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# Characterization of on-road CO, HC and NO emissions for petrol vehicle fleet in China city*

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**Abstract:** Vehicle emissions are a major source of air pollution in urban areas. The impact on urban air quality could be reduced if the trends of vehicle emissions are well understood. In the present study, the real-world emissions of vehicles were measured using a remote sensing system at five sites in Hangzhou, China from February 2004 to August 2005. More than 48000 valid gasoline powered vehicle emissions of carbon monoxide (CO), hydrocarbons (HC) and nitrogen oxide (NO) were measured. The results show that petrol vehicle fleet in Hangzhou has considerably high CO emissions, with the average emission concentration of 2.71%±0.02%, while HC and NO emissions are relatively lower, with the average emission concentration of $(153.72\pm1.16)\times10^{-6}$ and $(233.53\pm1.80)\times10^{-6}$, respectively. Quintile analysis of both average emission concentration and total amount emissions by model year suggests that in-use emission differences between well maintained and badly maintained vehicles are larger than the age-dependent deterioration of emissions. In addition, relatively new high polluting vehicles are the greatest contributors to fleet emissions with, for example, 46.55% of carbon monoxide fleet emissions being produced by the top quintile high emitting vehicles from model years 2000~2004. Therefore, fleet emissions could be significantly reduced if new highly polluting vehicles were subject to effective emissions testing followed by appropriate remedial action.

**Key words:** Remote sensing, Vehicle emission, Characterization
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## INTRODUCTION

On-road vehicles are responsible for a significant and rapidly increasing portion of the air pollution in the urban areas of China due to rapid growth of motor vehicle population. The State Environmental Protection Administration (SEPA) of China has identified motor vehicles emissions as the major source of urban air pollution in China (SEPA, 2004). As of 2004, on-road vehicles were estimated to contribute over 50% of the nitrogen oxides ($NO_x$) to large city's emission inventory (SEPA, 2004).

For the protection of atmospheric environment, many vehicle emissions measurements and estimations have been carried out to determine the emission reduction and evaluate the effectiveness of emission control strategies and regulations in order to meet the better air quality goals. Vehicle emission models are widely used tools to estimate vehicle emissions. Only a few countries, such as the US and those in Europe have developed reasonably accurate emissions estimation models such as MOBILE6 (USEPA, 2003), EMFAC2002 (USCARB, 2002) and COPERT III (Kouridis *et al*., 2000). They have often been modified and used in the developing countries, which lack the resources to develop a comprehensive emission model like China (Hao *et al*., 2000). However, since these models are designed only for their respective regions, not taking into account the differing technologies and conditions that exist in most developing countries, modification application would result in considerable errors. In addition, even applied in their

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own regions, the emission computational models' accuracy still remains uncertain (Singer and Harley, 1996; Gertler *et al*., 1997), since their emission factors are extrapolated from limited dynamometer testing and quite a number of high emitters are not involved.

Tunnel studies have long been recognized as important methods for measuring on-road vehicle emissions. In a tunnel study, air is sampled at the exit of the tunnel and the flow of both air and vehicles through the tunnel is measured. Based on the assumption that the air in the tunnel is uniformly mixed, the flux of pollutants through the tunnel is associated with all vehicles travelling the length of the tunnel (Pierson *et al*., 1996). The results are the average emissions from all vehicles passing through the tunnel. Tunnel study is the main method used to investigate the real-world vehicle fleet emissions in China where many highway tunnel tests have been carried out in several large Chinese cities (Wang *et al*., 2001; Deng *et al*., 2000). However, tunnel studies do not represent the full range of vehicle operating conditions, provide only limited information on the distribution of emission rates, and do not permit detailed classification of emitters (e.g. model year).

On-road vehicle exhaust emissions survey using remote sensing devices (RSD) provides a quick and effective method of monitoring exhaust emissions from in-use vehicle fleet under the normal driving operations. Vehicle speed and acceleration are measured by optically timing the passage of the wheels with two optical gates. Vehicle type information is assembled by obtaining an image of the vehicle's license plate and cross referencing these data with the city vehicle registration database. The application of remote sensing vehicle exhaust emissions testing system has been used in the polluted areas of US, Mexico, UK, Hong Kong and many other parts of the world to achieve different tasks such as the traffic fleet characterization for the low and high emitter profiling, inspection and maintenance (I/M) programs evaluation and fuel-based emission inventories development, etc. (Revitt *et al*., 1999; Wenzel, 2003; Chan *et al*., 2004; Pokharel *et al*., 2004).

Although remote sensing is widely used in the world (esp. in the developed countries and areas), few such surveys had been conducted in urban in Chinese mainland area and the trends and characteristics of real-world vehicle fleet emissions have not been well understood. In the present study, we have made a comprehensive assessment of the petrol vehicles emission characteristics by utilizing a dataset available from on-road optical remote sensing measurements on a large number of vehicles in Hangzhou, China, in 2004 and 2005. According to our knowledge, this was the first time such a system had been used in the Chinese mainland to provide comprehensive real-world characterization of vehicle fleet emissions.

## REMOTE SENSING MEASUREMENTS

### Experimental instrument

All remote sensing measurements were carried out by means of a 4-gas INSPECTOR IV® instrument from MD LaserTech Ltd., Tucson, Arizona, which uses tunable diode laser (TDL) technology to monitor CO and $CO_2$ emissions, and non-dispersive ultraviolet spectroscopy to measure HC and NO.

In this system, the diode lasers and ultraviolet beams, the source detector module and the vertical transfer mirror units are positioned on the opposite sides of a single traffic lane in a bi-static arrangement. As the vehicles drive by, the beam passes through the exhaust plume from the tailpipe, which absorbs some of the light. The exhaust plume path length and the density of the observed plume are highly variable from vehicle to vehicle, and are dependent on the height of the vehicle's exhaust pipe, wind, and turbulence behind the vehicle. For these reasons, the remote sensor can only directly measure ratios of CO, HC or NO to $CO_2$. The ratios of CO, HC or NO to $CO_2$ are constant for a given exhaust plume, and on their own are useful parameters for describing a hydrocarbon combustion system. The remote sensor used in this study reports the CO (%), HC ($\times10^{-6}$) and NO ($\times10^{-6}$) in the exhaust gas.

A device for measuring the speed and acceleration of vehicles driving past the remote sensor, which includes an emitter bar and a detector bar, was also used. The vehicle license plate can be captured by the color video camera system and the vehicle information can be obtained at a later stage. Meteorological conditions including temperature, humidity, wind speed and wind direction were also measured simultaneously. Fig.1 shows a schematic diagram of a remote sensing system that measures CO, $CO_2$, HC and NO setup on the road.

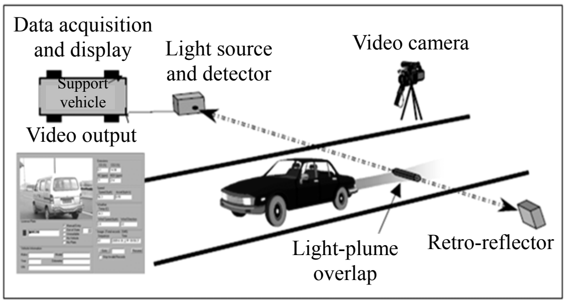


**Fig.1 Schematic diagram showing the remote sensing system in operation**

### Quality assurance calibrations

The field measurement should be initiated right after the completion of system calibrations at the site. Owing to the change of local environmental conditions (i.e. surrounding vehicle emission concentrations, wind speed and direction, etc.) from time to time and site to site, and the unavoidable road vibration, the system calibration should be carried out at least every two hours in order to obtain the best results. The CO and $CO_2$ are internally calibrated, and a puff of gas containing certified amounts of 1,3-butadiene and NO is released into the instrument's path, and the measured ratios from the instrument are then compared to those certified by the cylinder manufacturer. Since 1,3-butadiene is used to calibrate the instrument, all hydrocarbon measurements reported by the remote sensor are given as 1,3-butadiene equivalents.

### Monitoring site characteristics

The remote sensing data were collected at five sites in different areas in Hangzhou, China, during 2004 and 2005. The locations were selected to measure emissions from a broad range of road types and ages distributed throughout the local area. The relevant important characteristics of each site including the ranges of traffic flow rates, the ranges of vehicle speeds and accelerations, are described in Table 1. All five sites were located on streets with slightly uphill geometry, connected to major local arteries in such a way that it was reasonable to expect a negligible share of vehicles operating at cold start enrichment mode. The measurements were carried out during normal working hours on weekdays.

## RESULTS AND DISCUSSION

### Aggregate fleet emissions of CO, HC and NO

A total of 59185 vehicles were measured at these sites. Among them, 48905 petrol vehicle emission data were considered to be valid in terms of its velocity, acceleration and emission concentrations profiles. But only 69% of the valid measurements can be matched to the city registration records, and many of the misses are outside-city vehicles. The number of valid measurements in each site is shown in Table 1.

The mean vehicle fleet emissions and the corresponding median values in each site are shown in Table 2. Because of a considerable number of negative HC measurements, the HC concentration values were offset-adjusted in the manner described in Burgard *et al.*(2003). The differences between the mean and median values reflect the very skewed nature of the emission distributions. This is also demonstrated by emission contribution from the 10% dirtiest

**Table 1 Characterization of the five remote sensing measurement sites**

| | Dengsheng city street | Zhejiang arterial street | Fuxing bridge overhead road | Meiling tunnel | Gudun city street |
|---|---|---|---|---|---|
| Measurement period | Apr. and Oct. 2004 | Feb. 2004 | Nov. 2004, May 2005 | Jun. 2005 | Aug. 2005 |
| Traffic volume (vehicles/h) | 284~305 | 1021~1514 | 667~845 | 365~780 | 692~941 |
| Average measured speed (km/h) | 9.4~90.8 (41.41) | 8.4~75.0 (32.30) | 9.7~94.9 (44.45) | 15.9~64.4 (44.56) | 8.3~72.5 (39.65) |
| Vehicle acceleration (km/(h·s)) | −1.68~2.11 (0.16) | −1.74~1.74 (0.19) | −1.99~2.00 (0.06) | −2.22~2.23 (−0.01) | −1.85~1.64 (−0.10) |
| No. of valid CO readings | 9354 | 6025 | 18829 | 9802 | 2743 |
| No. of valid HC readings | 9929 | 6958 | 19783 | 10922 | 3308 |
| No. of valid NO readings | 9135 | 6163 | 19420 | 10723 | 3134 |

Note: The data in the brackets are the average ones

**Table 2 Summary of the fleet emissions in different sites**

| | Dengsheng city street | Zhejiang arterial street | Fuxing bridge overhead road | Meiling tunnel | Gudun city street | All |
|---|---|---|---|---|---|---|
| Mean CO (%) | 2.50 | 2.34 | 2.91 | 2.37 | 3.79 | 2.70 |
| Median CO (%) | 1.49 | 1.35 | 1.72 | 1.34 | 2.70 | 1.58 |
| Total CO from dirtiest 10% of fleet (%) | 40.5 | 36.3 | 34.0 | 38.7 | 27.7 | 34.74 |
| Mean HC ($\times10^{-6}$)* | 212 | 195 | 108 | 157 | 168 | 153.36 |
| Median HC ($\times10^{-6}$)* | 77 | 76 | 59 | 61 | 67 | 63 |
| Total HC from dirtiest 10% of fleet (%)* | 47.9 | 44.4 | 46.2 | 54.8 | 47.1 | 51.32 |
| Mean NO ($\times10^{-6}$) | 303 | 299 | 203 | 212 | 235 | 234.75 |
| Median NO ($\times10^{-6}$) | 150 | 152 | 116 | 119 | 123 | 123 |
| Total NO from dirtiest 10% of fleet (%) | 40.6 | 40.5 | 37.5 | 45.0 | 43.2 | 43.49 |

* These values have been HC offset adjusted as described in text

vehicles in Table 2. The most polluting 10% petrol vehicles are responsible for 34.74% of the total CO emissions, 51.32% of the total HC emissions and 43.49% of the total NO emissions, in average. The measurements in five sites show the same trends and the variability of average CO, HC and NO emissions in different sites are comparatively small, and mainly due to the local road condition, vehicle traffic fleet composition and volume, driving pattern, ambient condition, etc.

Remote sensing studies have typically found that automobile CO and HC emissions follow a gamma statistical distribution function (Zhang *et al.*, 1994). The previous NO remote sensing study also concluded that this is true for NO emissions (Zhang *et al.*, 1996). Thus emission data were gamma distribution fitted and the average emission concentrations of CO, HC and NO measured in this study were calculated as 2.71%±0.02%, $(153.72\pm1.16)\times10^{-6}$ (offset adjusted) and $(233.53\pm1.80)\times10^{-6}$, respectively. The skewness values for the emission distributions of CO, HC and NO are 1.23, 7.59 and 4.21, respectively.

## Distribution of vehicle emissions and the 'gross emitter'

For further analysis, the fleet emissions of CO, HC and NO were broken down into concentration categories, for each of which the relative number of vehicles measured and the total amount of pollutant discharged are given (Fig.2). The solid bars show the percentage of the fleet in a given emissions category, and the gray bars show the percentage of the total emissions contributed by the given category. This figure illustrates the skewed nature of vehicle emissions, showing that the majority of the vehicles are low emitters and contribute little to total fleet emissions.

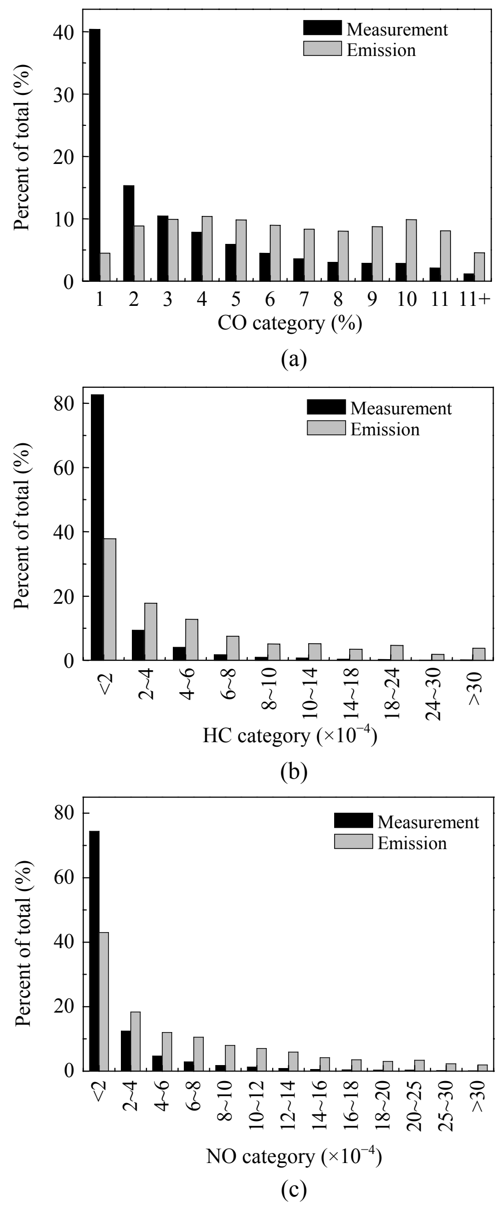


**Fig.2 CO (a), HC (b) and NO (c) expressed as percentage contribution to the fleet and the fleet emissions**

The lowest emission category (less than $200\times10^{-6}$), occupied by no less than 83% of the fleet for HC and more than 74% of the fleet for NO, is responsible for only 38% of the HC emissions and 43% of the NO emissions, respectively. And the cleanest 66% of the fleet (less than 3%, in volume) is responsible for only 23% of the CO emissions. Vehicles with CO concentration less than 1% are usually considered as clean emitters (Bishop *et al*., 2000). However, the vehicles emitting less than 1% CO only account for 40% of the fleet and contribute 4.5% of fleet emissions in Hangzhou.

**Variation of fleet average emissions with model year**

Average emission concentrations of CO, HC and NO of the aggregate petrol vehicles as a function of model years in Hangzhou are shown in Fig.3. The make/model year groups chosen are restricted to those containing at least 200 measurements. Since only a few vehicles made before 1992 were measured in our study, only 1992~2005 model year vehicles were analyzed. The average model year measured in this study is 2000. The error bars included in the plot are standard errors of the mean. These uncertainties were generated for these gamma distributed datasets by applying the central limit theorem. It should be mentioned that this is a standard sampling uncertainty, and should not be interpreted as an absolute uncertainty on the measurements, which may be affected by other undetermined factors—such as choice of roadway sites, time of day, season, etc.

In general, the average emission concentrations of CO, HC and NO for the aggregate petrol vehicles are inversely proportional to the model years as shown in Fig.3. Since 2000, two petrol vehicle emission standards for light duty vehicle have been implemented in China. The State I and State II emission standards, which is equivalent to Euro I and Euro II standards respectively, were implemented in China in January 2000 and July 2004, separately. And also since 2000, the mandatory of phasing out leaded petrol fuel regulation has also been implemented in China. The unleaded petrol fuel together with the use of three-way catalytic converter has significantly reduced the petrol vehicle emissions in China. If the baseline of petrol vehicle model years of 1992 and 2005 in Hangzhou sites were compared, the significant reduction of average emissions of 91.23% and 73.97% for HC and NO were observed, respectively. However, the CO emission reduction was only 52.65%. Apparently, CO emissions have not been controlled effectively. Since high CO emissions are a particularly useful indicator of poor vehicle maintenance and poor fuel economy, the quite number of high CO emitters in relatively new model years in China city indicates the great problems in regular emission testing program (I/M program) for in-use vehicles and poor fuel economy in China. Actually,

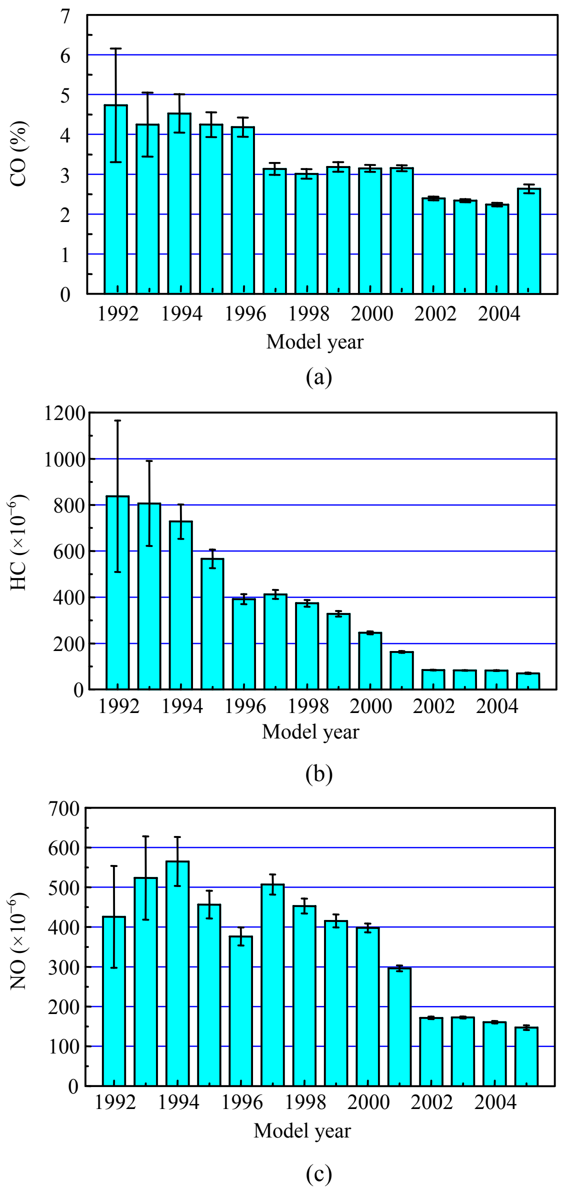


**Fig.3 Variation of fleet average emissions for CO (a), HC (b) and NO (c) with model years**

centralized idle testing is still the main method used in Chinese regular I/M program. The idle test has been proved to be far from effective for fuel-injected and catalytic converter equipped vehicles, which are the main vehicle population in China, now. In addition, the general vehicle fuel economy in China is about 20% lower than that in developed countries (Department Research Center for the State Council *et al*., 2001). These facts all consist with our analysis in this study.

The plot of NO concentration vs model year rises from model year 2005 to 1994 and then appears to decrease in model years prior to 1994. This has been observed previously (Pokharel *et al*., 2002) and is likely due to the tendency for older vehicles to lose compression and operate under fuel-rich conditions, both factors resulting in lower NO emissions. However, the somewhat relatively low NO emissions of the model years 1995 and 1996 measured in this study remain unexplained.

**Comparison to similar studies overseas**

To clearly understand the emission level of petrol vehicle fleet in Hangzhou, the average fleet emissions in this study were compared to those in the similar studies conducted in two US cities (Chan *et al*., 2004; Burgard *et al*., 2003; Bishop *et al*., 2003). The data displayed in Table 3 show that on average the Hangzhou fleet emits approximately 8 to 10 times amount of CO and 2 times amount of HC, by comparison to their US counterparts. It should be noticed that the average NO emission in Hangzhou (2005) is lower than those both in Denver (2003) and Chicago (2001).

**Table 3 Comparison of the Hangzhou fleet average emissions with other studies**

| Location | Vehicle number | Average CO (%) | Average HC ($\times10^{-6}$) | Average NO ($\times10^{-6}$) |
|---|---|---|---|---|
| Denver (2003) | 27702 | 0.35 | 88 | 456 |
| Chicago (2001) | 26054 | 0.26 | 94 | 316 |
| Hangzhou (2005) | 48905 | 2.71 | 153 | 233 |

It is well known that the USA has much stricter emission standards than China, so the result of comparatively lower NO emissions in Hangzhou seems unreasonable. In order to correctly understand the results, the average emissions by model year in the three sites were analyzed. Fig.4 shows that the average emissions of Hangzhou fleet in each model year are higher than their US counterparts for all the three pollutants. For example, the average 2005 model year emission for NO in Hangzhou is still as much as 2.33 and 1.57 times that of the 2001 model year emissions in Chicago and 2003 emissions in Denver, respectively. This is consistent with the stricter emission

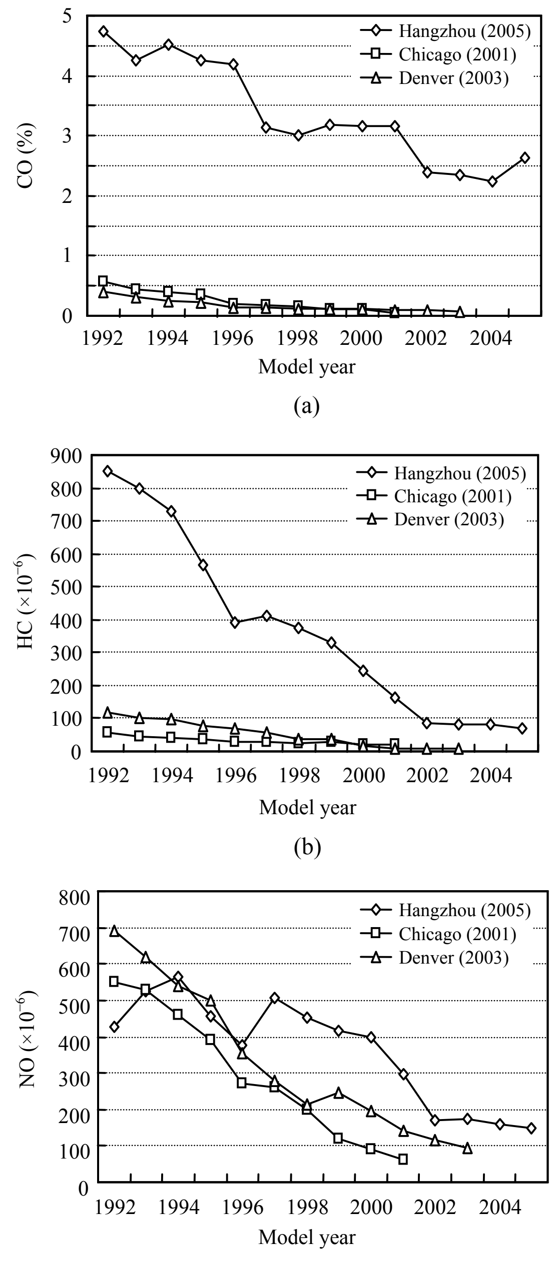


**Fig.4 Comparison with other remote sensing studies worldwide. (a) CO; (b) HC; (c) NO**

standards and more advanced control technologies applied in the US. However, compared to the average model year of 1994 observed in Chicago (2001) and Denver (2003), Hangzhou (2005) fleet has much newer average model year as 2000, which was caused by great annual vehicle population growth of above 25% in recent years. And the NO emissions in new model years (2001~2005) are much lower than before. These may explain the lower average NO emissions of overall fleet observed in Hangzhou.

Furthermore, according to Heywood (1988), lower level of $NO_x$ (mainly NO and a smaller proportion of $NO_2$) emissions is associated with rich fuel/air stoichiometric due to a lack of excess oxygen, when CO emission peak is caused solely by a lack of adequate air for complete combustion. Therefore quite higher average CO emission level in Hangzhou fleet is another reason for the relatively lower average NO emissions.

**Quintile analysis of vehicle emission concentrations by model year**

Plotting vehicle emission concentrations by model year, with each model year divided into emission quintiles, are shown in Fig.5. For HC and NO, the inverse relationship between average emission concentration and model year in each quintile has also been observed, though some fluctuation appears before model year 1997 which was explained before. That means average HC and NO emissions increase with vehicle age whether for the dirtiest vehicles or the cleanest vehicles. However, for CO, there was no obvious increase of emissions with the increasing vehicle age in the dirtiest vehicles (top quintile) in the Hangzhou fleet. But the trend of emissions increasing with vehicle age is more obvious when the vehicles become cleaner. This suggests that high emitting vehicles in new model years contribute a lot to the average emissions and that can also explain why the average emission concentrations of CO in new model years are still high.

On the other side, the highest polluting quintile of the newest vehicles emit more compared with the lowest emitting quintile of the oldest vehicles, which indicates that in-use emission differences between well maintained and badly maintained vehicles is larger than the age-dependent deterioration of emissions. Therefore, vehicle age alone cannot be used as

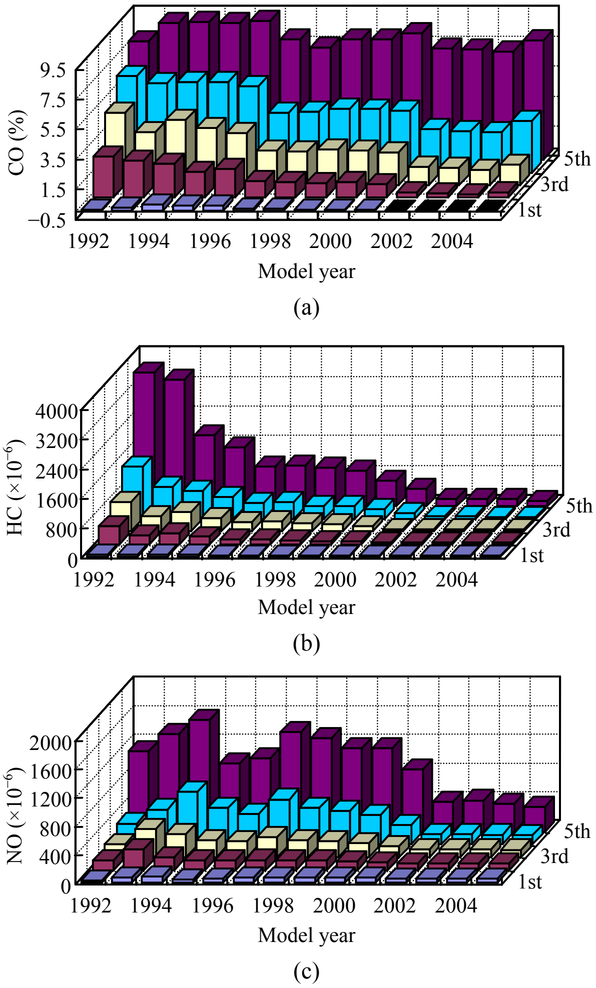


**Fig.5 Vehicle emission concentrations by model year, divided into quintiles. (a) CO; (b) HC; (c) NO**

an indicator of vehicle emissions, and that all vehicles of a given model year do not have the same emissions.

**Quintile analysis of model year contribution to fleet emissions**

Although emissions generally increase with the age of the vehicle, older vehicles do not contribute significantly to fleet emissions due to the small number of old vehicles on the road. Fig.6 shows the model year contribution to fleet emissions, divided into quintiles. The results suggest that relatively new high polluting vehicles are the greatest contributors to fleet emissions. From Fig.6, 46.55% of CO, 30.44% of HC and 38.44% of NO emissions are produced by the top quintile high emitting vehicles from model years 2000~2004. Another revealing fact is that, for all three major pollutants, the cleanest 40% of the vehicles, regardless of model year, make an essentially negligible contribution to the total emissions. This observation for HC and CO was first reported by Ashbaugh *et al.*(1992). Therefore, fleet emissions could be significantly reduced if those vehicles in the top quintile underwent effective emissions testing followed by appropriate remedial action.

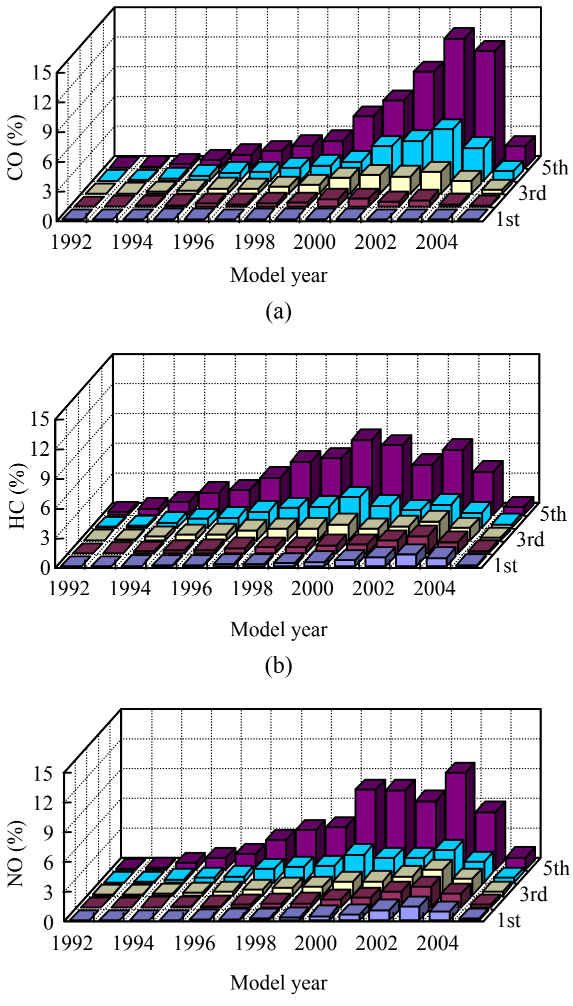


**Fig.6 Model year contribution to fleet emissions, divided into quintiles. (a) CO; (b) HC; (c) NO**

## Overlap of CO, HC and NO emissions for high emitters

The analysis of CO, HC and NO high emitters overlap was conducted to predict the abundance of vehicles that are high emitting for more than one pollutant measured. This type of analysis would allow calculation of one pollutant emission benefits resulting from fixing all high emitters of another pollutant. To this extent, we have analyzed our data to determine what percent of the top quintile of emitters of one pollutant are also in the top quintile for another pollutant. These data are in Table 4. The column heading is the pollutant whose top quintile is being analyzed, and the values indicate what percentage of the fleet are high emitters for the pollutants in the column and row headings. The values where the column and row headings are the same indicate the percentage that are high emitting in one pollutant. The "All" row gives the percentage of the fleet that is high emitting in all three pollutants.

**Table 4 Percent of all high emitters vehicles**

| Top 20% deciles | CO | HC | NO |
|---|---|---|---|
| CO | 20.00 | 5.46 | 2.55 |
| HC | 5.46 | 20.00 | 11.68 |
| NO | 2.55 | 11.68 | 20.00 |
| All | 1.66 | 1.66 | 1.66 |

Table 4 shows that 5.46% of the fleet are in the top quintile for both HC and CO but not NO; 2.55% of the fleet is high emitting for CO and NO but not HC. A 55.7% overlap of high HC and NO emitting vehicles was observed in our study fleet.

The preceding analysis gives the percent of vehicle that overlap but does not directly give emissions overlap. In order to assess the overall emissions benefit of fixing all high emitting vehicles of one or more pollutant, the percent of emissions were calculated. Table 5 shows that identification of the 20% high CO vehicles would identify an overall 63.82% of CO, 22.27% of HC and 4.94% of NO emission reduction. More efficiently, identification of the 20% high HC vehicles accounts for 67.93% of the total on-road HC, 41.71% NO and 22.27% CO emissions.

**Table 5 Percent of total emissions from high emitting vehicles**

| Top 20% Deciles | CO | HC | NO |
|---|---|---|---|
| CO | 63.82 | 22.27 | 4.94 |
| HC | 22.27 | 67.93 | 41.71 |
| NO | 4.94 | 41.71 | 61.04 |
| All | 3.77 | 5.53 | 3.52 |

## CONCLUSIONS

This remote sensing study has yielded significant "real world" information about emissions from vehicle fleet in Chinese city, Hangzhou. The key findings of the results are summarized as follows:

1. Petrol vehicle fleet in Hangzhou has considerably high CO emissions, with average emission concentration being 2.71%±0.02%, while HC and NO emissions are relatively lower, with the average emission concentration being $(153.72\pm1.16)\times10^{-6}$ and $(233.53\pm1.80)\times10^{-6}$, respectively.

2. The most polluting 10% petrol vehicles are responsible for 34.74% of the total CO emissions, 51.32% of the total HC emissions and 43.49% of the total NO emissions.

3. Relatively new high polluting vehicles are the greatest contributors to fleet emissions, with 46.55% carbon monoxide, 30.44% hydrocarbon and 38.44% nitrogen oxide fleet emissions produced by the top quintile high emitting vehicles from model years 2000~2004.

4. Considerable overlap of high HC and NO emitting vehicles was observed in the study fleet.

The results provided a baseline for emissions performance of the fleet so that the effectiveness of policies to reduce vehicle emissions can be monitored and also directly contribute to the objective to raise awareness of vehicle emissions and the need for vehicle maintenance. In conclusion, remote sensing offers benefits not possible with other methods and signals a way forward for methods to manage and reduce vehicle emissions in China.

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