On-board measurements of emissions from light-duty gasoline vehicles in three mega-cities of China

Hong Huo, Zhiliang Yao, Yingzhi Zhang, Xianbao Shen, Qiang Zhang, Yan Ding, Kebin He

1. Introduction

As a consequence of China’s rapid growth in vehicle population, motor vehicles have become one of the most significant pollution sources of the ambient environment in China (He et al., 2002; Zhang et al., 2009), and the vehicle pollution is expected to get even worse in the near future (Huo et al., 2011). Vehicles are a major contributor of urban CO, VOC, and NOx concentrations, the latter two of which are known as “precursors” of tropospheric ozone. Vehicle pollution has raised serious concern of the government and the public. Since the 1990s, China has implemented numerous measures to control vehicle emissions, and now controlling vehicle emissions is a major target for air quality improvement at both national and municipal levels in China.

The government’s implementation plan for vehicle emission control requires reliable mobile emission inventories, which should be developed on the basis of an accurate and comprehensive knowledge of emission factors of vehicles. So far, the understanding of the vehicle emission levels in China is very limited. Compared to the U.S. and European counties who perform a mass of vehicle emission measurements on a routine basis to enrich their public-accessible emission factor database, China may have conducted some on-road measurement studies undertaken in China, using five-gas analyzers or OBS-2200 system for light-duty gasoline vehicles (LDGVs) (Zhao et al., 1999; Tong et al., 2000; Wang et al., 2005a, 2008a; Yang et al., 2003; Yao et al., 2007; Oliver, 2008; Oliver et al., 2009), or OEM-2100 for buses and trucks (Wang et al., 2005b; Guo et al., 2007b), or SEMTECH-D analyzers for heavy-duty diesel trucks (HDDTs) and buses (Pan et al., 2005; Huang et al., 2007; Chen et al., 2007), however, the samples of these tests were either few (less 10) or old, so they could not cover all technology types of the current vehicle fleet in China. These measurement studies are helpful to increase the understanding of emission characteristics of individual vehicles in China.

This paper is the second in a series of three papers aimed at understanding the emissions of vehicles in China by conducting on-board emission measurements. This paper focuses on light-duty gasoline vehicles. In this study, we measured 57 light-duty gasoline vehicles (LDGVs) in three Chinese mega-cites (Beijing, Guangzhou, and Shenzhen), covering Euro 0 through Euro IV technologies, and generated CO, HC, and NOx emission factors and deterioration rates for each vehicle technology. The results show that the vehicle emission standards have played a significant role in reducing vehicle emission levels in China. The vehicle emission factors are reduced by 47–81%, 53–64%, 46–71%, and 78–82% for each phase from Euro I to Euro IV. Euro 0 vehicles have a considerably high emission level, which is hundreds of times larger than that of Euro IV vehicles. Three old taxis and four other Euro I and Euro II LDGVs are also identified as super emitters with equivalent emission levels to Euro 0 vehicles. Of the measured fleet, 23% super emitters were estimated to contribute 50–80% to total emissions. Besides vehicle emission standards, measures for restricting super emitters are equally important to reduce vehicle emissions. This study is intended to improve the understanding of the vehicle emission levels in China, but some key issues such as emission deterioration rates are yet to be addressed with the presence of a sufficient amount of vehicle emission measurements.

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(which is especially useful for micro emission models) but unable to provide a comprehensive picture of emission levels of Chinese vehicles. On the other hand, several remote sensing measurement have been conducted in China (Guo et al., 2007a; Zhou et al., 2005), which examined the in-use vehicle emission levels in Chinese cities, but these research only covered Euro 0, Euro I, and Euro II technologies and could not reflect the fast variation in vehicle emission levels in China. Due to the lack of sufficient measurement data, previous studies of estimating vehicle emissions in China (except those based on remote sensing data, such as Guo et al., 2007a) tend to determine the vehicle emission factors on the basis of the U.S. or European vehicle emission factor database (with or without adjustment).

This series includes three papers, intended to improve the understanding of vehicles emission levels in China by conducting on-board emission measurements. This paper is the second in this series, focusing on LDGVs. The first paper addresses the emissions from rural vehicles (Yao et al., 2011) and the third will address diesel trucks in China.

LDGVs now account for a very large share of the Chinese vehicle fleet and the share is increasing rapidly (from less than 50% in 2002 to 70% in 2009). The technology mix of the LDGV fleet is complex. China implemented the Euro I, Euro II, and Euro III emission standards in 2000, 2004, and 2007 for LDGVs, and the Euro IV standard is planned to be in place in 2012. Some large cities are ahead of the national schedule. For instance, Beijing implemented the Euro I, Euro II, Euro III, and Euro IV standards for LDGVs in 1999, 2003, 2005, and 2008, respectively. As China started the emission standards since 2000 and LDGVs usually serve for 15 years in China, the on-road LDGV fleet in China includes various emission control technologies, from Euro 0 (no emission control) to Euro IV. Table 1 presents our estimation on the share of each technology level out of the on-road LDGV fleet in China in 2009.

In this work, we measured CO, HC, and NOx emissions from 57 LDGVs under the real driving conditions in three Chinese megacities — Beijing, Shenzhen and Guangzhou — during 2008 and 2010. The measurements were performed using a portable emissions measurement system (PEMS). The vehicles measured covered Euro 0, Euro I, Euro II, Euro III and Euro IV technologies, and the model year ranges from 1992 to 2010.

2. Experimental section

We employed a PEMS produced by Sensors Inc. to measure vehicle emissions under real driving conditions. The PEMS consists of a SEMTECH-DS gaseous analyzer and an EFM-2 exhaust mass flow meter. SEMTECH-DS is able to test instantaneous emissions of gaseous pollutants, such as CO2, CO, HC, and NOx. SEMTECH-DS measures CO2 and CO with infrared absorption technology, NOx with ultraviolet absorption technology, and HC with a flame ionization detector. In addition, a temperature/pressure sensor and a GPS device were included to monitor environmental situation, and instantaneous location and speed. In addition, an EFM-2, a 2-inch exhaust flow measurement device, was used in this study to measure instantaneous exhaust mass flow rates from the vehicles. To assure the accuracy of the test results, the SEMTECH-DS was zeroed with pure nitrogen before each test and was calibrated with standard gases before the first test of the day (Yao et al., 2011; Liu et al., 2009).

During the tests, the PEMS was equipped inside the test cars. The test cars were driven following the traffic on pre-designed test routes. The test cars were rented from private car owners and car rental companies. A total of 57 LDGVs were measured in Beijing, Guangzhou, and Shenzhen, including six Euro 0 cars, nine Euro I cars, 22 Euro II cars, 13 Euro III cars and seven Euro IV cars, as shown in Table 2.

Table 2 presents the CO, HC and NOx emission factors under real driving conditions (g/km). During the tests, the PEMS was equipped inside the test cars. The test cars were driven following the traffic on pre-designed test routes. The test cars were rented from private car owners and car rental companies. A total of 57 LDGVs were measured in Beijing, Guangzhou, and Shenzhen, including six Euro 0 cars, nine Euro I cars, 22 Euro II cars, 13 Euro III cars and seven Euro IV cars, as shown in Table 2.

3. Experimental results

3.1. Emission factors under real driving conditions

We derived the CO, HC, and NOx emission factors of the vehicles from the measurement data. Figs. 1–3 present the CO, HC and NOx emission factors of the LDGVs measured in the three cities of China.
emission factors of LDGVs in Beijing, Guangzhou, and Shenzhen. Table 3 summarizes the average emission factors of the 57 LDGVs measured in the three cities. As shown, the variation in emission factors by technology shows a good agreement across the three cities. The emission level declines significantly as the vehicle technology improves. On average, the vehicle emission factors are reduced by 47–81%, 53–64%, 46–71%, and 78–82% for each phase from Euro I to Euro IV.

Euro 0 vehicles have a considerably higher emission level than other vehicle technologies. For instance, the CO emission factors of Euro 0 LDGVs are about two times those of Euro I vehicles, 3–12 times those of Euro II vehicles, 4–36 times those of Euro III vehicles, and 90–300 times those of Euro IV vehicles. For HC emission factors, Euro 0 vehicles are two times, 6–17 times, 21–65 times, 140–380 times higher than Euro I, Euro II, Euro III, and Euro IV vehicles, respectively. According to our measurement results, Euro 0 vehicles could generate hundreds of times more pollutants than Euro IV vehicles per unit distance driven. The Ministry of Environment Projection of China (MEP) (2010) reported that Euro 0 cars and light-duty trucks (known as yellow-labeled vehicles) for new ones (Ministry of Commerce of China et al., 2009), and the rebates were doubled (tripled for some vehicle types) in 2010 (Ministry of Commerce of China et al., 2010). However, the practical effect of this measure is yet to be evaluated.

Several studies have been performed in China to measure emissions from LDGVs. Our previous studies (Wang et al., 2005a; Yao et al., 2007) utilized a five-gas analyzer to measure 49 LDGVs on real roads in seven Chinese cities during 2003 and 2005. Guo et al. (2007a) collected on-road emission rates of approximately 32,000 vehicles using remote sensing instruments in Hangzhou during 2004 and 2005. Wang et al. (2008a) tested 7 LDGVs using a five-gas analyzer in Shenzhen in 2004 and 2005. By using a set of OBS-2200 system developed by Horiba, Oliver (2008) tested 74 cars in Tianjin in 2006 and 53 cars in Beijing in 2007. Fig. 4 compares the emission factors derived from this work and previous studies. Although these studies used different measurement instruments and conducted in different years, the emission factor results of each technology category are comparable among these studies after proper adjustment. For the same emission control technology, the emission factors obtained from this study are generally higher than those from previous studies, which might be caused by the fact that vehicle emissions could deteriorate over time. It is also observed from Fig. 4 that the magnitude of the differences in CO and HC emission factors between this study and previous studies are larger for older vehicles than for newer vehicles, and the possible reason could be that the emission deterioration rates (DRs) become higher when vehicles get older (Pollack et al., 2004; U.S. EPA, 2011).

The AP-42 document (Compilation of Air Pollutant Emission Factors) released by the U.S. Environmental Protection Agency (EPA) (2011) provides the DR values of LDGVs of model years from pre-1968 to 1998+, but emission deterioration of vehicles in China have not been looked into in previous studies or reported in available official documents. The EPA’s vehicle emission factor model (MOBILE model) has been used intensively in China during the past decades, so it is important to examine the discrepancy between the measurement results in China and the U.S. EPA data.

Although the numbers of vehicles measured in this study and our earlier study (Yao et al., 2007) were too few to generate reliable DR data, we tried to reveal the characteristics of emission deterioration levels of the measured vehicle fleet and compare them to the U.S. EPA data, as shown in Table 4. We consider two approaches to calculate the emission DRs: (1) by regressing the linear changes in emission factors against changes in accumulate mileage using the measurement results of this study, and (2) by dividing the difference in average emission factors obtained in this study and our previous study (Yao et al., 2007) by the time interval. Note that the U.S. EPA data are based on laboratory tests, while the DR values of this study are under real driving conditions. As Table 4 shows, the DR values from the two approaches show some inconsistency, which is attributed to manifold reasons but the primary reason is...
the fact that the number of samples are not statistically significant for either approach. Nevertheless, the DR values of the measured fleet in China are found in a comparable range to the U.S. EPA data in terms of order of magnitude. In general, the DRs of the measured fleet are 5–60% lower than those of the corresponding vehicles in the U.S.

Emission deterioration of Chinese vehicles has not been well addressed because vehicle emission measurements are very limited in China. It should be mentioned that the DRs presented in Table 4 are only for the measured fleet, and cannot represent the entire LDGV fleet in China. In order to obtain reliable and representative DRs, a far larger amount of measurements have to be conducted in more extensive regions in China, which will need widespread and sustained efforts from the government and the academic community, both domestically and internationally.

### 3.2. NEDC-based emission factors

China uses the European standard test procedure (New European Driving Cycle, NEDC) for the national emission standards. We converted the emission factors under real driving conditions to NEDC-based emission factors to evaluate how well Chinese LDGVs are compliant with the emission standards. We applied the International Vehicle Emission (IVE) model (a vehicle emission model developed by International Sustainable Systems Research Center and University of California at Riverside) to normalize the emission factors under real driving conditions to the NEDC-based emission factors. The normalization procedure is documented in our previous study (Yao et al., 2011).

Fig. 5 presents the NEDC-based CO, HC, and NOx emission factors of the vehicles measured in Beijing, Guangzhou, and

![Graph](image-url)

**Table 4**

<table>
<thead>
<tr>
<th></th>
<th>This study</th>
<th>Yao et al. (2007)</th>
<th>DR I</th>
<th>By regressing the results of this study</th>
<th>DR II</th>
<th>U.S. EPA (2011)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Emission Factors (A)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>CO g/km</td>
<td>33.4</td>
<td>23.9</td>
<td>0.35</td>
<td>g/km/10⁴ km</td>
<td>0.95</td>
<td>1970–1979, 1.00</td>
</tr>
<tr>
<td>Euro II</td>
<td>11.3</td>
<td>6.6</td>
<td>0.13</td>
<td>g/km/10⁴ km</td>
<td>0.44</td>
<td>1980–1992, 0.56</td>
</tr>
<tr>
<td>Euro II</td>
<td>4.1</td>
<td>3.04</td>
<td>0.11</td>
<td>g/km/10⁴ km</td>
<td>0.11</td>
<td></td>
</tr>
<tr>
<td><strong>Emission Factors (B)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Numbers of samples</td>
<td>57</td>
<td>49</td>
<td>57</td>
<td>57 + 49</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Euro II</td>
<td>3.6</td>
<td>2.0</td>
<td>–</td>
<td>0.16</td>
<td>0.16</td>
<td>1970–1979, 0.10</td>
</tr>
<tr>
<td>Euro II</td>
<td>0.70</td>
<td>0.54</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
<td>1980–1993, 0.03</td>
</tr>
<tr>
<td>Euro II</td>
<td>0.31</td>
<td>0.27</td>
<td>0.03</td>
<td>0.004</td>
<td>0.004</td>
<td>1994–1998, 0.03</td>
</tr>
<tr>
<td>NOx g/km</td>
<td>1.87</td>
<td>1.63</td>
<td>0.01</td>
<td>0.026</td>
<td>0.026</td>
<td>1973–1979, 0.028</td>
</tr>
<tr>
<td>Euro II</td>
<td>1.02</td>
<td>0.90</td>
<td>0.05</td>
<td>0.013</td>
<td>0.013</td>
<td>1980–1993, 0.031</td>
</tr>
<tr>
<td>Euro II</td>
<td>0.47</td>
<td>0.39</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>1994–1996, 0.032</td>
</tr>
</tbody>
</table>

*We assumed that LDGVs in China travel 20,000 km per year (He et al., 2005; Huo et al., 2009). Euro 0 LDGVs in China were considered to be equivalent, in terms of vehicle emission control levels, to the U.S. LDGVs that were produced in the 1970s (Hao et al., 2000). Euro I LDGVs in China are equivalent to the U.S. LDGVs of model years 1980–1993. Euro II vehicles in China are equivalent to Tier I LDGVs in the U.S. (1994+). Negative value.*
Shezhen, as well as the emission limit values of the standards for each technology level. Newer vehicles comply with the standards much better than older vehicles. The average CO emission factors of the Euro I, Euro II, Euro III, and Euro IV vehicles measured are 4.6 times, 1.9 times, equivalent to, and 40% of the standard limit values respectively, and the average NOx emission factors of the Euro I through Euro IV vehicles are 2.6 times, 2.2 times, 1.7 times, and 68% of the standard limits. Vehicles can meet the HC limit values for all phases, and Euro IV vehicles can even get 80% lower than the HC standard limit.

3.3. Super emitters

Super emitters usually represent a small fraction of the vehicle fleet but are responsible for a large fraction of the total vehicle emissions. Zhou et al. (2005)’s remote sensing study showed that 50% of CO, HC, and NOx emissions come from 15.9%, 14.0%, and 11.1% of the vehicle fleet in Beijing during 2002 and 2003. Therefore, removing super emitters from roads is considered to be an effective way to reduce mobile source emissions. Through this study, we identify three types of super emitters in China. Obviously, Euro 0 vehicles are one of them due to their poor emission control technology. Heavily-used taxis are another group of super emitters. The third group could be a combination of malfunctioning vehicles, improper or inadequate maintenance, damage, and owner/mechanic tampering (Zhang et al., 1995).

Taxis usually travel 3–6 times farther than non-taxi cars annually in China, therefore they are expected to have higher emission levels. Fig. 5 marks the nine taxi samples measured in this study (one Euro I, two Euro II, two Euro III, and four Euro IV). Euro I and Euro II taxis are observed to have higher emission factors than most other vehicles, but the emission factors of Euro III and Euro IV...
taxis are lower than the average, indicating that emission control units of taxis might have seriously malfunctioned due to the intensive use (the accumulated mileage readings of the measured Euro I and Euro II taxis were over 500,000 km). The Euro I taxi was seven years old and the two Euro II taxis were three and four by the time they were measured. China requires taxis to be scrapped after eight years of service (6 years in Beijing), while it seems that the service period of taxis should be further shortened given the poor emission performance of old taxis, and stringent inspection and maintenance procedure are needed for old taxis.

Besides Euro 0 vehicles and high mileage taxis, there are a number of super emitters whose emission factors times over the limit values. Taking Euro II LDGVs as an example, four out of the 22 measured vehicles have a CO emission factor over three times the limit values. Euro 0 vehicles produce an even more equivalent emission level to Euro 0 vehicles. Besides quickening the retirement of low-technology Euro 0 vehicles and heavily-used taxis, it is also important to reinforce the management to detect super emitters and prohibit them from running on roads.

Table 5 calculates the contributions of the super emitters identified in this study to the total emissions from the measured vehicle fleet. These three types of super emitters account for 23% of the fleet, but could contribute 60–80% to the total emissions under the assumption that all vehicles have the same annual vehicle kilometer traveled (VKT). Euro 0 vehicles produce an even more disproportionate share of total emissions, contributing 30–60% of the emissions with 10% of the fleet. On the other hand, cars are usually used less intensively when they get older and taxis tend to travel much more than other cars in China, therefore, if we take into consideration the changes in VKT among vehicles of different ages and uses (taxis and non-taxi), the contribution of the super emitters would decrease to 50–70%, but is still very high compared to their share of the fleet (23%). Old taxis become a major contributor, with only 5% of the fleet responsible for 20–32% of emissions. According to our estimation, eliminating an old taxi might double the emission reduction benefit than eliminating a Euro 0 car.

4. Conclusions and discussion

China has adopted a series of measures to control vehicle emissions, and implementing emission standards for new vehicles is one of the most effective measures. The first phase of the standard (Euro I) was implemented in 2000, now the Euro III emission standard has been in effect nationwide. In some mega-cities such as Beijing, Shanghai, Guangzhou and Shenzhen, Euro IV emission standard has been carried out in advance. Because China implemented four phases of emission standards within only 10 years and vehicles usually last for 15 years in China, the technology mix of the current vehicle fleet in China is complex, ranging from Euro 0 to Euro IV vehicles that differ in emission factors by hundreds of times. An accurate vehicle emission inventory for China requires not only precise technology mix information of the vehicle fleet but also an accurate understanding of emission levels of all major vehicle technologies on roads, which could only be acquired in the basis of a sufficient amount of emission measurements. This study attempts to take a step toward this understanding. We measured 57 LDGVs in three Chinese mega-cites (Beijing, Guangzhou, and Shenzhen), which covered the Euro 0 through Euro IV technologies, and generated emission factors and deterioration rates for each vehicle technology. However, it is important to mention that the results obtained in this study are subject to large uncertainties due to the limited number of samples measured. A lot more measurements are definitely needed for more reliable emission factors and deterioration rates. Also, the measurements should be conducted in more extensive regions to reduce uncertainties that might caused by different local conditions, such as driving patterns, altitude, temperature, oil quality, etc.

According to this study, vehicle emission standards have played a significant role in reducing vehicle emission factors of individual vehicles. Therefore, more stringent emission standards, such as Euro IV for the whole country and Euro V/VI for mega-cities, should be introduced as quickly as possible, especially during this period that vehicles are growing dramatically in China.

On the other hand, identifying and restricting super emitters is equally important to reducing vehicle emissions. Vehicle fleet turnover is a slow process (usually 15 years in China), so there are still a number of Euro 0 vehicles in operation in China. These vehicles could contribute significantly to total emissions because their emission factors are much higher than those of other vehicles. Scarping or restricting these vehicles would bring a great benefit in reducing vehicle emissions in China. In addition, this study found that Euro I and Euro II taxis were heavily polluting because the intensive use might have caused serious malfunction of emission control. Four LDGVs besides the Euro 0 vehicles and old taxis were observed to have equivalent emission levels to Euro vehicles, which could be regarded as another type of super emitters. These super emitters are responsible for a disproportionately large percentage of CO, HC, and NO emissions. According to this study, the super emitters identified accounted for 23% of the measured vehicle fleet, but could contribute 59–74% to CO emissions, 71–82% to HC emissions, and 51–58% to NOx emissions.

Table 5 Contributions of each type of super emitters to total emissions from the vehicle fleet measured in this study.

<table>
<thead>
<tr>
<th>Numbers</th>
<th>Share of the measured fleet</th>
<th>Contributions to total emissions of the measured fleet</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>CO</td>
</tr>
<tr>
<td>Assuming the same VKT for all vehicles</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Euro 0</td>
<td>6</td>
<td>10.5%</td>
</tr>
<tr>
<td>Euro I and Euro II Taxis</td>
<td>3</td>
<td>5.3%</td>
</tr>
<tr>
<td>Other super emitters</td>
<td>4</td>
<td>7.0%</td>
</tr>
<tr>
<td>All</td>
<td>13</td>
<td>22.8%</td>
</tr>
<tr>
<td>Considering variation in VKT by vehicle age and difference in VKT between taxis and non-taxi</td>
<td>6</td>
<td>10.5%</td>
</tr>
<tr>
<td>Euro I and Euro II Taxis</td>
<td>3</td>
<td>5.3%</td>
</tr>
<tr>
<td>Other super emitters</td>
<td>4</td>
<td>7.0%</td>
</tr>
<tr>
<td>All</td>
<td>13</td>
<td>22.8%</td>
</tr>
</tbody>
</table>

a Excluding Euro 0 and taxis.

b Variation factors of VKT were determined on the basis of VKT investigations we conducted in five cities (Beijing, Chengdu, and Foshan, Tianjin, and Yichang) during 2006 and 2010. For instance, taking the VKT level of new cars (excluding taxis) as 1.0, then the VKT levels of one-year, three-year, and five-year cars are 0.98, 0.93, and 0.85, respectively. The VKT level of new taxis is 5.3, and those of one-year, three-year, and five-year taxis are 5.3, 4.9, and 3.3 (Huo et al., in press).
Among the three types of super emitters in China, old taxis are the easiest for the government to identify and manage because most taxis in China belong to companies. In this sense, the government should impose strict measures on old taxis. While China has made effort to control Euro 0 vehicles, such effort is also needed for old taxis. In addition, taxis travel in urban areas more frequently than Euro 0 cars do, especially in the cities where Euro 0 vehicles are forbidden in urban central areas (e.g. Beijing, Guangzhou, and Shenzhen), therefore, having old taxis scrapped quickly can also offer great benefit in urban air quality improvement.

Vehicles have become a large pollution source in China. As vehicles grow in China, the vehicle pollution issue is becoming more serious and complicated, and addressing the issue relies on multiple effective measures, which should be based on extensive emission measurements and comprehensive modeling studies. The accumulation of fundamental vehicle emission factors and modeling methodology have been improved over the last decades in China, but are not yet sufficient compared to those of the U.S. and European countries. China is now the largest vehicle producer and seller in the world and is expected to be the largest vehicle owner in the world in 10–15 years (Huo et al., 2007), simulating vehicle emissions in China accurately in magnitude and distribution will be of a great significance to regional and global air quality and climate.

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