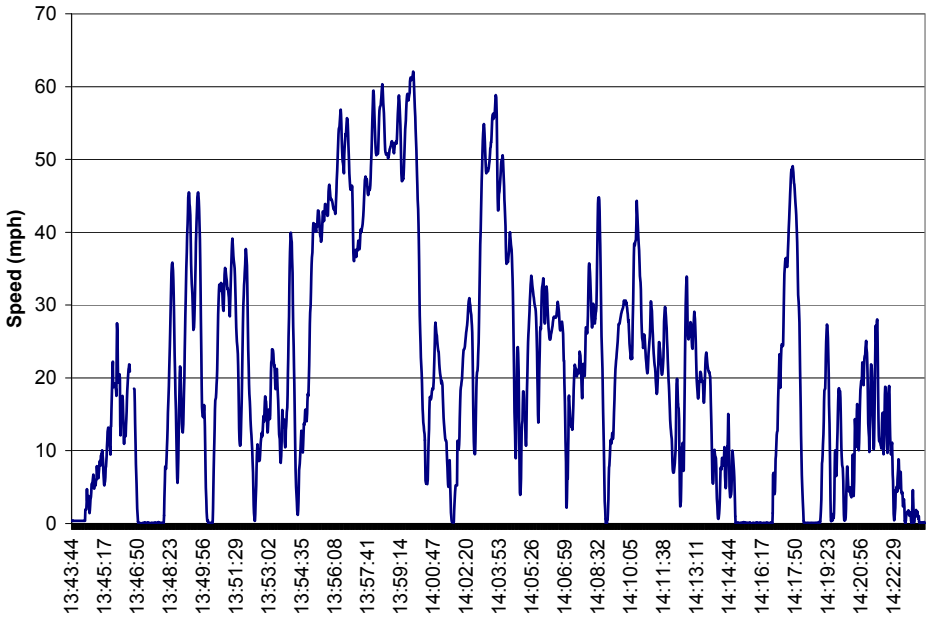

Figure C-e Speed Trace during Test 38 in Beijing

- Distance travelled: 14.16 miles (22.65 km)
- Duration: 2402 seconds
- Average speed: 21.22 mph (33.95 km/h).

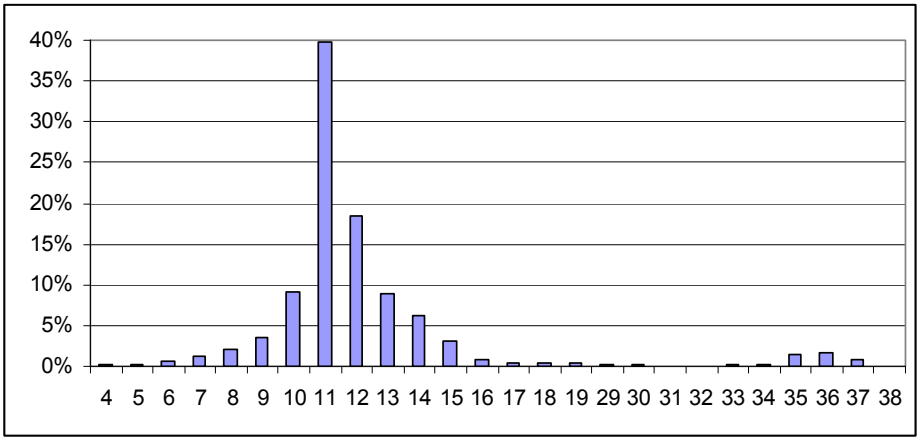

Figure C-f Power Bin Distribution of Test 38

Test 38 is more aggressive than the FTP cycle. The power bin distribution chart shows that some time was spent in power bins 33–37. Recall that emission rates in high power bins are many times higher than emission rates in low power bins. Consequently, the normalized emissions for this vehicle are lower than the actual emissions monitored during the on-road test.

D. IVE Vehicle Technology Classification

Light Duty Gasoline Vehicles		Light Duty Diesel Vehicles		Light Duty Vehicles (Ethanol, Natural Gas, Propane, retrofits, etc)		Heavy Duty Gasoline Vehicles		Heavy Duty Diesel Vehicles		Heavy Duty Vehicles (Ethanol, Natural Gas, Propane, etc)	
Air/Fuel	Control	Air/Fuel	Control	Air/Fuel	Control	Air/Fuel	Control	Air/Fuel	Control	Air/Fuel	Control
Carburetor	None	Pre-Chamber Inject.	None	Carburetor/Mixer	None	Carburetor	None	Pre-Chamber Inject.	None	Carburetor	None
Carburetor	2-Way	Pre-Chamber Inject.	Improved	Carburetor/Mixer	2-Way	Carburetor	2-Way	Direct Injection	Improved	Carburetor	2-Way/EGR
Carburetor	2-Way/EGR	Direct Injection	EGR+	Carburetor/Mixer	2-Way/EGR	Carburetor	2-Way/EGR	Direct Injection	EGR+	Carburetor	3-Way/EGR
Carburetor	3-Way	FI	PM	Carburetor/Mixer	3-Way	Carburetor	3-Way	FI	PM	FI	3-Way/EGR
Carburetor	3-Way/EGR	FI	PM/NOx	Carburetor/Mixer	3-Way/EGR	Carburetor	3-Way/EGR	FI	PM/NOx		
Single-Pt FI	none	FI	EuroI	Single-Pt FI	2-Way	FI	none	FI	EuroI		
Single-Pt FI	none/EGR	FI	EuroII	Single-Pt FI	2-Way/EGR	FI	2-Way	FI	EuroII		
Single-Pt FI	2-Way	FI	EuroIII	Single-Pt FI	3-Way	FI	2-Way/EGR	FI	EuroIII		
Single-Pt FI	2-Way/EGR	FI	EuroIV	Single-Pt FI	3-Way/EGR	FI	3-Way	FI	EuroIV		
Single-Pt FI	3-Way	FI	Hybrid	Multi-Pt FI	3-Way	FI	3-Way/EGR	FI	EuroV		
Single-Pt FI	3-Way/EGR			Multi-Pt FI	3-Way/EGR	FI	EuroI	FI	Hybrid		
Multi-Pt FI	none			Multi-Pt FI	3-Way/EGR	FI	EuroII				
Multi-Pt FI	none/EGR				ZEV	FI	EuroIII				
Multi-Pt FI	3-Way					FI	EuroIV				
Multi-Pt FI	3-Way/EGR					FI	EuroV				
Multi-Pt FI	3-Way/EGR										
Multi-Pt FI	LEV										
Multi-Pt FI	ULEV										
Multi-Pt FI	SULEV										
Multi-Pt FI	EuroI										
Multi-Pt FI	EuroII										
Multi-Pt FI	EuroIII										
Multi-Pt FI	EuroIV										
Multi-Pt FI	Hybrid										

Note: The IVE model includes 1328 technology classifications based on fuel type, engine technology, and control technology, plus 45 user defined technologies. The table above indicates the various types of technologies allowed in the IVE model (now shown in the table above, but 2-wheelers and 3-wheelers are also included). Each technology includes three engine (or vehicle) size classifications and three use (total kilometers driven) categories.

References

ACEA, Alliance, EMA and JAMA 2006, *Worldwide Fuel Charter -- fourth edition*.

Beijing Environmental Protection Bureau 1998-2007, *Beijing Environmental Status 1998-2007*.

Beijing Municipal Government 1998, *Urgent Measures to Control Air Pollution*, Beijing.

Beijing Quality and Technology Supervision Bureau 2007. "Diesel fuels for motor vehicles" (DB11/239-2007). Beijing.

Beijing Quality and Technology Supervision Bureau 2004. "Diesel fuels for motor vehicle use" (DB11/239-2004). Beijing.

Cai, H. & Xie, S. 2007, "Estimation of vehicular emission inventories in China from 1980 to 2005", *Atmospheric Environment,* vol. 41, no. 39, pp. 8963-8979.

Chang, C. 2006, *Automobile Pollution in China: Enforcement of and Compliance with Vehicle Emission Standards*, Ph.D. dissertation, Stanford University, Stanford, CA.

Dan, M., Zhuang, G., Li, X., Tao, H. & Zhuang, Y. 2004, "The characteristics of carbonaceous species and their sources in PM2.5 in Beijing", *Atmospheric Environment,* vol. 38, no. 21, pp. 3443-3452.

Duan, F.K., He, K.B., Ma, Y.L., Yang, F.M., Yu, X.C., Cadle, S.H., Chan, T. & Mulawa, P.A. 2006, "Concentration and chemical characteristics of $PM_{2.5}$ in Beijing, China: 2001–2002", *Science of the Total Environment,* vol. 355, no. 1-3, pp. 264-275.

Gallagher, K.S. & Oliver, H.H. 2005, "Providing Low-Sulfur Fuels for Transportation Use: Policy Options and Financing Strategy in the Chinese Contest." Conference paper. Internet access: http://belfercenter.ksg.harvard.edu/publication/3207/.

General Administration of Quality, Supervision, Inspection and Quarantine of China, 2006, "Gasoline for motor vehicles" (GB1790-2006). Beijing.

Hao, J., He, D., Wu, Y., Fu, L. & He, K. 2000, "A study of the emission and concentration distribution of vehicular pollutants in the urban area of Beijing", *Atmospheric Environment,* vol. 34, no. 3, pp. 453-465.

Hao, J., Hu, J. & Fu, L. 2006, "Controlling vehicular emissions in Beijing during the last decade", *Transportation Research Part A: Policy & Practice,* vol. 40, no. 8, pp. 639-651.

He, C. & Wang, Q. 2006, "Vehicle Emission Factors Determination Using CMEM in Beijing", *Research of Environmental Sciences,* no. 01.

He, K.B., Yang, F., Ma, Y., Zhang, Q., Yao, X., Chan, C.K., Cadle, S., Chan, T. & Mulawa, P. 2001, "The characteristics of PM2.5 in Beijing, China", *Atmospheric Environment,* no. 35, pp. 4959-4970.

International Sustainable Systems Research Center 2008, *IVE Model User Manual, Version 2.0*. Internet access: www.issrc.org.

International Sustainable Systems Research Center 2007, *A Study of the Emissions from Diesel Vehicles Operating in Beijing, China.* Internet access: http://www.efchina.org/FReports.do?act=detail&id=241.

International Sustainable Systems Research Center 2004, *IVE Model: Field Data Collection Activities*. Internet access: www.issrc.org.

Jimenez, J. L., 1999, *Understanding and Quantifying Motor Vehicle Emissions with Vehicle Specific Power and TILDAS Remote Sensing,* Ph.D. dissertation, Massachusetts Institute of Technology, Cambridge, MA.

Liu, H., He, C., Lents, J., Davis, N., Osses, M. & Nikkila, N. 2005, *Beijing Vehicle Activity Study*. Unpublished report.

Liu, H., He, K., Wang, Q., Huo, H. & Lents, J. 2007, "Comparison of Vehicle Activity and Emission Inventory between Beijing and Shanghai", *Journal of the Air & Waste Management Association (1995),* vol. 57, pp. 1172-1177.

National Bureau of Statistics of China 2007, *China Statistical Yearbook,* China Statistics Press, Beijing.

National Environmental Protection Agency of China 1996, *Ambient Air Quality Standards of China*, Beijing.

Oliver, H.H., Gallagher, K.S., Tian, D.L. & Zhang, X.H. 2009, *China's Fuel Economy Standards for Passenger Vehicles: Rationale, Process, and Impacts*. Harvard Kennedy School, Belfer Center for Science and International Affairs, Discussion Paper, Cambridge, MA. Internet access: http://belfercenter.ksg.harvard.edu/publication/18893/.

Oliver, H.H., Zhang, J., Li, M., Qian, G., Qin, K., Liu, H., He, K., Davis, N. & Lents, J. 2008, *In-Use Vehicle Emissions in China -- Tianjin Study*, Harvard Kennedy School, Belfer Center for Science and International Affairs, Discussion Paper, Cambridge, MA. Internet access: http://belfercenter.ksg.harvard.edu/publication/18645/.

State Environmental Protection Administration 1999, "Hazardous materials control standards for motor vehicle gasoline" (GWKB001-1999). Beijing.

State Quality, Technology, and Supervision Bureau of China 2000, "Light diesel fuels" (GB252-2000). Beijing.

United States Environmental Protection Agency 2002, *Methodology for Developing Modal Emission Rates for EPA's Multi-Scale Motor Vehicle and Equipment Emission System*, EPA420-R-02-027.

Wang, H., Chen, C., Huang, C. & Fu, L. 2008a, "On-road vehicle emission inventory and its uncertainty analysis for Shanghai, China", *Science of the Total Environment,* vol. 398, no. 1-3, pp. 60-67.

Wang, Y.X., McElroy, M.B., Munger, J.W., Hao, J., Ma, H., Nielsen, C.P. & Chen, Y. 2008b, "Variations of O_3 and CO in summertime at a rural site near Beijing", *Atmospheric Chemistry and Physics Discussions,* no. 8, pp. 10397-10414.

Wang, Y., Zhuang, G., Tang, A., Yuan, H., Sun, Y., Chen, S. & Zheng, A. 2005, "The ion chemistry and the source of $PM_{2.5}$ aerosol in Beijing", *Atmospheric Environment,* vol. 39, no. 21, pp. 3771-3784.

Westerdahl, D., Wang, X., Pan, X. & Zhang, K. M. 2009, "Characterization of On-Road Vehicle Emission Factors and Microenvironmental Air Quality in Beijing, China", *Atmospheric Environment,* vol. 43, no. 3, pp.697-705.

World Health Organization 2006, *Air Quality Guidelines: Global Update 2005*. Internet access: http://www.euro.who.int/Document/E90038.pdf.

Xie, S. & Song, X. 2006, "Calculating Vehicular Emission Factors with COPERTIII Mode in China", *Environmental Science,* no. 03.

Zhou, Y., Fu, L. & Cheng, L. 2007, "Characterization of In-Use Light-Duty Gasoline Vehicle Emissions by Remote Sensing in Beijing: Impact of Recent Control Measures", *Journal of the Air & Waste Management Association (1995),* vol. 57, no. 9, pp. 1071-1077.