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In-Use Vehicle Emissions in China — Tianjin Study

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In-Use Vehicle Emissions in China — Tianjin Study

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Executive Summary

Rapid economic growth, growing mobility and increasing purchasing power and demand for goods have made China one of the fastest growing auto markets in the world. From 1990 to 2006, the total number of registered civil-use vehicles in China grew from about 5.5 million to 37 million (not including motorcycles and agricultural vehicles).[2] The majority of these vehicles are used in populous metropolitan areas. Consequently, vehicle emissions have become an increasingly conspicuous contributor to air pollution in Chinese urban areas.

Despite the fact that China has made much progress in setting up standards regulating new vehicle emissions and fuel quality, the understanding of environmental performance of in-use vehicles has been rather poor. What are the real-world emission characteristics of in-use vehicles in China? To what extent do vehicles on the road actually meet their respective emission standards? What are the emission contributions of various vehicle categories in a city? How do vehicle emissions worsen over time? What is the actual quality of the vehicle fuels sold in different parts of China? How do vehicle technologies, traffic conditions, and fuel quality influence the total amount of mobile emissions in a city?

It is self-evident that such knowledge is essential for developing effective strategies to improve urban air quality by systematically controlling on-road vehicle emissions. From March 2005 to December 2006, a research team, headed by the Energy Technology Innovation Policy research group at Harvard University and in collaboration with the China Automotive Research Center, Tsinghua University (the Department of Environmental Science and Engineering), and the International Sustainable Systems Research Center (associated with University of California, Riverside), carried out a project in Tianjin to study emissions from on-road vehicles.

The research team monitored on-road vehicle emissions with remote sensing devices first in summer 2005 and then tested emissions from a sample of light-duty gasoline vehicles with portable emission measurement systems in spring 2006. It also collected vehicle activity data in spring 2006 using methods such as parking lot surveying, tracking of typical driving patterns with global positioning system (GPS) devices, and monitoring of traffic flow with video cameras. Relying on the International Vehicle Emissions Inventory model developed by the College for Environment Center for Environmental Research and Technology (CE-CERT) at the University of California, Riverside, Global Sustainable Systems Research (GSSR), and the International Sustainable Systems Research Center (ISSRC), the team generated the mobile emission inventories (including conventional air pollutants,

[2] In 2006, there were about 88 registered motorcycles and 16 million agricultural vehicles. See China Automotive Yearbook 2007.

greenhouse gases, and toxicants) for Tianjin in different seasons and estimated potential pollution reductions from various policy options.

In summary, the research team achieved the following six objectives through the Tianjin study:

1) Obtained basic data on in-use vehicle emissions, gasoline quality, patterns of vehicle use, and traffic conditions in Tianjin;

2) Assessed the composition and emission characteristics of the in-use vehicle fleet in the city;

3) Demonstrated state-of-art technologies for testing vehicle emissions in real world conditions;

4) Established vehicle emissions inventories for Tianjin using the International Vehicle Emissions model;

5) Identified highly polluting vehicle groups; and

6) Provided policymakers with study results and policy implications.

The major findings of Tianjin study are summarized as the following:

1. Composition of the in-use vehicle fleet in Tianjin

a. Passenger cars, taxis, buses, trucks, and motorcycles account for 61%, 17%, 7%, 9%, and 5% of total vehicles on the road respectively.

b. Most of the passenger cars are very new (less than 4 years old), and about half of them have engines smaller than 1.5 liters. Most of the light-duty vehicles are equipped with multi-point fuel injection systems and three-way catalytic converters. However, 13% of passenger cars and 35% of taxis are still using carburetors.

c. Most of the trucks and buses run on diesel fuel and have already accumulated high mileage. Fourteen % of buses are equipped with carburetors and have no end-of-pipe emission control devices.

d. The total distance traveled by all vehicles in Tianjin is about 38 million kilometers per day. Light-duty vehicles together contribute to 82% of all distance traveled (passenger cars, 64%; taxis, 18%), buses and trucks contributed 11% and 8% of total distance traveled respectively.

2. Emission characteristics of the fleet

a. The Tianjin fleet generates 690 tons of carbon monoxide (CO), 84 tons of volatile organic compounds (VOC), 158 tons of nitrogen oxides (NO_x), 2 tons of sulfur oxides (SO_x), 6 tons of particulate matter (PM), and about 13.4 thousand tons of carbon dioxide (CO_2) on a typical spring day.

b. Light-duty gasoline vehicles are the major contributors to CO and VOC emissions. Passenger cars account for 60% and 54% and taxis account for 21% and 28% of all mobile VOC and CO emissions respectively.

c. Carbureted gasoline vehicles contribute to a disproportionally high share of CO and VOC emissions. Carbureted light-duty vehicles account for only 15% of total distance traveled but they contribute to about one third and one half, respectively, of the total mobile CO and VOC emissions. Carbureted buses account for only 2% of total distance traveled, but they contribute to about 16% and 12% of the total mobile CO and VOC emissions.

d. Diesel trucks and buses account for most of the mobile PM and NO_x emissions (trucks: 44% and 27%; buses: 54% and 56%).

e. The emission data collected through remote sensing devices indicate that the dirtiest 20% of vehicles in Tianjin contribute to 77%, 70%, and 55% of CO, hydrocarbon (HC), and NOx emissions. In terms of vehicle types, mini multi-purpose vans, minibuses, and minicars are the most polluting light-duty vehicles.

3. Gasoline quality

a. The average sulfur content of the 36 gasoline samples was 280 ppm (parts per million), which is higher than the maximum sulfur concentration specified for vehicles meeting Euro III emission standards (150 ppm) consistently.

b. The average olefins concentration is 28% (by volume), and none of the samples could meet the Euro III standards (18%).

c. Benzene content is generally high. About two thirds of sampled gasoline could not meet the Euro III standards (1% by volume).

d. Lead content in gasoline was extremely low, which shows that China has done an excellent job in phasing out lead additives.

4. Emission reductions in various policy scenarios

a. Replacing the 12,000 taxis without three-way catalytic converters with new cars that can meet Euro III emission standards will lead to a reduction of 15% and 26% of total mobile CO and VOC emissions.

b. Replacing the 70,000 passenger cars without three-way catalytic converters with new cars that can meet Euro III emission standards will lead to a reduction of 15% and 24% of total mobile CO and VOC emissions.

c. Replacing 1,930 carbureted buses with diesel buses that can meet Euro III emission standards will lead to a reduction of 4% and 10% of total mobile CO and VOC emissions, but an increase of 6% total NO_x emissions.

d. Making 9,700 high-mileage diesel buses meet Euro III emission standards will lead to a decrease of 43% and 14% total mobile PM and NO_x emissions.

e. Making the 27,300 high-mileage diesel trucks meet Euro III emission standards will lead to a 42% and 11% decrease in total mobile PM and NO_x emissions.

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Acronyms and Abbreviations

BEF	Base Emission Factor
CATARC	China Automotive Technology and Research Center
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
EGR	Exhaust Gas Recirculation
EPB	Environmental Protection Bureau
ESP	Environmental Systems Products Holding Inc.
ETIP	Energy Technology Innovation Policy research group
FTP	Federal Test Procedure
GPS	Global Positioning System
HC	Hydrocarbon
HDV	Heavy-duty Vehicles
HCLD	Hot Chemi-Luminescence Detector
HFID	Hot Flame Ionization Detector
IF	Infrared
I/M	Inspection & Maintenance
IQR	Interquartile Range
ISSRC	International Sustainable Systems Research Center
IVE	International Vehicle Emission model
LDV	Light-duty Vehicles
MEC	Modal Emissions Cycle
MOE	Ministry of Environmental Protection (of China)
MPFI	Multi-Point Fuel Injection
MPV	Multi-Purpose Vehicles
NCHRP	National Cooperative Highway Research Program
NDIF	Non-dispersive Infrared
NO	Nitric Oxide
NO_x	Nitrogen Oxides
OBS	On-Board System
PC	Passenger Cars
PEMS	Portable Emission Measurement System
PM	Particulate Matter
PPM	Parts Per Million
RON	Research Octane Number
RPM	Revolutions per Minute
RSD	Remote Sensing Device
SEPA	State Environmental Protection Administration (of China)
SO_2	Sulfur Dioxide

SO_x	Sulfur Oxides
SPFI	Single-Point Fuel Injection
SUV	Sport-Utility Vehicle
SULEV	Super Ultra Low Emission Vehicle
THC	Total Hydrocarbons
TWC	Three-Way Catalytic Converter
UDDC	Urban Dynamic Driving Schedule
ULEV	Ultra Low Emission Vehicle
USEPA	United States Environmental Protection Agency
UV	Ultraviolet
VA	Vehicle Activity
VMT or VKT	Vehicle Miles/Kilometers Travelled
VOC	Volatile Organic Compounds
VOCE	Vehicle Occupancy Count Enumerator
VSP	Vehicle Specific Power

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1. Background

1.1 Need for Mobile Emissions Study

Rapid economic growth, growing needs for goods and personal transportation, and more disposable income in the Chinese people's hands have made China one of the fastest growing auto markets in the world. From 1990 to 2006, the total number of registered civil-use vehicles in China grew from 5.5 million to nearly 40 million (motorcycles and agricultural vehicles are not included). The majority of these vehicles are used in populous metropolitan areas. Consequently, vehicle emissions have become an increasingly conspicuous contributor to air pollution in Chinese urban areas.

At the 2007 annual conference for the Development of China Auto Industry held in Tianjin in September 2006, Li Xinming, the deputy director of the Pollution Control Department of the State Environmental Protection Agency (SEPA, which was renamed Ministry of Environment after being promoted to the ministry level in March 2008), stated that air pollution in most large Chinese cities was caused by both coal-burning and vehicle emissions. Despite the achievements in reducing the ambient concentrations of SO_2 and CO in most cities by measures curbing emissions from coal burning, the concentrations of nitrogen oxides and inhalable particulates, especially PM2.5 (particular matters with diameters less than 2.5 micrometers) have increased in recently years, largely due to growing mobile emissions.

Research of many prominent Chinese atmospheric scientists has provided robust evidence for Mr. Li's statement. For example, Jimin Hao, et al. (2005) estimated that vehicle emissions account for about 70% of NO_x and 76% of CO concentrations and about 46% of volatile organic compounds (VOC) emissions in Beijing. Source apportionment of ambient fine particles showed that vehicular emissions are a major source of high PM2.5 concentrations in megacities such as Beijing (Song, et al. 2006 & 2002; Zhu, et al. 2005) and Shanghai (Feng, et al. 2006; Zhang, et al. 2004). Using satellite data analyzed through a chemical transport model, Wang et al. (2007) concluded that restricting the total number of vehicles on the road during the Sino-African Summit in November 2006 did greatly reduce the total NO_x emissions in Beijing.

SEPA has been well aware of the potential environmental ramifications that could be brought out by a rapidly growing vehicle fleet. Since the late 1990s, it has promulgated a series of progressively stricter emissions standards for new vehicles. The stringency of these standards is similar to the corresponding European series. The nationwide emissions standards for new vehicles include: EURO I (from January 1, 2000 to June 30, 2004), EURO II (from July 1, 2004 to June 30, 2007), Euro III (from July 1, 2007 to June 30, 2010) and Euro IV (beginning July 1, 2010).

A few megacities which have been plagued by especially serious vehicular pollution have adopted the standards ahead of the national schedule. Beijing has taken the lead. It implemented Euro I standards on 1999, Euro II standards on January 1, 2003, and

Euro III standards on December 30, 2005. Euro IV standards took effect in Beijing on March 1, 2008, which is more than two years ahead of the national schedule.[3]

The American and European experiences have demonstrated that the deployment of advanced vehicle emissions control technologies must be accompanied by the supply of correspondingly good-quality fuels. Levels of lead, sulfur, benzene, olefins, octane number, and vapor pressure can all impact vehicle emissions (Faiz, 1996). China successfully phased out leaded gasoline in 2000 and moved to improve other aspects of fuel quality. Starting at the beginning of 2000, the central government required that the sulfur content of gasoline be below 800 parts per million (ppm) [4] and that of diesel to be less than 2,000 ppm. It further strengthened the requirement for gasoline (from 800 ppm to 500 ppm) starting July 1, 2005. However, the Chinese gasoline quality has consistently lagged behind its vehicle emission standards.[5]

Beijing is one exception. Driven by the high political salience to provide clean air for the 2008 Olympics and backed by the central government, Beijing has been able to negotiate with a couple of oil refineries located in its vicinity to overhaul their refining facilities so they can provide cleaner fuel for the Beijing market. Beijing had made mobile fuel suppliers reduce the sulfur content 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.[6]

Despite all the progress made in regulating new vehicle emissions and fuel quality, the understanding of the environmental performance of in-use vehicles has been rather poor. What are the real-world emission characteristics of vehicles actually on the road in China? To what extent do these in-use vehicles actually meet their respective emission standards? What are the emission contributions of different vehicle categories in a city? How do vehicle emissions worsen over time? What is the actual quality of the vehicle fuels sold in different parts of China? How do vehicle technologies, traffic conditions, and fuel quality influence the total amount of mobile emissions in a city?

It is self-evident that such knowledge is essential for developing effective strategies to improve urban air quality by controlling on-road vehicle emissions systematically and cost-effectively. However, these data heretofore were unavailable in China. To investigate these questions, the idea of conducting on-road vehicle emissions and fuel quality testing in selected Chinese cities was first conceived at the Energy Technology Innovation Policy (ETIP) research group, John F. Kennedy School of

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[3] Beijing EPB requires new light-duty diesel trucks to meet Euro IV emission standards by January 1, 2007. New models sold after December 30, 2005 must have on-board diagnostic systems.

[4] See "Hazardous Substances Standards for Mobile Fuels" by SEPA, GWKB001-1999.

[5] The 2006 national standards for gasoline (GB17930-2006) stipulate that sulfur content in gasoline must be lowered to 150 ppm for EURO III emission standards; however, due to lack of sufficient preparation of oil companies, the requirement did not get implemented jointly with the EURO III standards in July 2007. The national oil companies believe that 2010 is a reasonable time line for them to provide EURO III gasoline nationwide.

[6] The sulfur requirements for diesel fuel in Beijing have also been strengthened significantly: less than 500 ppm by October 1, 2004, less than 350 ppm by July 1, 2005, and less than 50 ppm by January 1, 2008. China plans to strengthen the limit of sulfur content in gasoline to 150 ppm nationwide in 2010.

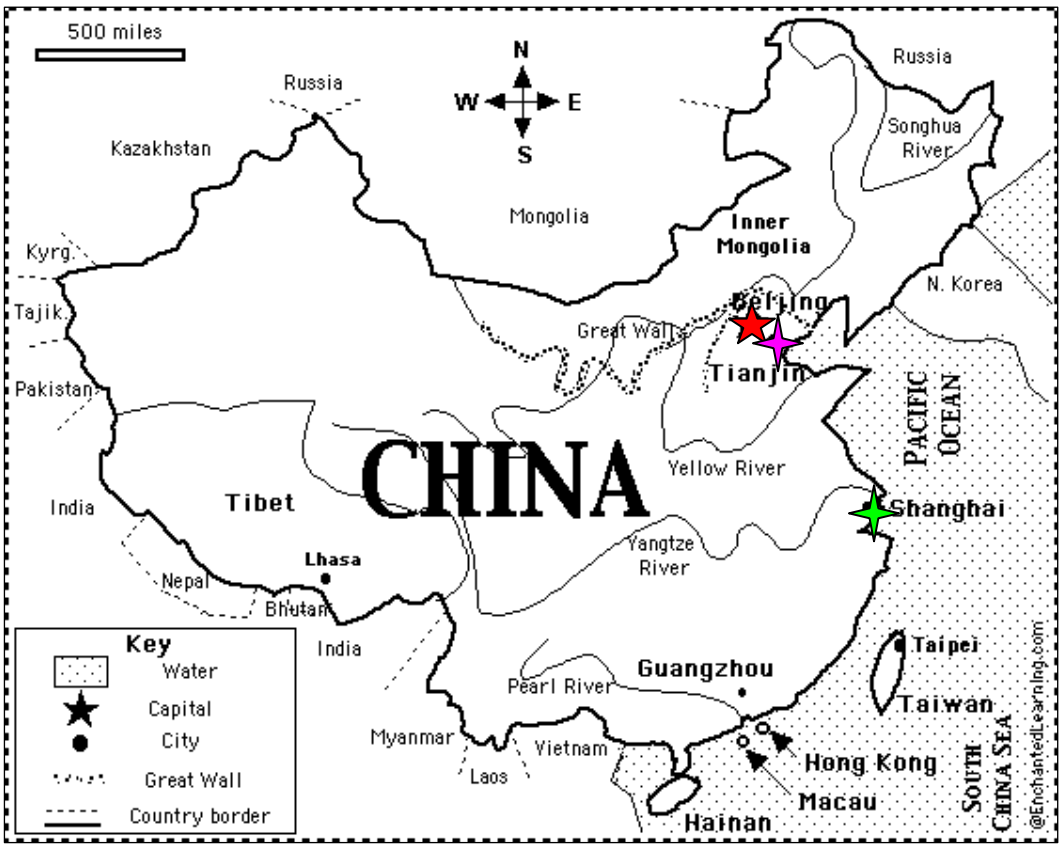
Government, Harvard University, in the fall of 2004. After a few rounds of conversations and discussions with Chinese environmental officials, experienced U.S. researchers, potential Chinese partners, possible sponsors, and equipment providers, a research partnership was formally formed in spring 2005.

The research partnership intended to conduct the study in three major Chinese cities: Tianjin, Beijing, and Shanghai. Tianjin study has been concluded in the spring of 2007 while data collection in Beijing has been completed in the spring of 2008.

The locations of these three cities are shown in Figure 1-1. The partnership considered the following reasons when selecting the study cities:

- Size and composition of urban vehicle fleet
- Geographic location
- Variation in local vehicle emission control policies, inspection & maintenance (I/M) programs, and fuel quality
- Local support
- Demonstration impacts

Figure 1-1 Location of the Three Study Cities



Tianjin was chosen to be the first study city mainly because one of the key Chinese research partners, CATARC, is located in Tianjin. CATARC's headquarters, major vehicle emission testing laboratories, and related technical personnel are located in Tianjin; such facilities and experienced personnel are critical in securing, calibrating, testing, and applying emission measurement equipment. Furthermore, preparing and carrying out data collection in the field demands significant local knowledge and access to local resources and cooperation. CATARC's network in Tianjin was instrumental in obtaining local support. Conducting the first study in Tianjin turned out to be logistically sound.

1.2 Goals

The research partnership aimed to achieve following six goals through this project:

1) Obtain basic data on in-use vehicle emissions and fuel quality in selected Chinese cities and make these data publicly available;

2) Assess the emission characteristics of in-use vehicle fleet in these cities;

3) Demonstrate state-of-art technologies and methodologies for testing vehicle emissions in real world conditions in China;

4) Establish vehicle emissions inventories for the selected cities using the International Vehicle Emissions (IVE) model;

5) Identify the major factors that have contributed to high vehicle emissions in these cities and explore how factors such as fuel quality, maintenance habits, I/M programs, and traffic conditions impact vehicle emissions in the real world, if the data collected in the field warrant such an exploration.

6) Provide national policymakers and city officials with results and policy implications.

1.3 Overall Methodology

Because fleet composition, vehicle technology distribution, fuel quality, local driving modes, and I/M programs vary across cities, the project employs a multiple case–study method in the selected Chinese cities. The study is to be carried out in one city at a time. In each city, the project team collects data through the following four approaches:

1) Use Remote Sensing Devices (RSD) to monitor the urban fleet (emissions, speed, and images of license plates) at selected sites. Data collected through RSD are used to describe the overall emission characteristics of the whole fleet. When matched

with registration data, RS data are used to characterize the composition of the fleet (e.g., age, technology, and type) and to establish the relations between emissions and factors such as vehicle age, technology, and type (see Chapter 2 for details).

2) Use Portable Emission Measurement Systems (PEMS) for accurate measurements of emissions from carefully selected vehicles under a wide range of operation modes. These data are used to establish the relations between emissions and operation modes [defined as vehicle specific power (VSP) and engine stress; see Sections 2.3 and 3.3 for details] of different types of local vehicles and, eventually, used to obtain local emission factors (see Chapter 3 and 5 for details). The tested vehicles were a representative sample of a variety of popular local vehicle classified with their emission control technologies (the relevant information is generated through analyzing RSD data or vehicle activity data).

3) Collect vehicle activity information. This part includes three subsets of data collection (see Chapter 4 for details):

- Actual vehicle usage rate: use video cameras to record traffic flow at representative intersections to obtain the typical compositions of traffic flow on different types of roads) and conduct parking lot surveys to obtain data on vehicle miles traveled (VMT, or, vehicle kilometers traveled in the case of China) and use of air conditioning.
- Vehicle specific technology: use parking lot surveys to understand the typical engine and emission control technologies employed by local vehicles.
- Typical urban driving pattern: use global positioning system (GPS) devices to track driving patterns of vehicles in four categories (i.e., cars, taxis, trucks, and buses) and use vehicle occupancy count enumerators (VOCE) to record numbers and patterns of starts of vehicles in these categories.

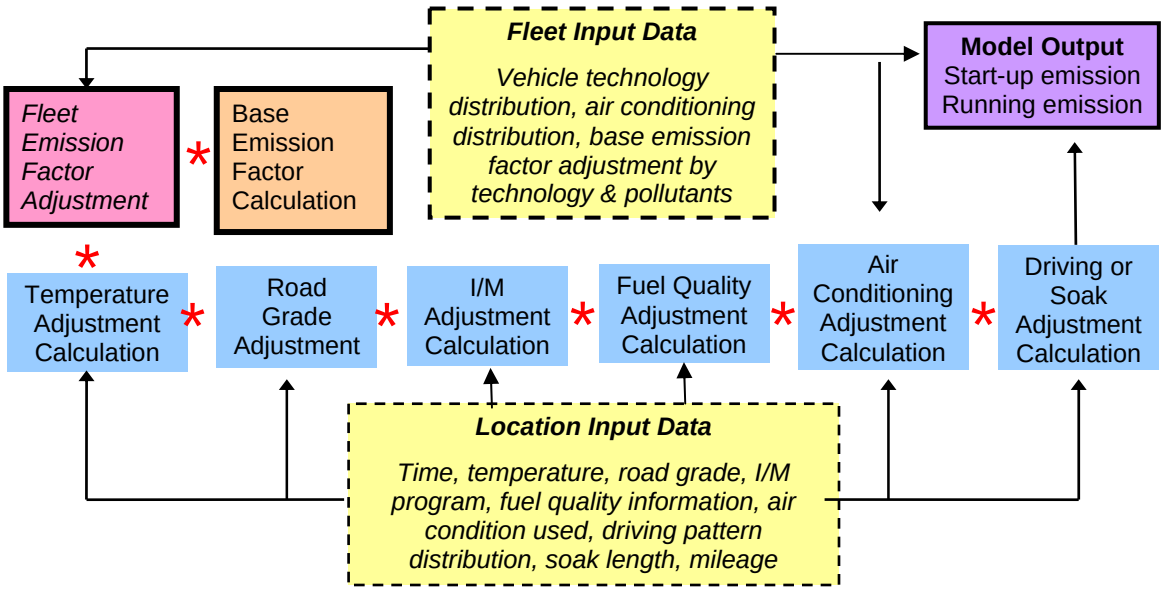
4) Test samples of local gasoline to understand the overall quality of gasoline available in the local market.

The International Vehicle Emissions (IVE) model, jointly developed by the College of Environment Center for Environmental Research and Technology (CE-CERT) at the University of California, Riverside, Global Sustainable Systems Research (GSSR), and the International Sustainable Systems Research Center (ISSRC), is used to estimate vehicle emissions (including conventional air pollutants, greenhouse gases, and toxic pollutants) of a study area during different time periods.[7] The model needs three critical inputs: vehicle emission rates, vehicle activity, and vehicle fleet distribution. Results from emission testing with PEMS and the vehicle activity study will provide the necessary local inputs to the model.

[7] The model is particularly developed for use in developing countries, where existing information on both traffic and vehicles is lacking.

The process of estimating emissions in IVE model is depicted in Figure 1-2. 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, EMFAC2002, extensive measurements made at CE-CERT, and some international data sources)[8] 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. As shown in the figure, three sets of critical local information: emission correction factor, fleet information, and location information (indicated in italics) are needed to create accurate emissions inventories.

Figure 1-2 Structure of International Vehicle Emissions Model



First, the corrected emission rate 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.)

[8] 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.

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 traveled, while incorporating the distribution of various driving/starting conditions during a certain period of time, as shown in equation (2) and (3):

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

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

$Q_{[t,\ running]}$: 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[9]
D: distance traveled by that vehicle category
$\bar{U}_C$: average velocity in a particular location
$\bar{U}_{FTP} *(D / \bar{U}_C)$: 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 are: correction factors for base emission rates, the total distance traveled by the local fleet, the fraction of distance travelled by every major vehicle category, the average velocity of a particular location, the distribution of driving pattern (defined as time distribution in the 60 VSP bins, see Section 3.2), and the distribution of the soaking pattern for each type of vehicle category. As we will show in later 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.

1.4 Research Partnership

Four parties comprised the project team for the Tianjin study: ETIP, CATARC, Tsinghua University (Department of Environmental Science and Engineering), and ISSRC. The general roles and tasks of partners are listed in Table 1-1.

CATARC and ETIP were jointly responsible for fundraising, overall coordination, and overall planning. During project implementation in Tianjin, the CATARC team was responsible for vehicle emissions testing (with both RSD and PEMS) and fuel quality testing. The Tsinghua team was responsible for the actual vehicle activities study. The CATARC and Tsinghua teams took the lead in fieldwork planning, fieldwork team organization, protocol development; data collection, cleaning, processing, and analysis; and summarization of their work and findings. ETIP oversaw and participated in all

[9] Refer to the following USEPA website for details on the FTP cycle: http://www.epa.gov/otaq/sftp.htm.

major research activities and led the project overall report writing. ISSRC served as the technical adviser to the whole project and provided training to other members of the project team.

Table 1 -1 Matrix of Partner Roles

Role	*CATARC*	*ETIP*	*Tsinghua*	*ISSRC*
Overall coordination	**	**	*	
Overall planning	**	**	*	♦
Protocol development for emissions testing	**	*		♦
Monitoring vehicle emissions with RSD	**	*		
RSD data cleaning and processing	**	*		
RSD data analysis	**	**		
Vehicle emission testing with PEMS	**	*		♦
PEMS data cleaning and processing	**	*		♦
PEMS data analysis	**	**		♦
Report on emissions testing with PEMS	**	*		♦
Protocol development for VA studies		*	**	♦
VA data collection in the field	**	*	**	♦
VA data cleaning and processing			**	♦
VA data analysis			**	♦
Report on VA studies		*	**	♦
Integration of all data with IVE Model	*	**	**	♦
Overall Technical Report	**	**	*	♦
Policy Report	**	**	*	*
Seminar to Present Results	**	**	**	*
Policymaker Briefings	**	**	**	*

NOTE: **represents a leading role; *represents a supporting role; and ♦ means an advisory role.

1.5 Tianjin Study Schedule

The study in Tianjin took almost two years. It took much longer than the partnership had envisioned, but the study was conducted in a robust and systematic way. After all, Tianjin was the first study city, and much planning, exploration, learning, reviewing, and modification during the project implementation process was needed. In addition, coordinating schedules of all partners for collective activities (such as data collection and training) was a challenging task. Major research activities of the team are summarized in Table 1-2.

Table 1-2 Tianjin Study Schedule

Time period	*Major activity*
January–March 2005	Preliminary preparation - Overall conceptualization - Technical conceptualization - Formation of partnership
March 2005	Tianjin Study kick-off meeting
April–July 2005	Preparation for vehicle emissions testing with RSD - Securing equipment - Obtaining local cooperation - Selecting testing sites
August 2005	Data collection with RSD - On-site training - 13 days of data collection at 3 sites - On-site data screening Fuel sampling
September–December 2005	RSD data cleaning and processing Fuel quality testing
January–March 2006	Preparation for on-road emission testing with PEMS and VA study - Securing equipment and preparation workshop - Conducting bench test - Developing data collection plan and protocol - Obtaining local support - Organizing participants of the field work - Securing testing vehicles and local personnel
March–April 2006	Data collection (VA and PEMS) - On-site training - 13 days of vehicle emission data collection, 9 days of VA data collection - On-site data screening and evaluation
May–September 2006	Data cleaning and processing and analysis (VA and PEMS)
October–December 2006	Data integration, overall report writing
January 2007	Tianjin study review meeting
February–May 2007	Revising and completing report

2. Measuring Emissions with Remote Sensing Devices[10]

2.1 Instrument Design

Remote sensing is a way to measure pollution levels of vehicle emissions without interrupting traffic flow. Unlike most equipment used to measure emissions, remote sensing devices (RSD) do not need to be connected to vehicles. The whole measurement process (of one vehicle) takes less than one second. When set up at a proper site with continuous traffic flow, a set of RSD can measure emissions of thousands of vehicles in a few hours. RSD has been proven to be a useful and efficient tool to monitor vehicle fleets. It can complement traditional mobile source emission control programs. To date, RSD technology has been used in the United States to identify gross emitters, screen clean vehicles, evaluate the effectiveness of I/M programs, and assess overall emission characteristics of a fleet of interest.[11]

For the purpose of our study, we are most interested in using RSD to characterize and evaluate the overall emissions of the light-duty-vehicle fleet in Tianjin.

As illustrated in Figure 2-1, a typical set of RSD consists of four parts:[12]

(1) Source and detector module — The RSD systems measure vehicle emissions by monitoring the intensity of a narrow infrared (IR) and ultraviolet (UV) beam of light at characteristic wavelengths. The source module casts the IR and UV light first, and then a transfer mirror module reflects IR and UV light back to a series of detectors that monitor the change in intensity of the IR and UV light, due to the absorption of IR and UV light by the various pollutants in the air.

(2) Video camera — When a vehicle passes by the testing site, a video camera captures an image of the vehicle's license plate. Relying on the license number, one can obtain detailed information on this vehicle (such as emission control technology, age, mileage, displacement, etc.) from the local vehicle registration database.

(3) Speed and acceleration measurement system — Speed and acceleration sensors record the speed and acceleration of each vehicle at the moment when it passes the testing site. Since the instantaneous emissions of a vehicle are largely influenced by its operating conditions, the operating

[10] Original data in this chapter were collected and screened by the CATARC team.

[11] The USEPA has issued a series of guidelines for these purposes of RSD, e.g., EPA420-R-96-004 (for identifying gross emitters), EPA420-P-98-008 (for screening clean vehicles), and EPA420-B-04-010 (for evaluating I/M programs). For a history of RSD in the United States, refer to the ESP website: http://www.esp-global.com/rsd/?P=sensing&S=history&T=default.

[12] A more detailed explanation can be found at the website of the Environmental Systems Product Holding Inc, the RSD provider. www.esp-global.com/rsd/.

conditions must be controlled and considered to obtain emissions within reasonable range (elaborated in later sections).

(4) Data processing and video display — Emissions, speed and acceleration and photo images are stored in a computer and monitored by an operator on the site.

Figure 2-1 Measuring On-Road Vehicle Emissions with RSD

Source: The illustration is taken from the website of Environmental Systems Products (ESP) Holdings Inc., "How RSD works". http://www.esp-global.com/rsd/?P=sensing&S=howrsdworks&T=default.

2.2 Site Selection

According to the experts at the Environmental Systems Products (ESP) company which provided RSD, four criteria need to be considered when selecting sites for monitoring on-road vehicle emissions with RSD:[13]

(1) Regional specifications — All socio-economic classes of vehicles are represented; the types of vehicles of interest (in the case of our study in Tianjin, light-duty vehicles) are maximized; and cold start potential is minimized (to avoid high emissions during cold starts).

(2) Traffic specification — The total number of vehicles passing by a monitoring site should range between 200 and 2,000 per hour; average vehicle speed should range between 8 kilometers per hour (km/hr, 5mph) to 104 km/hr (65 mph); the difference between maximum and minimum vehicle speed should not exceed 16 km/hr (for camera settings); vehicles should be under slight acceleration; and

[13] The information was provided by ESP to the project team directly, not in a published format.

there should not be plume overlapping (i.e., vehicles are not too close to each other.)

(3) Lane specifications — Traffic flows only in one direction; one RSD should be set up for each lane (preferably, a one-lane road with a width between 4 and 6 meters is the ideal type of road); monitoring sites should have wide, solid shoulders to ensure the safety of the operator and equipment; and sites should be dry and without much dust.

(4) Ambient conditions – Humidity ranges from 0% to 90%. No condensation or rain should occur during measurement. Sites should have consistent lighting.

Based on these requirements and our knowledge of Tianjin's road and traffic conditions, we pre-selected and then surveyed eight possible sites. At each of the eight sites, the survey team counted the number of vehicles passing by within a period of ten minutes and estimated the average vehicle speed. The team also took note of the conditions of the road, width of the shoulders, and the surrounding areas. The team counted 50–100 vehicles passing by those sites in 10 minutes and estimated the average speed ranging from 30 to 50 km/hr.

After tabulating the information collected at the eight sites, the research team chose three sites that satisfied the RSD siting criteria best. Figure 2-2 illustrates the locations of the three RSD sites in Tianjin.

The locations of the three sites represent the varied development levels in different Tianjin districts. Site A is located at the border of urban and suburban Tianjin (urban areas are shown in color in Figure 2-2), representing the least developed urban areas of the city. Site C is close to the downtown business district, representing the most developed areas in the city. Site B represents areas with a medium development level. All the sites have a slight upward incline of 0.2 degrees. Table 2-1 summarizes the information of the three sites.

Figure 2-2 Three RSD Monitoring Sites in Tianjin

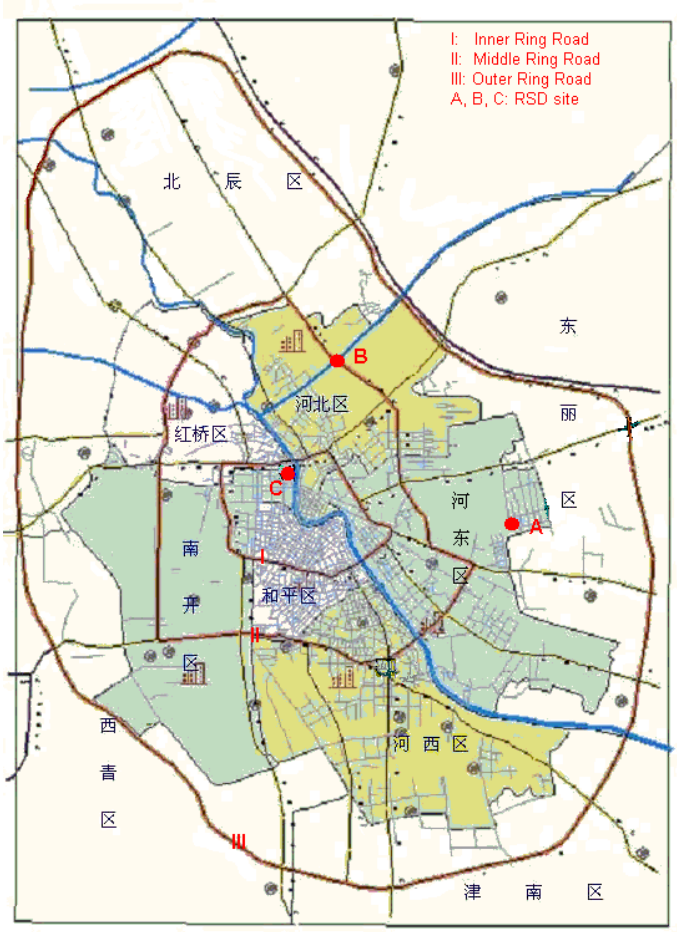


Table 2-1 Characteristics of the Three RSD Monitoring Sites

Site	*Location*	*Level of Economic development**	*Inline (degree)*	*Duration of Monitoring (days)*
A	Between middle and outer ring road	Low	0.2	4
B	Middle ring road	Medium	0.2	4
C	Inner ring road	High	0.2	5
Subtotal	3	N. A.	N. A.	13

Note: * The level of economic development is relative to that of other districts in the city.

2.3 Data Collection and Processing

From August 18 to 31, 2005, we collected data on vehicle emissions, speed, and acceleration, and license numbers with a set of RSD at the three sites highlighted in Figure 2-2. During the thirteen days, the RSD took over 51,000 sets of measurements. The system software indicated 22,502 records as valid measurements,[14] and 93.8% of these measurements were accompanied with legible license images. Over 14,600 light-duty vehicles (LDV) were monitored at least once at the three sites. If duplicate license plates are excluded, the total count of LDV monitored at the three sites reached 15,134. Table 2-2 summarizes the data collected at the three RSD sites.

Table 2-2 Statistics of the RSD Measurements in Tianjin

Site	*Number of valid measurements*	*Number of valid measurements with legible license number*		*Total number of LDV monitored*
		All	*LDV*	
A	4,820 *	4,451	3,176	--
B	9,088	8,632	5,657	--
C	8,594	8,026	6,296	--
Subtotal	22,502	21,109	15,134	14,623

Note: * With the intention of minimizing the impact of RSD set-up on local traffic, the RSD study team tried to avoid the morning and evening traffic peaks at the first site. Fewer measurements were taken at the first site. Data collection at the rest two sites covered rush hour traffic.

Of all the LDV that passed by the RSD sites during the data collection period, one particular brand (Xiali cars, which were made locally in Tianjin) accounted for about 30% (4,416 out of 14,623), Chinese-style mini multi-purpose vans (they often have very small engines displacement and are used for transporting both goods and people) account for about 25%. The rest were various cars and Sport-Utility Vehicles (SUV).

In order to conduct meaningful analysis on vehicle emissions, the team sought relevant information of those LDVs whose emissions were captured by the RSD from the local vehicle administration bureau. Of the 14,623 LDV whose emissions were measured validly by the RSD, we obtained the registration information for 6,107.[15] The information

[14] The software installed in the computer (which is a component of the RSD) evaluates the measurements of vehicle emissions and speed/acceleration and then indicates the validity of the measurements.

[15] Vehicle registration information is neither well organized nor accessible to the general public in China. After much negotiation, the bureau agreed to provide information for half of the total LDVs captured by the RSD camera. The team grouped the 14,623 LDVs according to their makes and models and then made a list of 7,320 vehicles from the stratified sample. The selected vehicles include both the most common LDV in Tianjin (e.g, Xiali, Santana, and mini Multi-Purpose Vehicles) and less common cars. The list was submitted to the vehicle administration bureau for registration information. Information of some vehicles was not useable because it was obviously incorrect. The bureau refused to disclose the information of

included vehicle manufacturer, model year, first registration date, ownership type, and engine and emission control technology.

Since vehicle emissions vary dramatically for different operating modes and since a RSD system monitors mobile emissions generated at a particular second, it is necessary to harmonize measurements based on the operating conditions of vehicles to make sensible comparison. In the past few 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.[16] 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):[17]

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

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)

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

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

Figure 2-3 illustrates the relationships between VSP and CO, HC, and NO emissions (the mean values) by vehicles of different age groups. The charts show that CO and HC emissions do not increase significantly when a vehicle operates within a certain range of VSP. In contrast, NO emissions change more dramatically when VSP increases above zero. When a vehicle operates at high VSP values (higher than 22), its CO and HC emissions increase significantly.

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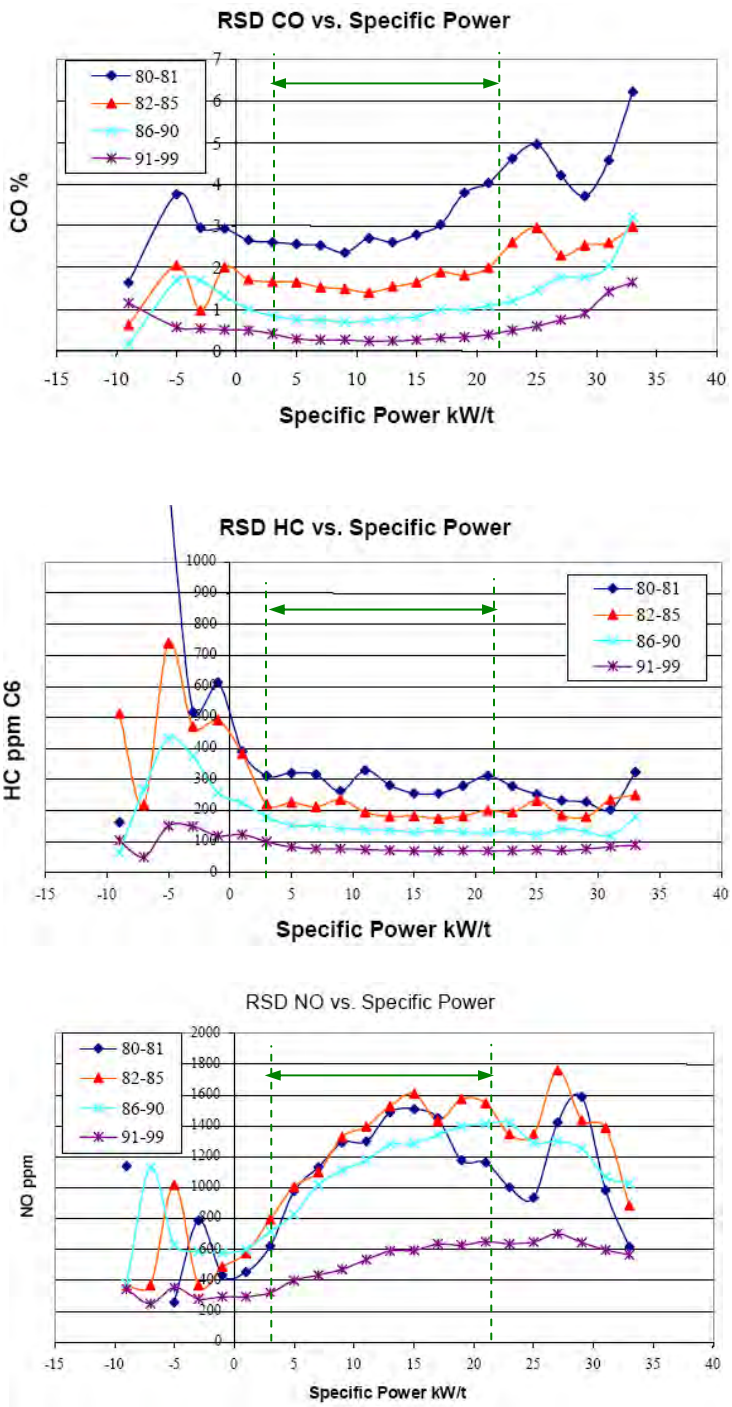
vehicles with high-profile and military license plates. In the end, we were only able to obtain reliable registration information for 6,107 LDVs.

[16] The next version of MOVE model (USEPA's mobile vehicle emissions model) will incorporate VSP as well.

[17] Different researchers have developed slightly different formulas to calculate VSP, but the results of different formulas are quite similar.

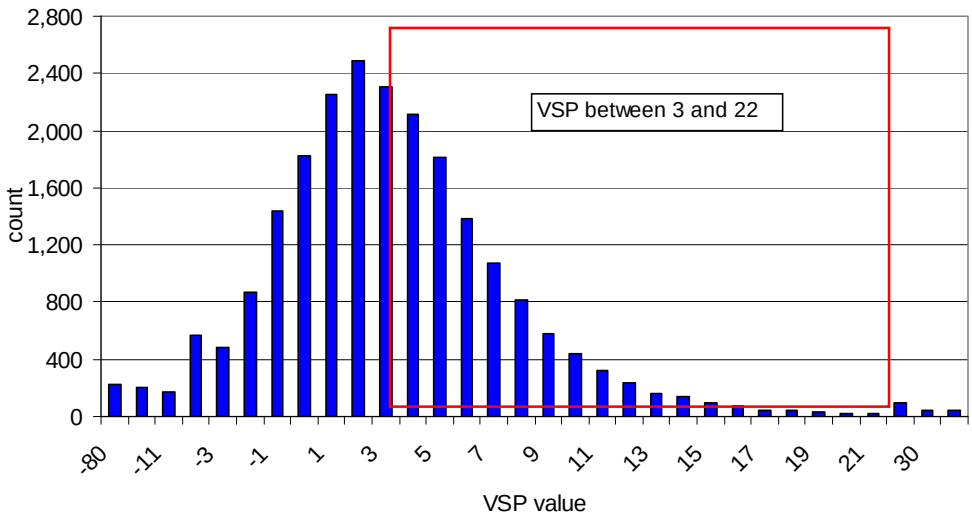
Figure 2-3 Emissions vs. Vehicle Specific Power (RSD Measurement)



Source: USEPA (2004), "Guidance on Use of Remote Sensing for Evaluation of I/M Program Performance". The charts were cited from a multi-year Denver RSD study by Donald Stedman and his colleagues. Their data and publications can be found at http://www.feat.biochem.du.edu/reports.html.

Figure 2-4 shows the distribution of VSP at the three RSD sites in Tianjin. Only about 50% of vehicles passing the three sites were operating within the desirable power range (3≤VSP≤22). The grade at all three sites was greater than zero. Therefore, according to equation 5, only when a vehicle decelerated at those sites, its calculated VSP would be less than zero. Speed measurements showed that about 17% vehicles decelerated considerably when they passed by the testing sites, which led to negative VSP values and reduced emissions. About one third of vehicles went by the testing sites cautiously, with very low speed and/or acceleration, which led to very low VSP (0<VSP<3). Only about 1% vehicles were driven rather aggressively, with VSP larger than 22.

Figure 2-4 VSP Frequency Distribution at 3 RSD Sites



One can minimize the impacts of load and driving behavior on vehicle emissions by constraining the range of VSP. To be on the safe side, the USEPA (2004) suggested using the VSP range between 5 and 20 for evaluating local I/M program performance in its relevant guidance. In our case, given that emissions do not change dramatically when VSP is slightly lower than 5 and higher than 20 and that vehicles in Chinese cities often operate in low VSP range (as illustrated in Figure 2-4, and will be further explored in Chapters 3 and 4), we chose a range between 3 and 22 as the desirable VSP range.

After applying the criterion of the desirable VSP range to all the valid measurements, we were only left with less than twelve thousand measurement records for general emission analyses of the overall fleet. As shown in Table 2-3, the data set was reduced to 4,017 records when we applied all the following criteria to the measurements: validity of measurements, desirable VSP, and availability of vehicle registration information. Thus, the analyses on the relationships between emissions and technology, emissions and age, and emissions and vehicle type were carried out only based on these 4,017 records.

Table 2-3 Statistics of RSD Measurements after VSP Screening

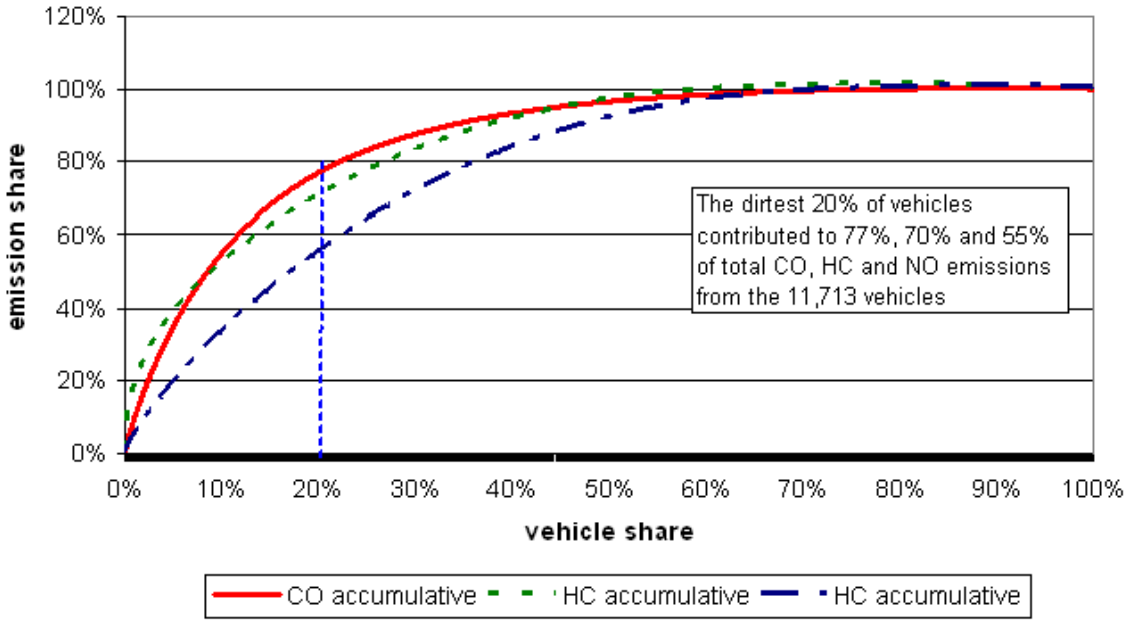
	Count of valid measurements	*Count of LDV measurements matched with registration data*	*Count of LDV matched with registration data*
All	22,502	7,637	6,106
3≤VSP≤22	11,713	4,017	3,500
% within desirable VSP range	52%	53%	57%

2.4 Results

Emissions Contribution of the Dirtiest Vehicles

Our analyses on the one-second emission data of the 11,713 records indicated that a small percentage of dirtiest vehicles monitored contributed to a significant large share of vehicular emissions at these sites. As illustrated in Figure 2-5, 80% of CO, HC, and NO emissions are released by the 22%, 27%, and 36% of the dirtiest vehicles. The dirtiest 10% of vehicles contributed to about 54%, 52%, and 33% of the total CO, HC, and NO emissions, and the dirtiest 20% of vehicles contributed to about 77%, 70%, and 55% of the total CO, HC, and NO emissions (to simplify the analysis, we assumed that vehicle fuel economy was identical for all vehicles when they passed by the testing sites).

Figure 2-5 Vehicle Emission Contribution in Tianjin (Result from 3 RSD sites)



The average emissions of all vehicles with valid measurements and VSP (11,713) were much higher than that of the LDVs matched with registration data (4,017, see Table 2-3). The average VSP of the formal set of vehicles at the three RSD sites was 6.68 while that of the latter set was 6.97, which indicated both sets of vehicles had a similar operating mode when passing the RSD sites (see Table 2-4). The average CO, HC, and NO concentrations in the exhaust of the former set of vehicles were about 40% to 50% higher than those of the latter set of vehicles. The vehicles not matched with registration data were conspicuously dirtier than those matched with registration data. Such a finding is reasonable since vehicles with matched registration data concerned only LDVs, and LDVs are generally cleaner than trucks and buses.

Table 2-4 Emissions of Vehicles with/without Matched Registration data

	Average CO (%)	*Average HC (ppm)*	*Average NO (ppm)*	*Average VSP*
All records with valid measurements and VSP (11,713)	0.94	504	1,121	6.68
Matched with registration data (4,017)	0.64	297	730	6.97
Not matched (7,696)	1.10	612	1,325	6.50

We further examined the composition of the dirtiest 20% of vehicles, i.e., the 2,342 vehicles of the 11,713 vehicles that emit the most CO, HC, or NO at the time of the RSD test (see Table 2-5). For CO emissions, cars accounted for 65% of the 2,342 dirtiest vehicles (their emission share was 68%, and their average CO concentration was 3.7%), mini MPVs accounted for 24% of the 2,342 dirtiest vehicles (their emission share was 22% and their average CO concentration was 3.2%), vans, buses, and trucks accounted for about 4%, 1%, and 3% (their emissions shares were also 4%, 1%, and 3% respectively, and their average CO concentrations were 4.0%, 3.5%, and 3.4% respectively).

For HC emissions, cars accounted for 47% of the 2,342 dirtiest vehicles (their emission share was 44%, and their average HC concentration was 1,637 ppm), mini MPVs accounted for 33% of the 2,342 dirtiest vehicles (their emission share was 38%, and their average HC concentration was 2,030 ppm), vans, buses, and trucks accounted for 4%, 3%, and 10% (their emissions shares were 4%, 3%, and 9% respectively, and their average HC concentrations were 1,721 ppm, 1,697 ppm, and 1,477 ppm).

For NO emissions, cars accounted for 27% of the 2,342 dirtiest vehicles (their emission share was 27%, and their average NO concentration was 1,029 ppm), mini MPVs accounted for 29% of the 2,342 dirtiest vehicles (their emission share was 44%, and their average NO concentration was 1,605 ppm), vans, buses, and trucks accounted for 5%, 17%, and 20% (their emissions shares were 4%, 8%, and 16% respectively, and their average NO concentrations were 882 ppm, 515 ppm, and 813 ppm).

Table 2-5 Composition of the Dirtiest 20% of Vehicles (2,342 out of 11,713)

	CO		*HC*		*NO*	
	Number share	*Emissions share*	*Number share*	*Emissions share*	*Number share*	*Emissions share*
Mini MPV	24%	22%	33%	39%	28%	44%
Car	65%	68%	47%	45%	27%	27%
Van	4%	4%	4%	4%	5%	4%
SUV	1%	1%	1%	1%	2%	1%
Bus	1%	1%	3%	3%	17%	8%
Truck	3%	3%	10%	9%	20%	16%
Other	2%	1%	2%	0%	1%	0%

These results indicated that in comparison, mini MPVs were the most significant HC and NO emitters. Cars contributed to a big share of CO and HC emissions because of the large number of them on the road. Trucks and buses were noticeable NO emitters, probably because most of the trucks and buses had diesel engines. Among the dirty mini MPVs, three brands (Huali, Songhuajiang, and Hafei) on average were dirtier than other brands (such as Changan and Yiqi). One particular brand (Xiali) stood out as the gross emitter, especially in terms of NO emissions (140% more polluting than other dirty cars).

A considerable percentage of on-road, light-duty vehicles (LDV) in Tianjin generated emissions at a rate higher than the emission standards for in-use vehicles existing in Beijing.[18] Beijing Phase I standards are effective for in-use vehicles that had been made before Euro I standards (for new vehicles) took effect in 1999; while Phase II standards are effective for in-use vehicles that had been made to meet either Euro I or Euro II standards. We found that a fair share of in-use vehicles in Tianjin could not meet the Beijing standards. For the 4,017 sets of measurements on LDV emissions, about one tenth would have failed to meet the Phase I requirements for CO and NO emissions, and more than one quarter would have failed to meet the Phase I requirement for HC (see Table 2-6). When Phase II emission standards were used as the reference line, 19% of CO measurements, 42% of HC measurements, and 30% of NO measurements would have failed. This means that considerable amounts of mobile emissions can be avoided if Tianjin strengthens its I/M program.

[18] Here, we used Beijing emissions standards for in-use light-duty vehicles as reference (see Beijing EPB and Beijing Quality and Technology Supervision Bureau, 2006, "Limits and measurement methods for exhaust pollutants from in-use gasoline vehicles under steady-state loaded mode."). The national standards for in-use vehicles are more relaxed, only equivalent to Beijing Phase I standards, even though most vehicles on the road were produced after Euro II standards (for new vehicles) had taken effect.

Table 2-6 Vehicle Emissions in Comparison with Standards

			Failure rate (of the 4,017 measurements)
Beijing Phase I standards * (for LDVs)	CO (%)	2.0	9%
	HC (ppm)	290	27%
	NO (ppm)	2350	10%
Beijing Phase II standards * (for LDVs)	CO (%)	0.7	19%
	HC (ppm)	95	42%
	NO (ppm)	850	30%

Note: * The Beijing standards are slightly different for LDVs in different weight groups. Here, we use the slackest ones for each of the pollutants.

Technology Distribution of LDVs with Matched Registration Information

After obtaining matching vehicle registration information from the local vehicle administration bureau, the team used the data collected by the RSD system at the three sites to describe the composition of Tianjin LDV fleet and then analyzed the general emission characteristics of each subset of vehicles. The knowledge on the technology composition of Tianjin LDV fleet was also critical for selecting representative testing vehicles for on-board vehicle emission testing (see Chapter 3). Based on the historical trend of vehicle engine and emission control technology deployment, we had anticipated that LDVs in Tianjin likely employed one of the nine categories of engine and emission control technologies (see Table 2-7).

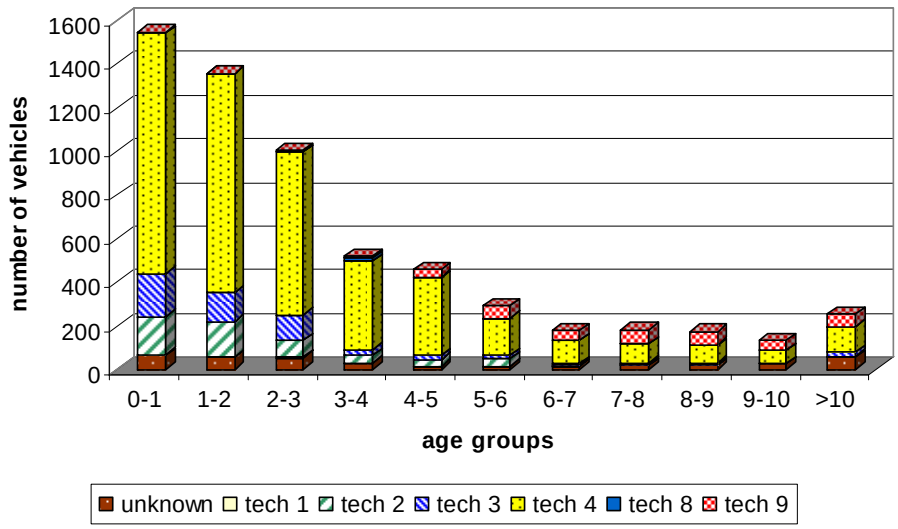
Table 2-7 Vehicle Classification by Engine and Emission Control Technology

Category	*Emission Control Technology*
1	Multi-Point Fuel Injection (MPFI), Exhaust Gas Recirculation (EGR) & Close-coupled Three-way Catalytic Converter (CCTWC)
2	MPFI, EGR, TWC
3	MPFI, CCTWC
4	MPFI, TWC
5	Single-Point Fuel Injection (SPFI), EGR, CCTWC
6	SPFI, EGR, TWC
7	SPFI, CCTWC
8	SPFI, TWC
9	Carburetor, no emission control

Among the 14,623 LDVs monitored at the three RSD sites, we obtained registration information on 6,106 vehicles (see Table 2-2). We believe that these vehicles comprised a reasonably representative sample of the overall Tianjin LDV fleet. Figure 2-6 depicts the age and technology distribution of these vehicles. The sample shows that the Tianjin LDV fleet was very young. As of September 2005, the average age of these 6,106

vehicles was 3.7 years old; about one quarter of these LDVs were less than one year old; and about two thirds of these LDVs were less than 3 years old.

Figure 2-6 Technology and Age Distributin of LDVs (6,106 LDVs with registration data)



As shown in Figure 2-6, we did not see any vehicles belonging to the category 5, 6, and 7 (vehicles equipped with both single-point fuel injection system and sophisticated emission control technology). Technology 4 was the most common vehicle technology (multi-point fuel injection {MPFI} and three-way catalytic converter {TWC}), containing almost 70% of the 6,106 vehicles. It was still the most prevailing technology combination even among the very new vehicles. Nevertheless, technology 2 (MPFI, EGR, and TWC) and 3 (MPFI and CCTWC) started gaining more popularity among the vehicles made after 2002. These two technology groups accounted for 8.5 and 9.1 percent of the 6,106 vehicles respectively. Technology 9 (carbureted vehicles without any emission control technology) were a big share of the vehicles made before 1999 when China's central government issued the first emission standards (equivalent to Euro I) for new LDVs. Technology 8 (carbureted vehicles with TWC) and technology 1 were very rare (26 and 6 out of 6,106). Based on these findings, we decided that technology 2, 3, 4, and 9 were to be the focus of on-board emission testing study in the second phase of our project in Tianjin. We saw few vehicles more than 10 years old equipped with advanced emission control technologies. These vehicles were typically foreign-made. RSD monitoring results showed that the emission control technologies generally had stopped working. This was probably caused by lack of proper and consistent maintenance.

In addition to classifying vehicles based on the engine and emission control technologies, we grouped the 6,016 LDVs into eight types based on the Chinese official way of classifying vehicles (GB9417-89). The eight vehicle types were summarized in Table 2-8. Among these vehicles, regular sized cars (their engine size is between 1.6 and

2.5 liters) were the dominant type (47%), and mini MPVs comprised the next largest group (28%).

Table 2-8 Vehicle Classification based on Function and Size

	Subcategory	*Engine size (liter)*	*Number*	*Percent**
Car	1) Mini	≤1.0	54	0.9%
	2) Eco	>1.0 and ≤1.6	657	10.8%
	3) Regular	>1.6 and ≤2.5	2,876	47.1%
	4) Maximum	>2.5	243	4.0%
MPV	5) Mini	≤1.3	1,721	28.2%
("bread-loaf")	6) Regular	>1.3	191	3.1%
Bus	7) Mini	Length ≤ 3.5 m	32	0.5%
SUV	8) all		313	5.1%
LDVs with inconsistent information			19	0.3%
Total			*6,106*	*100.0%*

Note: * Because we used stratified sampling methodology, the percentage should not be interpreted as the share of these vehicle types in the Tianjin LDV fleet.

Emission Characteristics of the 3,500 LDVs with Matched Registration Information and Valid VSP

Among the 6,106 LDVs with matched registration data, only 3,500 vehicles had VSP values falling within the range of 3 to 22 (see Table 2-3). Thus, we could only rely on the RSD measurements of these 3,500 vehicles to analyze the relationships between emissions and technology, vehicle types, and age.

Fortunately, the technology and vehicle type compositions of this subset of LDVs were rather similar to those of the 6,106 LDVs, as illustrated in Figure 2-7-a and 2-7-b. The age and technology group distributions of the 3,500 LDVs were also very close to those of the 6,106 LDVs (compare Figure 2-6 to Figure 2-8). Therefore, it was reasonable to believe that the emission characteristics of the 3,500 vehicles represent the emission characteristics of the LDV fleet in Tianjin fairly well.

Figure 2-7-a Vehicle Technology Distrubtion
(the set of 6,016 LDVs vs. the subset of 3,500 LDVs)

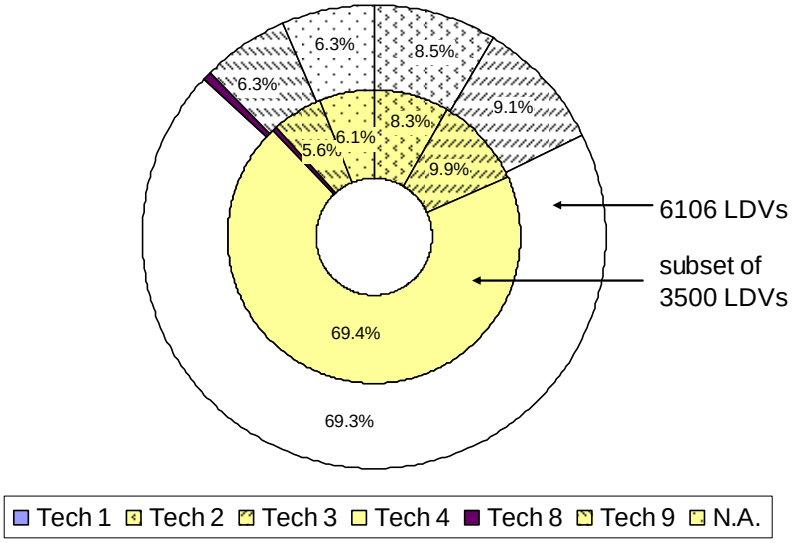


Figure 2-7-b Vehicle Type Distribution
(the set of 6,016 LDVs vs. the subset of 3,500 LDVs)

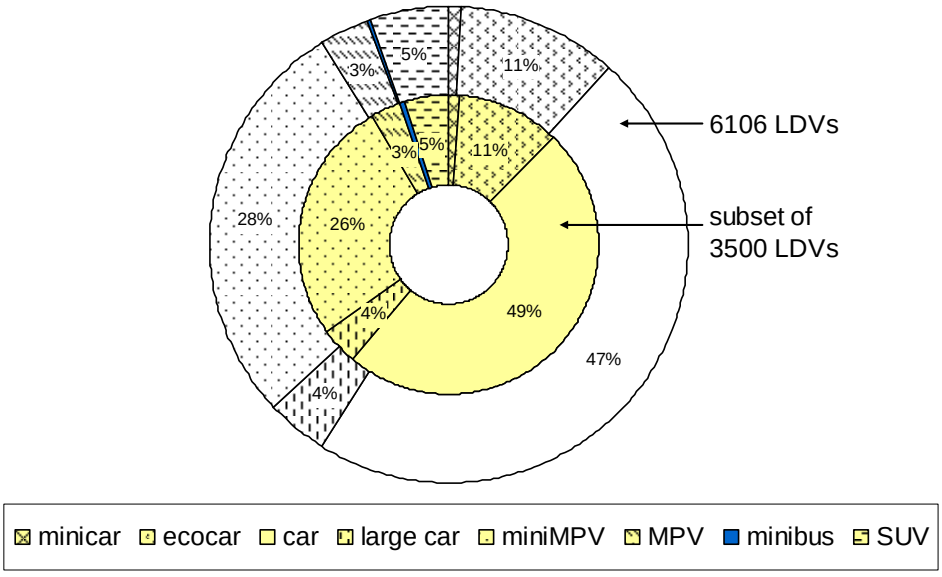


Figure 2-8 Age Distribution of Vehicles with Valid VSP (3500)

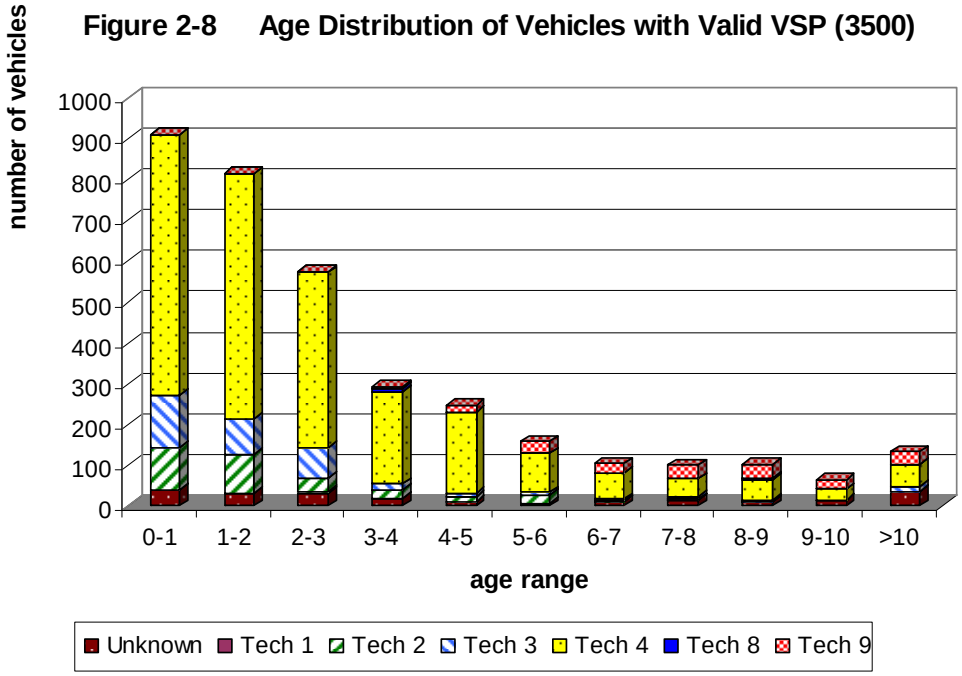


Table 2-9 gives the distribution of the 3,500 vehicles by their engine and emission control technology. Vehicles with MPFI and TWC dominate, accounting for nearly 70% of the sample. The average VSP values of different technology groups are similar, indicating the vehicles were operating under similar conditions.

Table 2-9 Vehicle Distribution by Engine & Emission Control Technology
(3,500 Vehicles)

Technology	*Number*	*Percent*	*Average VSP*
1	4	0.1%	6.89
2	292	8.3%	6.91
3	347	9.9%	7.52
4	2,430	69.4%	6.98
8	16	0.5%	6.36
9	196	5.6%	6.24
Unknown	215	6.1%	7.32
Subtotal	*3,500*	*100%*	*7.01*

As shown in Figure 2-9-a, b, and c,[19] carbureted vehicles (technology 9) were the most polluting vehicle group. The average CO, HC, and NOx emissions of this group were 2.7, 2.8, and 1.5 times higher than the average emissions of the 3,500 vehicles. Carbureted vehicles on average emitted 11, 18, and 5 times more CO, HC, and NO than vehicles with MPFI, EGR, and TWC (technology 2), the cleanest vehicle group in Tianjin. About 96% of carbureted vehicles could not meet the Beijing Phase I standard for HC (see Figure 2-9-b), and 45% of them could not meet Beijing Phase I CO standard. Vehicles with SPFI and TWC (technology 8) were rare, but they were rather dirty; they emitted 1.3, 0.43, and 0.45 times more on average than the 3,500 vehicles as a whole.

It is noticeable that the average CO and NO emissions by vehicles equipped with MPFI, EGR, and TWC (technology 2) and vehicles with MPFI and CCTWC (technology 3) were way below the Beijing Phase II requirements for in-use vehicles, which correspond to Euro I standards. Technology 2 and 3 became more popular only after 2002 (see Figure 2-6) as automakers responded to the Chinese "Euro II" standards for new vehicles. The HC emissions of these vehicles were relatively close to the Beijing Phase II requirement for HC.

The average CO and NO emissions of vehicles with MPFI and TWC (technology 4) were below the Beijing Phase II requirements, but the average HC emission of this group was almost two times higher than the Beijing Phase II requirement.

The range of the central 50% of emission values for carbureted vehicles (technology 9) was much greater than that of other vehicle technology groups, indicating the emission variation of this group was much larger. In contrast, the central 50% of the emissions from the vehicles with MPFI, EGR, and TWC (technology 2) and that of the vehicles with MPFI and CCTWC (technology 3) were much more narrowly distributed. The range of central 50% of emissions for vehicles with MPFI and TWC (technology 4) was also considerably greater than those of technology 2 and 3. In comparison with technology 9 (5–7%), technology 2, 3, and 4 all had a considerably higher share of outliers (10–14%, the black and open circles in the boxplots). This observation is consistent with the knowledge that emissions from vehicles equipped with MPFI and emission control technologies are more sensitive to transient operating conditions and the working condition of their emission control devices than carbureted vehicles. With the exception of vehicles with carburetors, the median emission values of all other groups were very close to values of the first quartiles. This indicates that the majority of vehicles in technology 2, 3, and 4 groups were relatively clean. The outliers probably had contributed to a very high share of pollution.

[19] Here are some notes on how to read a boxplot: the box part of the plot displays the interquartile range (IQR, the middle 50%) of a distribution. The line within a box represents the median. The dotted line (red in the color version of this report) represents the mean. The black and empty circles represent moderate and extreme outliners. Moderate outlines are the data that fall between the 3rd quartile + 1.5*IQR and the 3rd quartile + 3*IQR or between 1st quartile — 1.5*IQR and the 1st quartile — 3*IQR. Extreme outliers are those data that lie beyond the 3rd quartile + 3*IQR and the 1st quartile — 3*IQR. The vertical lines extending from the box indicate the smallest and largest values in the distribution that are not considered as outliers.

Figure 2-9-a Distribution of CO Emissions by Emission Control Technology

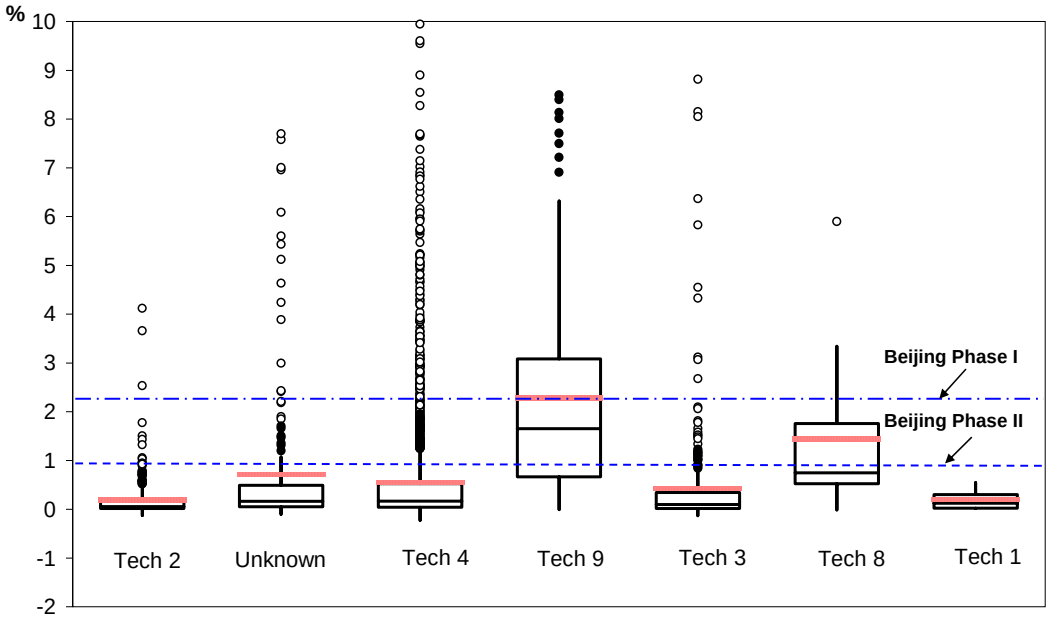


Figure 2-9-b Distribution of HC Emissions by Emission Control Technology

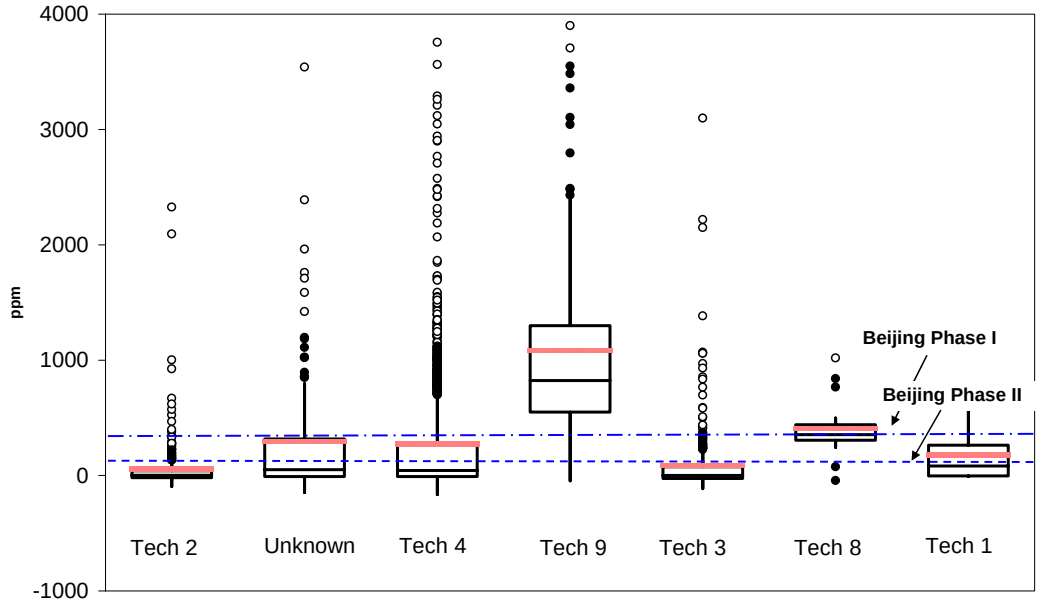
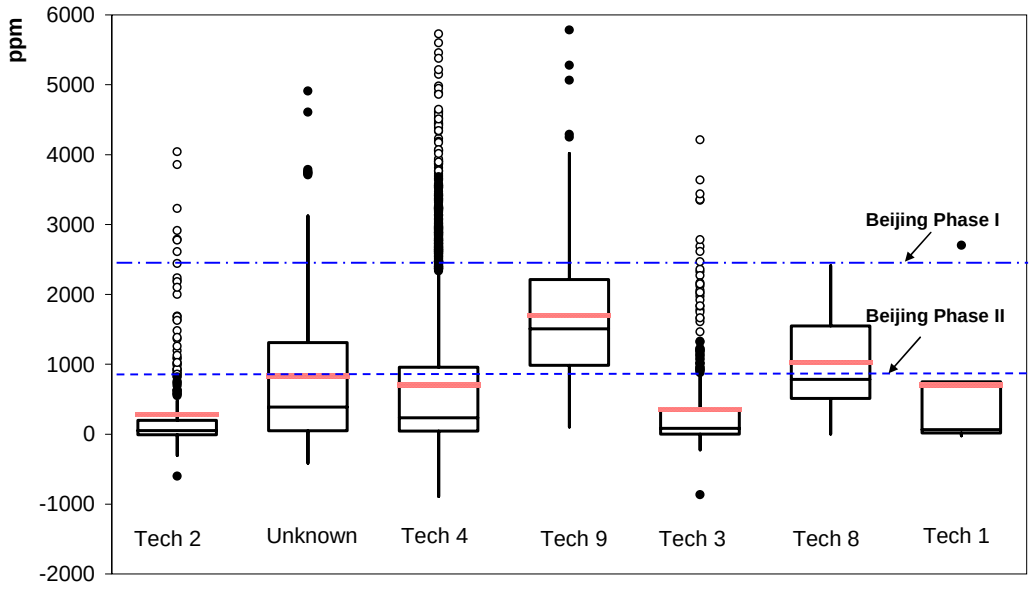


Figure 2-9-c Distribution of NO Emissions by Emission Control Technology



We also grouped the 3,500 vehicles into eight groups based on the Chinese vehicle type classification (as listed in Table 2-10). Medium-size cars (engine size between 1.6 to 2.5 liters) accounted for almost one half of the sample. Small MPVs accounted for about one quarter. The average VSP values of different types were rather close, so we believe that operating mode should not contribute much to the difference in emissions.

Table 2-10 Vehicle Distribution Based on Function and Size
(3,500 Vehicles)

Type	*Number*	*Percent **	*Average VSP*
Car-mini	34	1.0%	6.64
Car-eco	390	11.1%	6.70
Car	1,712	48.9%	7.35
Car-max	128	3.7%	8.00
MPV-mini	920	26.3%	6.32
MPV	120	3.4%	7.34
Minibus	23	0.7%	6.74
SUV	162	4.6%	7.11
Unknown	11	0.3%	6.42
Subtotal	3500	100%	7.01

Note: * Because this is a stratified sample, these ratios don't accurately represent the actual use of different type of vehicles in Tianjin. They cannot be interpreted as the frequency at which these types of vehicles passed by the three RSD sites. More regular cars ("Car" in Table 2-10) were chosen due to the high variation in the car models.

Figure 2-10-a, b, and c illustrate the emissions distribution of these eight vehicle types. Overall, minibuses and mini MPVs were the most polluting vehicles in Tianjin. The average CO emission of the 23 minibuses in our sample was 1.3 times higher than that of the whole sample and 2.3 times higher than the average CO emissions of the cleanest vehicles, the medium-sized car group. The average CO emission of minibuses was even higher than the Beijing Phase I standard, while the average CO emission of mini MPVs was higher than the Beijing Phase II standard. Mini MPVs were the worst HC emitters. On average, they released HC at the concentration of 550 ppm, which was twice the average HC concentration of the whole sample and much higher than the Beijing Phase I standard (290 ppm). Minibuses also emitted HC at a concentration (355 ppm) higher than the Beijing Phase I standard. It seemed that HC emissions were difficult for automakers in China to control: all vehicle types except MPVs could not meet the Beijing Phase II requirement for HC. NO emissions of SUVs, mini MPVs, and large cars were higher than other vehicle groups.

The boxplots below show that the central 50% of emissions were more concentrated for cars, MPVs, and SUVs than that for minibuses and mini MPVs, implying that a much higher percentage of vehicles in the Car, MPV, and SUV groups were relatively clean. Yet, there were quite a few emission outliers for the Car, MPV, and SUV groups.

Figure 2-10-a Distribution of CO Emissions by Vehicle Type

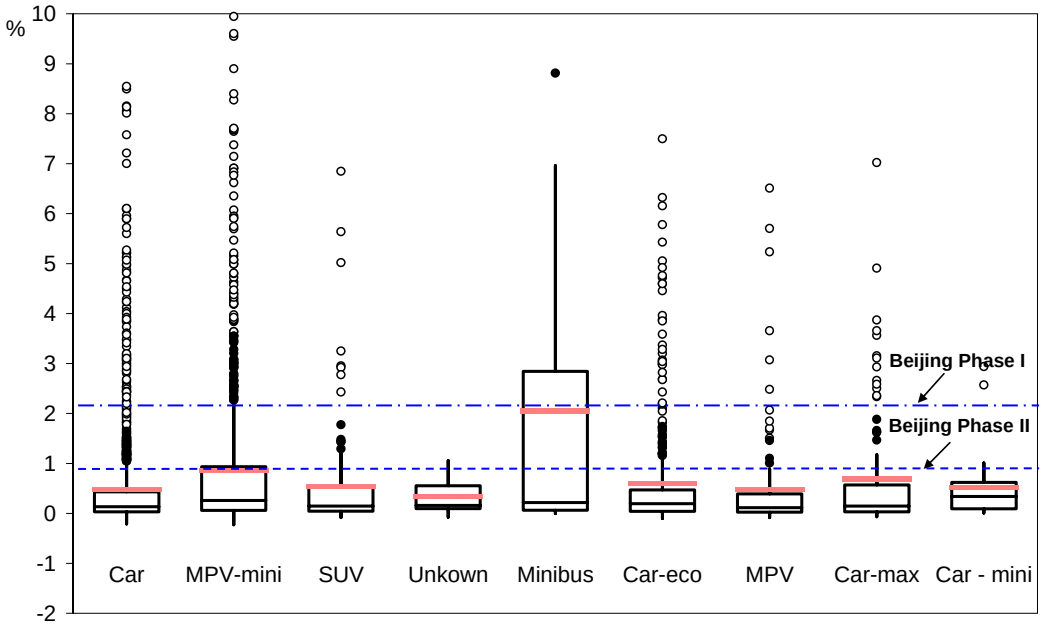


Figure 2-10-b Distribution of HC Emissions by Vehicle Type

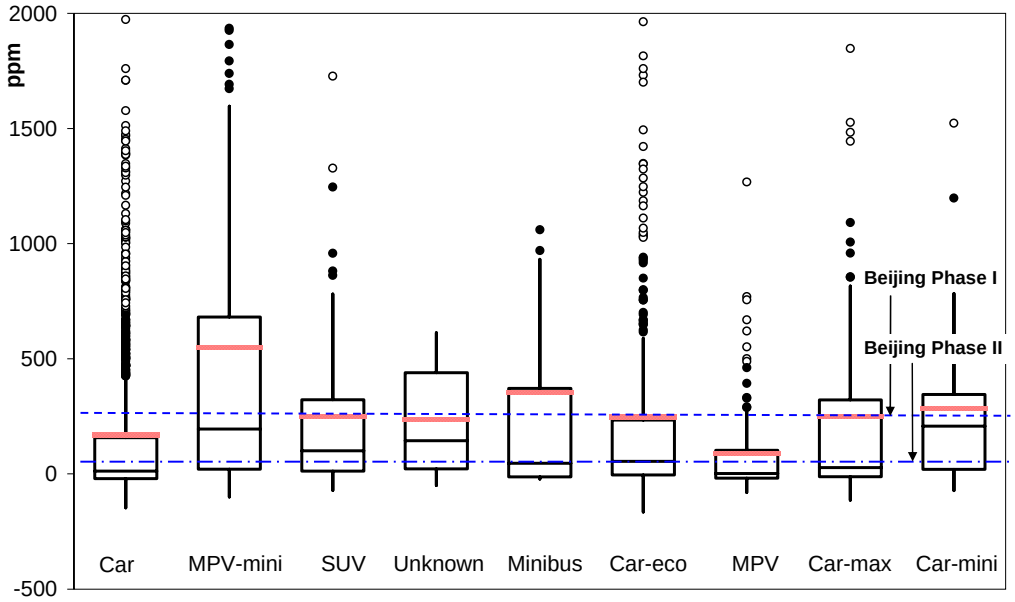
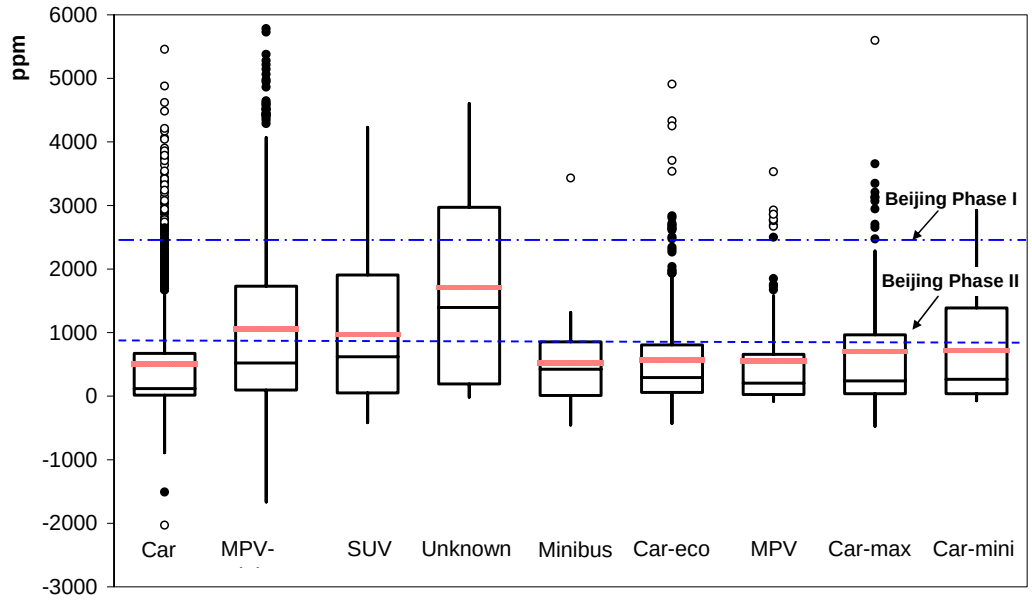
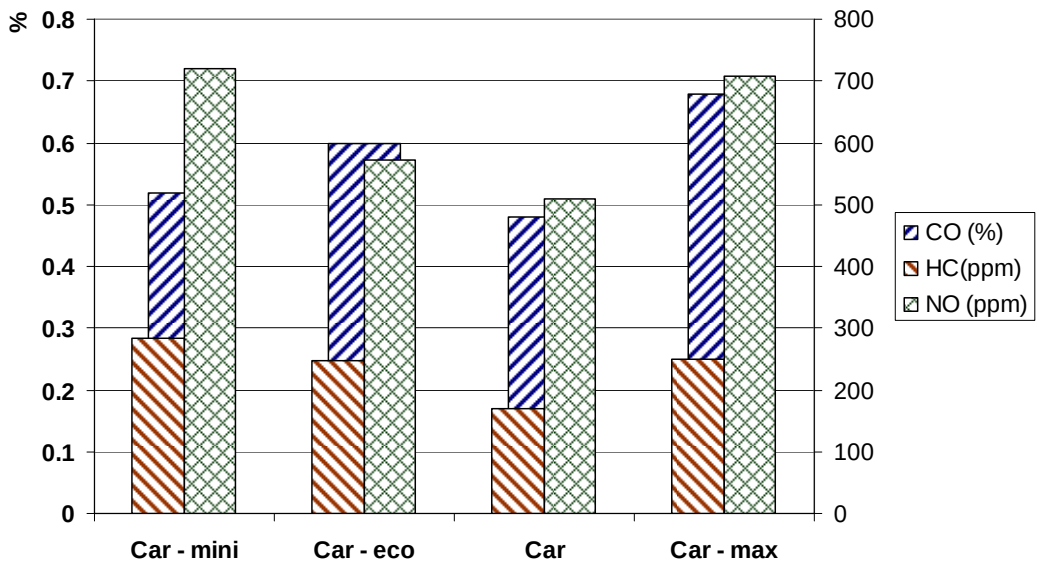


Figure 2-10-c Distribution of NO Emissions by Vehicle Type



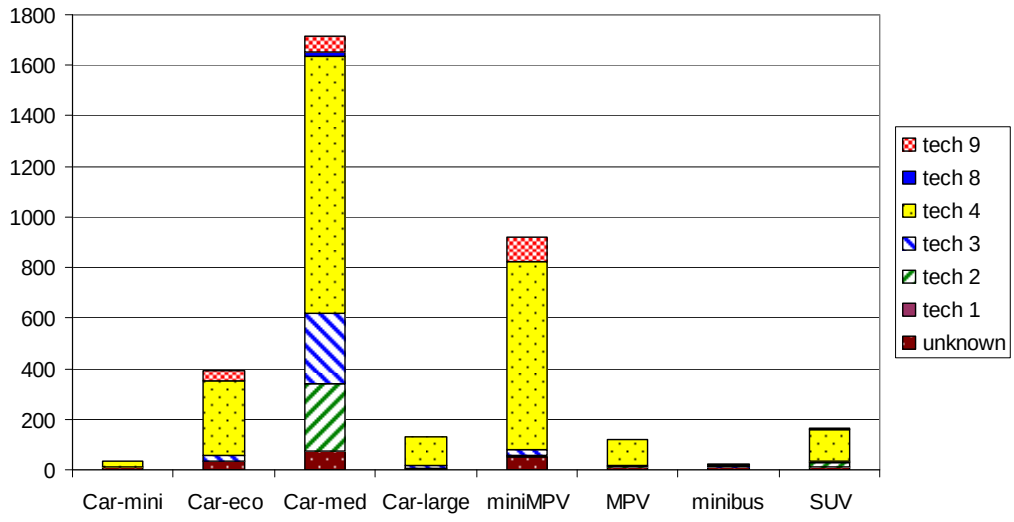
Among the four car categories based on engine size, medium-sized cars on average were the cleanest, while the minicars and cars with large engines seemed to be much less effective in emission control (as illustrated in Figure 2-11).

Figure 2-11 Emissions of Cars with Different Engine Sizes



To some extent, the difference in the emission control technologies employed by different vehicle type groups could explain the variation in their average emissions. As illustrated in Figure 2-12. The vehicle type group which had high emissions often had a high share of vehicles equipped with carburetors (e.g., about 11% of mini MPVs have carburetors) or a high share of vehicles with MPFI and a conventional TWC. In contrast, the vehicle group (medium-sized car) that had a significantly higher share of vehicles equipped with better emission control technology (CCTWC or EGR) was cleaner overall.

Figure 2-12 Distribution of Emission Control Technology by Vehicle Type



The average age of the 3,500 vehicles was about 3.6 years; about two thirds of them were less than 3 years old (see Table 2-11). The average VSP values of different vehicle age groups were similar, indicating that these vehicles were operating under a similar condition at the time of their RSD test.

Figure 2-13-a, b, and c illustrate changes in the emission characteristics of different vehicle age groups. It is evident that Chinese vehicles on the whole were getting cleaner over years. The Chinese "Euro I" emission standards took effect in Beijing in January 1999 and became nationwide in January 2000, and the Chinese "Euro II" standards took effect in Beijing in January 2003 and became nationwide in July 2004. Beijing adopted the "Euro III" standard at the end of 2005, and China adopted it nationwide in July 2007. As shown in Figure 2-13, these emission standards had significant impacts on the environmental performance of new vehicles in the Chinese market. There were two obvious decreases in emissions from vehicles made circa the years 2000 and 2003.

Figure 2-13 also shows that emission variations of new vehicles were much less than those of the older vehicles (the interquartile ranges were narrower). This indicates that environmental performance was more consistent among newer vehicles.

It seemed that the effectiveness of emission control devices on many vehicles which were designed to meet Euro I standards had deteriorated considerably. For example, 72% of the HC and 65% of NO measurements of the LDVs made in 2000 were higher than the corresponding Beijing standards for in-use vehicles made after 1999. 35% of the CO measurements of vehicles made in 2000 were higher than the Beijing standard. For LDVs made in 2001, 35%, 63%, and 49% of CO, HC, and NO emission measurements were higher than the Beijing standards. Even for LDVs made in 2002, those ratios were still high: 25%, 49%, and 33%. The biggest challenge for automakers in China seems to be the consistent control of HC emissions.

Table 2-11 Vehicle Distribution by Age (3,500 Vehicles)

Age (years)	*Number*	*Percent*	*Average VSP*
<1	911	26.0%	6.98
1-2	816	23.3%	7.29
2-3	576	16.4%	6.89
3-4	293	8.4%	7.02
4-5	247	7.1%	6.74
5-6	157	4.5%	6.82
6-7	103	2.9%	7.12
7-8	99	2.8%	6.19
8-9	102	2.9%	7.22
9-10	63	1.8%	6.81
>10	133	3.8%	7.06
Subtotal	*3500*	*100%*	*7.01*

Figure 2-13-a Distribution of CO Emissions by Age Group

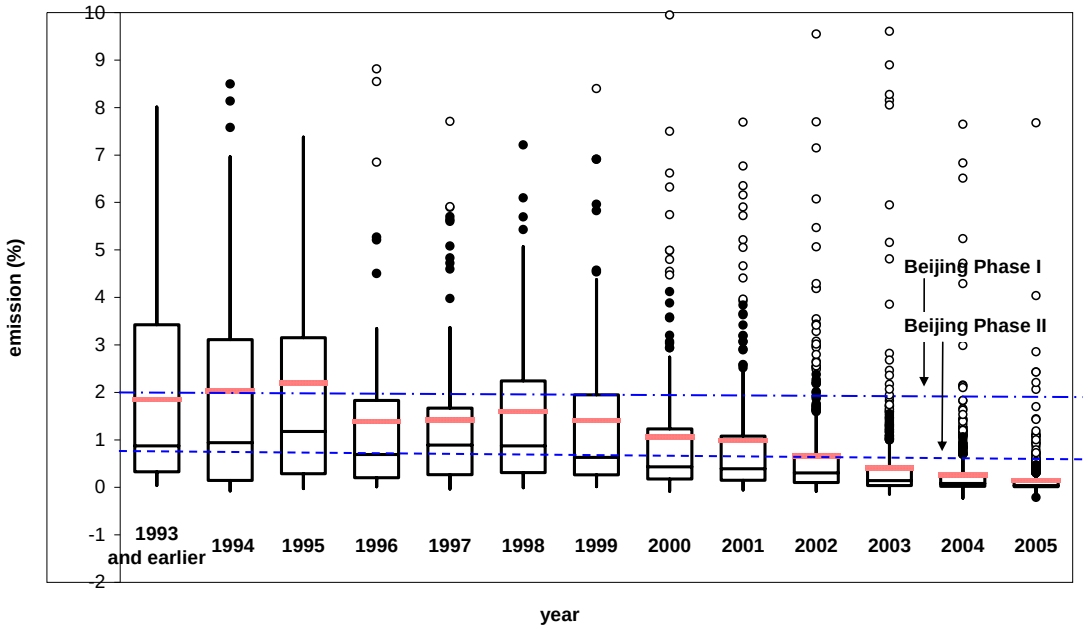


Figure 2-13-b Distribution of HC Emissions by Age Group

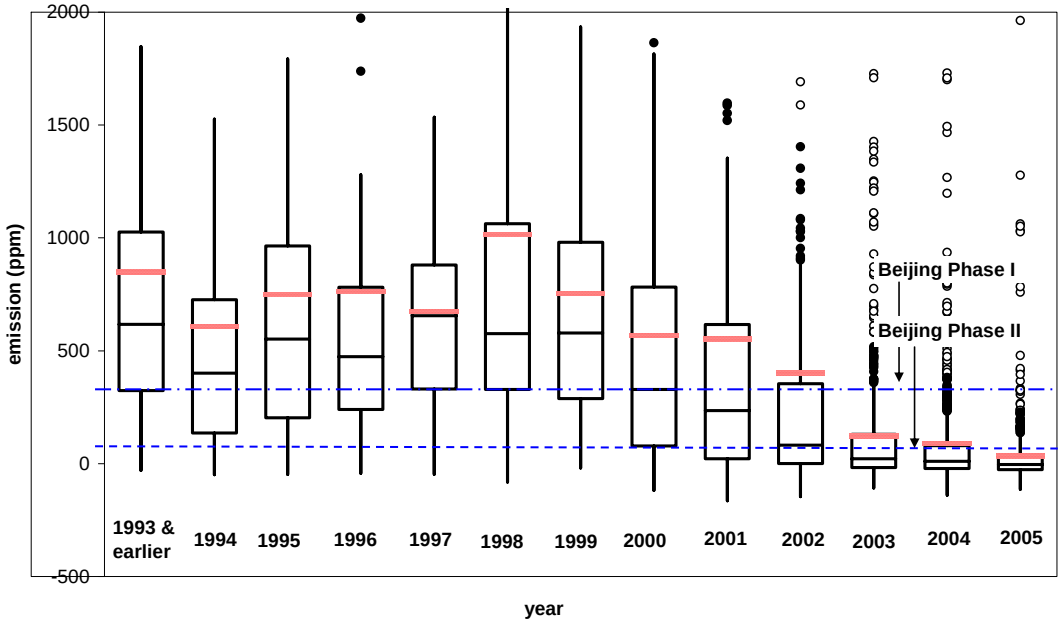
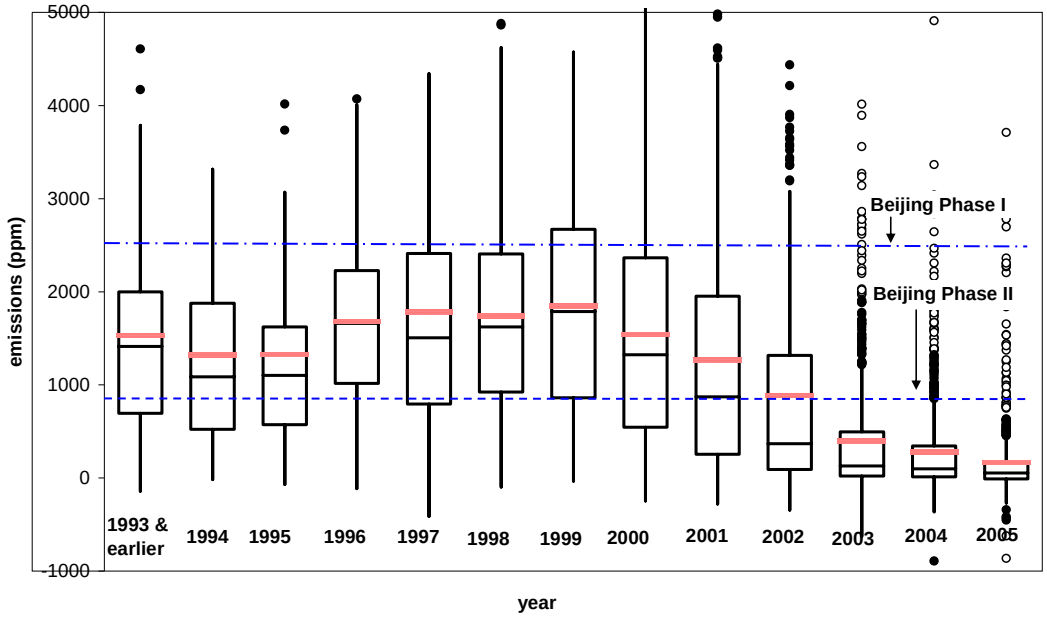


Figure 2-13-c Distribution of NO Emissions by Age Group



We further analyzed how the effectiveness of the emission control devices changed over time by examining the group of vehicles equipped with MPFI and TWC (technology 4). This group was chosen because it contained a large number of measurements (2,430 in total) and included vehicles of various ages. As shown in Table 2-12, the majority vehicles in the technology 4 group were less than 3 years old.

Figure 2-14-a, b, and c show a very clear trend: the average emissions of CO, HC, and NO all increased dramatically with the aging of vehicles in the technology 4 group. Comparing vehicles less than one year old with those that are about 8 years old, one can see that the average CO emission increased from 0.16% (less than one-year old vehicles) to 1.35% (8-year-old vehicles), the average HC emission increased from 33 ppm to 1,313 ppm, and the average NOxemission increased from 134 ppm to 2,256 ppm.

Table 2-12 Vehicle Age Distribution of Tech Group 4

Age	*Freq*	*%*	*Average VSP*
1	453	18.64%	6.82
2	615	25.31%	7.19
3	493	20.29%	6.85
4	285	11.73%	6.97
5	193	7.94%	6.78
6	122	5.02%	6.99
7	74	3.05%	7.54
8	50	2.06%	6.23
9	44	1.81%	7.50
10	40	1.65%	6.80
>10	61	2.51%	7.51

Figure 2-14-a Vehicle CO Emission vs. Age (Technology 4)

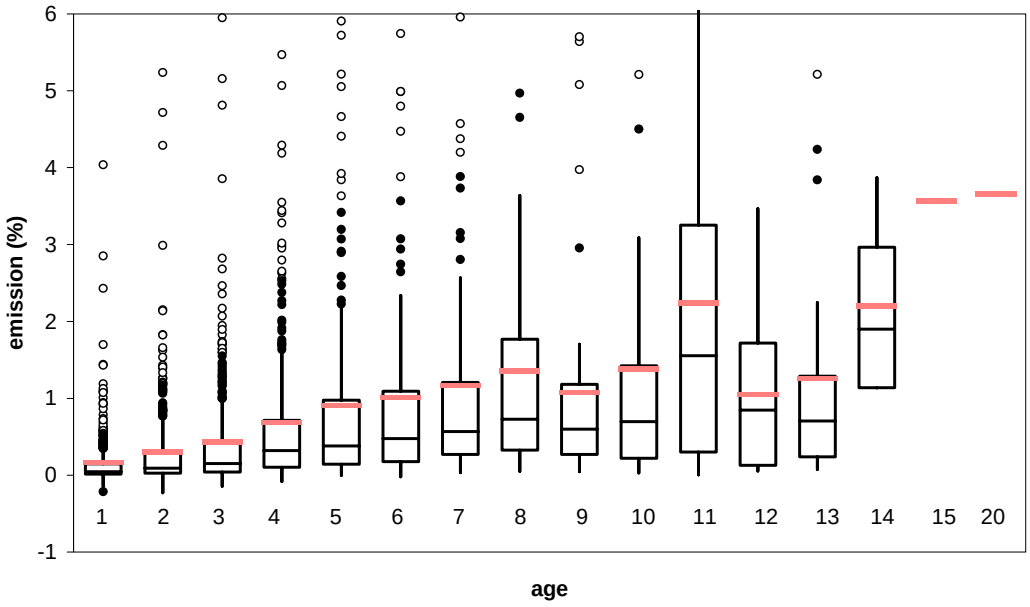


Figure 2-14-b Vehicle HC Emission vs. Age (Technology 4)

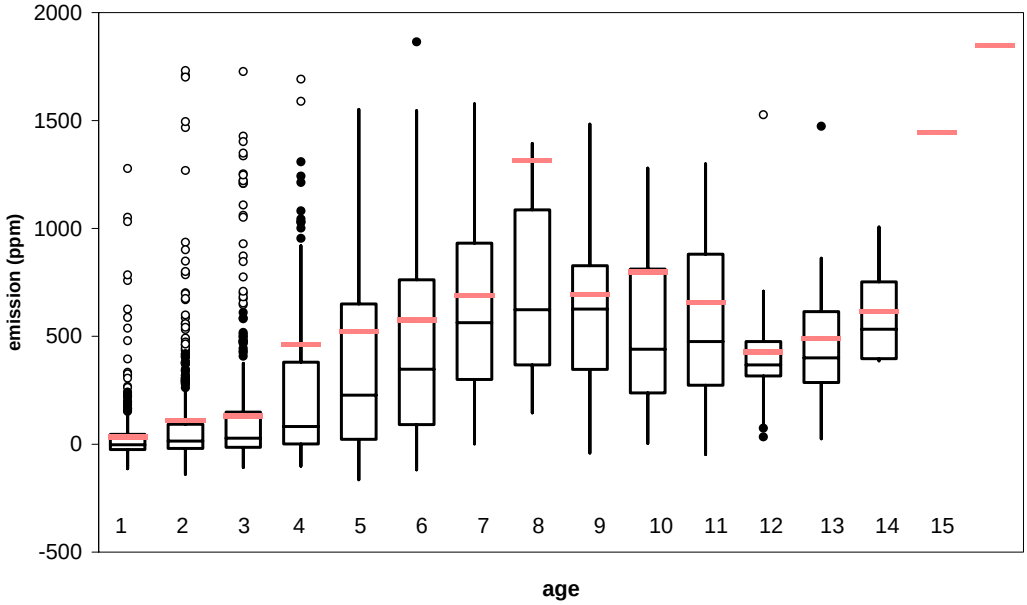
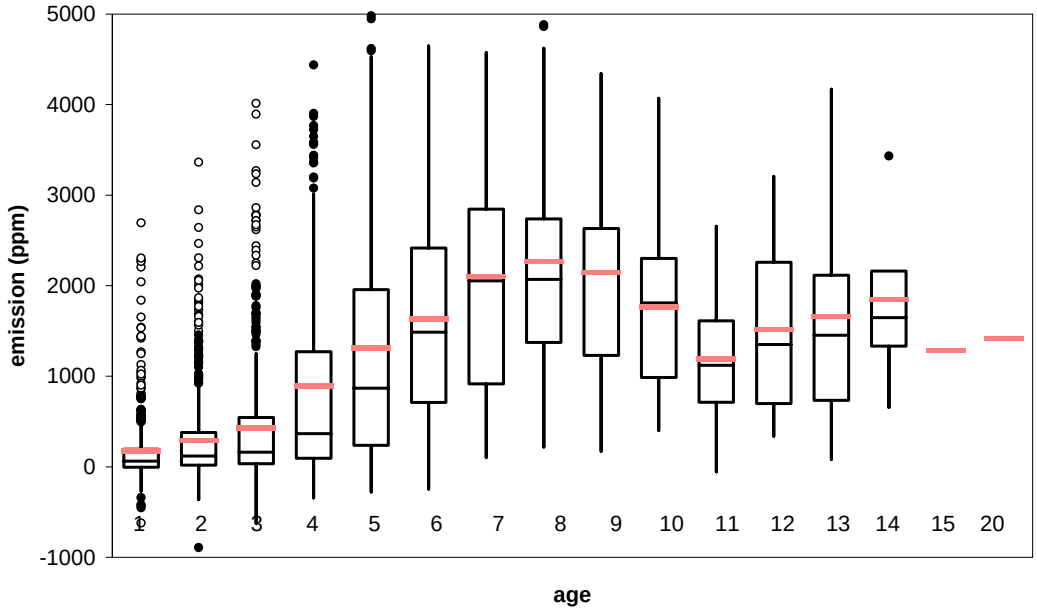


Figure 2-14-c Vehicle NO Emission vs. Age (Technology 4)



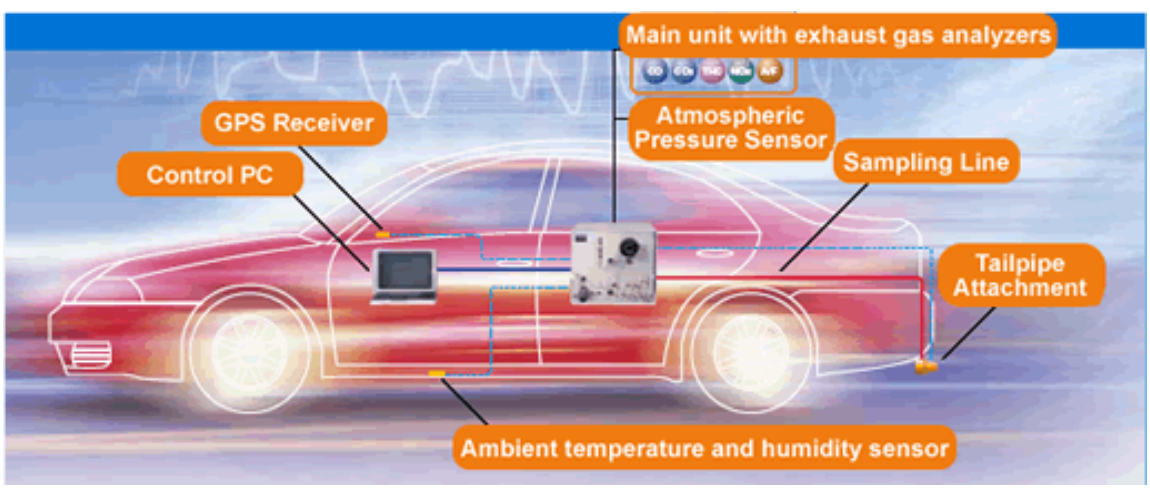
3. Measuring Emissions with Portable Emission Measurement Systems[20]

3.1 Instrument Design

During the second stage of Tianjin study, we used a set of OBS-2200 system by Horiba 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. It measures the CO, CO_2, total hydrocarbon (THC), NO_x, and air/fuel ratio produced by a moving vehicle. At the same time, the system calculates the weight of exhaust gas generated and the fuel consumption per unit of distance traveled.

As illustrated in Figure 3-1, a GPS receiver and a variety of other sensors provided position data and an overview of the driving environment (temperature and humidity) in real time. A heated type of non-dispersive infrared (NDIR) analyzer and a MEXA-1170 hot flame ionization detector (HFID) measured CO, CO_2, and THC concentrations in the vehicle emissions, without water extraction. A hot chemi-luminescence detector (HCLD) measured NO_x concentration. Flow sensors with USEPA-licensed technology measured the tailpipe flow. In addition, we used three bottles of standard gases to calibrate and test the sensors and two 100 amp-hour, 12 volt lead acid batteries to power the system during on-road testing in Tianjin.

Figure 3-1 Illustration of the OBS-2200 system



Source: Horiba website http://www.emd.horiba.com/2006site/products/obs2000.html.

To understand how well the OBS-2200 system would perform, we compared it with a constant volume sampler (CVS)[21] emissions measurement system by measuring

[20] Original data used in this section were collected, screened, and processed by the CATARC team under the advice of Nicole Davis.

the emissions of a vehicle on the dynamometer roller simultaneously with two systems. Figure 3-2-a, b, c, d, and e illustrates the results of the test. These charts show that the measurements of the two systems were very close; thus, we were satisfied with the accuracy of the OBS-2200 system for the purpose of our study.

Figure 3-2-a CO Measurements by the OBS and CVS Systems

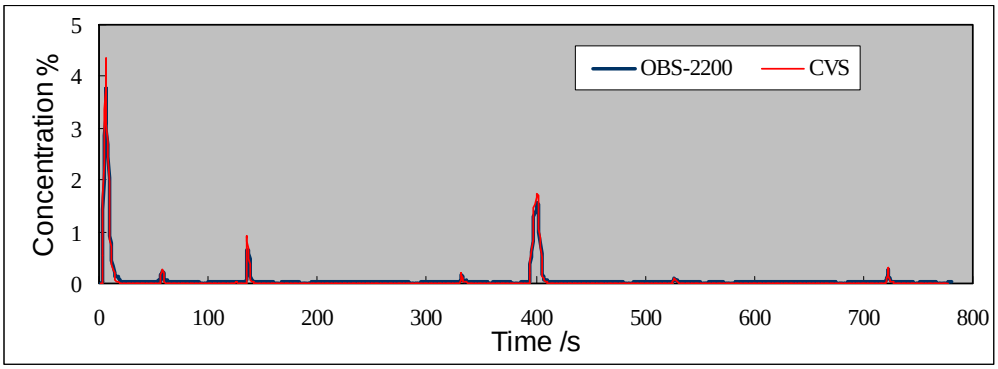


Figure 3-2-b CO_2 Measurements by the OBS and CVS Systems

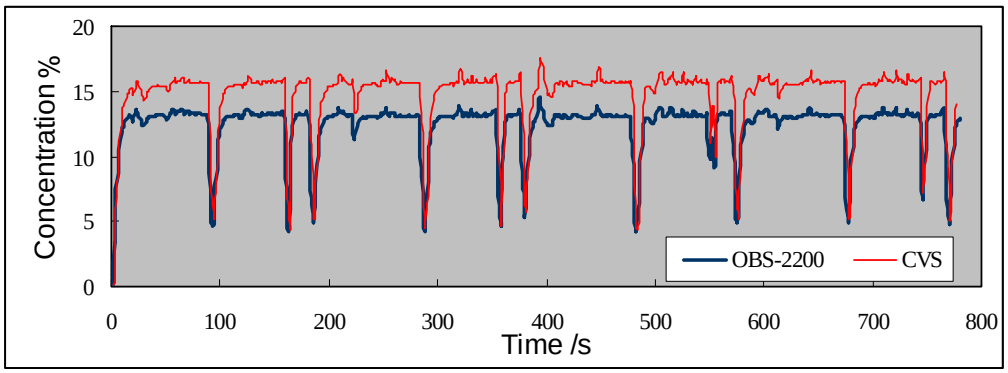
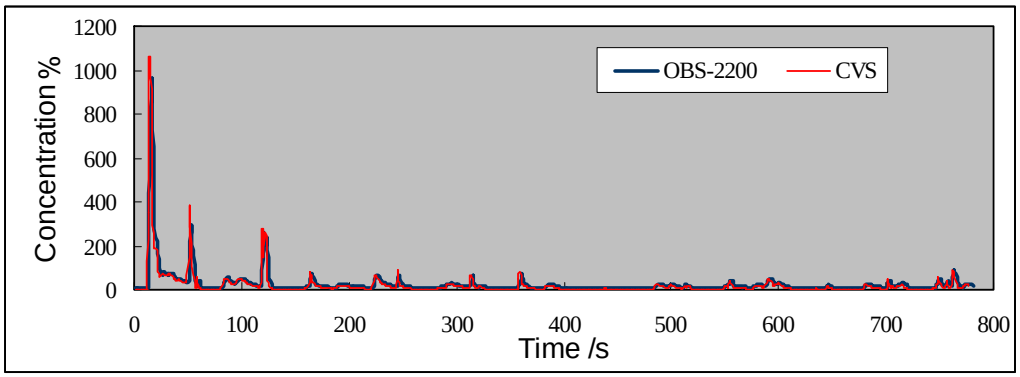


Figure 3-2-c NO_x Measurements by the OBS and CVS Systems



[21] CVS systems, which have been used more than 35 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 accurate in measuring vehicle emissions (with the exception of extremely low emissions).

Figure 3-2-d THC Measurements by the OBS and CVS Systems

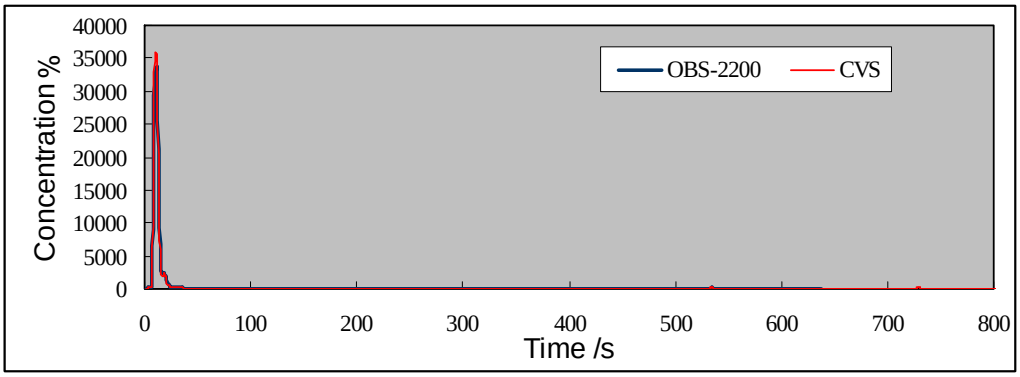
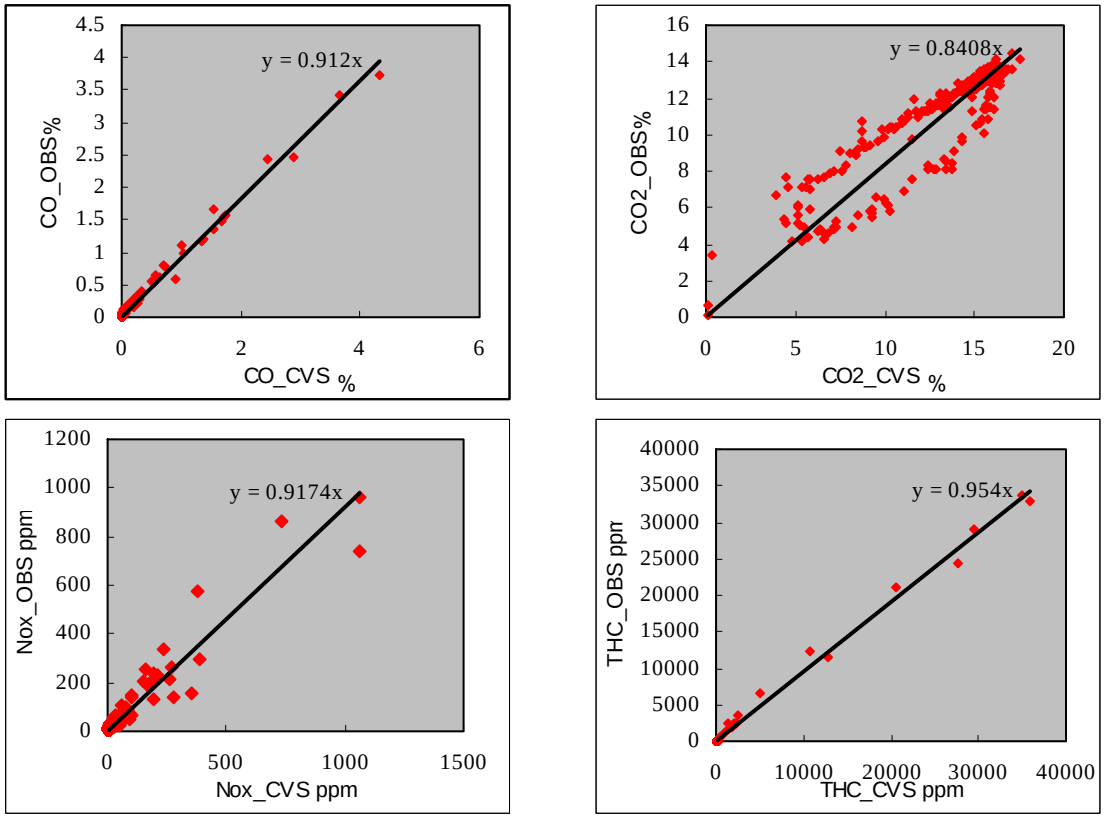


Figure 3-2-e Correlation between Measurements by the OBS and CVS systems



3.2 Route Selection and Vehicle Sample

Route for Real-time Emission Testing

The key purpose of doing on-board system (OBS) emissions testing with PEMS is to establish the relation of emissions and VSP in the study area. To achieve this, the tested vehicle must be operated under a wide variety of driving conditions when the PEMS is taking emission measurements.

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

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, the Automobile Testing Lab of CATARC served as the headquarter office and vehicle preparation site); and

3) There should be some turning-around points so 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 3-3, the route started and ended at the Automobile Testing Lab of CATARC. The route was about 15 kilometers long, comprised of three types of roads: about 2 km of residential/business district roads (such roads often had many intersections, characterized by low speed and stop-and-go driving), about 9 km of arterial roads (they had fewer intersections and moderate speed), and about 4 km of urban expressways (the sections had almost no intersections and free-speed traffic most of the time). It took 30 to 50 minutes to finish the route, depending on the traffic condition at the time of the test.

Figure 3-3 Route for OBS Emissions Testing in Tianjin

Sample Vehicles

According to the Central Limit Theorem, the mean of a sample ($\bar{x}$) taken from a probability distribution with mean μ and standard deviation σ follows a normal distribution, with a mean of μ and standard deviation of $\sigma / \sqrt{n-1}$. Statistically, we can be confident that the sample mean ($\bar{x}$) has about 70% of probability of being within the range of $\pm \sigma / \sqrt{n-1}$ of μ.

$$I_{70\%} = \pm \sigma / \sqrt{n-1} \qquad \textbf{(6)}$$

$I_{70\%}$: 70% confidence interval
σ: standard deviation of the sample
n: sample size

In the case of vehicle emissions, σ is often close to the sample mean. The above equation then becomes:

$$I_{70\%} = \pm M / \sqrt{n-1} \qquad \textbf{(7)}$$

M: measured sample mean

Therefore, if we want the measured sample mean to have a 70% probability of being within 20% of the actual mean of the population, we would need a sample size of 26.

The Central Limit Theorem tells us that the larger the sample is, the more likely that the sample mean would be close to the actual mean of the population. To ensure that there would be a moderate level of confidence in the OBS testing result, ISSRC experts recommend that at least 20–30 vehicles (40–50 would be ideal) within each important vehicle technology category should be tested. However, the amount of available resources did limit the maximum number of vehicles tested during the Tianjin study.

Because the major purpose of on-board system vehicle emissions testing is to establish the relationships between emissions and VSP of the major local vehicle technology groups, the technology distribution of sampled vehicles for PEMS testing does not have to be the same as the technology distribution of the whole fleet studied. Instead, each technology group should have enough vehicles tested to generate reliable results.

The project team tested emissions of 74 vehicles during a period of 12 days (from March 28 to April 8, 2006). The RSD study conducted in the summer of 2005 had shown that there were four major vehicle technology groups in Tianjin (refer to Chapter 2, Table 2-7, and Figure 2-6): vehicles with MPFI, EGR, and TWC (technology 2); vehicles with MPFI and CCTWC (technology 3); vehicles with MPFI and vehicles with MPFI and

TWC (technology 4); carbureted vehicles (technology 9). Thus, the 74 vehicles were selected from these four vehicle groups.

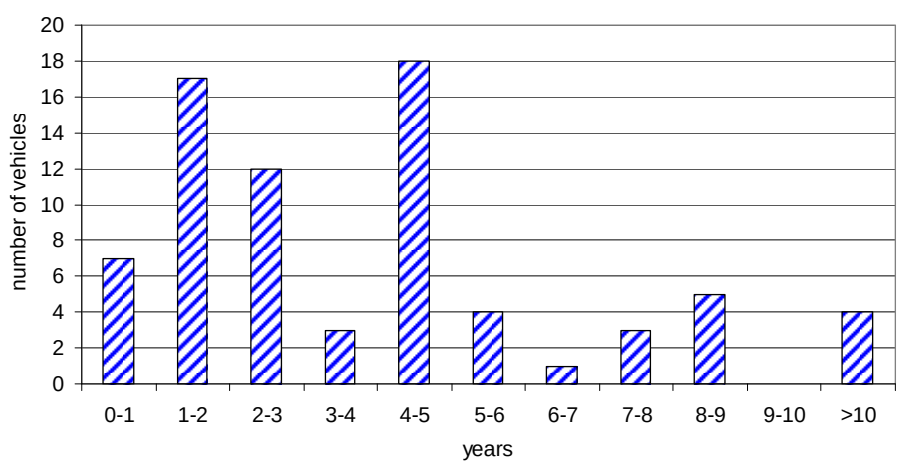
Table 3-1 describes the distribution of the 74 sample vehicles by technology and engine size. Given that LDVs with MPFI and TWC (technology 4) accounted for 70% of all LDVs in Tianjin (refer to Chapter 2) and their ages varied within a much wider range than vehicles in other technology groups, we chose more vehicles in this group for emissions testing with PEMS. The average age of all sample vehicles was 3.9 years, which was very close to the average age of the LDV fleet in Tianjin (3.7 years, see Chapter 2). Nevertheless, the age distribution of the 74 sample vehicles was different from the age distribution of the overall LDV fleet. We believe (as demonstrated in the RSD study) that emission characteristics of vehicles within the same technology group are likely to be similar when the vehicles are new, so the share of new vehicles in the sample was smaller than the share of these vehicles in the overall fleet.

Table 3-1 Distribution of 74 Sample Vehicles for OBS Test

By technology			*By engine size*		
Technology group	*Number*	*Percent*	*Liter **	*Number*	*Percent*
2 (MPFI, EGR & TWC)	12	16%	<1.5	39	53%
3 (MPFI & CCTWC)	16	22%	1.5-3.0	32	43%
4 (MPFI & TWC)	32	43%	>3.0	3	4%
9 (carburetor)	14	19%			
Subtotal	*74*	*100%*		*74*	*100%*

Note: * The classification of engine size here was based on the classification criteria of IVE model, not the Chinese method used in Chapter 2.

Figure 3-4 Age Distribution of 74 Sample Vehicles



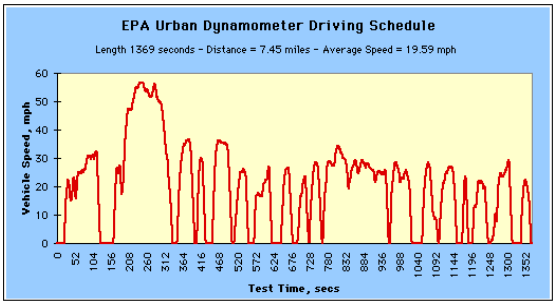
3.3 Data Collection and Processing

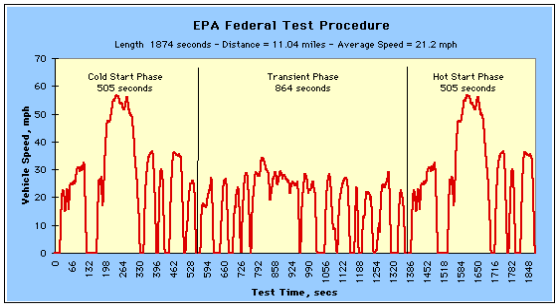
During the 12 days of emission testing with the OBS-2200 system, the project team tested 6 or 7 vehicles per day. It usually took about 90 minutes to prepare a vehicle, (to mount, warm up, and calibrate the instrument), drive the vehicle along the testing route, and dismount the instrument from the vehicle. The OBS-2200 system must be warmed up before it can take measurements accurately. The temperature of the sampling hose, HFID channel, and NDIR channel must reach 190, 190, and 60°C respectively. It took the OBD-2200 system about one hour to reach these temperatures from room temperature (the low temperature in Tianjin was still close to 0°C in late March). It took about 15 minutes to warm up the system between 2 consecutive tests. In addition, since we wanted to capture the cold start emissions, the vehicles to be tested on a particular day were secured and parked at the preparation site on the previous evening to ensure a cold start.

After emissions and position data had been obtained for each test, the team went through the following steps for data cleaning and processing:

1) Assess the overall validity of a test (on-site, immediately after each test),
2) Align the time for flow, emission measurements, and speed,
3) Weed out unreasonable GPS data,
4) Group second-by-second driving conditions and emissions of a tested vehicle into 60 power bins (based on VSP and engine stress calculation. Detailed are explained in the next 2 pages),
5) Create the correlation between average emission and driving condition (defined as 60 power bins) for a particular vehicle technology group, using the method of linear fitting,
6) Calculate the total emissions of different tested vehicles as if they were operated on a LA4[22] driving cycle, using the emissions–power bin relationships established in step 5)
7) Calculate the emissions of the tested vehicles on a LA4 driving cycle, using the default emissions–power bin relationships built in the IVE model (which are based on emissions data of thousands of vehicles), and

[22] LA4 cycle is also called the USEPA Urban Dynamometer Driving Schedule (UDDS), or the "city cycle". It represents a city driving condition (in Los Angeles in the early 70s). The USEPA FTP cycle is composed of the UDDS followed by the first 505 seconds of the UDDS, as shown in the two charts below. The charts are from USEPA website: http://www.epa.gov/nvfel/testing/dynamometer.htm.





8) Calculate base emission correction factors by comparing the average emissions of a particular vehicle technology group calculated from steps 6 and 7.

ISSRC had developed computer programs for calculating VSP, for grouping driving conditions and emissions on a second-by-second basis, for establishing the correlation between measured emissions and VSP bins, and for calculating the base emission correction factors. However, assessing the validity of data and aligning time still demanded sound judgment based on human experience. We determined that the measurements of 4 out of the 74 vehicles were not usable, due to reasons such incorrect flow measurement, vehicle malfunction, and unreasonable CO emission measurements.

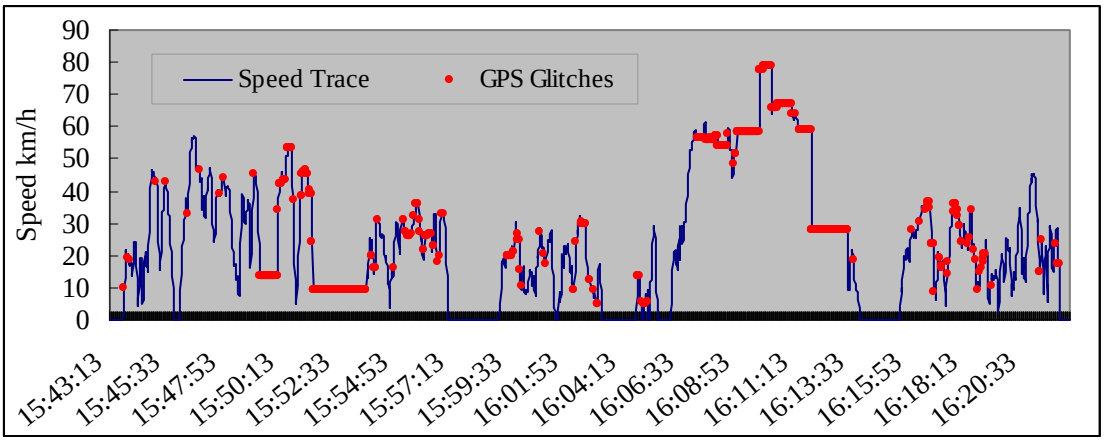
Time Alignment

The time alignment between the vehicle speed, tailpipe flow measurement, and gas concentrations is critical for producing accurate second by second emission estimates. In our study, a GPS unit, which was a part of the OBS-2200 system, measured vehicle speed during the on-road tests. Flow measurements were made by a pitot tube flow measurement device. Flow measurements were immediate while speed and concentration measurements were delayed by a few seconds. The time alignment was initially established by observing the flow measurements and then comparing them to the concentration and vehicle speed measurements. This allowed an approximation of the appropriate time alignment between the speed, flow, and concentration measurements.

GPS Data Weeding

The GPS receiver obtained second-by-second position information of a vehicle during the on-road test. Velocity, acceleration, and grade were then calculated from the position information. We found that during the on-road emissions testing in Tianjin, the GPS receiver had glitches and could not receive satellite signals for a very brief period occasionally. For example, when the vehicle was driven under shields such as cloverleaf junctions or tunnels, the receiver sometimes failed to receive information from the satellites. In addition, the communication between the receiver and the satellites sometimes experienced interference from radio devices on the ground near the driving route. When such an event occurred, the receiver could not obtain and record the new position data. Instead, it kept recording the data of the last second when it did receive satellite signals. As a result, stagnant speed was seen in the speed trace (as shown in Figure 3-5). Incorrect speed information would lead to wrong VSP and engine stress calculation, which would distort the relationships between emissions and VSP bins that we were building. Thus, when GPS measurements were unreasonable, we discarded all the data related to those seconds.

Figure 3-5 GPS Glitches in a Speed Trace



Emission and Power Bin

After using various statistical methods to analyze a large pool of on-road and dynamometer emission data[23] collected at a minimum frequency of 1 Hz, researchers at CE-CERT and ISSRC drew the conclusion that vehicle specific power (VSP, see section 2.3 for its definition and formula) is the single most important parameter for determining vehicle emissions. It can explain about 65% of emissions. However, the researchers also found that emission estimates based on VSP perform best for CO_2, but not completely satisfactory for other emissions such as CO, HC, NO_x, 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 20 seconds of operation and implied engine revolutions per minute (RPM, see equation below). [24]

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

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

The driving pattern of any vehicle (or any road) during a certain period of time thus can be divided into 60 power bins based on the calculation of instantaneous VSP and engine stress (20 groups for VSP and 3 modes for engine stress). Table 3-2 shows the demarcation of VSP bins and stress modes. Bin 1-11 corresponds to the driving condition

[23] 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)
- On-road PEMS data collected on several Tier 1 LDVs (EPA)
- On-road, track and dynamometer data collected from ULEV and SULEV LDVs (CRC), and
- On-road heavy duty diesel vehicle data from a set of several vehicles collected (Cocker).

[24] Source: ISSRC (2004), IVE Model User Manual. Appendix C. Available at: www.issrc.org.

of deceleration or going down a hill, Bin 12 corresponds to idling, while Bin 13 and above correspond to driving under a constant speed, acceleration, and going up a hill.

Table 3-2 VSP Bins and Stress Modes *

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

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

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

* Source: ISSRC (2004), IVE Model User Manual. Appendix C. Available at: www.issrc.org.

Figure 3-6-a and 3-6-b illustrate the relations of emission versus power bin for closed-loop, catalyst-equipped and carbureted, no-catalyst gasoline vehicles respectively.[25] (Vehicles with these technologies are most commonly seen in the Chinese passenger fleet.). Figure 3-6-c shows the correlation of emission versus power bin for diesel vehicles. It is clear that gasoline and diesel vehicles have very different emissions even for the same power bins.

[25] Source: ISSRC (2004), IVE Model User Manual. Appendix C. Available at: www.issrc.org.

Figure 3-6-a Emission vs. Power Bin for Closed-loop, Catalyst-equipped Gasoline Vehicles

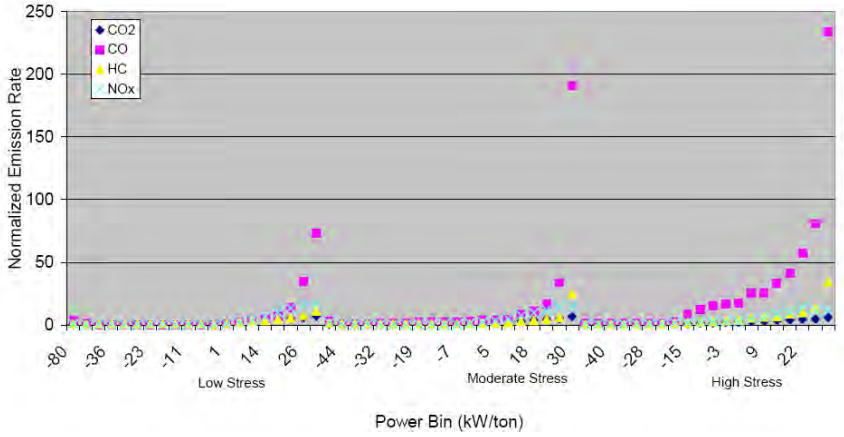


Figure 3-6-b Emission vs. Power Bin for Carbureted, No-catalyst Gasoline Vehicles

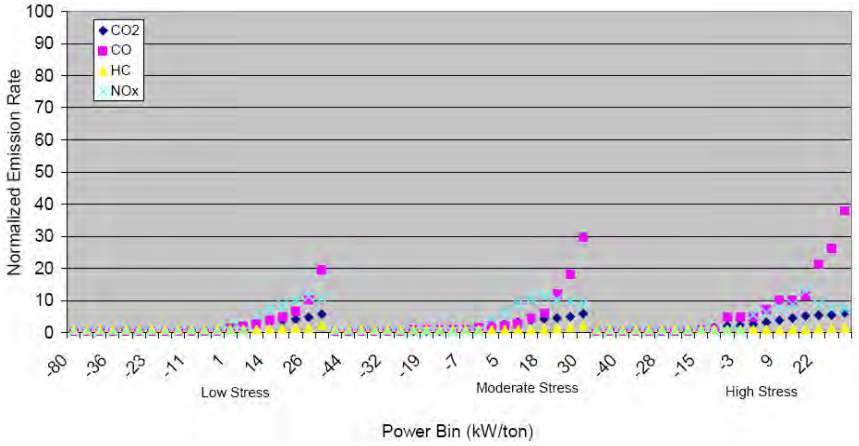


Figure 3-6-c Emission vs. Power Bin for Diesel Vehicles

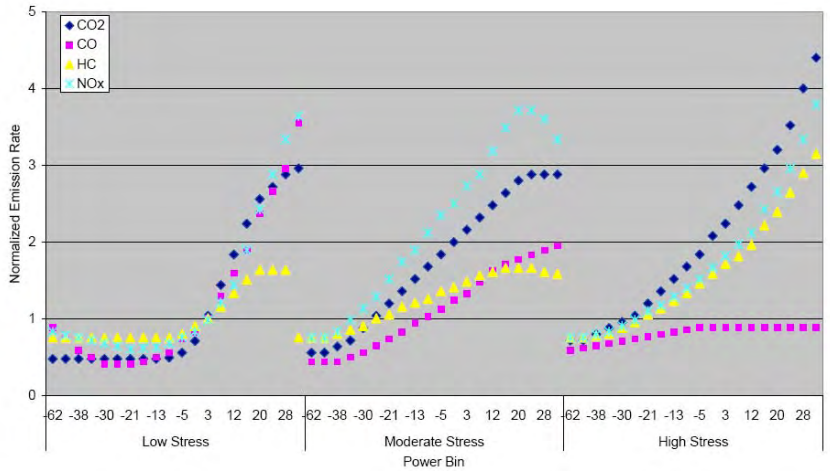


Figure 3-7-a gives an example of the second-by-second VSP value of a tested vehicle during the PEMS testing, and Figure 3-7-b shows the distribution of related power bin frequency. They shows that the vehicle was operated within a narrow VSP range (-20 to 20 in figure a) and VSP bin range (9 to 15 in figure b). The overall traffic condition on the selected driving route simply did not allow driving in high power bins (high engine stress, such as hard acceleration at high speed) to occur.

Figure 3-7-a VSP Distribution During a PEMS Test

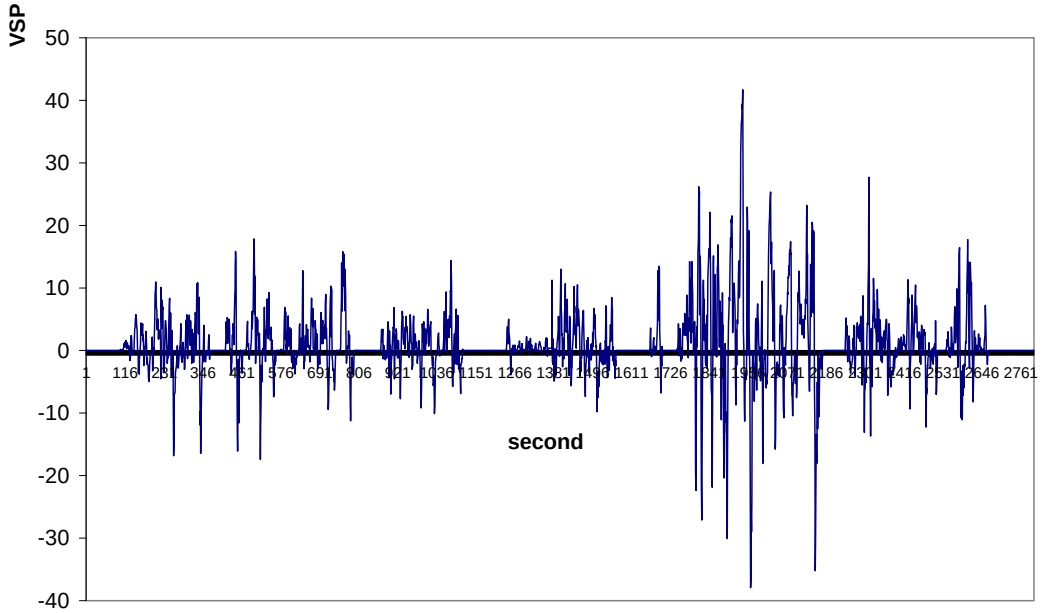
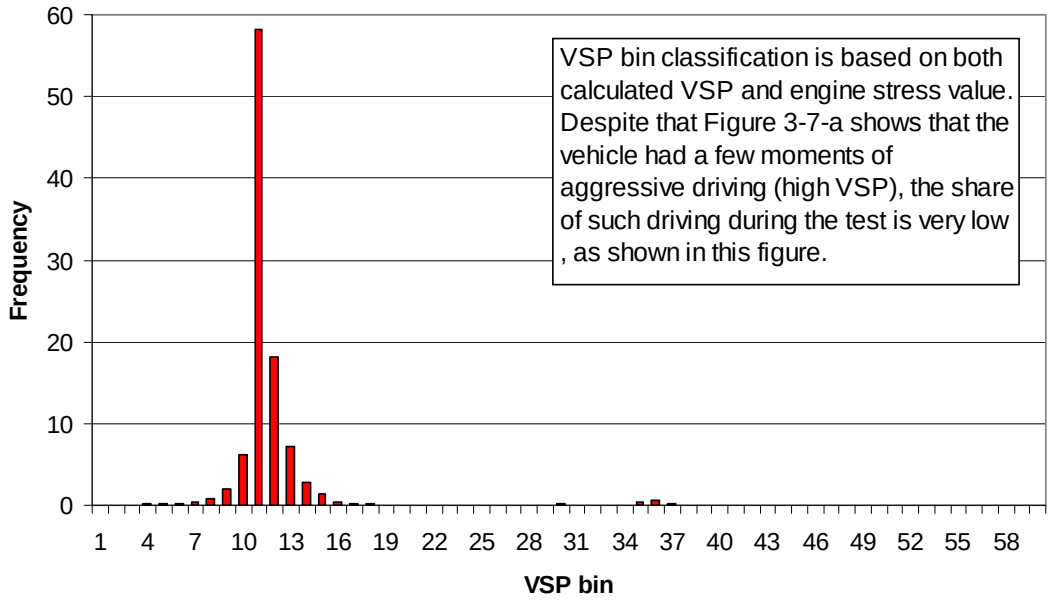


Figure 3-7-b VSP Bin Distribution during a PEMS Test



3.4 Results

Actual Running Emissions

Following the detailed vehicle classification in the IVE model,[26] we put the 70 tested vehicles into 15 subcategories based on their emission technology. The actual emission factors (running emission) of each subcategory during the road test were summarized in Table 3-3. These results show that carbureted vehicles were the dirtiest; low-mileage vehicles with MPFI, TWC, and EGR were the cleanest. However, since every vehicle was operated under different driving conditions during the test, the impacts of driving on emissions were embedded in these data.

Table 3-3 Emission Factors of Sample Vehicles during Road Test

IVE Class	*Vehicle category description*	*Number*	*CO (g/km)*	*CO_2 (g/km)*	*NO_x (g/km)*	*THC (g/km)*
0	Carburetor, 1.5-3.0 liters low mileage	2	*35*	*196*	*1.5*	*6.2*
2	Carburetor, 1.5-3.0 liters high mileage	6	37	179	1.6	5.2
5	Carburetor, >3.0 liters, high mileage	3	37	243	3.2	6.5
31	Carburetor, TWC, 1.5-3.0 liters, medium mileage	1	44	227	2.9	2.6
117	MPFI, TWC, <1.5 liters, low mileage	22	9	223	0.6	1.0
118	MPFI, TWC, <1.5 liters, medium mileage	3	9	202	1.0	0.5
119	MPFI, TWC, <1.5 liters, high mileage	3	5	188	0.7	0.6
120	MPFI, TWC, 1.5-3.0 liters, low mileage	11	11	305	0.5	0.8
121	MPFI, TWC, 1.5-3.0 liters, medium mileage	7	10	294	0.9	0.5
122	MPFI, TWC, 1.5-3.0 liter, high mileage	2	5	249	0.8	0.5
126	MPFI, TWC, EGR, <1.5 liters, low mileage	1	1	297	0.0	0.2
129	MPFI, TWC, EGR, 1.5-3.0 liters, low mileage	2	4	329	0.5	0.4
130	MPFI, TWC, EGR, 1.5-3.0 liters, medium mileage	1	22	388	0.9	1.0
131	MPFI, TWC, EGR, 1.5-3.0 liters, high mileage	3	5	327	0.3	0.2
133	MPFI, TWC, EGR, >1.5-3.0 liters, medium mileage	1	3	395	0.3	0.2
134	MPFI, TWC, EGR, >1.5-3.0 liters, high mileage	2	27	343	2.1	3.7

[26] See ISSRC (2004), IVE Model Manual, Appendix B, Developments of Base Emission Rates, the workbook.

Normalized Running Emissions

To eliminate the impact of driving conditions, we used a piece of software developed by ISSRC to normalize the emissions of each subcategory to a FTP cycle (only the running emission segments were normalized).[27] The results are shown in Table 3-3. Comparing Table 3-3 and 3-4, one can see that the emission values in Table 3-4 (normalized) are lower that those in Table 3-3 (road test) for the same group of vehicles. This is expected because the FTP cycle is usually not quite as aggressive as real-world driving. As illustrated in Figure 3-8-a, b, and c, carbureted vehicles again emitted significantly more pollutants than vehicles in other categories (i.e., with MPFI and emission control devices) after normalization. On average, carbureted vehicles emitted about 4, 3, and 6 times more CO, NO_x, and THC than vehicles with MPFI and end-of-pipe emission control devices.

Table 3-4 Emissions Factors of Sample Vehicles on a Hypothetic FTP cycle

IVE Class	*Vehicle category description*	*Number*	*CO (g/km)*	*CO_2 (g/km)*	*NO_x (g/km)*	*THC (g/km)*
0	Carburetor, 1.5-3.0 liters low mileage	2	29	139	1.3	4.5
2	Carburetor, 1.5-3.0 liters high mileage	6	31	142	1.5	4.1
5	Carburetor, >3.0 liters, high mileage	3	26	196	2.6	5.3
31	Carburetor, TWC, 1.5-3.0 liters, medium mileage	1	38	202	2.5	2.4
117	MPFI, TWC, <1.5 liters, low mileage	22	7	168	0.5	0.8
118	MPFI, TWC, <1.5 liters, medium mileage	3	6	159	0.7	0.4
119	MPFI, TWC, <1.5 liters, high mileage	3	3	141	0.6	0.5
120	MPFI, TWC, 1.5-3.0 liters, low mileage	11	6	212	0.3	0.5
121	MPFI, TWC, 1.5-3.0 liters, medium mileage	7	5	205	0.6	0.3
122	MPFI, TWC, 1.5-3.0 liter, high mileage	2	3	204	0.5	0.4
126	MPFI, TWC, EGR, <1.5 liters, low mileage	1	1	169	0.0	0.1
129	MPFI, TWC, EGR, 1.5-3.0 liters, low mileage	2	3	253	0.4	0.3
130	MPFI, TWC, EGR, 1.5-3.0 liters, medium mileage	1	13	288	0.7	0.7
131	MPFI, TWC, EGR, 1.5-3.0 liters, high mileage	3	4	263	0.3	0.1
133	MPFI, TWC, EGR, >1.5-3.0 liters, medium mileage	1	1	213	0.2	0.1
134	MPFI, TWC, EGR, >1.5-3.0 liters, high mileage	2	9	268	1.4	2.6

[27] Actual emissions per second of a tested vehicle were first put into 60 power bins (based on the calculated second-by-second VSP and engine stress values); then we synthesized an emission-vs.-power bin curve for that vehicle using linear regression method. Next, we calculated the emissions of the vehicle as if it were driven under a FTP cycle, using the synthesized emission-vs.-power bin curve.

Figure 3-8-a Average CO Emissions by Different Vehicle Class

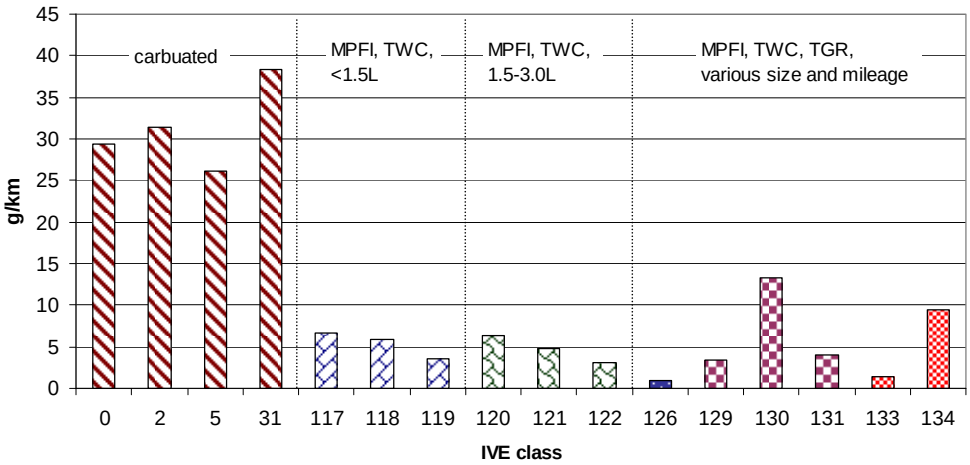


Figure 3-8-b Average NO_2 Emissions by Different Vehicle Class

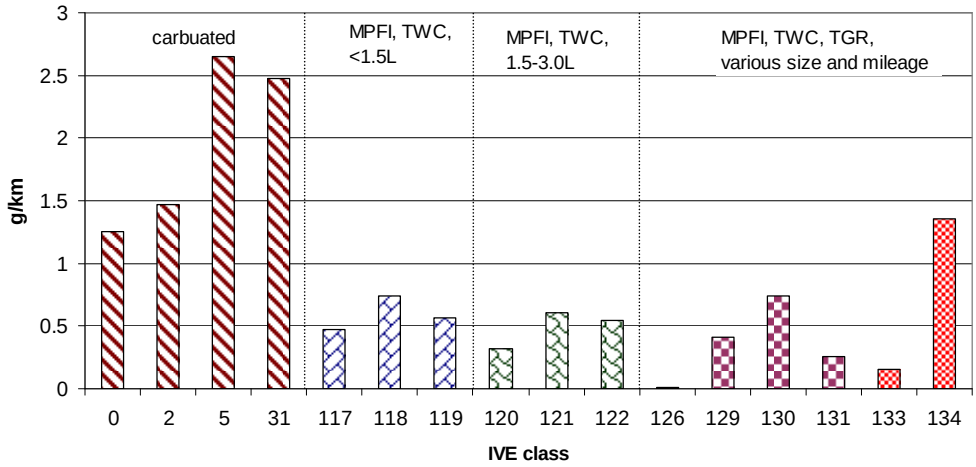
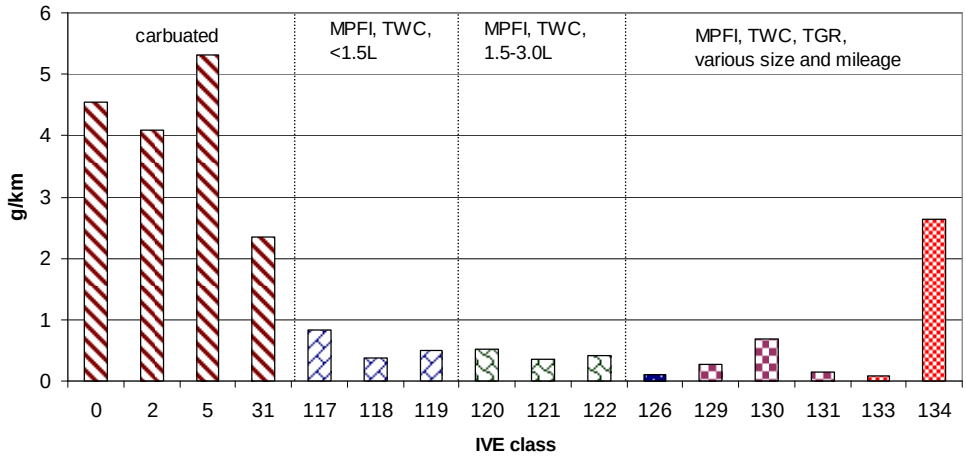


Figure 3-8-c Average THC Emissions by Different Vehicle Class



Because the sample size of some subcategories was rather small, emission trends across vehicle categories could not be taken too literally. For example, despite that Figure 3-8-a indicates CO emissions decrease from IVE class 117 to 119 (vehicles with MPFI and TWC, but average mileage increases from 117 to 119), such a trend is obviously not reasonable. Another example is the vehicles in class 130 (MPFI, TWC, EGR, engine size is larger than 1.5 but smaller than 3.0 liters, medium mileage). They had unusually high emissions in comparison with vehicles with similar technology and engine size but higher mileage. Because the vehicle-to-vehicle variability was large in some vehicle technology groups and the sample size was small, we must be cautious about to what extent the sample vehicles in one category can represent the whole vehicle population of that category.

Confidence Intervals

To understand to what extent the emission factor of tested vehicles in one subcategory could reflect that of the whole vehicle population in that subcategory, we calculated the 90% confidence intervals for the emission factors of each of the vehicle subcategories. The results were summarized in Table 3-5. Emissions of vehicles equipped with MPFI and TWC seemed to vary more than those of carbureted vehicles. Compared with other pollutants, CO_2 emissions were most consistent among vehicles within the sample group. The large range of 90% confidence intervals indicated that vehicles in the same subcategories had a large range of actual emissions. The large range for the average emissions of the 22 vehicles in IVE class 117 (vehicles with MPFI, TWC, and low mileage) was particularly unexpected, since these vehicles were all new and required to meet the same emissions standards.

The data in Table 3-5 show a clear indication of the need to collect larger samples of vehicles to have improved confidence in the results of the testing. Although data were successfully retrieved from 70 vehicles in Tianjin, very few vehicles were left in a technology subgroup after they were categorized. A combination of the innate nature of the variation in emissions from vehicle to vehicle and the limited number of tests caused quite large confidence limits in many cases. If one looks at all vehicles combined, the confidence interval improves because of the increase of sample size (see the last row of the table). The confidence interval for CO_2 was the smallest, and the confidence intervals for other pollutants ranged from 3% to 142%. Overall, there is much room for improving the stringency of these result data by increasing the sample size.

Table 3-5 90% Confidence Intervals* for Average Emissions (computed for each IVE class)

IVE class	*Vehicle category description*	*Number*	*CO*	*CO_2*	*NO_x*	*THC*
0	Carburetor, 1.5-3.0 L, low mileage	2	20%	8%	1%	44%
2	Carburetor, 1.5-3.0 L, high mileage	6	27%	11%	37%	20%
5	Carburetor, >3.0 L, high mileage	3	51%	3%	47%	51%
31	Carburetor, TWC, 1.5-3.0 L, medium mileage	1	n.a.	n.a.	n.a.	n.a.
117	MPFI, TWC, <1.5 L, low mileage	22	70%	6%	39%	68%
118	MPFI, TWC, <1.5 L, medium mileage	3	60%	10%	40%	93%
119	MPFI, TWC, <1.5 L, high mileage	3	55%	7%	99%	69%
120	MPFI, TWC, 1.5-3.0 L, low mileage	11	64%	12%	49%	62%
121	MPFI, TWC, 1.5-3.0 L, medium mileage	7	29%	13%	19%	31%
122	MPFI, TWC, 1.5-3.0 L, high mileage	2	110%	4%	131%	142%
126	MPFI, TWC, EGR, <1.5 L, low mileage	1	n.a.	n.a.	n.a.	n.a.
129	MPFI, TWC, EGR, 1.5-3.0 L, low mileage	2	125%	26%	147%	78%
130	MPFI, TWC, EGR, 1.5-3.0 L, medium mileage	1	n.a.	n.a.	n.a.	n.a.
131	MPFI, TWC, EGR, 1.5-3.0 L, high mileage	3	102%	12%	102%	69%
133	MPFI, TWC, EGR, >3.0 L, medium mileage	1	n.a.	n.a.	n.a.	n.a.
134	MPFI, TWC, EGR, >3.0 L, high mileage	2	3%	5%	7%	25%
All Vehicles		70	26%	5%	21%	29%

Note: * It means that we are 90% confident that emissions of a similar vehicle would fall within the x% of the reported average emission values.

Emissions of Vehicles with TWC and Close-Coupled TWC

Among the 70 vehicles validly tested, 32 vehicles were equipped with MPFI and TWC, and 16 vehicles were equipped with Close-Coupled TWC. The two groups of vehicles had similar average age, but they had rather different running and start emissions.

Table 3-6 shows that the average start CO, NO_2, and THC emissions of vehicles with MPFI and TWC were 40%, 90%, and 33% higher than those of vehicles with MPFI and CCTWC. From Figure 3-9-a, b, c, and d, one can see that the two vehicle technology groups have similar engine size and CO_2 emissions, but quite different CO, NO_2, and THC emissions. The former vehicle group not only generated more running emissions than those of the latter group, the values of their emissions also spread over a large range. This indicates the TWC technology used in the vehicles sold in China in general is not as advanced and reliable as the CCTWC technology used there. This is consistent with the Chinese situation: the automakers that had employed CCTWC technology on their cars to meet the Euro III standards ahead of the national implementation schedule are typically international companies targeting high-end vehicle markets; while TWC was originally employed to meet the Euro II standards and widely used by both international and domestic companies.

Table 3-6 Start Emissions by Vehicles with MPFI & TWC or CCTWC

	Number of vehicles	*Average age*	*Valid start emission measurements*	*CO (g/200s)*	*NO_2 (g/200s)*	*THC (g/200s)*
TWC	32	3.2	28	27.9	0.6	4.0
CCTWC	16	2.7	14	19.8	0.3	3.0

Figure 3-9-a CO Emissions of Vehicles with TWC and CCTWC

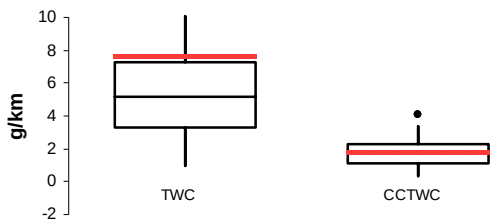


Figure 3-9-b NO_2 Emissions of Vehicles with TWC and CCTWC

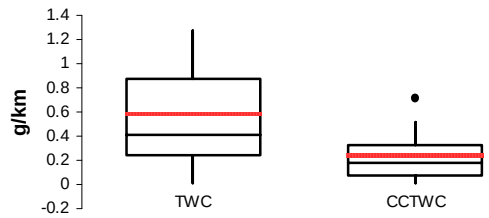


Figure 3-9-c THC Emissions of Vehicles with TWC and CCTWC

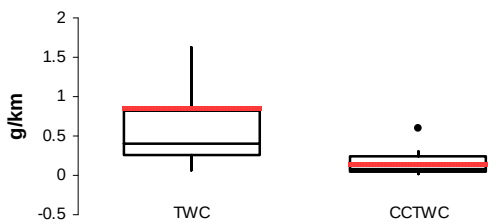
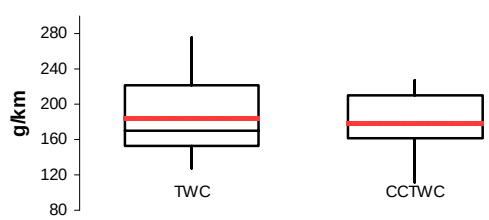


Figure 3-9-d CO_2 Emissions of Vehicles with TWC and CCTWC



Grouping the 48 vehicles equipped with TWC and CCTWC by age, we analyzed their average emissions over time. There is not a clear trend of performance improvement over time. In particular, CO and THC emissions fluctuated considerably, as shown in Figure 3-10-a and c. NO_2 and CO_2 emissions of such vehicles dropped slightly over the years.

Nevertheless, the sample size for each year was rather small (see Figure 2-6) so that any gross emitter in an age group would have had great impact on the average emission value of that group. In addition, the age distribution of this particular subsample does not represent the age distribution of such vehicles in the Tianjin fleet (compare Figure 3-11 and Figure 2-6). Thus, we decided that we couldn't draw any conclusions on the overall emission trend of this subfleet (vehicles with TWC and CCTWC) based on the 48 vehicles tested. It also confirmed that classification based on technology group rather than age (model year) made more sense, as the case of IVE model.

Figure 3-10-a CO Emissions of Vehicles with Catalysts

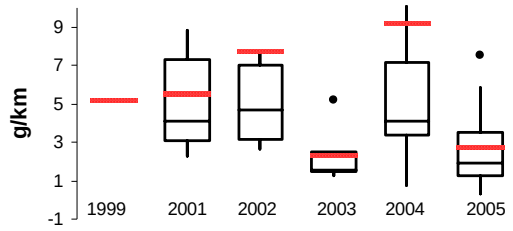


Figure 3-10-b NO_2 Emissions of Vehicles with Catalysts

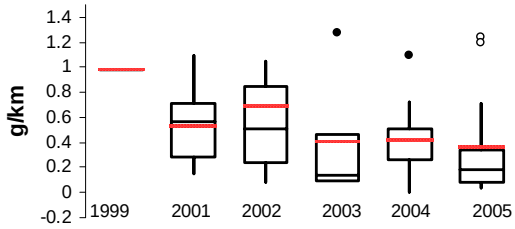


Figure 3-10-c THC Emissions of Vehicles with Catalysts

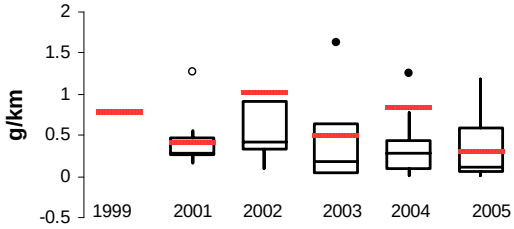


Figure 3-10-d CO_2 Emissions of Vehicles with Catalysts

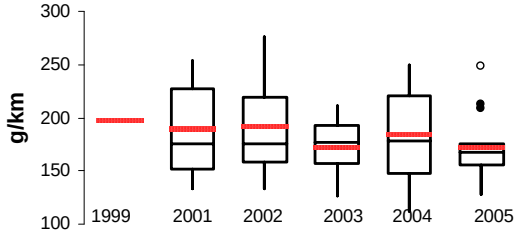
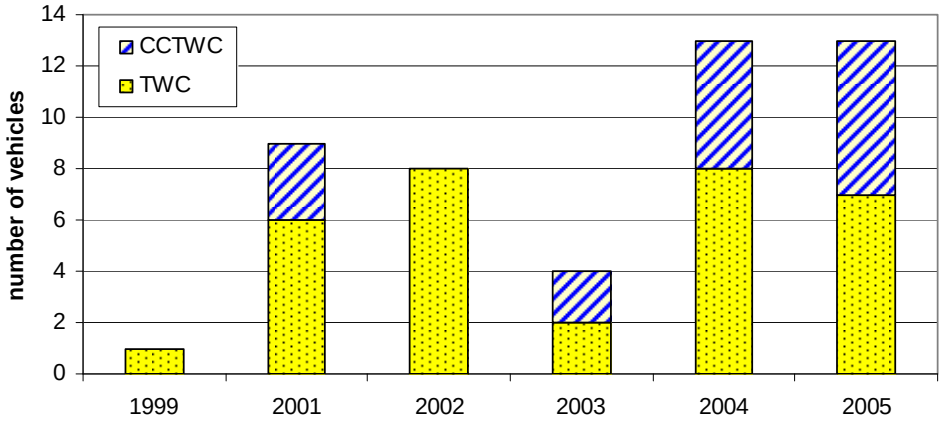


Figure 3-11 Catalyst Technology Distribution over Time



4. Vehicle Activity Study[28]

4.1 Methodology and Equipment

Information on fleet composition and driving patterns is critical for calculating vehicle emission inventories, as explained earlier in Section 1.3. Information on average velocity of a particular location, fraction of travel by each vehicle category, and fraction of each type of driving all needed to be collected locally.

Fleet Composition

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

1) Videotaping traffic on various roadways to collect the proportion of various types of on-road vehicles. We recorded the traffic flow on 9 roads (they were good representations of three types of roads: expressways, arteries, and residential roads in three urban districts with different economic development levels) during daytime hours (7:00 am to 9:00 pm). The fleet mix observed on these 9 roads was then extrapolated throughout the city, following the distribution of various urban road types.

2) Surveying vehicles at parking lots, bus terminals, taxi stops, and truck stops to determine the distribution of specific vehicle technologies (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 three different urban districts.

Driving Pattern

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

1) Collecting speed and acceleration distribution on different local roads with GPS devices. The GPS devices were installed on different types of vehicles (passenger car, taxi, bus, and truck) to collect their driving patterns in Tianjin. For the driving patterns of passenger cars, we first selected three districts with different economic development levels (low-income, high-income, and center business districts). Next, in each district, a representative driving route (including

[28] Data collection, cleaning, and processing of this section were completed by the Tsinghua team under the advice of Nicole Davis and Jim Lents.

a section of urban expressway, a section of multi-lane arterial road, and a section of residential road) was selected. The whole route took 45–60 minutes to finish. A driver drove a car equipped with a GPS device on the route continuously, following the traffic flow. A taxi and a truck instrumented with respective GPS devices were driven by their drivers for everyday use, and their driving patterns were recorded by those GPS devices automatically. Meanwhile, a student carried a GPS device and took rides on buses to record the driving pattern of local buses.

The GPS data was then screened and processed to generate second-by-second speed and acceleration profiles (the IVE model uses the 60 power bins, see section 3.3 for detailed description) for the four different types of vehicles during different times of day. The driving pattern distributions were later matched with the emissions–power bin relationships to generate actual local emissions data.

2) Start distribution. The vehicle activity (VA) team used devices called vehicle occupancy count enumerators (VOCEs, which record the voltage change when an engine starts and turns off) to record the start pattern of private cars, taxis, and trucks. Engine start of each vehicle was recorded continuously for a period of five to seven days.

4.2 Route Selection and Data Collection

The VA team collected vehicle activity data in Tianjin from March 25 to April 4, 2006. Figure 4-1 shows the driving routes and videotaping sites in Tianjin. On the map, driving routes are highlighted with yellow while sites are noted as A_1-A_3, B_1-B_3, and C_1-C_3. Areas A, B, and C represent high income areas, business districts, and low income areas in Tianjin respectively. The 1, 2, 3 videotaping sites in each area are located on an urban expressway, an artery, and a residential road.

Table 4-1 summarizes the types of data on VA and driving pattern, the devices used to collect these data, and the numbers of valid data points obtained in Tianjin. Using 4 GPS units, the VA team collected velocity, acceleration, altitude, longitude, and latitude data from 3 passenger vehicles for 6 days, one taxi for 3 days, 1 bus for 3 days, and one truck for 3 days. General fleet composition was collected with two video cameras, concurrently with the driving pattern study. Traffic flow at the 9 sites (as highlighted in Figure 4-1) was recorded with these 2 cameras for different hours of a day (20 minutes of each hour). Data on specific vehicle technology were collected through a survey of 1,201 cars, 781 buses, 44 trucks, and 48 taxis. During the parking lot survey, the VA team hired an experienced local automobile technician for his advice on vehicle technology and age.

Figure 4-1 Focus Areas and Routes for VA Study in Tianjin

Table 4-1 Vehicle Activity Data Collected in Tianjin

VA activity item	*Device used*	*Type of data collected*	*Valid data points*
Driving Pattern	GPS	Second-by-second velocity, UTC, altitude, longitude, attitude, number of satellite	PC: 195,203 seconds Taxi: 91,218 seconds Truck: 27,436 seconds Bus: 46,247 seconds
Start pattern	VOCE	Starting and stopping time	227 days (vehicle day)
Traffic composition	Video camera	Vehicle, license plate, load	42 hours, 840 minutes in total
Specific technology	--	License number, model year, fuel, engine size, automaker, age, mileage, AC, transmission, TWC, fuel injection, maintenance	Passenger cars: 1201 Buses: 781 Trucks: 44 Taxis: 48

4.3 Data Processing

Cleaning and processing VA data was a very time consuming effort. To process the traffic flow information captured on video tapes, a reviewer looked though all the tapes and recorded different types of vehicles captured on the tapes at different sites in each hour. Vehicle survey data was tabulated to describe the distribution of specific technologies, such as mileage, age, emission control technology, engine size, and fuel injection, etc. With a software program developed by ISSRC, the GPS data were processed to generate the power bin distribution of driving on different roads. (Table 4-2 describes the classification of driving on different roads in this study.) Data recorded by VOCE was processed by another ISSRC-developed program to convert the recorded voltage changes to the amount and the type of starts.

Table 4-2 Vehicle Location Definition

Name	*Description*
PCHwy	Passenger vehicle driving on Freeways
PCRes	Passenger vehicle driving on Residential Roadways
PCArt	Passenger vehicle driving on Arterials
Taxi	Taxi operating under normal operating conditions
Bus	Bus operating under normal operating conditions
DTruck	Delivery Truck operating under normal operating conditions

Eventually, all processed the VA data were put into two Excel files. One file (the fleet file) contains the specific technology distribution of the local fleet (based on the survey data). [29] The other one (the location file) contains processed information such as totally mileage driven, start patterns, traffic composition, and distribution of driving patterns (second-by-second) on different types of roads during the day. These two files are later fed into the IVE model to generate emission inventories for Tianjin.

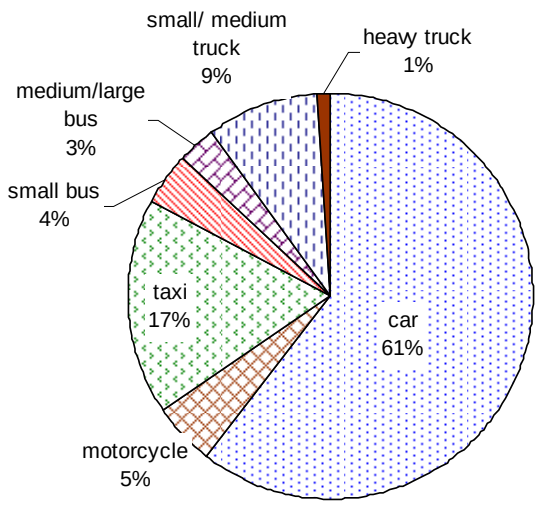
[29] There are totally 1371 specific technology groups in the IVE model, but usually, only about 100 would be relevant to a specific location.

4.4 Results

Fleet Composition

Extrapolating the traffic composition recorded at the 9 selected sites to the whole city, we obtained the overall fleet composition in Tianjin. As shown in Figure 4-2, in spring 2006, passenger cars were the most often used vehicles in Tianjin (accounting for 61% of road use), and taxis were the next (17%). Public transportation vehicles (various buses) accounted for 7% of road use while trucks contributed to 10% of road use.

Figure 4-2 Composition of On-Road Vehicles in Tianjin



Specific Technology Distribution

Vehicle technology survey indicated that among passenger vehicles (taxis were not included), 80% of the vehicles were equipped with MPFI and TWC and had engines less than 3 liters and low mileage (less than 80 km). It is noteworthy that there was still a considerable share of vehicles (13%) equipped with carburetors, and most of them had been used for quite some years and had accumulated high mileage (>160 km). Except for small carbureted vehicles, almost all passenger vehicles in Tianjin were equipped with air conditioners.

It was surprising to learn that over one third of taxis (35%) were carbureted vehicles. Most of the remaining taxis were equipped with MPFI and TWC. Among the latter group of taxis, 71% had small engines (less than 1.5 liters), and the rest were equipped with engines larger than 1.5 liters but less than 3.5 liters. Given the high use of taxis in the city, we speculated that these carbureted vehicles must have contributed a significantly high share of mobile emissions, which was verified with model results described in Section 6.3.

Figure 4-3-a Specific Technology Distribution of Passenger Vehicles

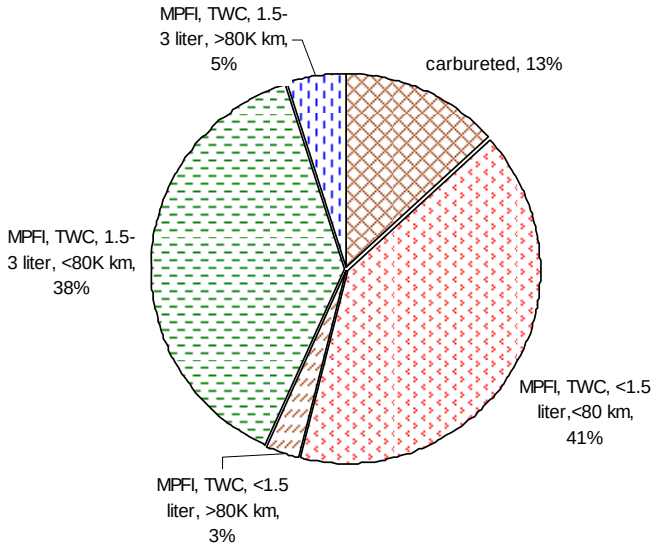
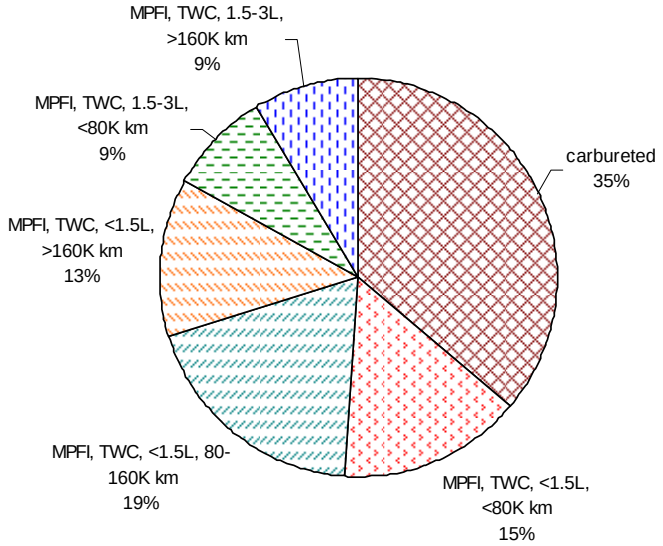


Figure 4-3-b Specific Technology Distribution of Taxis



About two thirds of the trucks surveyed in Tianjin were heavy diesel trucks, and 86% of them had accumulated mileage over 160 km (Figure 4-3-c). Light- and medium-sized diesel trucks accounted for about 16% and 13% of the total trucks and an additional 4% of the trucks used gasoline for fuel. With the exception of light, gasoline-fueled, and low-mileage trucks, most trucks did not have any emission control technology. It is likely that some of the diesel trucks employed some sort of improved combustion technology. Nevertheless, the high mileage, heavy diesel trucks were likely to be a significant source of mobile PM emissions.

Our survey showed that none of the buses in Tianjin had air conditioners. About 14% of buses in Tianjin ran on gasoline, and the rest ran on diesel fuel. The gasoline-fueled buses were equipped with carburetors and had no emissions control at all. Diesel buses had no explicit end-of-emission control technology. The bus fleet in Tianjin was rather old, and over three quarters of the buses had accumulated mileage over than 160,000 km. Given the employed technology and age of and high total daily kilometers driven by public buses, the buses in Tianjin could be a big contributor to total mobile emissions (see Figure 4-3-d).

Figure 4-3-c Specific Technology Distribution of Trucks

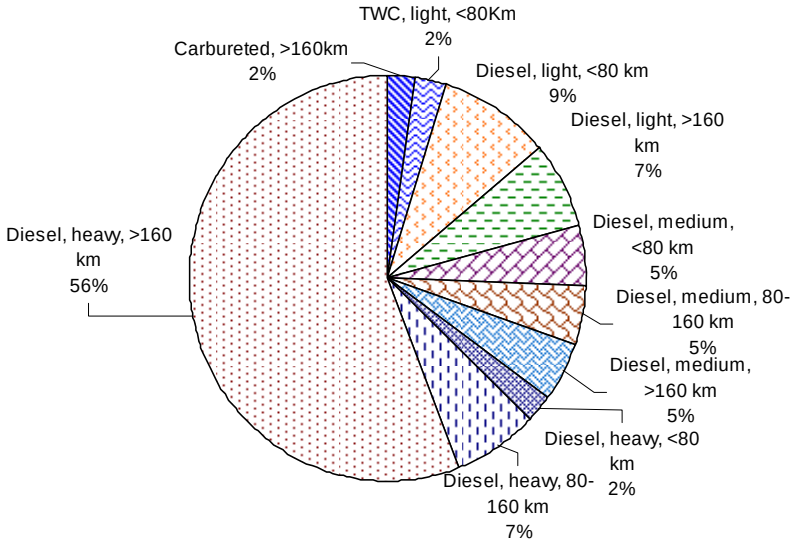
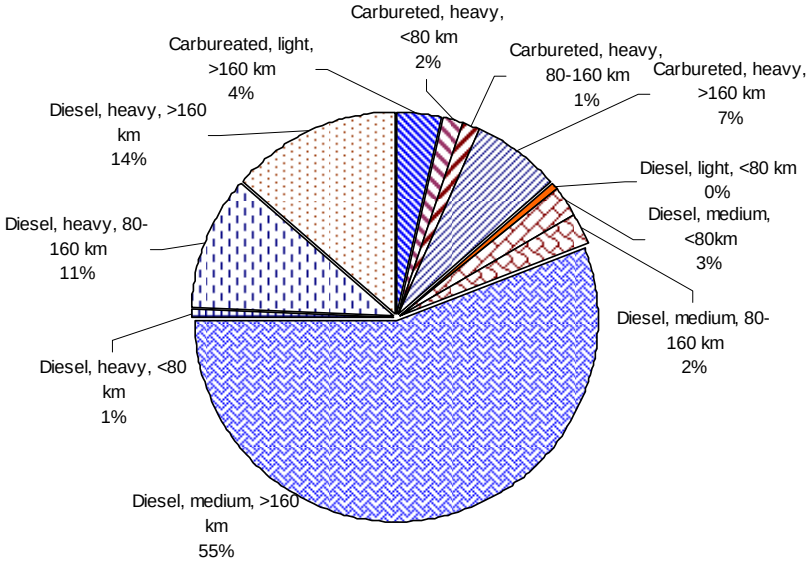


Figure 4-3-d Specific Technology Distribution of Buses

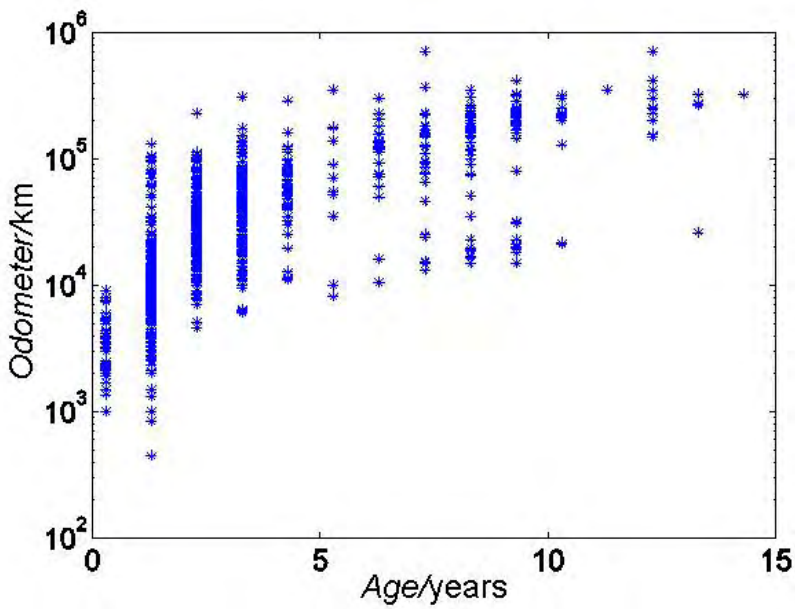


Distance Traveled by Vehicle Categories

Our survey of over 1,200 passenger cars showed that the average age of Tianjin passenger vehicles was about 3.8 years (it is very close to the finding of RSD study). Figure 4-4 illustrates the distribution of passenger vehicle mileage accumulated over time in Tianjin.

A polynomial regression of average mileage versus age led to equation (8). The second derivative of the equation was negative, indicating that unlike the common trend in developed countries, the average mileage driven by passenger cars in Tianjin did 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 technologies over years.

Figure 4-4 Mileage Accumulated by Passenger Vehicles over Time



$$O_P = 608.37A^2 + 11700A \qquad (8)$$

$R^2 = 0.9777$

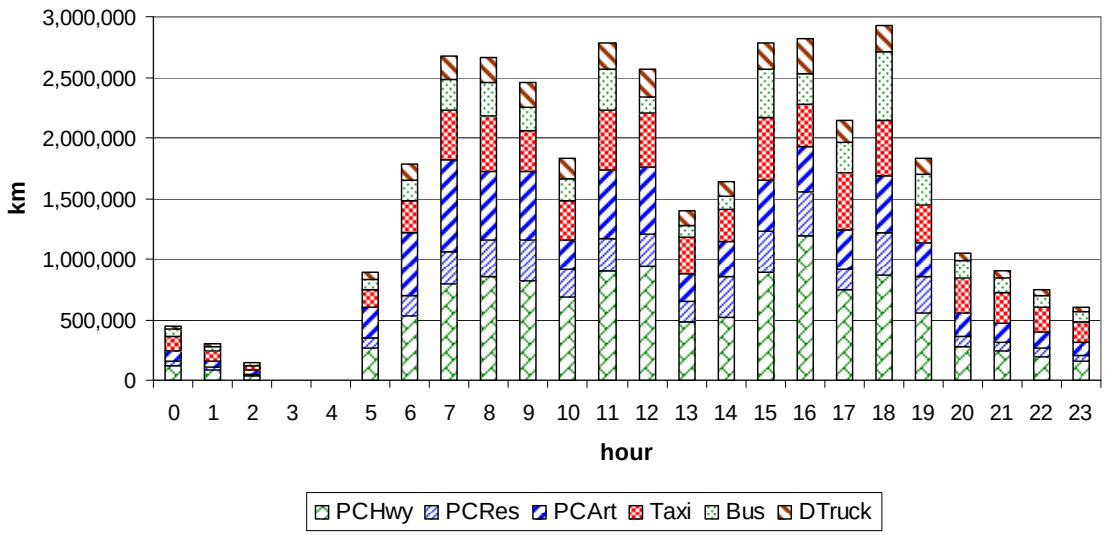
A: average vehicle age ($A \leq 11$)

Combining information of mileage driven per day of a passenger vehicle and the overall number of passenger vehicles registered in Tianjin, we obtained the total distance driven by passenger vehicles in Tianjin. Knowing the share of passenger vehicles in the local traffic composition at different hours (which had been established through videotaping traffic flow), we then deduced the total distance driven by all vehicles at

different hours in Tianjin. Similarly, we calculated the total distance traveled by Tianjin truck fleet and bus fleet.

Figure 4-5 shows total distance traveled by major vehicle categories in Tianjin. At the time of our field work, the total distance traveled by all vehicles in Tianjin totaled about 37.6 million kilometers per day. Passenger vehicles accounted for about 63% of total distance traveled (indicated as lower three blocks in each column), among which about one half of the total passenger vehicle travel occurred on urban expressways, one third on arterial roads, and the rest on residential roads. Taxis and buses accounted for about 18% and 11% of total travel respectively. Trucks accounted for only about 8% of travel in Tianjin. In terms of distribution of total travel over time, it was evident that total vehicle activity increased in the early morning after 5 am and reached the first peak during the morning rush hour (7am to 9 am). Another traffic peak occured around noon and then again in the late afternoon and early evening.

Figure 4-5 Distribution of Distance Traveled by Vehicle Type



Driving Pattern Distribution

Figure 4-6 illustrate the average speed distribution of different type of vehicles during the day (derived from GPS data). Trucks had the highest average velocity (because they were often driven on highways instead of on crowded residential and business district roads). The average speeds on highway, arterial, and residential roads were about 28, 22, and 15 km per hour, which are considerably lower than the average traffic speed in cities of developed countries. On all roads, traffic slowed down during the morning and evening rush hours and at noontime as well. It seems that much effort could be put into improving traffic management to reduce congestion in Tianjin.

Figure 4-6 Average Speed during the Day

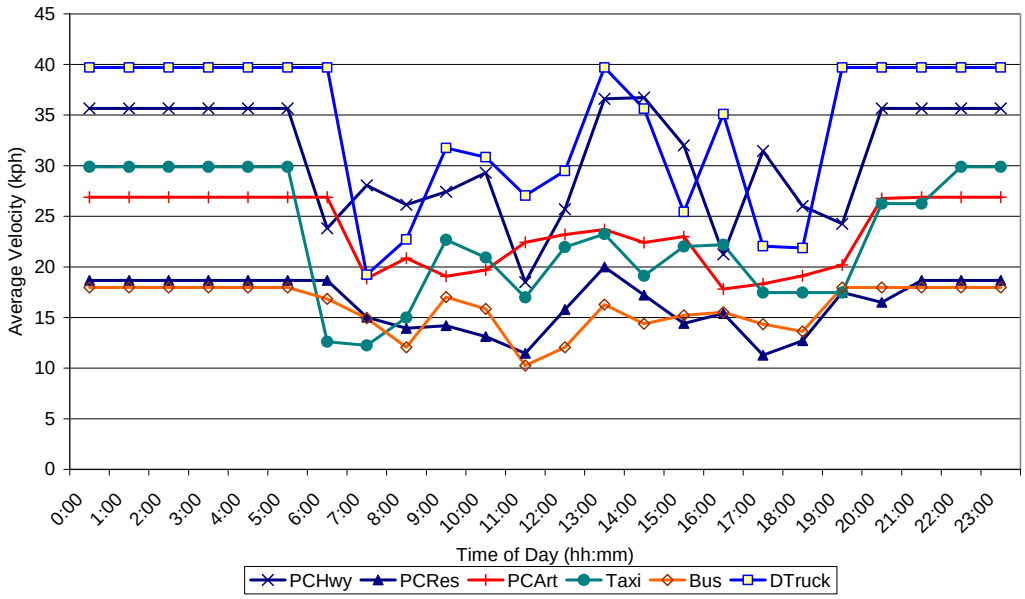


Figure 4-7-a and b show the time distribution of driving conditions (percentage of time spent in each of the 60 power bins) on PC highway and PC arterial roads at 8 am, 12 pm, and 8 pm. Overall, vehicles traveled at a rather low speeds on all types of road, all the time, since the majority of the driving modes in the figures were distributed near bin 12 (the idling state). Only during non-rush-hour times on highway, did we occasionally see aggressive driving with high VSP and engine stress values (see the right corner of Figure 4-7-a).

Figure 4-7-c and d illustrate the distribution of driving patterns on different types of roads at 8 am and 8 pm. During the morning rush hour (8 am), traffic on all three types of roads was slow, and vehicles on the whole spent over 50% time at power bin 12. At 8 pm, more aggressive driving occurred on highway and arterial roads. Vehicles spent less time at power bin 12 and more time at higher power bins.

Figure 4-7-a Distribution of Driving Pattern on PC Highway

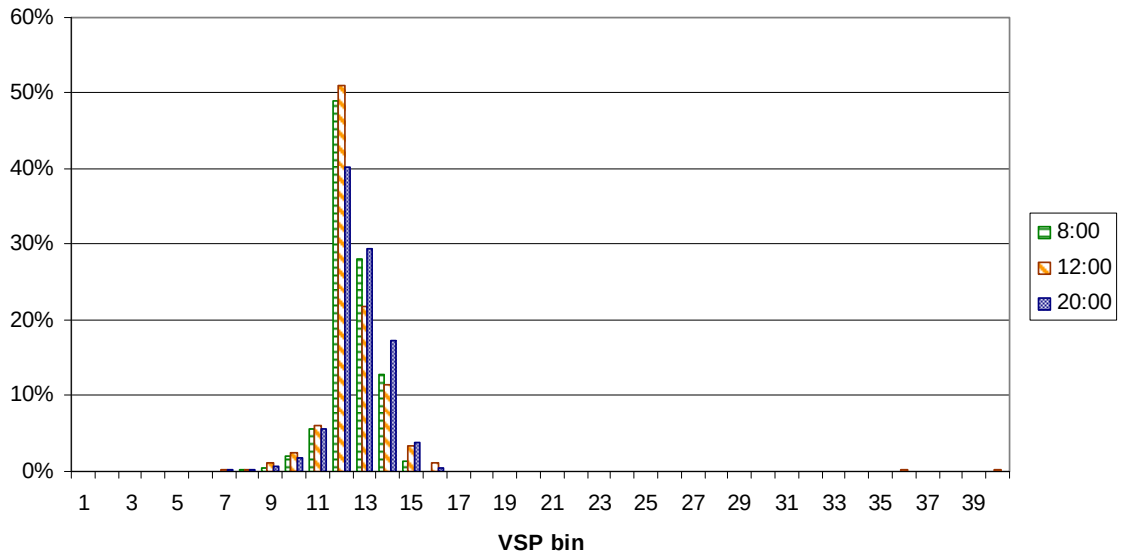


Figure 4-7-b Distribution of Driving Pattern on PC Arterial

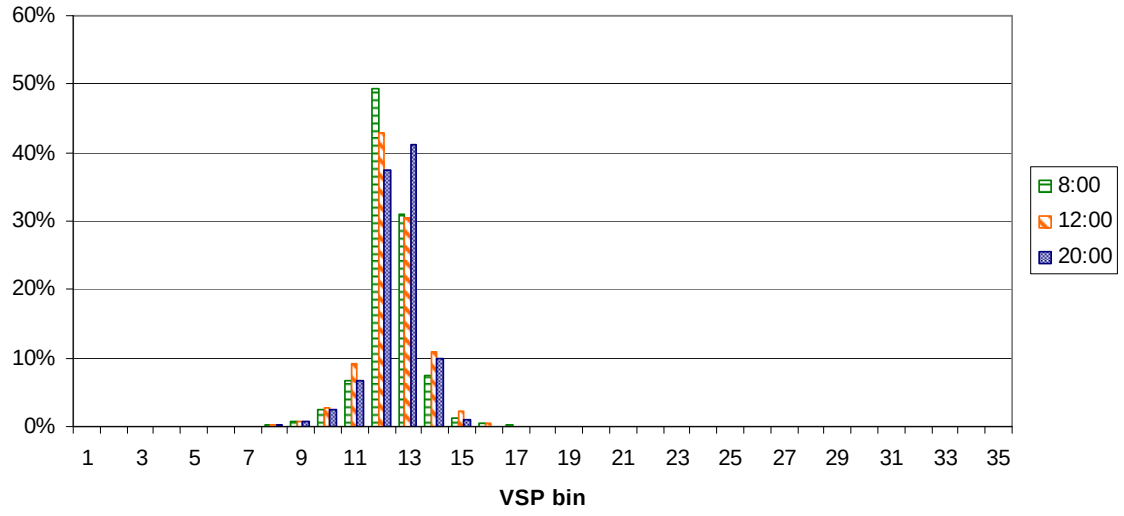


Figure 4-7-c Distribution of Driving Pattern at 8 am

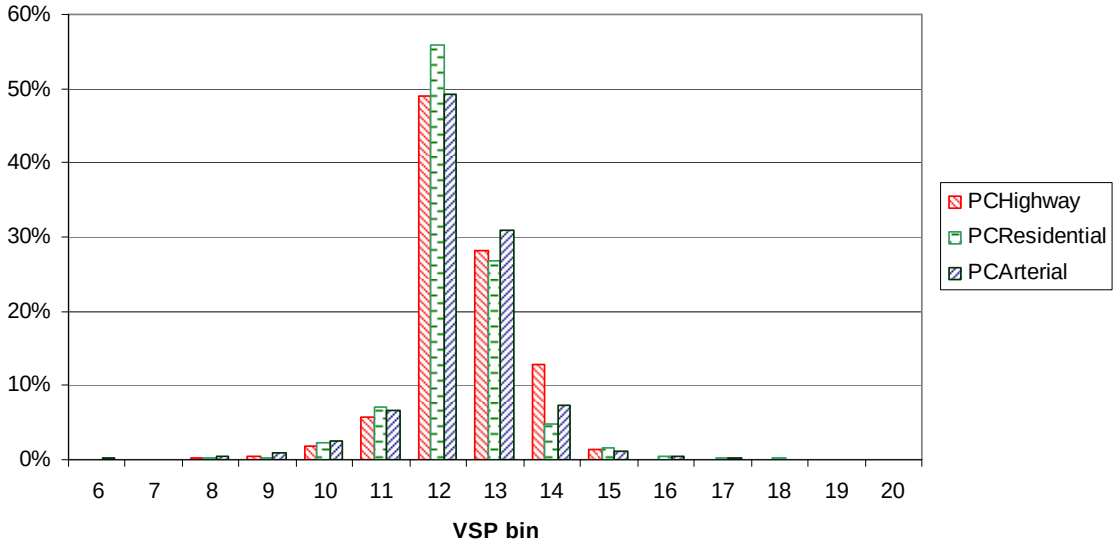
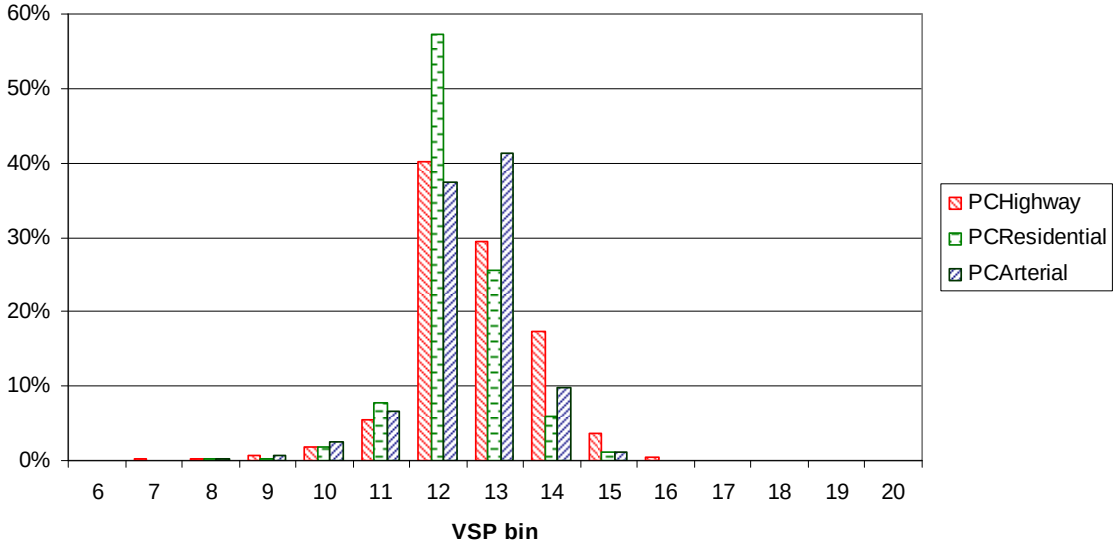


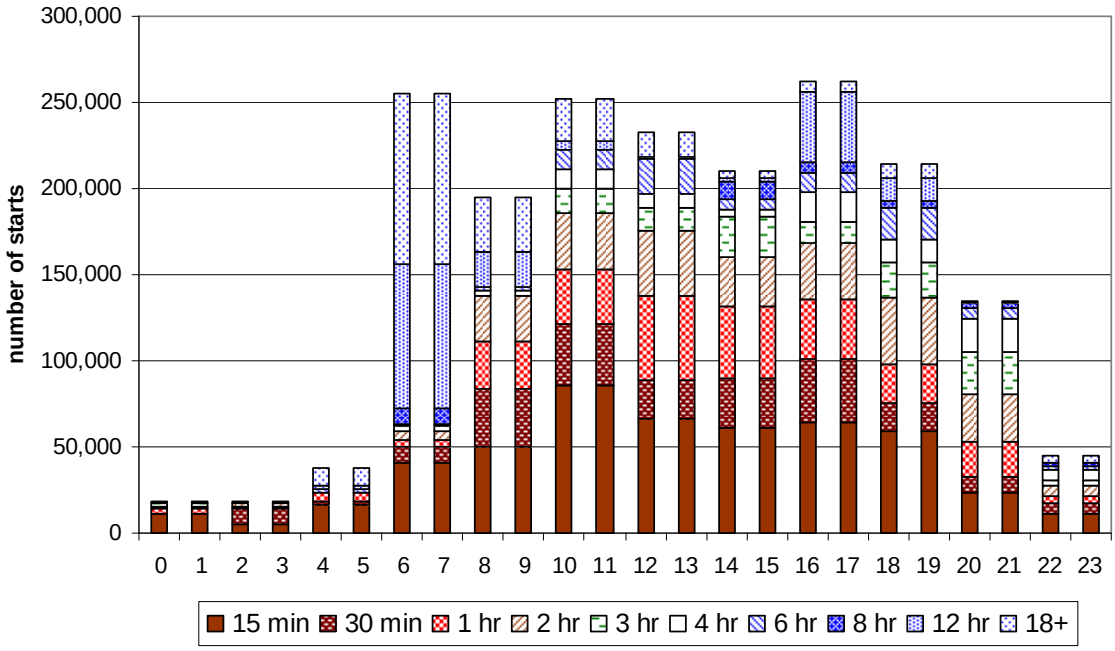
Figure 4-7-d Distribution of Driving Pattern at 8 pm



Start Distribution

Figure 4-8 illustrates the types and the amounts of engine starts per day. In Tianjin, cold starts (the engine of a vehicle was turned off for at least 4 hours) mainly occurred in the early morning (6–8 am), while warm starts were often seen during daytime. Catalysts in a TWC need to be warmed up before they can function properly; thus, more THC and CO emissions are expected to be seen during a cold start. Because cold starts are mainly concentrated in the morning, we anticipated that THC and CO emissions would peak in the morning as well.

Figure 4-8 Start Distribution of Passenger Vehicles



5. Fuel Quality Testing[30]

In addition to vehicle technology itself, fuel quality is the other factor greatly influencing engine performance and emissions. Often, advanced engine technologies and emission control devices need clean-burning fuels to ensure their best performance. For instance, octane number indicates gasoline's ability to resist anti-ignition and thus influences engine performance. Sulfur reduces the efficiency of catalysts and adversely affects heated exhaust gas oxygen sensors. Olefins can boost octane number but they can also lead to gum formation and deposits in the intake system. As a chemically reactive species, olefins that have evaporated into the atmosphere contribute to ozone formation. Their combustion products form toxic dienes. Aromatics are linked to the formation of combustion chamber deposits (which can increase tailpipe emissions such as HC and NO_x). 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 emissions, especially during cold operation and rapid acceleration.

For our study in Tianjin, we decided to obtain information on fuel quality so that we could infer whether the gasoline sold in Tianjin was of a high enough quality for vehicles designed to meet Euro II and Euro III emission standards to function well. In addition, the international vehicle emission model requires us to put in the specifications of gasoline and diesel fuel in a study area.

5.1 Summary of Gasoline Samples

In summer 2005, the research team collected 18 random gasoline samples in Tianjin and had the contents of these samples tested. Prior to that, CATARC had obtained the quality data of other 18 gasoline samples through a different study. Table 5-1 summarizes the statistics of the 36 samples. Most of the samples (30 out of 36) were from stations owned or associated with three companies: Sinopec (17), PetroChina (7), and Shell (4). The other six samples were from stations owned by small private companies or individuals. Gasoline with an octane number of 93 was the most popular grade, so 23 samples branded as 93# gasoline were collected.[31]

The contents (of all 36 samples) that were tested included: research octane number (RON), motor octane number (MON),[32] sulfur, olefins, oxygenates, aromatics,

[30] The CATARC team was in charge of obtaining the fuel samples and commissioning the tests.
[31] In China, different grades of gasoline are labeled and priced based on their research octane number. For example, gasoline with research octane number high than 90 and lower than 93 is labeled as 93# gasoline.
[32] RON correlates best with low speed, mild-knocking conditions while MON is linked with high-temperature knocking conditions and with part-throttle operations. RON is usually higher than MON. In North America, (RON+MON)/2 is used to specify the octane rating.

benzene, manganese, and lead. In addition, the 18 samples collected through the support of this project also had their methanol and iron contents tested.

Table 5-1 Statistics of Gasoline Samples

Owner	*Octane number*	*Sample*
Sinopec	90	3
	93	12
	97	4
PetroChina	90	1
	93	5
	97	1
Shell	90	1
	93	2
	97	1
Other private	90	2
	93	4
Total	90	7
	93	23
	97	6
		36

5.2 Testing Results

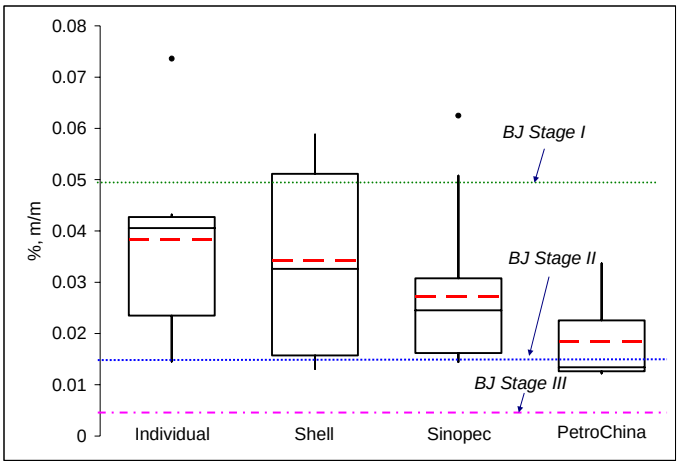
The gasoline samples were tested for both research octane number and motor octane number. Using Beijing standards for gasoline (DB11/238-2004, Stage I, which match Euro II emission standards) as the benchmark, we found that 6 of the 36 samples (2 labeled as 90#, 3 labeled as 93#, and one labeled as 97#) failed to meet the octane number requirements. Five of these samples failed in both RON and combined octane number. One failed only in combined octane number. Three of these failed samples were taken from 3 separate stations owned by PetroChina, 2 were taken from 2 separate stations owned by individuals, and one was taken from a station by Sinopec. In the worst case, the difference between the labeled RON and actual RON was about 5.7, and the difference between required and measured combined octane number was 4.4.

Figure 5-1-a, b, c, d, and e show the average contents of sulfur, olefins, aromatics, benzene, and manganese of the 18 samples by station ownership. As explained in a Chapter 2, the higher and lower borders of the boxes in the chart represent the boundaries within which the middle 50% of data are located. The short solid lines within the boxes are the medians, and the short broken lines represent average values. Vertical lines above and under the boxes indicate the highest and lowest values among the moderate outliers,

and black dots are the extreme outliers.[33] The long, upper dotted line represents the Beijing Stage I requirement for gasoline quality, effective from October 1, 2004 to June 30, 2005; the long, lower dotted line represents Beijing Stage II requirement, effective from July 1, 2005 to the end of 2007. The long, broken lines on some charts are the Stage III requirements, which just took effect at the beginning of 2008. The Beijing limits for benzene concentrations are the same for Stage II and Stage III.

Stage I requirements are the fuel specifications that matched China's national light-duty vehicle emission standards II (equivalent to Euro II), and Stage II requirements are for emission standards III. Similarly, Stage III requirements for fuel quality in Beijing are to ensure that vehicles designed to meet emission standards IV can deliver the environmental performance. Despite the fact that Tianjin did not require local fuel distributors to comply with Beijing fuel quality standards, we believed that mobile fuel retailers in Tianjin were likely to rely on the same providers (i.e., refineries) as those in Beijing, given the proximity of the two cities. Thus, the chemical contents of mobile fuels in Tianjin are likely to be similar to the specifications of the Beijing standards.

Figure 5-1-a Distribution of Sulfur Content by Station Ownership (ppm)



[33] Refer to Chapter 2, footnote 19 on page 25 for the definition of outliers.

Figure 5-1-b Distribution of Olefins Content by Station Ownership

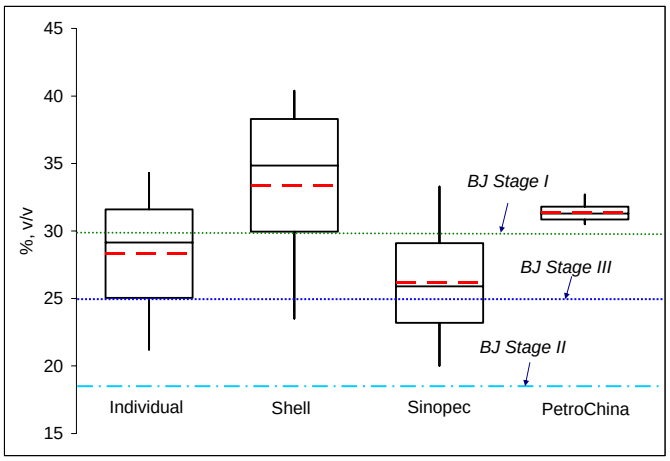


Figure 5-1-c Distribution of Aromatics Content by Station Ownership

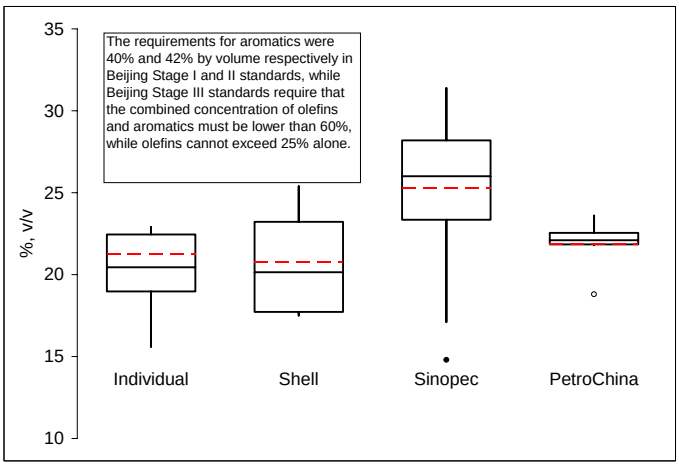


Figure 5-1-d Distribution of Benzene Content by Station Ownership

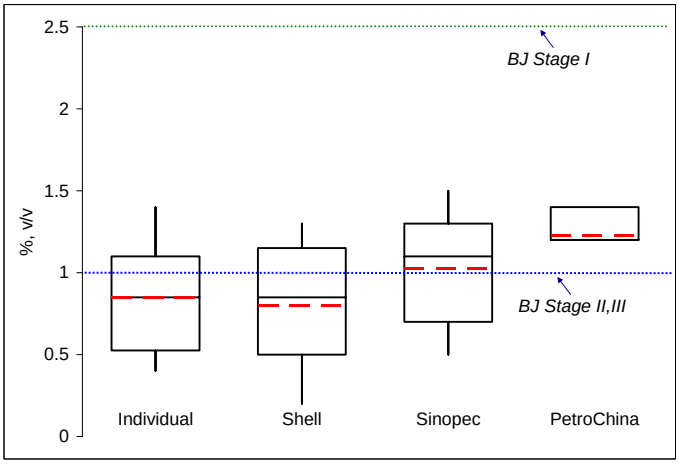
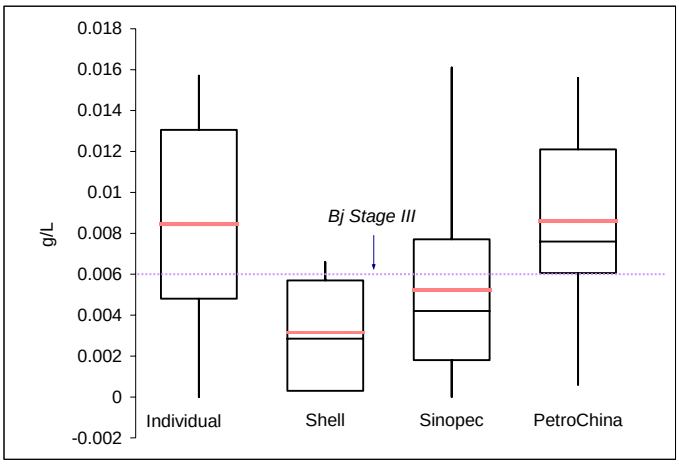


Figure 5-1-e Distribution of Manganese Content by Station Ownership



Fully aware that sulfur in mobile fuels interferes with the proper functioning of catalysts, Beijing has strengthened its requirement for sulfur content of gasoline in local markets dramatically since 2004. The permitted maximum sulfur concentration in gasoline dropped from 800 ppm (national standards) to 500 ppm in October 2004, but dropped again to 150 ppm in July 2005. It then further decreased to 50 ppm at the beginning of 2008.[34] The average sulfur content of the 36 gasoline samples in Tianjin was 280 ppm. Samples from the 7 stations owned by PetroChina had the lowest average sulfur content (185 ppm), while samples from stations owned by individuals had the highest average sulfur content (384 ppm). Four samples had sulfur at a concentration higher than 500 ppm; 9 samples had sulfur at a concentration lower than 150 ppm. Sulfur content of worst sample was as high as 736 ppm.

As of summer 2005, olefins concentration was tested to be high in most of the 36 samples. The average olefins concentration was 28% (by volume). Fifteen of the samples could not meet the Beijing I requirement for olefins concentration (30%), and none could meet the Beijing II requirement for olefins (18%).[35] Samples taken from Sinopec stations seemed to have slightly lower olefins concentration than samples from stations owned by other companies.

Beijing's requirements on aromatics[36] has been relatively relaxed (40% and 42% by volume respectively for Stage I and II), and all the samples met the 40% concentration requirement set in 2004 standards, as shown in Figure 5-1-c.

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[34] The sulfur content requirement for diesel fuel was 500 ppm from October 1, 2004 to June 30, 2005 and has been 350 ppm since July 1, 2005. Beijing further dropped it to 50 ppm starting from January 1, 2008.

[35] The Stage III fuel standards from 2008 onwards contain the same requirement for olefins as the current one.

[36] Although aromatics increase engine deposit and tailpipe emissions, they are good octane components and high-energy density fuel molecules. Olefins and aromatics concentrations in gasoline are negatively correlated, pushing down one often leads to an increase in the other. Therefore, the Beijing Stage III standards give a combined concentration requirement for olefins and aromatics (60%).

Benzene concentration varies significantly among the 36 samples, despite the fact that the average value is close to the Beijing Stage II requirement (1% by volume). Twenty-one samples could not have met the Beijing Stage II standard. Shell stations on average had gasoline with the lowest benzene concentration while PetroChina stations had gasoline with relatively high benzene content.

Manganese in gasoline has not been regulated in China until now. Beijing did not set a limit for manganese in its Stage I and II standards, but it included one (0.006 gram per liter) in its Stage III standards. The average concentration of manganese of the 36 samples (0.0063 g/L) was close to the future limit, but 15 samples contained manganese at a concentration higher than 0.006 g/L. It seemed that retail stations under Shell and Sinopec had gasoline with lower manganese concentrations than those under PetroChina or individual owners.

All our samples met requirements for other regulated contents, such as lead and iron concentrations and evaporative pressure.

We examined fuel specifications by fuel octane number as labeled at the pump. The results are reflected in Figure 5-2-a, b, c, d, and e. Premium gasoline with high octane number (labeled as 97#) had much lower sulfur level than the other two kinds of gasoline (180 ppm vs. 300 ppm). It was not surprising that 97# gasoline had high concentrations of aromatics and manganese given that both types of compounds can boost octane number. Both 93# and 97# gasoline had benzene concentrations that were higher than the Beijing Stage II requirement.

Figure 5-2-a Distribution of Sulfur Content by RON

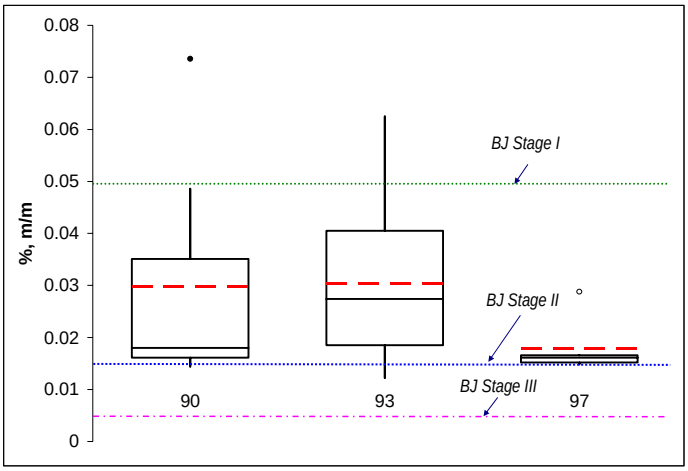


Figure 5-2-b Distribution of Olefins Content by RON

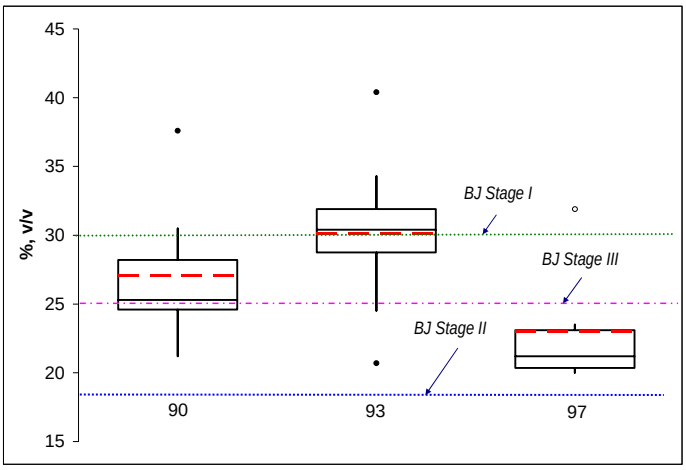


Figure 5-2-c Distribution of Aromatics Content by RON

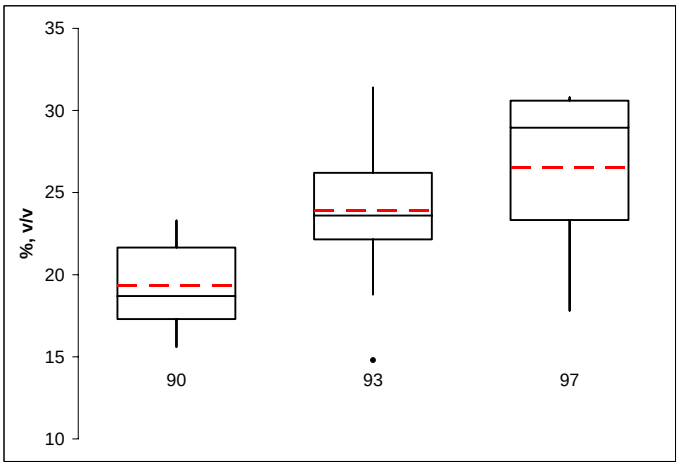


Figure 5-2-d Distribution of Benzene Content by RON

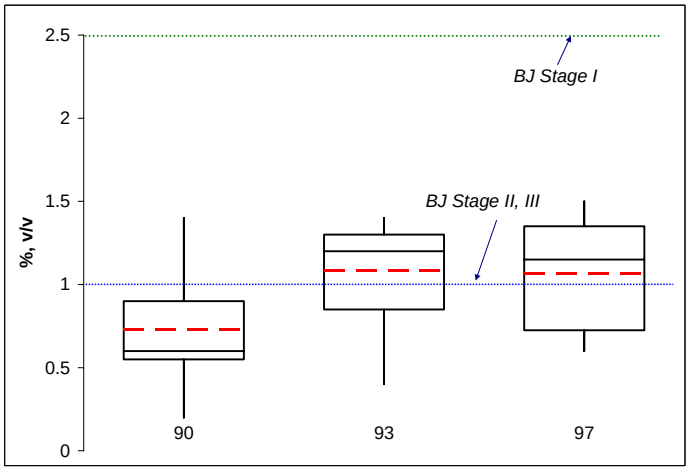
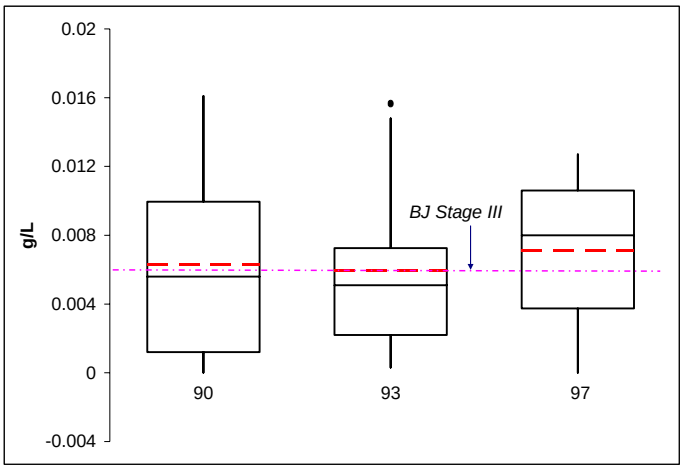


Figure 5-2-e Distribution of Manganese Content by RON



6. Using IVE Model to Estimate Mobile Emission Inventory

In Chapters 3 and 4, we explained what information was essential for estimating emission inventory with the IVE model, i.e., vehicle emission factors, local fleet composition, vehicle technology distribution, and vehicle use. The original data collected in the field were cleaned, processed, and converted into a format that can be read by the IVE model.

In this chapter, we first estimate mobile total emissions by vehicle category and time of day using the default base emission factors of the model. We then provide the correction factors for the base emissions of light-duty vehicles and compare the difference between two estimations (using corrected and uncorrected base emission factors). Next, we explore the impacts of climate conditions on vehicle emissions. Last, we estimate the emission reduction benefits of potential intervening policies.

6.1 Emissions Estimation Using Default Base Emission Factors

After running the IVE model with Tianjin fleet files (they include specific technology distributions for passenger cars, taxis, trucks, and buses) and location files (they include information such as distance traveled 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), we obtained emissions by each type of vehicle for every hour of the day. The hourly weather conditions (temperature and relative humidity) of March 30, 2007 were used.[37] Gasoline quality tests show that gasoline sold in Tianjin had the following attributes: the sulfur concentration was about 300 ppm, the benzene concentration was about 1.5%, and the oxygenate concentration was about 1%. Thus, we decided that the fuel quality in Tianjin was moderate.

Using the default values of base emission factors, the IVE model estimated that the Tianjin fleet generated about 683 tons of CO, 73 tons of VOC, 165 tons of NO_x, 2 tons of SO_x, 6 tons of PM, and 14.7 thousand tons of CO_2 on a typical day in early spring. The total amount of vehicular emissions and the emission factors of Tianjin fleet are summarized in Table 6-1.

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

Table 6-1 Total Vehicle Emissions and Emission Factors in Tianjin (Using Default BEF in IVE)

	Total Emissions (tons/day)	*Emission Factor* (g/km)*
CO	683	18.12
VOC w/evaporation	73	1.94
NO_x	165	4.38
SO_x	2	0.05
PM	6	0.17
CO_2	14,672	389.79

Note: * Emission factors were obtained by dividing total emissions by the total distance travel per day (37,640,384 km).

Figure 6-1 illustrates the emissions contribution by different types of vehicles in the city. As shown in the figure, in spring 2007, light-duty vehicles together contributed to 82 percent of all distance traveled (passenger cars accounted for 64% and taxis accounted for 18% of all distance traveled) in Tianjin, buses and trucks contributed to 11% and 8% of total distance traveled respectively. The contributions of a certain type of vehicle to total distance traveled were different from their contributions to total vehicular emissions. In particular, taxis accounted for high shares of VOC and CO emissions (33% and 25%); buses accounted for significantly high shares of PM and NO_x emissions (53% and 54%); and trucks also accounted for significant high shares of PM and NO_x emissions (44% and 25%). The contribution to PM emissions by light-duty gasoline vehicles in Tianjin is negligible.

Figure 6-1 Emission Contributions by Vehicle Type

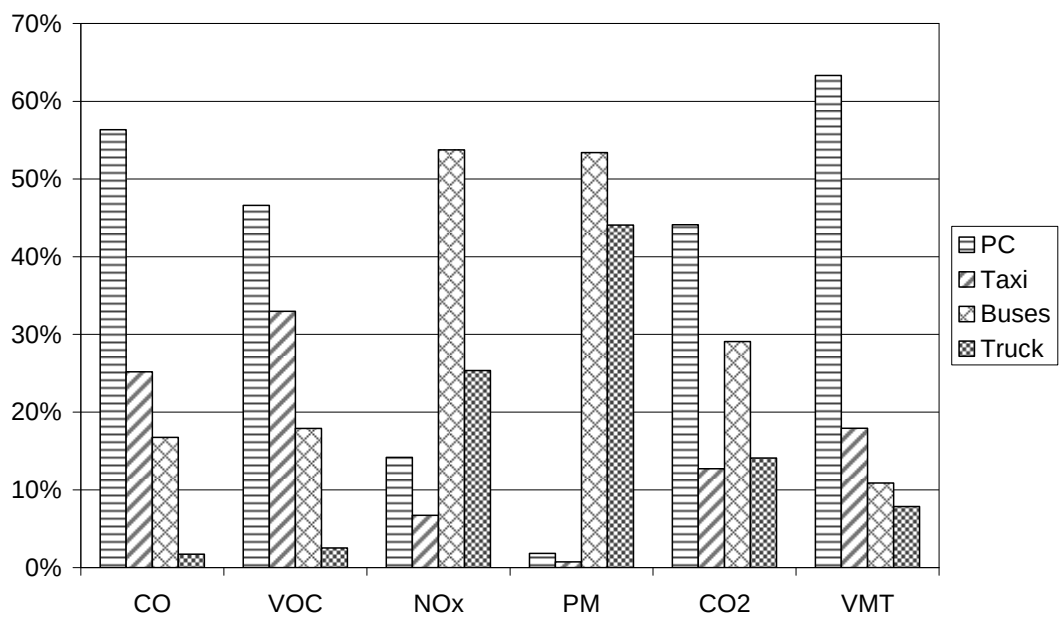


Figure 6-2-a, b, c, and d show the trends of vehicular CO, NO_x, VOC, and PM emissions during a spring day. There were three emissions peaks: early in the morning (6–8 am), noon (11 am to noon), and late afternoon to early evening (3–7 pm). These peaks were caused by high vehicle use during those hours. Start emissions of CO and VOC contributed more to total CO and VOC emissions than those of NO_x and PM. Start emissions CO and VOC peaked in the early morning when most of the starts were cold starts. This was because light-duty vehicles accounted for majority of CO and VOC emissions; for LDVs with functioning three-way catalytic converters, cold start emissions often account for a large share of total emissions.

Figure 6-2-a CO Emissions During a Spring Day (without BEF Correction)

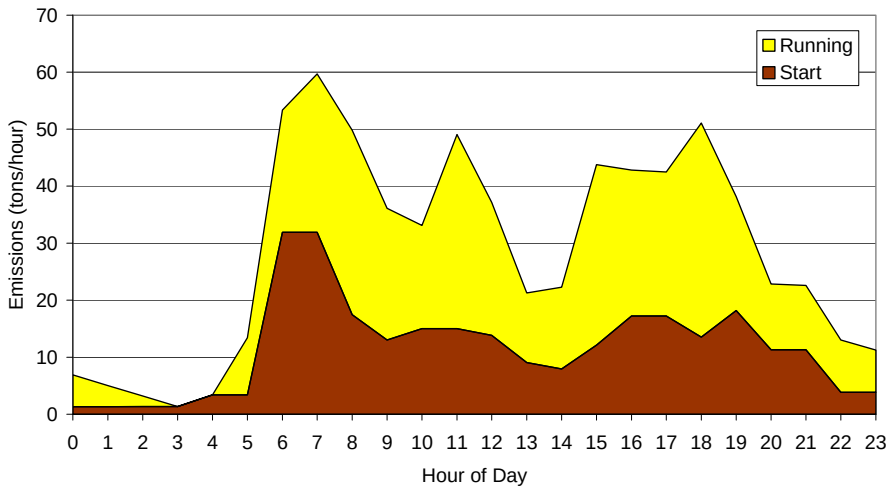


Figure 6-2-b NOx Emissions During a Spring Day (without BEF Correction)

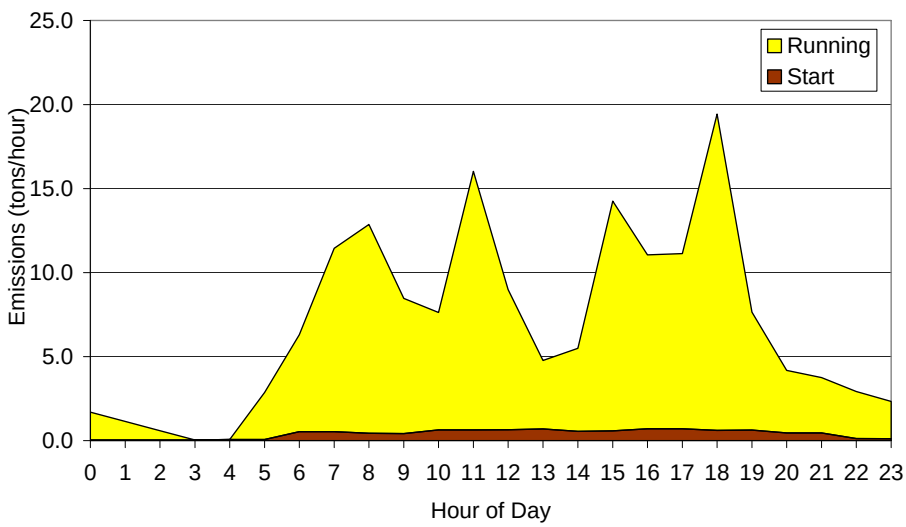


Figure 6-3-c VOC Emissions During a Day (without BEF Correction)

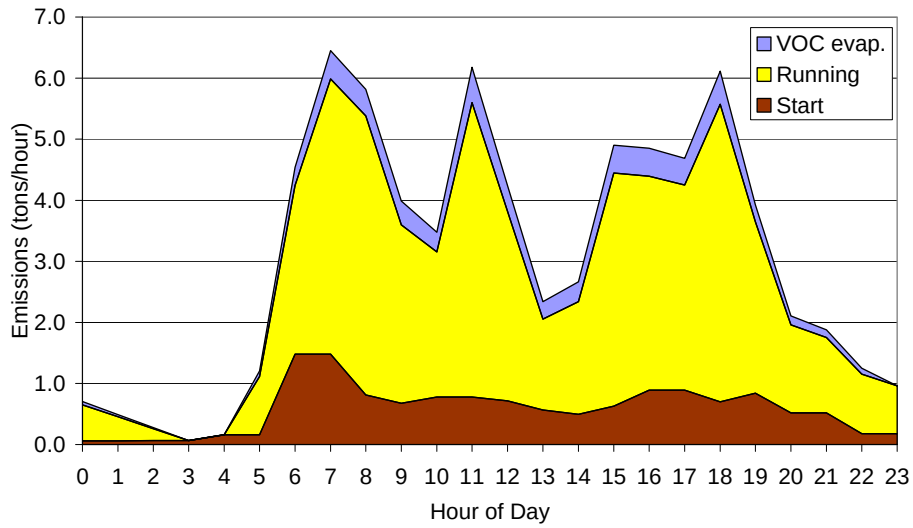
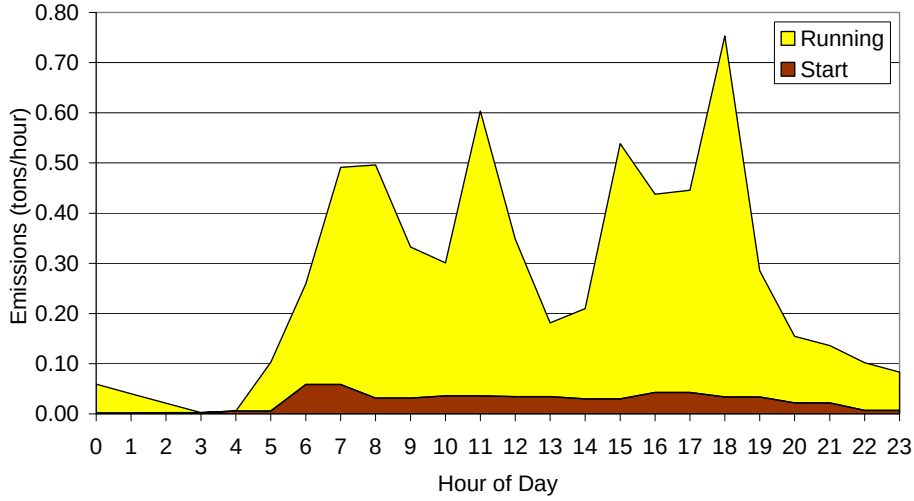


Figure 6-2-d PM Emissions during a Spring Day (without BEF Correction)



6.2 Base Emission Correction Factors (for LDV only)

The most accurate estimation of vehicular emission inventory requires the establishment of the relationships between emission rate and power-bin for each type of local vehicle. However, because of the road and traffic conditions in Tianjin, we could not obtain driving conditions of high engine stress and high vehicle specific power when we did on-road vehicle emissions testing with PEMS. Furthermore, when the limited numbers of tested vehicles were grouped into subcategories, there were often only a very few vehicles left in each technology class. A very small sample may not accurately

reflect the average emissions of the technology groups studied. Thus, the emissions–power bin relationships established with a limited number of emission measurements and within a limited range of driving conditions in Tianjin were far from desirable. To address this issue, we reasoned that it was more appropriate to rely on the emissions–power bin relations built upon a large amount of vehicle emissions data under a complete range of driving conditions. The emission measurements of the sampled local vehicles were processed and used to modify the emissions–power bin relations built in the IVE model. (Refer to Section 3.3 for the steps for correcting base emission factors.)

Table 6-2 shows the average running emissions of the 16 vehicle subcategories mostly seen in Tianjin if they were run on a Federal Testing Protocol (FTP) cycle (see footnote 22 for the cycle), based on the default emissions–power bin relationships embedded in the IVE model. Comparing the values in Table 3-4 and Table 6-2, we obtained the base emission correction factors for these vehicle subcategories (shown in Table 6-3). If a correction factor is greater than 1, the actual emission factor of a local vehicle subcategory is higher than the IVE value and vice versa. If a correction factor is equal to1, we can deduce that the actual emission factor is about the same as the default value in the IVE model.

Table 6-2 Average Running Emissions of 16 Vehicle Subcategories on a FTP Cycle (Derived with the Emissions–power bin Relations in the IVE model)

IVE Class	*Vehicle category description*	*Number*	*CO (g/km)*	*CO_2 (g/km)*	*NO_2 (g/km)*	*THC (g/km)*
0	Carburetor, 1.5-3.0 L, <80 km	2	22.25	239.00	2.00	3.26
2	Carburetor, 1.5-3.0 L, >160 km	6	34.22	215.22	2.15	5.16
5	Carburetor, >3.0 L, >160 km	3	34.22	261.96	2.15	5.16
31	Carburetor, TWC, 1.5-3.0 L, 80-160 km	1	13.69	305.74	1.96	0.77
117	MPFI, TWC, <1.5 L, < 80 km	22	1.50	188.14	0.29	0.08
118	MPFI, TWC, <1.5 L, 80-160 km	3	2.27	186.60	0.37	0.20
119	MPFI, TWC, <1.5 L, >160 km	3	6.94	178.84	0.52	0.36
120	MPFI, TWC, 1.5-3.0 L, < 80 km	11	1.06	238.98	0.58	0.09
121	MPFI, TWC, 1.5-3.0 L, 80-160 km	7	5.02	232.25	0.67	0.28
122	MPFI, TWC, 1.5-3.0 liter, >160 km	2	10.94	222.14	0.80	0.58
126	MPFI, TWC, EGR, <1.5 L, < 80 km	1	1.50	188.14	0.20	0.08
129	MPFI, TWC, EGR, 1.5-3.0 L, < 80 km	2	1.06	238.98	0.41	0.09
130	MPFI, TWC, EGR, 1.5-3.0 L, 80-160 km	1	5.02	232.25	0.47	0.28
131	MPFI, TWC, EGR, 1.5-3.0 L, >160 km	3	10.94	222.14	0.56	0.58
133	MPFI, TWC, EGR, >1.5-3.0 L, 80-160 km	1	6.13	302.93	0.57	0.35
134	MPFI, TWC, EGR, >1.5-3.0 L, >160 km	2	12.43	291.85	0.68	0.71

Table 6-3 Correction Factors for Running Emissions

IVE Class	*Vehicle category description*	*IVECF CO*	*IVECF CO_2*	*IVECF NO_2*	*IVECF THC*
0	Carburetor, 1.5-3.0 liters, <80 km	1.3	0.6	0.6	1.4
2	Carburetor, 1.5-3.0 liters, >160 km	0.9	0.7	0.7	0.8
5	Carburetor, >3.0 liters, >160 km	0.8	0.7	1.2	1.0
31	Carburetor, TWC, 1.5-3.0 liters, 80-160 km	2.8	0.7	1.3	3.1
117	MPFI, TWC, <1.5 liters, <80 km	4.4	0.9	1.6	11.0
118	MPFI, TWC, <1.5 liters, 80-160 km	2.6	0.9	2.0	1.8
119	MPFI, TWC, <1.5 liters, >160 km	0.5	0.8	1.1	1.4
120	MPFI, TWC, 1.5-3.0 liters, <80 km	6.0	0.9	0.6	6.1
121	MPFI, TWC, 1.5-3.0 liters, 80-160 km	1.0	0.9	0.9	1.2
122	MPFI, TWC, 1.5-3.0 liter, >160 km	0.3	0.9	0.7	0.7
126	MPFI, TWC, EGR, <1.5 liters, <80 km	0.6	0.9	0.1	1.3
129	MPFI, TWC, EGR, 1.5-3.0 liters, <80 km	3.1	1.1	1.0	3.2
130	MPFI, TWC, EGR, 1.5-3.0 liters, 80-160 km	2.7	1.2	1.6	2.4
131	MPFI, TWC, EGR, 1.5-3.0 liters, >160 km	0.4	1.2	0.5	0.2
133	MPFI, TWC, EGR, >3.0 liters, 80-160 km	0.2	0.7	0.3	0.3
134	MPFI, TWC, EGR, >3.0 liters, >160 km	0.8	0.9	2.0	3.7

As shown in Table 6-3, without correction, the IVE model seems to overestimate CO_2 running emissions in general (i.e., IVE correction factors are less than 1), with the exception of medium- and large-sized vehicles equipped with EGR. The IVE model seems to significantly underestimate CO and THC emissions of low-mileage vehicles equipped with multi-point fuel injection (MPFI) and three-way catalytic converter (TWC) since the average correction factor is as high as 6. The model somewhat underestimates the CO and THC emissions of medium-mileage vehicles equipped with MPFI and TWC. In contrast, the model seems to underestimate CO and THC emissions of high-mileage vehicles with MPFI and TWC.

Because some of the vehicle technology subcategories included only very few samples, to increase the confidence in our results, we felt it was necessary to combine certain vehicle technology categories when estimating correction factors for base emission factors. Emission characteristics (technology group and possible deterioration over time) were the two main considerations when we combined vehicle subcategories. We also decided not to correct base emission factors of a technology group at all if there were too few vehicles tested. (Recall the discussions on the desirable sample size and confidence interval in Sections 3.2 and 3.4).

The combined results of running emissions are shown in the left half of Table 6-5. We put all carbureted vehicles in one group, vehicles with MPFI and TWC but with different mileages in three groups, and vehicles with MPFI and TWC and EGR in another group. Within a combined group, if the correction trends of different subcategories were similar (i.e., all values were greater than 1 or less than 1), we then calculated the weighted correction factors; if the correction trends were inconsistent (some values were

greater than 1 while some were less than 1), we did not change the base emission factors (i.e., correction factors were 1).

To calculate the correction factors for start emissions, we grouped vehicles into two big categories: those with carburetors and those with MPFI. The average start emissions were calculated for these two big groups and then compared with start emission values in the IVE model. The results are shown in Table 6-4. It is clear that without correction, the IVE model would significantly overestimate all the start emissions from carbureted vehicles. It would also tend to overestimate CO_2 and NO_x start emissions for vehicles with MPFI, but to underestimate CO and THC start emissions of these vehicles.

Table 6-4 Correction Factors for Start Emissions

Pollutant	*Technology*	*Measured Cold Start*	*IVE Cold Start*	*IVE CF*
CO	Carburetor	14	156	0.1
	Fuel Injection	39	36	1.1
CO_2	Carburetor	49	152	0.3
	Fuel Injection	69	170	0.4
NO_2	Carburetor	-0.1	3.3	0.0
	Fuel Injection	1.0	1.4	0.7
THC	Carburetor	3.0	10.8	0.3
	Fuel Injection	4.1	3.2	1.3

Correction factors for both running emissions and start emissions are listed in Table 6-5 by vehicle technology groups.

Table 6-5 Combined Base Emission Correction Factors

		IVE Correction Factor Running Emission factor				*IVE Correction Factor Cold Start Emission*			
		CO	*CO_2*	*NO_2*	*THC*	*CO*	*CO_2*	*NO_2*	*THC*
Carbureted vehicles									
all	0,2,5	1	0.7	1	1	0.1	0.3	0	0.3
MPFI with TWC									
low-mileage	117, 120	4.9	0.9	1.0	9.4	1.1	0.4	0.3	1.3
Medium	118, 121	1.5	0.9	1.5	1.4	1.1	0.4	0.3	1.3
High	119, 122	0.4	0.8	1.0	1.0	1.1	0.4	0.3	1.3
MPFI with TWC and EGR									
all	126-134	1	1	1	1	1.1	0.4	0.3	1.3

6.3 Emissions Estimation after Correcting BEF for LDV

We obtained corrected emissions for light-duty vehicles by running the IVE model with the input of base emission correction factors. Figure 6-3 and 6-4 illustrate the changes in the total emission of light-duty vehicles after the base emission factors were corrected. With BEF correction, the total CO emissions of passenger cars on highway (PC highway fleet) increased by about 52 tons per day (i.e., from 66 tons to 118 tons per day), an increase of 80%; while CO emissions of other LDV fleets (PC Residential, PC Arterial, and Taxi) decreased by 9%, 4%, and 15% respectively (see figure 6-4). VOC emissions from the four types of LDV fleets all increased — PC Highway, PC residential, and PC arterial fleets increased by about 6, 2, and 2 tons per day (64%, 19%, and 16%) respectively. Interestingly, NO_x emissions from PC residential, PC arterial, and taxi fleets decreased by 36%, 40%, and 10% respectively. Despite the fact that the CO_2 emissions of all LDV fleets seemed to decrease by a large quantity with the correction of base emission factors, the percentage of change was actually rather small—only about 1 to 2 %.

Figure 6-3 Comparing Emissions of LDVs with/without BEF Correction

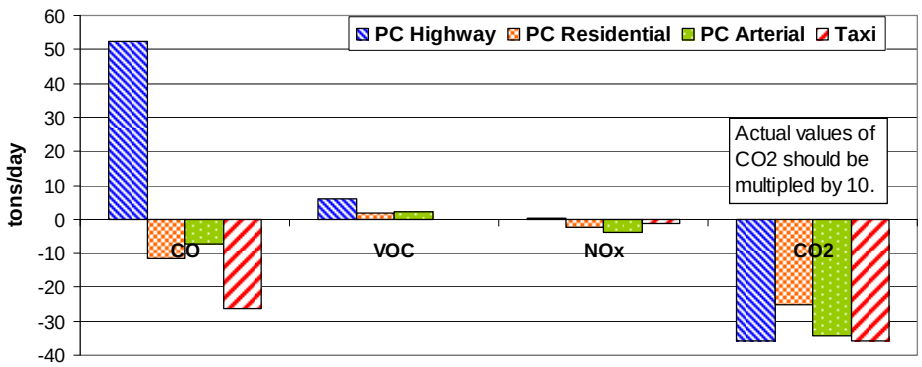
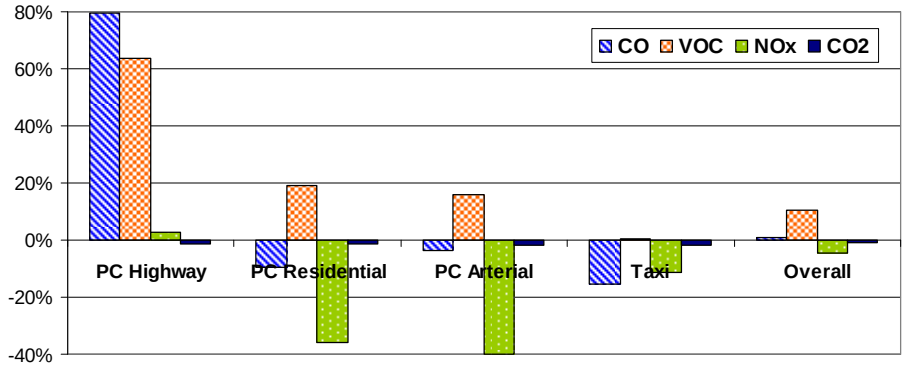
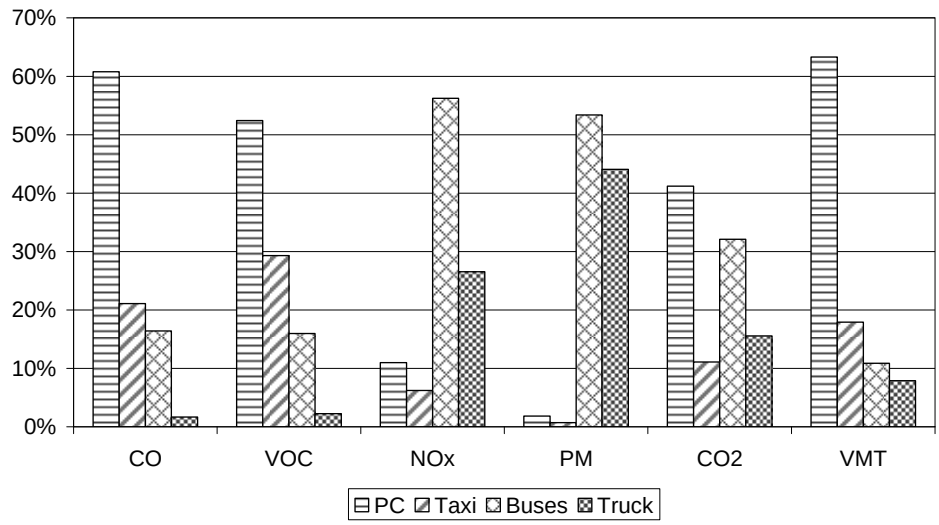


Figure 6-4 Emission Changes of LDVs with/without BEF Correction



After having corrected the base emission factors for LDVs, we recalculated the contributions to total vehicle emissions by different types of vehicles (see Figure 6-5). Comparing Figure 6-1 with 6-5, one can see that the contributions of the Tianjin PC fleet to total mobile CO and VOC emissions increased by 5 and 7 %; the contributions of the PC fleet to total mobile NO_x and CO_2 emissions both decreased by 3 percent. The contributions of the taxi fleet to the total vehicular CO and VOC emissions dropped by about 4 % respectively (The changes of its contributions to total vehicular NO_x and PM emissions were negligible).

Figure 6-5 Emission Contributions by Vehicle Type (with BEF correction)



After correcting the base emission factors for LDVs, we noticed the following changes of total daily vehicular emissions: VOC emissions increased the most—by 10 percent (or 84 tons in total), while total daily NO_x emissions (158 tons) decreased by about 5 %. Total daily CO emissions (690 tons) increased by 1 %, while total daily CO2 emission (13,360 tons) decreased by 1 %.

Figure 6-6-a, b, c, and d show hourly vehicle emissions of the Tianjin fleet on an early spring day (meteorological data for March 30, 2007 were used). Comparing these charts with Figure 6-2-a, b, c, and d, one can see that the overall trends of daily vehicle emissions remained the same. The contributions of start emissions of CO and VOC to total emissions decreased considerably (by 9 and 8 % respectively), and the contribution of start emissions of NO_x to total NO_x emissions also decreased somewhat (a net decrease of 2 %). In particular, with the correction of BEF, start emissions of CO and VOC attributed much less to total CO and VOC emissions in the early morning (6–8 am). At 6 am, the share of start CO emission to total CO emissions decreased from more than one half to one third; and that of VOC to total VOC emissions decreased from one third to one fifth.

Figure 6-6-a CO Emissions during a Spring Day (BEF corrected for LDV)

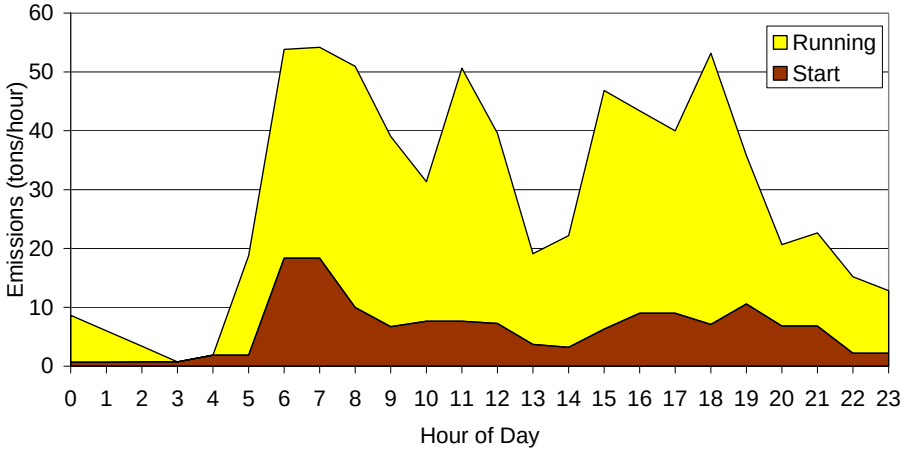


Figure 6-6-b NOx Emissions during a Spring Day (BEF corrected for LDV)

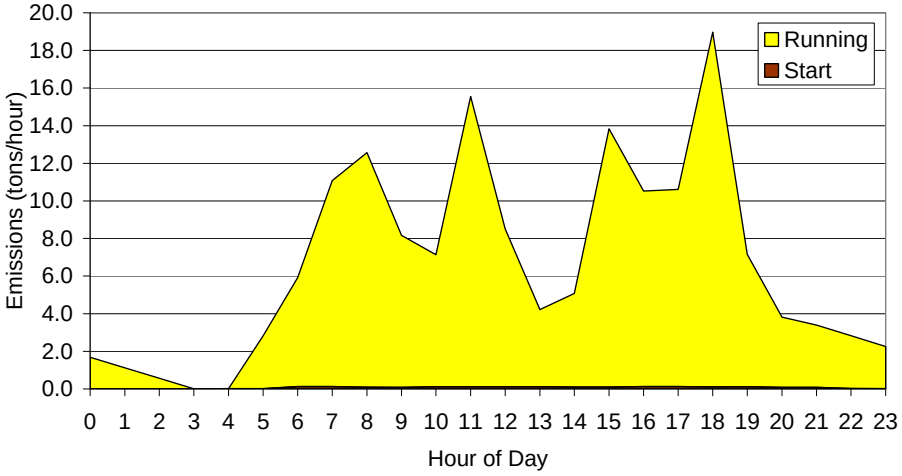


Figure 6-6-c VOC Emissions during a Spring Day (BEF corrected for LDV)

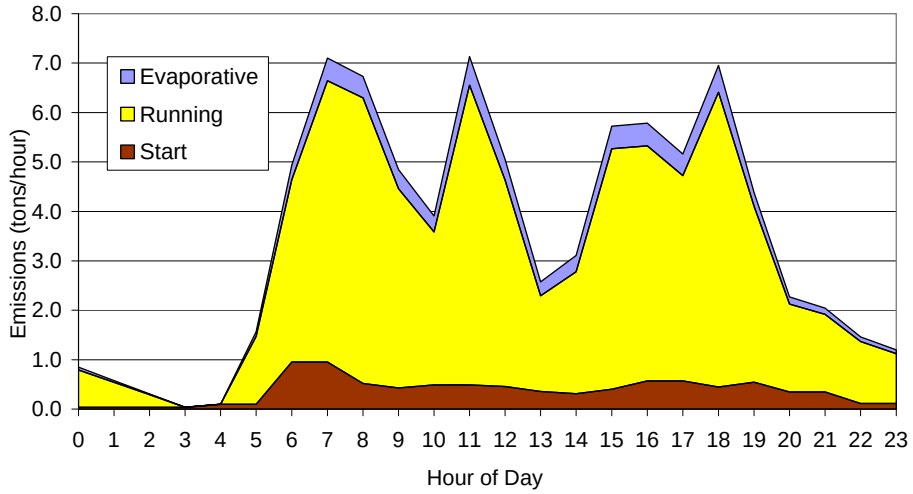
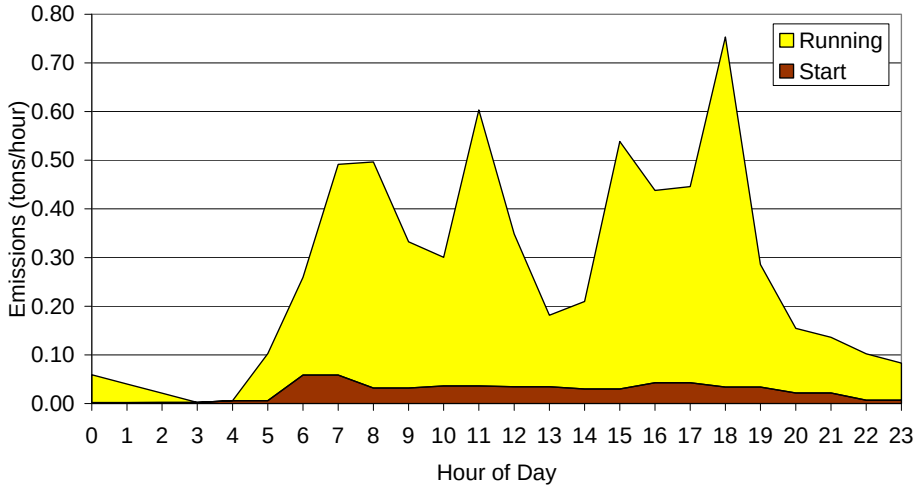


Figure 6-6-d PM Emissions during a Spring Day (BEF corrected for LDV)



6.4 Vehicle Emissions in Different Seasons

To understand the impacts of climate conditions on vehicle emissions, we estimated emissions of the same fleet on a winter and a summer day, in addition to the emissions on a spring day. We kept the inputs of fleet composition, traffic flow, vehicle start, and travel patterns constant while adjusting the different seasons. Figure 6-7-a and b show the average hourly temperature and humidity of July 30, 2006, January 10, 2007, and March 30, 2007. During a hot summer day, the daily temperature in Tianjin ranged between 26 and 33°C; while on a cold winter day, daily temperature could drop below 0°C. Daily temperature varies most dramatically in the spring when the difference between high and low temperatures can be as great as15°C. Located on the coast of north China, Tianjin has high humidity during the summer and winter, although the humidity can be low on spring afternoons.

Figure 6-7-a Hourly Temperature in Different Seasons

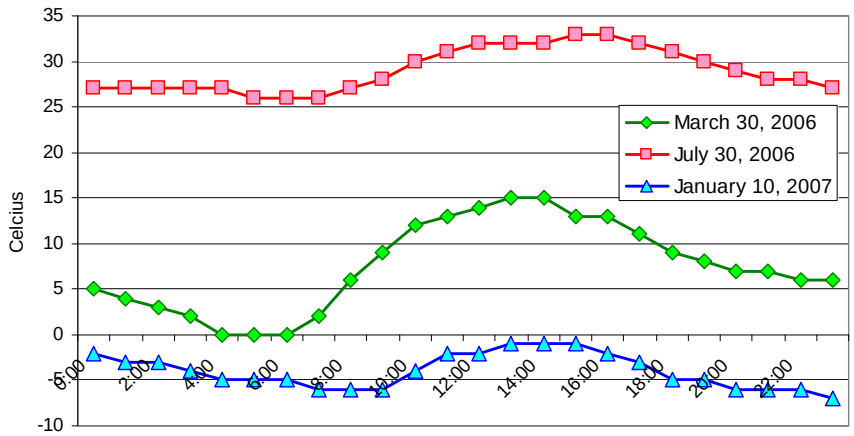
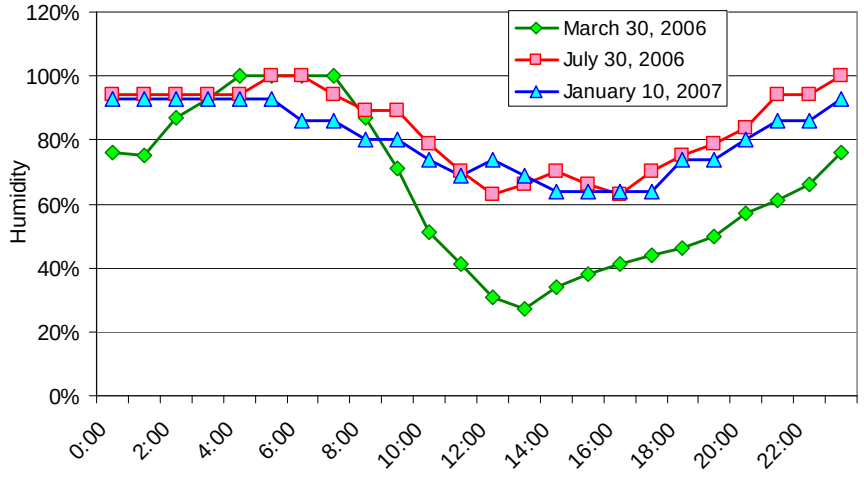
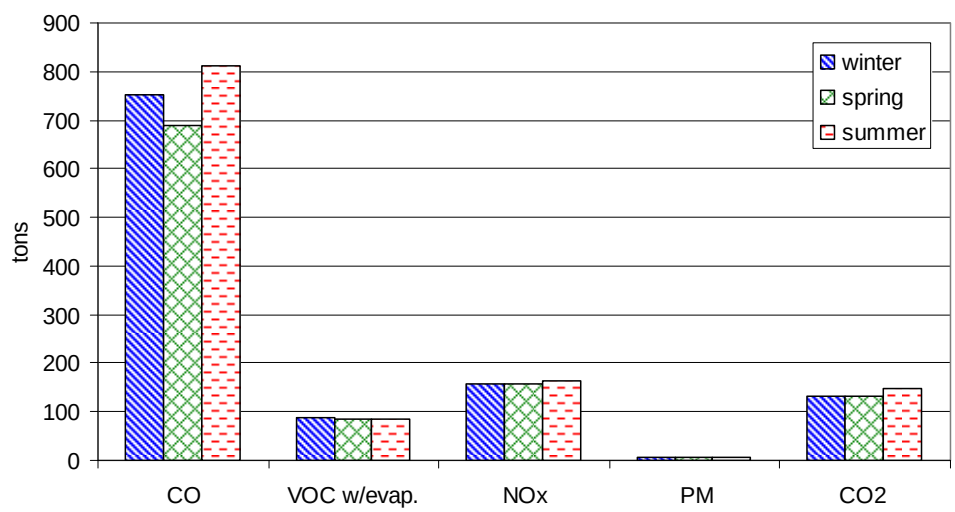


Figure 6-7-b Hourly Humdity in Different Seasons



As shown in Figure 6-8, total daily mobile emissions of almost all pollutants were lowest in spring and highest in summer (with exception of VOC emissions). We believe that use of air conditioning was the major cause of overall higher vehicular emissions in the summer. With the change of season, CO emissions varied most significantly (18%), while the variation of daily CO_2 emissions was also noticeable (10%). Daily VOC and NO_x emissions tended to increase slightly when temperature was higher (i.e., their daily emissions in summer were about 3% greater than those in spring). PM emissions of Tianjin fleet did not seem to vary much throughout a year.

Figure 6-8 Daily Vehicular Emissions in Different Seasons



Note: the values of CO_2 emissions should be multiplied by 100.

Climate conditions influence the proportion of start and running emissions drastically. Table 6-6 summarizes daily start and running emissions of CO, VOC, NO_x, and CO_2 in 3 different seasons. Total start emissions of CO on a cold winter day are 3 times that of a hot summer day, while total start emissions of VOC on a cold winter day are about twice that of a hot summer day. In contrast, daily running emissions of CO in winter are only three quarters of those in summer; and daily running emissions of VOC in winter are slightly less (about 5%) than those in summer. The start emissions of CO and VOC are higher in winter because the ambient temperature is low in the winter mornings so it takes more time for a three-way catalytic converter to warm up and function properly during a cold start. The running emissions of CO (and other pollutants) are highest in summer because the use of air conditioning leads to more consumption of gasoline. The contributions of running emissions to total emissions (for CO and VOC) in summer time are illustrated in Figure 6-9-a and b (refer to Figure 6-7-a and c for comparison).

Table 6-6 Daily Start and Running Vehicular Emissions in Different Seasons (tons)

	CO		*VOC*		*NO_x*		*CO2*	
	start	*running*	*start*	*running*	*start*	*running*	*start*	*running*
Winter	192	559	15	74	2	156	129	13,232
Spring	149	541	9	75	2	156	129	13,232
Summer	66	747	7	78	2	161	129	14,690

Figure 6-9-a CO Emissions during a Summer Day (BEF corrected for LDV)

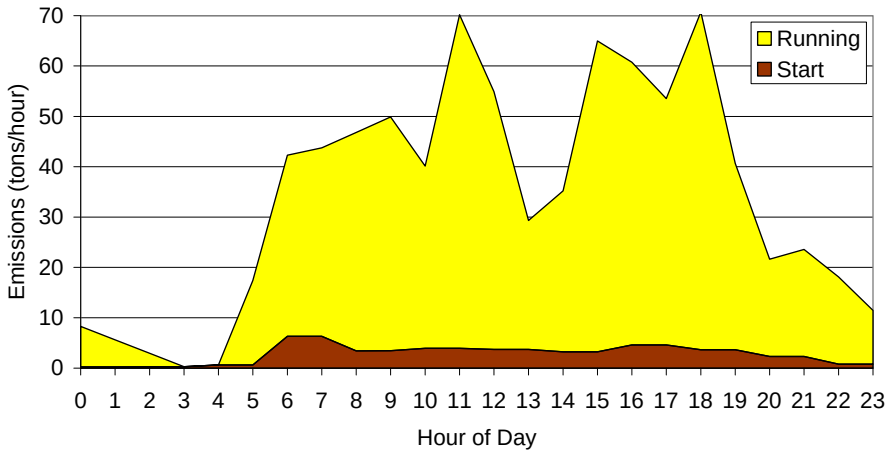


Figure 6-9-b NOx Emissions during a Summer Day (BEF corrected for LDV)

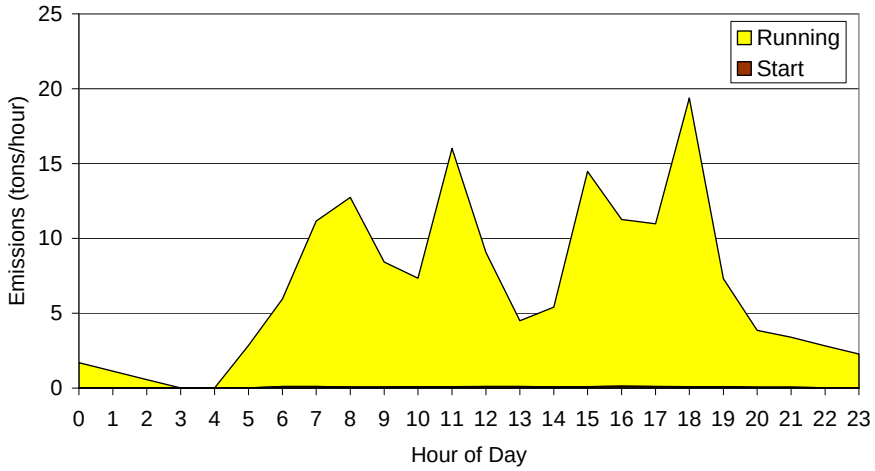


Figure 6-9-b NOx Emissions during a Summer Day (BEF corrected for LDV)

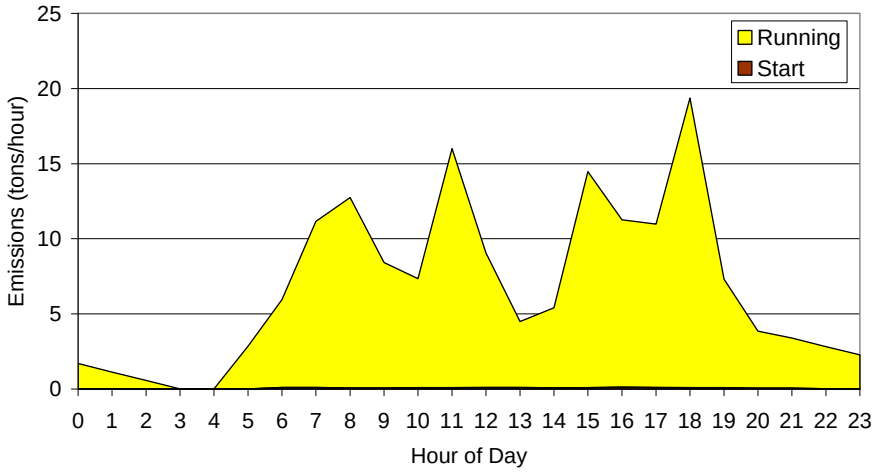
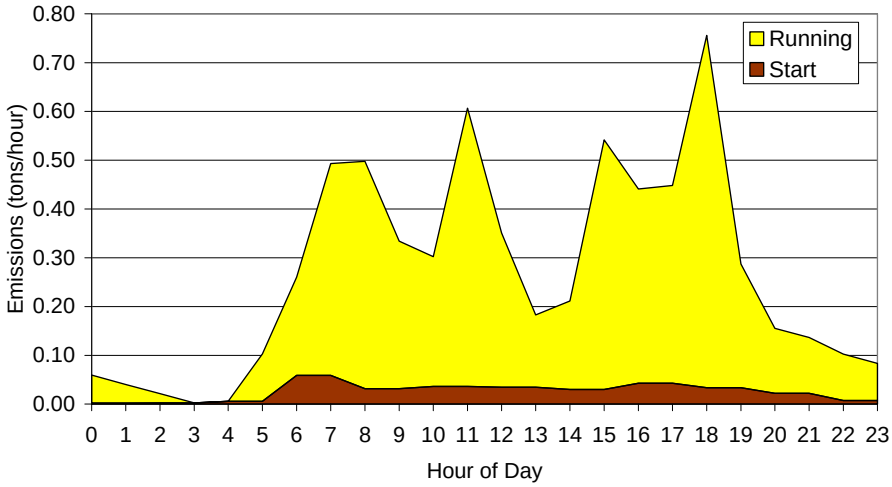


Figure 6-9-d PM Emissions during a Summer Day (BEF corrected for LDV)



6.5 Emission Reductions of Possible Policy Scenarios

Emissions by Vehicle Subcategories

To further distinguish emissions contributions by different types of vehicles, we put vehicles into subcategories based on five criteria[38]: fuel injection technology, type of fuel (e.g., gasoline, diesel, or natural gas, etc.); engine size (weight in the case of trucks and number of seats in the case of buses); mileage traveled; and emission control technology. Our vehicle activity study in Tianjin revealed there were 30 vehicle subcategories in Tianjin (the first column of Table 6-7 describes the codes and technologies for each subcategories). Using the information on the total distance traveled by Tianjin PC, taxi, truck, and bus fleets and the appearance frequency of these subcategories in the total of surveyed vehicles (refer to Section 4.4), we obtained the percentage of travel by each of these 30 vehicle subgroups. The IVE model then produced the total emissions by these subcategories during each hour of a day.

Table 6-7 shows the contributions to total mobile CO, VOC, $NO_{x,}$ and PM emissions and the share of daily travel by these 30 vehicle subgroups. Figure 6-10 illustrated the contributions of the 10 most conspicuously dirty subgroups (i.e. the subgroups whose contributions to one or more pollutants were larger than 1.5%). The codes in the legend in Figure 6-10 are consistent with the first column of Table 6-7 and that of Table 6-2.

A close examination of Table 6-7 and Figure 6-10 revealed 4 trends:

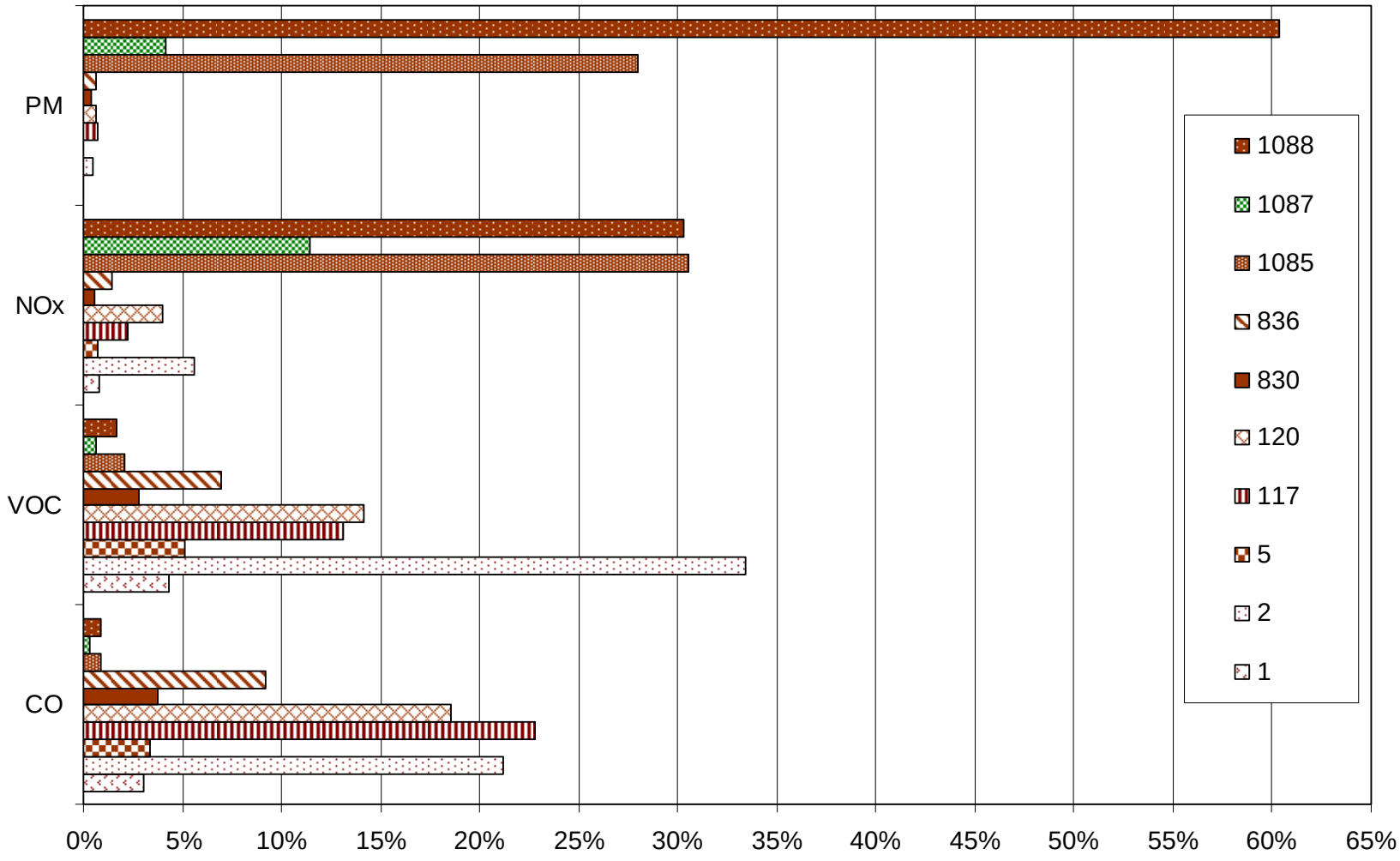
1) Overall, carbureted vehicles accounted for disproportionally high shares of CO and VOC emissions. Carbureted light-duty vehicles (sub-technology group 1 to 6) accounted for only about 15% of total distance traveled but they contributed to about one half and one third of the total mobile VOC and CO emissions. Carbureted buses (and some trucks, i.e., subgroup 830 to 836) accounted for less than 3% of total distance traveled but they contributed to about 16% and 12% of the total mobile CO and VOC emissions.
2) Diesel vehicles (trucks and buses) were the major culprits of mobile NO_x and PM emissions. They accounted for 17% of total distance traveled, but contributed to 80% and 96% of NO_x and PM emissions. The majority of these diesel vehicles had already accumulated mileage greater than 160 kilometers.
3) In general, high-mileage carbureted vehicles emitted more pollutants than low-mileage carbureted ones. For instance, high-mileage carbureted cars (subgroup 2 and 5) accounted for about 10% of total distance traveled, but they contributed to about 24% and 38% of total mobile CO and VOC emissions.

[38] These criteria were the same as the ones used in the IVE model.

Table 6-7 Contributions to Emissions and Distance Travel by Vehicle Subcategory

Technology	*Share of total daily Emissions*				*Share of Travel*
	CO	*VOC*	*NO_x*	*PM*	
0 Pt: Auto/SmTk : Lt : Carb : None : PCV : <80K	2%	2%	1%	0%	1%
1 Pt: Auto/SmTk : Lt : Carb : None : PCV : 80-160K	3%	4%	1%	0%	2%
2 Pt: Auto/SmTk : Lt : Carb : None : PCV : >160K	**21%**	**33%**	6%	0%	**9%**
3 Pt: Auto/SmTk : Med : Carb : None : PCV : <80K	1%	2%	0%	0%	1%
4 Pt: Auto/SmTk : Med : Carb : None : PCV : 80-160K	1%	1%	0%	0%	0%
5 Pt: Auto/SmTk : Med : Carb : None : PCV : >160K	3%	5%	1%	0%	1%
6 Pt: Auto/SmTk : Hv : Carb : None : PCV : <80K	0%	0%	0%	0%	0%
100 Pt: Auto/SmTk : Lt : MPFI: none : PCV : 80-160K	0%	0%	0%	0%	0%
101 Pt: Auto/SmTk : Lt : MPFI: none : PCV : >160K	1%	1%	0%	0%	0%
117 Pt: Auto/SmTk : Lt : MPFI: 3Wy : PCV : <80K	**23%**	**13%**	2%	1%	**28%**
118 Pt: Auto/SmTk : Lt : MPFI: 3Wy : PCV : 80-160K	2%	2%	1%	0%	**5%**
119 Pt: Auto/SmTk : Lt : MPFI: 3Wy : PCV : >160K	1%	1%	0%	0%	3%
120 Pt: Auto/SmTk : Med : MPFI: 3Wy : PCV : <80K	**19%**	**14%**	4%	1%	**26%**
121 Pt: Auto/SmTk : Med : MPFI: 3Wy : PCV : 80-160K	2%	1%	1%	0%	2%
122 Pt: Auto/SmTk : Med : MPFI: 3Wy : PCV : >160K	1%	2%	1%	0%	2%
123 Pt: Auto/SmTk : Hv : MPFI: 3Wy : PCV : <80K	0%	0%	0%	0%	0%
125 Pt: Auto/SmTk : Hv : MPFI: 3Wy : PCV : >160K	0%	0%	0%	0%	0%
830 Pt: Tk/Bus : Lt : Carb : None : PCV : >160K	**4%**	**3%**	1%	0%	1%
834 Pt: Tk/Bus : Hv : Carb : None : PCV : <80K	2%	1%	0%	0%	0%
835 Pt: Tk/Bus : Hv : Carb : None : PCV : 80-160K	1%	1%	0%	0%	0%
836 Pt: Tk/Bus : Hv : Carb : None : PCV : >160K	**9%**	**7%**	1%	1%	1%
900 Pt: Tk/Bus : Lt : FI : 3Wy : PCV : <80K	0%	0%	0%	0%	0%
1080 Ds: Tk/Bus : Lt : Dir-Inj : Improved : None : <80K	0%	0%	1%	0%	1%
1082 Ds: Tk/Bus : Lt : Dir-Inj : Improved : None : >160K	0%	0%	1%	1%	1%
1083 Ds: Tk/Bus : Med : Dir-Inj : Improved : None : <80K	0%	0%	2%	1%	1%
1084 Ds: Tk/Bus : Med : Dir-Inj : Improved : None : 80-160K	0%	0%	2%	1%	1%
1085 Ds: Tk/Bus : Med : Dir-Inj : Improved : None : >160K	1%	2%	**31%**	**28%**	**6%**
1086 Ds: Tk/Bus : Hv : Dir-Inj : Improved : None : <80K	0%	0%	1%	0%	0%
1087 Ds: Tk/Bus : Hv : Dir-Inj : Improved : None : 80-160K	0%	1%	**11%**	**4%**	2%
1088 Ds: Tk/Bus : Hv : Dir-Inj : Improved : None : >160K	1%	2%	**30%**	**60%**	**6%**

Figure 6-10 Emission Contributions by Major Vehicle Subcategories



4) In comparison with carbureted vehicles, light-duty vehicles equipped with multi-port fuel injection (MPFI) systems and three-way catalytic converters (TWC) emitted considerably fewer pollutants. They accounted for 66% of total distance traveled, but their contributions to total mobile emissions were much less (48% CO, 34% VOC, 9% NO_x, and 2% PM).

Policy Scenarios and their Emission Reduction Effects

The above analysis led us to believe that carbureted vehicles should be the targeted vehicle groups if CO and VOC emissions from mobile sources are to be controlled, and high-mileage diesel vehicles should be the focus if vehicular NO_x and PM emissions are to be controlled in Tianjin. Since Euro III emission standards for new vehicles took effect nationwide in China on July 1, 2007, all new vehicles sold in the Chinese market should meet at least Euro III standards. In this section, we estimate the amount of emissions that can be avoided if the most polluting vehicles are replaced with vehicles of similar size and function but in compliance with Euro III standards, or, in the case of heavy trucks and buses, if they are retrofitted to meet Euro III standards. The assumed scenarios include the followings:

Scenario 1 Replace all carbureted taxis with new cars that can meet Euro III standards (size distribution remains the same);

Scenario 2 Replace all carbureted passenger cars with new cars that can meet Euro III standards (size distribution remains the same);

Scenario 3 Replace all carbureted buses and trucks with diesel buses and trucks that can meet Euro III standards (size distribution remains the same);

Scenario 4 Make all high-mileage diesel buses meet Euro III standards (size distribution remains the same);

Scenario 5 Make all high-mileage diesel trucks meet Euro III standards (size distribution remains the same).

In all these different scenarios, we assume that the traffic conditions in Tianjin remain constant, and that all new vehicles will have air conditioners. The daily temperature and humidity profile of the early spring are used for all scenario simulations. We also assume moderate gasoline and diesel fuel quality (the sulfur content of gasoline was about 300 ppm and that of diesel fuel was about 500 ppm).

Scenario 1

If all the taxis without three-way catalytic converters were replaced by new cars that can meet Euro III emission standards, significant reductions in CO and VOC emissions would be achieved. As shown in Figure 6-11-a and 6-11-b, CO and VOC emissions from the taxi fleet would be cut by about 107 and 22 tons per day. NO_x emissions would be reduced by about 7 tons per day. The reduction of PM emission will be less visible though. As the result, total mobile CO and VOC emissions will have significant decreases (15% and 26% respectively). Recall that there were about 12,000 taxis without TWC (most of them were equipped with carburetors), and they accounted for only 7% of total distance traveled in Tianjin. It is thus evident that replacing these taxis with cleaner cars would be both effective and efficient in reducing mobile CO and VOC emissions.

Figure 6-11-a Emission Reductions: Replacing Carbureted Taxis with Euro III Cars

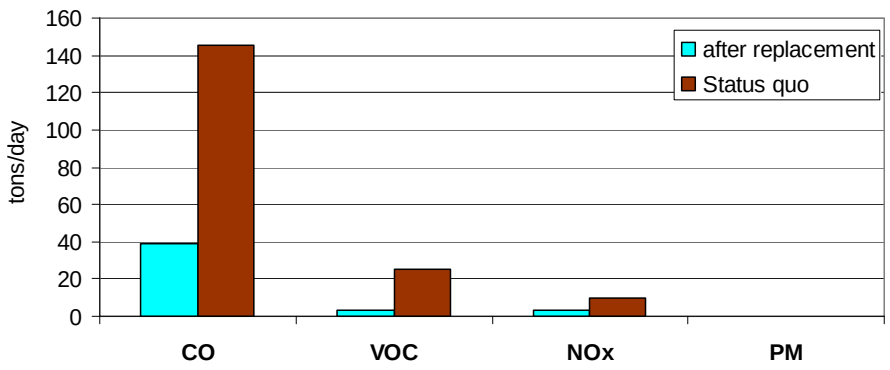
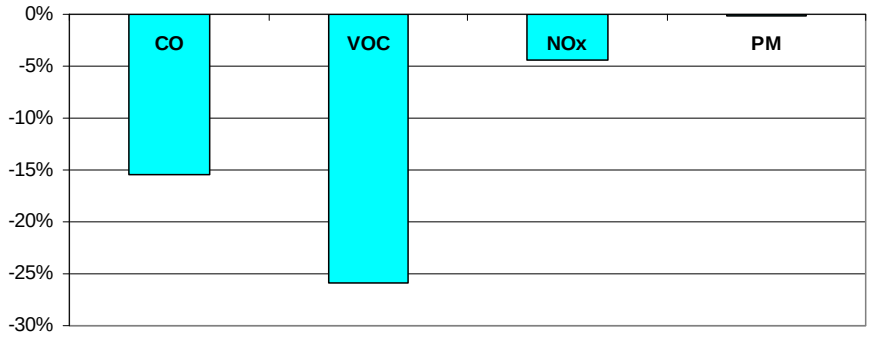


Figure 6-11-b Change of Overall Vehicular Emissions (Scenario 1)



Scenario 2

There were nearly 70,000 passenger cars in Tianjin without TWC (among which, 66,600 were equipped with carburetors, and the rest were equipped with multi-point fuel injection systems), and they traveled about 3.2 million kilometers per day in total (8.3% of total vehicle distance traveled). As illustrated in Figure 6-12-a and 6-12-b, if all these passenger cars were replaced by new cars that could meet Euro III emission standards, CO and VOC emissions would decrease by 106 and 20 tons per day respectively. NO_x emissions would drop 6 tons per day. This measure would cut 15% and 24% of total vehicular CO and VOC emissions.

Figure 6-12-a Emission Reduction: Replacing Carbureted PCs with Euro III Cars

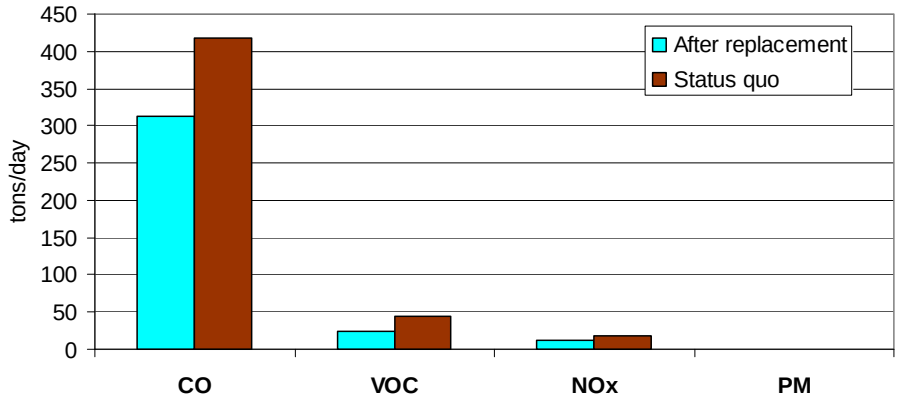
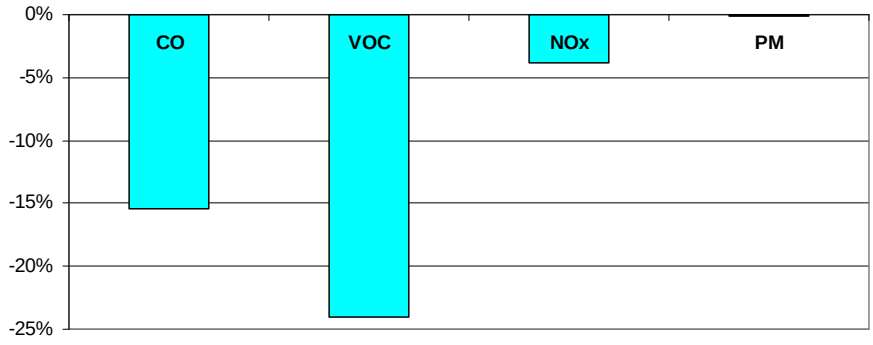


Figure 6-12-b Change in Overall Fleet Emissions (Senario 2)



The emission reduction benefits of Scenario 2 are similar to those of Scenario 1, but 5 times more cars would need to be replaced in Scenario 2. Thus, Scenario 1 is more economical than Scenario 2 in cutting mobile CO and VOC emissions.

Scenario 3

There were about 1,930 gasoline buses in Tianjin, and their daily travel accounted for about 1% of total distance traveled in Tianjin. Equipped with carburetors, but with no emission control devices, these buses emitted about 16% and 12% of total vehicular CO and VOC emissions in Tianjin. As shown in figure 6-13-a and b, replacing these buses with Euro III buses (diesel) would lead to a reduction of 97 and 8 tons of CO and VOC emissions respectively, (i.e., about 14% and 10% of total vehicular CO and VOC emissions). However, a switch of fuel from gasoline to diesel would cause a slight increase of NO_x emissions by 6 tons (4%).

Figure 6-13-a Emission Reduction: Replacing Carbureted Buses with Diesel, Euro III Buses

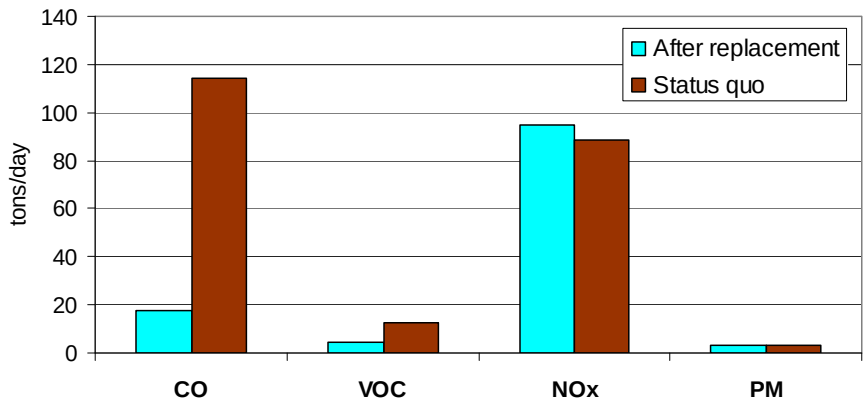
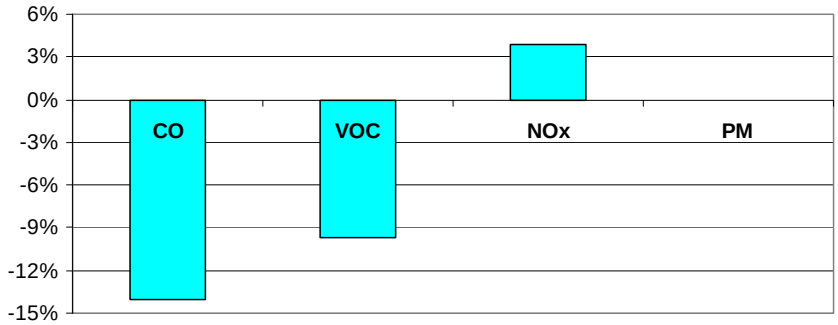


Figure 6-13-b Change of Overall Vehicular Emissions (Scenario 3)



Scenario 4

As we have learned, high-mileage buses and trucks are the main contributors to vehicular NO_x and PM emissions in Tianjin. In this scenario, we assume that all high-mileage, diesel buses (there were about 9,700 in total, 80% of which were medium-size and the rest were large-size) would be replaced by diesel buses that could meet Euro III emission standards (or, retrofitted to meet the standards). With this measure, the total PM and NO_x emissions from the bus fleet would decrease significantly, by about 2.8 and 22 tons per day respectively (see Figure 6-14-a). The decrease of total mobile PM and NO_x emissions would be about 43% and 14% (see Figure 6-14-b). However, the total CO and VOC emissions from the bus fleet would increase slightly, by 18 and 4 tons per day respectively.

Figure 6-14-a Emission Reduction: Replacing High-mileage Buses with Euro III Buses (Diesel)

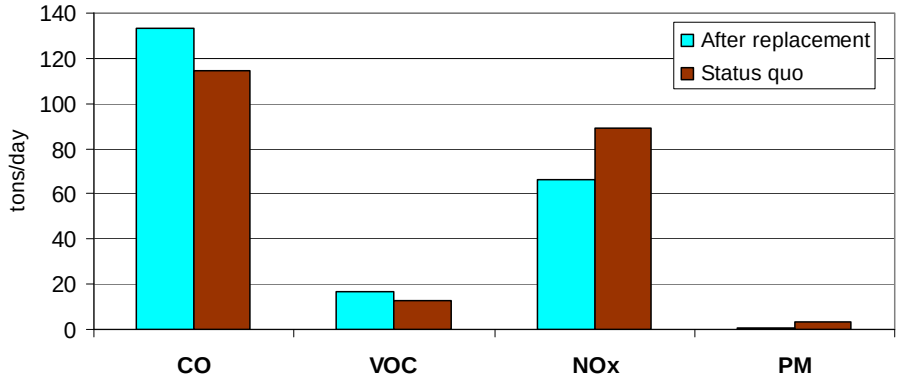
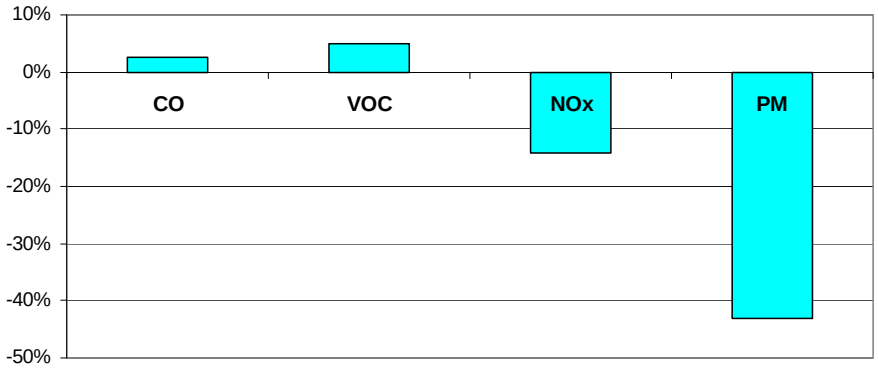


Figure 6-14-b Change of Overall Vehicular Emissions (Scenario 4)



If Scenario 3 and 4 are implemented together, the environmental effects would be balanced somewhat. The total reduction of PM would be about the same. However, the reductions of CO and VOC emissions under the combined situation would be about 20% and 30% lower than if Scenario 3 were implemented alone, and reduction of NO_x emissions would be about 30% less than if Scenario 4 were implemented alone.

Figure 6-15-a Emission Reduction: Replacing High-mileage Diesel Buses with Euro III Diesel Buses

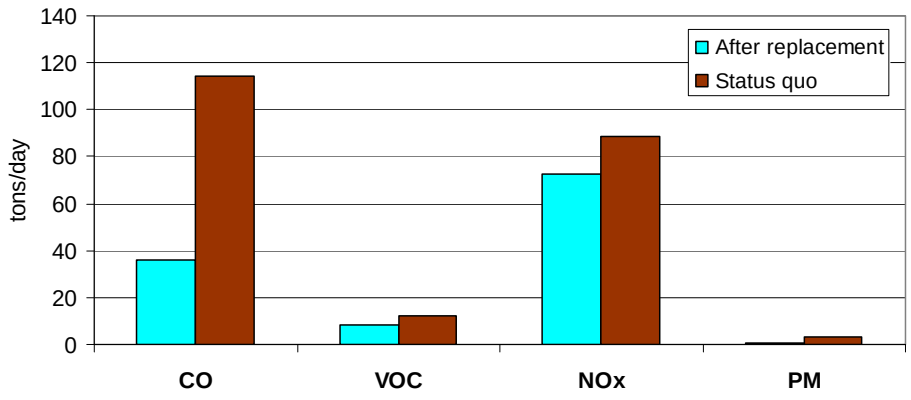
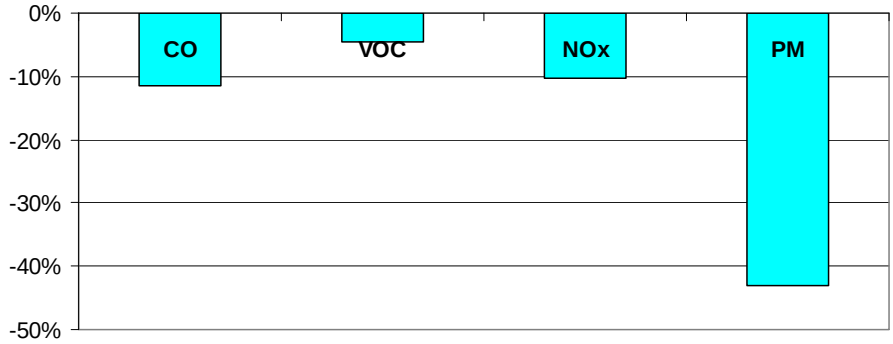


Figure 6-15-b Change of Overall Vehicular Emissions (Scenario 3 + 4)



Scenario 5

Similar to high-mileage diesel buses, high-mileage diesel trucks also contributed a considerably higher share of NO_x and PM emissions (refer to Table 6-7). There were about 27,300 high-mileage diesel trucks in Tianjin, and 83% of them were heavy trucks. As illustrated in Figure 6-16-a and b, retrofitting these high-mileage diesel trucks so they would meet Euro III standards (or replacing them with new ones that can meet Euro III standards) would lead to noteworthy reductions of PM and NO_x emissions. Total vehicular PM emissions would be cut by 2.5 tons per day, and NO_x emissions would be cut by 11 tons per day. This measure would lead to 42% and 11% decrease in total mobile PM and NO_x emissions. However, CO and VOC emissions would increase very slightly.

Figure 6-16-a Emission Reductions: Replace High-mileage Trucks with Euro III Trucks (Diesel)

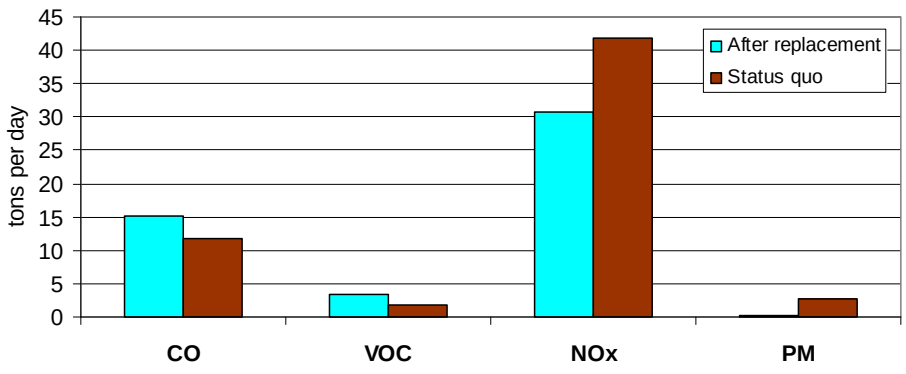
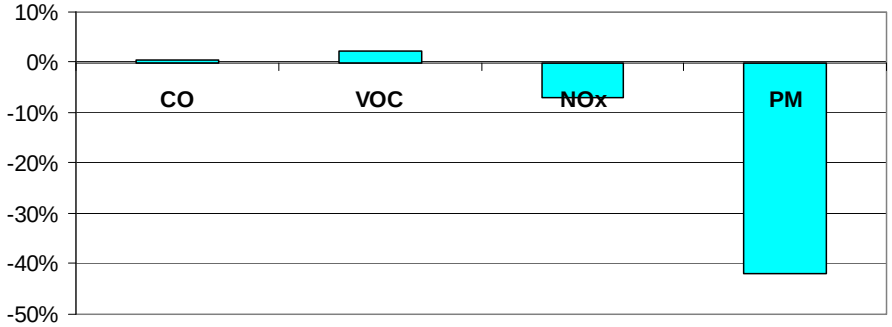


Figure 6-16-b Change of Overall Vehicular Emissions (Scenario 5)



Conclusions

7.1 Summary of Major Results

Our study on in-use vehicle emissions in Tianjin led to the following accomplishments:

1) We collected original data on in-use vehicle emissions, gasoline quality, pattern of vehicle use, and traffic conditions in Tianjin.

a. The 13 days of data collection with a set of remote sensing devices at 3 sites generated about 22,500 valid sets of measurements in total. A further screening of data based on VSP range (between 3 and 20) left us with 11,700 sets of measurements for final analysis. Each set of measurements included the concentrations of CO, CO_2, HC, NO, particulates (smoke), speed, and acceleration.

b. We tested the on-road emissions of 74 passenger vehicles with a set of portable emissions measurement systems on a 15-km driving route. For each vehicle, we had 1,800 to 2,800 seconds of emission, exhaust temperature, flow rate, and location measurements. Pollutants measured during these tests included CO, CO_2, THC, and NO_x. Location measurements include latitude, longitude, and altitude.

c. We surveyed about 1,200 cars, 780 buses, 44 trucks, and 48 taxis for specific technology distribution. We videotaped road traffic for 42 hours for 3 types of roads at 9 locations. We collected vehicle start patterns of 59 vehicles for 227 days in total, and we captured second-by-second driving conditions of personal cars, taxis, trucks, and buses with GPS devices for a week.

d. We obtained quality information of 36 gasoline samples in Tianjin. The parameters tested include research octane number, motor octane number, concentrations of sulfur, olefins, oxygen, aromatics, benzene, manganese and lead, density, and unwashed gum.

2) We assessed the composition and emission characteristics of the in-use vehicle fleet in the city, and identified high polluting vehicle groups.

Our vehicle activity study revealed the following characteristics of the Tianjin fleet:

a. The total distance traveled by all vehicles in Tianjin was about 38 million kilometers per day. Light-duty vehicles together contributed to 82 percent of all distance traveled (passenger cars, 64%; taxis, 18 %), buses and trucks contributed to 11% and 8% of total distance traveled respectively.

b. Most of the passenger cars were very new (less than 4 years old) and about half of them had engines small than 1.5 liters. Most of the light-duty vehicles were

equipped with multi-point fuel injection systems and three-way catalytic converters. However, it was noteworthy that 13% of passenger cars and 35% of taxis were still using carburetors.

c. Most of the trucks and buses ran on diesel fuel and had already accumulated high mileage. Fourteen percent buses used gasoline, were equipped with carburetors, and had no any end-of-pipe emission control devices.

d. The average speeds on highway, arterial, and residential roads were about 28, 22, and 15 km per hour. Urban traffic was not smooth in the daytime, but it was particularly slow during the morning rush hours. The speed also decreased around noon and in the early evenings.

The remote sensing study showed the following emission trends:

a. Light-duty vehicles sold in China have become cleaner over the last 10 years. In particular, there were two obvious decreases in the average emissions of vehicles made circa the years 2000 and 2003, when the first two sets of Chinese vehicle emissions standards (the Chinese equivalent of "EURO I" and "EURO II") entered into force.

b. The dirtiest 20% of the vehicles in Tianjin contributed to 77%, 70%, and 55% of the total mobile CO, HC, and NOx emissions (refer to Figure 2-5). Among the 20% of the dirtiest vehicles in our sample (11,700 sets of measurements), domestic-brand mini multi-purpose vans were the most significant HC and NOx emitters. Trucks and buses were the most noticeable NOx emitters. Passenger cars contributed to a big share of CO and HC emissions simply because of their large number (Table 2-5).

c. A considerable percentage of on-road passenger vehicles in Tianjin generated emissions at a rate higher than the national emission standards for in-use vehicles. The emissions measurements of 4,017 light-duty vehicles indicated that meeting the HC emission standard was the biggest challenge for in-use cars in Tianjin. About one quarter of these vehicles failed to meet the HC emission standards for in-use vehicles. About one tenth of these vehicles failed CO and HC emission standards for in-use vehicles. In addition to mini MPVs, many domestic-brand minibuses and minicars also stood out as gross polluters.

d. For light-duty vehicles of different vintage but with similar engine and emission control technology, the deterioration of their environmental performance over time was evident. As of summer 2005, a very high share of light-duty vehicles made in early 2000s could not meet the emissions standards that they had been officially certified with, especially their HC emissions.

3) <u>Relying on the International Vehicle Emissions model, we modified base emission factors based on our emissions test and established vehicle emissions inventories for Tianjin</u>.

a. The Tianjin fleet generated 690 tons of CO, 84 tons of VOC, 158 tons of NOx, 2 tons of SOx, 6 tons of PM, and about 13.4 thousand tons of CO_2 on a typical spring day.

b. Light-duty gasoline vehicles were the major contributors to CO and VOC emissions. Passenger cars accounted for 60% and 54%, and taxis accounted for 21% and 28% of all mobile VOC and CO emissions.

c. Carbureted gasoline vehicles contributed to disproportionally high share of CO and VOC emissions. Carbureted light-duty vehicles accounted for only 15% of the total distance traveled, but they contributed to about one third and one half of the total mobile CO and VOC emissions. Carbureted buses accounted for only 2% of total distance traveled, but they contributed to about 16% and 12% of the total mobile CO and VOC emissions.

d. Diesel trucks and buses accounted for most of the mobile PM and NO_x emissions (trucks: 44% and 27%; buses: 54% and 56%), despite that they only accounted for 8% and 11% of total distance traveled respectively.

4) Demonstrated state-of-art technologies for testing vehicle emissions in real world conditions.

This project was one of the first endeavors in China to investigate emissions from in-use vehicles systematically, using both portable emission measurement system and remote sensing devices. The IVE model was designed to meet the challenges faced by many cities in less developed countries where vehicle emissions data and traffic data are lacking, when they try to understand their mobile emissions. We demonstrated that the model is a practical and useful tool for establishing mobile emission inventories under such conditions. We embraced the concept and utility of vehicle specific power (VSP) in establishing accurate relationships between instantaneous emissions and driving condition. The power bin approach that we applied through the IVE model to build local mobile emission inventory was the most recent advancement in this field, and it has been incorporated by the USEPA in its next generation of MOBILE model.

7.2 Policy Implications

Our Tianjin study yielded to the following insights regarding vehicle emissions control in China. The first three concerning general policies at the national level and the remaining three are more specific to Tianjin.

1) The most powerful policy instrument for bringing down the emissions levels of new vehicles is compulsory emission standards.

We saw from the RSD study that there were significant reductions of average emissions by vehicles manufactured circa 2000 and 2003. The time coincided with the time when the Phase I and Phase II Chinese emissions standards entered into force. We believe that it is necessary for the Chinese government to continuously tighten the national emissions standards for new vehicles. Given that the demand for personal vehicles will remain strong for many years, and given that most of the vehicles will be purchased and used in already heavily-polluted cities, the Chinese government must make sure that total mobile emissions will not grow much even though vehicular population grows rapidly.

As of today, the rigorousness of Chinese emission standards lags considerably behind that of developed countries. Products of international auto companies have prevailed in Chinese markets. Thus, tighter standards will not be an onerous burden to these auto companies since they have already developed technologies to meet very stringent standards in developed countries.

2) Low-end auto products in China are often associated with poor environmental performance.

Three types of light-duty vehicles stand out as gross emitters in Tianjin: mini MPVs, minibuses and minicars. These vehicles are at the low end of light-duty vehicle markets. A considerable number of such vehicles were made in the late 1990s and early 2000s. They are equipped with carburetors and no emission control devices at all. The newer ones should have been certified in compliance with emissions standards when they were sold, however, our RS testing results imply quite a few did not meet the standards.

Although the low-end auto products do satisfy the demands of a big section of first-time Chinese consumers, the government should enhance its enforcement of product approval and certification process. It needs to make sure that all auto products are in compliance with emission and safety requirements before they are allowed to enter the market.

3) Scrapping carbureted light-duty vehicles will be an effective way to reduce CO and VOC emissions from mobile sources.

Our study shows that replacing the 12,000 carbureted taxis with cars of similar size in compliance with the currant emission standards will lead to about a 26% reduction of all mobile VOC emissions and a 5% reduction of all mobile CO emissions in Tianjin. Replacing the 70,000 personal, carbureted, light-duty vehicles with cars meeting current emission standards will lead to similar results. Giving that a carbureted car emits 14 times more criterion pollutants than a car that can meet Euro III standards, accelerating fleet turnover rate will likely help improving air quality in most cities.

4) Replacing gasoline buses with diesel buses that can meet current emission standards will lead to considerable reductions of VOC and CO levels, while replacing or retrofitting dirty, high-mileage diesel buses will lead to significant reductions of PM and NO_x emissions.

In the case of Tianjin, replacing the 1,930 gasoline buses will reduce the total mobile VOC and CO emissions by 10% and 4% respectively. Replacing or retrofitting 9,300 high-mileage diesel buses will cut total mobile PM and NO_x emissions by 43% and 14% respectively.

The municipal government in Tianjin should start a conversation with taxi or public transportation companies to create a timetable for cleaning up/replacing dirty taxis or buses. These vehicles usually have the highest mileage traveled per day and emit a disproportionally high share of pollutants. To help taxi and bus companies shoulder the costs, the government may consider providing some kinds of financial incentives (e.g, subsides or tax break) for the early retirement (or retrofitting) of dirty taxis and buses.

5) <u>The Tianjin municipal government needs to enhance its Inspection and Maintenance programs for in-use vehicles</u>.

We found that a considerable percentage of the light-duty vehicles made in the early 2000s could not meet their certified emission standards any more. This indicates that Tianjin lacked an effective I/M program to ensure that in-use vehicles are in consistent compliance with emission standards.

Currently, in many Chinese cities, passing emission tests is supposed to be a prerequisite for annual vehicle registration. However, the questions as to what extent the tests are carried out by inspection stations honestly and rigorously and how local environmental protection agencies can supervise those stations remain to be answered.

As China is getting richer and more vehicles are manufactured and put into use each year, the environmental and energy implications of this rapidly growing China fleet will continue to be a hot topic deserving of much attention. In this study, we have only focused on the emission characteristics of the Tianjin fleet with the intention to provide knowledge for reducing local mobile emissions most effectively and efficiently. In addition to offering concrete research results to the public and Chinese government, we also provide an example on how to evaluate mobile emissions by the best method possible within reasonable resources.

There are many issues beyond the scope of this study and yet the knowledge about them is critical for building a comprehensive program for controlling mobile pollution. For instance, what is the current status of I/M programs in Tianjin? How could they be improved? What is the relation between urban congestion and mobile emissions? What is the relation between local air quality and mobile emissions? What determines the deterioration of the environmental performance of in-use vehicles? How had the quality of mobile fuels influenced the emission performance of in-use vehicles? To answer all these questions, considerable amounts of resources and concerted research actions by multiple government agencies and research institutes are needed.

The ultimate challenge is to apply this knowledge to policies. The government must be determined to protect the environment and human health; must be able to overcome opposition to put in place effective policies and programs; and must be able to mobilize resources and public support to enforce these policies and programs fiercely.

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