

RESPONSE TO REFEREE'S COMMENTS

Response for Referee 1

The paper describes a methodology to develop a high temporal-spatial resolution vehicle emission inventory for the urban area in Beijing based on the local emission factors and near real time (NRT) traffic data. I do find this paper very interesting and the authors have addressed all the previous comments in the revised copy of the paper. However, the following points need to be clarified, as well, for the benefit of the reader.

1. According to the authors, the Underwood model was used because of the best fitting effect among the Greenshields, Greenberg, and Underwood models. However, the authors haven't provided any comparison method and result.

Response: Thanks for your comment. Considering the structure and length of the article, we had simply described the comparison method and results in this paper. The detailed comparison method and results is as follows: Based on the traffic volume observed by the video identification data and traffic speed collected by floating car data, Greenshields, Greenberg, and Underwood models has been fitted respectively for three road types. And the above traffic speed data on 40 roads and in all periods were not zero. The goodness of fit (R^2) of Underwood model in the three speed-flow models was the best, as shown in STable 1-3. Therefore, Underwood model has been used to estimate traffic volume from traffic speed on every road segment in Beijing, and the parameters of Underwood model in different road types was different.

STable 1. Comparison of model equations and goodness of fit on urban freeways

Model	Equations	R^2
Greenshields model	$V = 98.14u(1 - \frac{u}{68.82})$	0.7588
Greenberg model	$V = 367.77ue^{-\frac{u}{18.27}}$	0.6779
Underwood model	$V = 56.05uln\frac{78.23}{u}$	0.8030

STable 2. Comparison of model equations and goodness of fit on artery roads

Model	Equations	R^2
Greenshields model	$V = 141.96u(1 - \frac{u}{45.72})$	0.6618
Greenberg model	$V = 252.40ue^{-\frac{u}{19.41}}$	0.8197
Underwood model	$V = 52.73uln \frac{63.14}{a}$	0.8576

STable 3. Comparison of model equations and goodness of fit on local roads

Model	Equations	R^2
Greenshields model	$V = 70.10u(1 - \frac{u}{45.73})$	0.5919
Greenberg model	$V = 88.28ue^{-\frac{u}{19.40}}$	0.7855
Underwood model	$V = 25.62uln \frac{63.13}{u}$	0.8364

2. I am wondering if the NOx emission rates showed in Fig 6 are for specific road types in Beijing (one specific freeway, one specific artery road, and one specific local road)? or they are average of NOx data on all the freeways, artery roads, and local roads in Beijing?

Response: In Fig 6, the data showed the average of NOx emission rates on freeways, artery roads and local roads in Beijing.

Response for Referee 3

As a typical metropolis, the vehicle emission factor and emission inventory in Beijing have been established by different teams and through various methods. The paper presented a high-temporal-spatial resolution vehicle emission inventory through NKT traffic data combined with COPERT model, and also provided vehicle emission of

pollutants in Beijing, etc. For the whole study, Authors do a lot of innovative work to gain good result, which provides a reference to Beijing or other cities in improving air quality. In view of the discussion to the paper, need further improvement towards the paper.

1 Title According to the title, the whole study concludes two parts, and the paper is part 1. The title of the paper cannot summarize well the whole content of the paper. Because the paper only built a high temporal-spatial resolution emission inventory, not more content describe the impact on air quality of Beijing.

Response: Thanks for your suggestion. The paper is the first part working in all. The impact on air quality of Beijing was described in a companion paper, which name is “Development of a vehicle emission inventory with high temporal–spatial resolution based on NRT traffic data and its impact on air pollution in Beijing – Part 2: Impact of vehicle emission on urban air quality”.

2 Abstract The abstract still need huge improvement to be concise. Authors use more words to describe study aim, etc. Abstract should summarize results and conclusions.

Response: Thank you for your suggestion. We had modified the abstract according to your remind, as follows: This paper presents a bottom-up methodology based on the local emission factors, complemented with the widely used emission factors of Computer Programme to Calculate Emissions from Road Transport (COPERT) model and near real time (NRT) traffic data on road segments to develop a vehicle emission inventory with high temporal-spatial resolution (HTSVE) for the Beijing urban area. To simulate real-world vehicle emissions accurately, the road has been divided into segments according to the driving cycle (traffic speed) on this road segment. The results show that the vehicle emissions of NO_x, CO, HC and PM were 10.54×10^4 , 42.51×10^4 and 2.13×10^4 and 0.41×10^4 Mg, respectively. The vehicle emissions and fuel consumption estimated by the model were compared with the China Vehicle Emission Control Annual Report and fuel sales thereafter. The grid-based emissions were also

compared with the vehicular emission inventory developed by the macro-scale approach. This method indicates that the bottom-up approach better estimates the levels and spatial distribution of vehicle emissions than the macro-scale method, which relies on more information. Based on the results of this study, improved air quality simulation and the contribution of vehicle emission to ambient pollutant concentration in Beijing have been investigated in a companion paper (He et al. 2015).

3 Results and Discussions “3.25 comparison between fuel consumption and fuel sales”, the section has not too much relation with the whole the paper.

Response: This section was aimed to evaluate the accuracy of vehicle emission inventory through the comparison between estimated fuel consumption and fuel sales in Beijing urban area indirectly.

4 Tables and Figures “Table 2” and “Table 3” can be integrated into a table. Table 2 shows weekday variation, whereas Table 3 presents weekend variation. They are put into a table to provide a comparison. Similarly, “Table 4” and “Table 5” can be combined a table.

Response: Thank you for your suggestion. We had integrated two set of table in the paper.

6 Technical errors The same as “8 to 9 am”, “from 5 to 6 p. m” should be “5 to 6 p. m”.

Response: Thank you for your advice. We had revised these clerical errors.

List of relevant changes made in the manuscript

NO.	Page	Line	Remark
1	page 1	line 2,3	
2	page 1	line 21	Delete two sentences
3	page 1	line 24,25	
4	page 2	line 1-4	
5	page 9	line 2-4	
6	page 10	line 9	
7	page 10	line 19	
8	page 11	line 20	
9	page 12	line 12	
10	page 13	line 24	
11	page 14	line 5	
12	page 15	line 9-11	
13	page 21	line 1	
14	page 22	line 1	
15	page 23	line 1	
16	page 32	line 2,3	

1 **Development of a vehicle emission inventory with high temporal–spatial**
2 **resolution based on NRT traffic data and its impact on air pollution in Beijing**

3
4 **Part 1: Development and evaluation of vehicle emission inventory**

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19
20 **Abstract:**

21 This paper presents a bottom-up methodology based on the local emission factors,
22 complemented with the widely used emission factors of Computer Programme to
23 Calculate Emissions from Road Transport (COPERT) model and near real time (NRT)
24 traffic data on road segments to develop a vehicle emission inventory with high
25 temporal-spatial resolution (HTSVE) for the Beijing urban area. To simulate real-world
26 vehicle emissions accurately, the road has been divided into segments according to the
27 driving cycle (traffic speed) on this road segment. The results show that the vehicle
28 emissions of NO_x, CO, HC and PM were 10.54×10^4 , 42.51×10^4 and 2.13×10^4 and
29 0.41×10^4 Mg, respectively. The vehicle emissions and fuel consumption estimated by
30 the model were compared with the China Vehicle Emission Control Annual Report and
31 fuel sales thereafter. The grid-based emissions were also compared with the vehicular
32 emission inventory developed by the macro-scale approach. This method indicates that
33 the bottom-up approach better estimates the levels and spatial distribution of vehicle

1 emissions than the macro-scale method, which relies on more information. Based on
2 the results of this study, improved air quality simulation and the contribution of vehicle
3 emission to ambient pollutant concentration in Beijing have been investigated in a
4 companion paper (He et al. 2015).

6 **1. Introduction**

7 Air pollutants from gases to particulates in megacities are associated with a mixture of
8 various sources, including primary/secondary and natural/anthropogenic sources, and
9 air pollution has become a major concern for human health (An et al. 2013). Emissions
10 from human activities and natural processes can react with ozone and light to form
11 secondary pollutants, which are more difficult to analyse. Resulting from the
12 complexities of local to regional emissions, the term “complex atmospheric pollution”
13 has emerged in the last decade (Chan and Yao, 2008; Fang et al., 2009). Driven by rapid
14 industrialization and urbanization, Beijing, the capital city of China, has received
15 extensive global attention regarding its contribution to the atmospheric environment.
16 Numerical model simulation is a very effective tool for proportionally estimating
17 contributions to air pollution from various sources under certain atmospheric conditions
18 (Cheng et al., 2007; Wang and Xie, 2009). The accuracy of emission source inventory
19 is the key for air quality numerical simulation. In recent years, transportation emissions
20 have become the most significant emission source in Chinese megacities (e.g., Beijing)
21 (He et al., 2002). There are different opinions of quantitative research regarding the
22 pollution contribution of vehicle emissions (Song et al., 2006; Cheng et al., 2013; Wu
23 et al., 2014).

24 Numerical model simulation is an effective method of quantifying a portion of on-road
25 vehicle emissions accounting for air pollution, particularly in different periods and
26 regions. However, numerical model simulation relies heavily on the accuracy of
27 mesoscale meteorological models and emission inventories, which have shown

1 significant improvements in the past two decades resulting from the development of
2 new physical parameterization and data assimilation techniques. Although plenty of
3 research exists on the climate characteristics of Beijing (An et al. 2007; Wu et al., 2014),
4 no integrated emission inventory model simultaneously reflects the factors of traffic
5 volume, speed and fleet composition at a particular road segment. Therefore, the
6 accuracy of emission source inventory in an air quality numerical simulation has
7 become a challenge.

8 The establishment of vehicle emission inventory requires a large amount of data, such
9 as emission factors, traffic activity, fleet composition, and the combined situation of
10 these factors, which is strongly influenced by the local driving circle, road information,
11 traffic characteristics, etc. Until recently, most of the emission inventories in Chinese
12 cities have been developed by utilizing the MOBILE model from the U.S.
13 Environmental Protection Agency (EPA) or similar macro-scale models (Hao et al.,
14 2000; Fu et al., 2001; Cai and Xie, 2007; Guo et al., 2007), in which the inventory
15 approach is defined as a top-down method. For this method, the emission factors are
16 uniform for the same vehicle category in the entire study region, combined with the
17 number of kilometres travelled (VKT) for each vehicle fleet, to estimate the average
18 emissions on the large geographic scale. Then, emissions are allocated as required by
19 the air quality model to hourly or daily emissions by the local time varying
20 characteristic and allocated to grid cells by the local population and/or road density.

21 However, there are some limitations in the top-down methodology. For example, the
22 same emissions factors under average speed circumstances cannot reflect the influences
23 of velocity changes at different road segments at different times; the spatial and
24 temporal distribution method cannot reflect the dramatically difference of traffic flow
25 characteristics on various road segments (Reynolds, 2000). Thus, the macro-scale
26 emission inventories may not reflect the real emission conditions for on-road vehicle in
27 the city, and the low spatial and temporal resolutions are also limited in the application

1 of air quality models. Additionally, because the strategies are converted to individual
2 vehicles (e.g., requiring stricter emission limits for new vehicles, strengthening the
3 management of in-use vehicles, eliminating high-emitting vehicles) and transportation
4 management (e.g., developing public transportation, improving travel conditions,
5 adopting traffic control measures), the top-down inventories are not able to assess the
6 effects of air quality improvement from the implemented strategies because of the
7 limited reflection of spatial and temporal variation in complex urban traffic conditions.
8 Therefore, more accurate and higher resolution vehicle emission inventories are
9 currently needed in Beijing.

10 There are two obstacles in the establishment of vehicle emission inventory including
11 reliable vehicular emission factors based on the local vehicle emission conditions and
12 comprehensive traffic data (e.g., traffic volume, speed and fleet composition)
13 displaying the traffic flow characteristics of each road (Wang, 2008). With the
14 deepening of research, there were some higher resolution vehicle emission inventories
15 in Chinese cities established based on bottom-up methodology (Wang, 2008; Huo, 2009;
16 Wang, 2009; Zhou et al., 2015). However, most of those inventories had some
17 limitations in reflection on real-time variation of vehicle emission on each road, due to
18 the lack of collection methodology of real-time traffic data.

19 Driven by the development of traffic data observation technology, the conventional
20 loop coil detector and video detector are gradually turning to a high cost-benefit sensor
21 system. This system now makes the acquisition of mass fine traffic data feasible.
22 Meanwhile, the rapid development of geographic information system (GIS) and global
23 positioning system (GPS) technology makes a strong connection between traffic
24 activity data and road information. Infrastructure sensors and floating cars are believed
25 as the main sources for the current traffic data collection. The infrastructure sensors
26 consist of fixed-point detectors installed in roads, and floating cars are consist of mobile
27 probe vehicles (e.g., buses and taxis) with GPS positioning devices. The information

1 collected by the infrastructure sensors from static point of a road, which is lacking of
2 space coherence, is difficult to cover the entire road network of the city (Naranjo et al.,
3 2012).

4 Floating cars collect information from the vehicles that travelled on the road segments,
5 data which is then utilized to estimate the average speeds, traffic intensity and other
6 relevant conditions (e.g., congestion status). However, the temporal and spatial
7 resolution of current traffic data are too low to establish hour-scale and road-scale
8 vehicle emission inventory. It needs near real time (NRT) traffic data on entire network,
9 which can be collected by integration of the floating car data, radio frequency
10 identification data and video identification data.

11 The purpose of this paper is to develop a high temporal-spatial resolution vehicle
12 emission inventory for Beijing based on local emission factors and NRT traffic data
13 using a bottom-up methodology. The road system of Beijing, the capital of China,
14 consists of urban freeways, artery roads, collector roads and local roads. The scope of
15 this research is the area within the sixth ring road and the surrounding area, which is
16 the main activity area for people in Beijing. This project is divided into two parts: Part
17 A elaborates on the development of a high temporal-spatial resolution vehicle emission
18 inventory in Beijing, and Part B analyses the effect of vehicle emissions on urban air
19 quality.

20 **2. Methodology and Data**

21 In this study, a vehicle emission inventory model based on bottom-up methodology was
22 used to develop an inventory for vehicular emissions. The model simulated the
23 emissions for each road segment during each hour, depending on the traffic volume and
24 the emission rates of these vehicles on the road segment during the period:

$$25 \quad Q_{i,j}^p = \sum_c EF_{c,v}^p \times VT_{c,i,j} \times L_i \quad (1)$$

1 where $Q_{i,j}^p$ are the emissions of pollutant p on road segment i at moment j, g/h; $EF_{c,v}^p$
2 is the emission factor of pollutant p for vehicle category c at speed v, g/km; $VT_{c,i,j}$ is
3 the traffic volume of category c on road i at moment j, veh/h; L_i is the length of road
4 i, km. The total urban emission is the sum of the vehicle emissions on all roads.

5 There are three necessary elements for the model: emission factors, vehicle activity and
6 road segment information. Emission factors are based on the mass of the laboratory
7 measurement and the on-road measurement data. The vehicle activity included traffic
8 volume, average speed and fleet composition on the entire road segment. Road
9 information consists of road length, line number and road type (including freeway,
10 artery road, collector road and local road) of each road segment. In terms of the traffic
11 speed on this segment, the road has been divided into fine segmentations and was
12 grouped as urban freeway, artery road, or local road (a local road consists of collector
13 roads and residential roads because of the little differences between them in Beijing).

14 **2.1 Emission factors**

15 It is widely known that vehicle emission rates are largely related to vehicle
16 characteristics, including vehicle classification, utilization parameters, operating
17 conditions, and environmental conditions. The vehicle characteristics comprise vehicle
18 category, fuel type and vehicle emission control level; the utilization parameters
19 involve vehicle age, accumulated mileage, inspection and maintenance; the operating
20 conditions includes cold or hot starts, average vehicle speed and the influence of driver
21 behaviour; the environmental conditions include ambient temperature, humidity and
22 altitude.

23 Due to the significant differences among different vehicle classification, the emission
24 factors were classified by the vehicle classification and modified by the utilization
25 parameters, operating conditions and environmental conditions in Beijing. With the
26 existing classification method of the Ministry of Environmental Protection and the

1 Ministry of Transport in China, vehicles have been classified as follows: 1) vehicle
2 category was classed as a light duty vehicle (LDV), middle duty vehicle (MDV), heave
3 duty vehicle (HDV), light duty truck (LDT), middle duty truck (MDT), heavy duty
4 truck (HDT), bus or taxi; 2) fuel type was classified as gasoline, diesel or other (e.g.,
5 liquefied natural gas or compressed natural gas); 3) vehicle emission control levels were
6 classified as Pre-China I, China I, China II, China III, China IV and China V, which
7 were respectively equivalent to Pre-Euro, Euro I, Euro II, Euro III, Euro IV and Euro
8 V.

9 The emission factors were corrected by the widely used emission factors of Computer
10 Programme to Calculate Emissions from Road Transport (COPERT) model on the basis
11 of local emission factors. The local emission factors were collected from a mass of
12 measuring data from the Tsinghua University and China Automotive Technology &
13 Research Center, such as bench testing and on-road vehicle emissions measurements in
14 Beijing (Huo, 2009; Hu et al., 2012; Wu et al., 2012; Wang et al., 2013). Meanwhile,
15 the fuel consumption (FC) factors for vehicles were measured and included in this
16 model. The emission factors of NO_x, HC, CO, PM and the fuel consumption factors of
17 gasoline and diesel are shown in Fig. 1.

18 **2.2 Vehicle Activity**

19 The model based on the NRT traffic volume and speed of the road segment, which were
20 collected by the NRT floating car data and video identification data in 2013, was
21 utilized to simulate the emission inventory. The fleet composition was collected by
22 traffic survey data and vehicle registration information in Beijing.

23 According to the GPS data from on-road vehicles, the floating car data covered
24 information within two weeks for the entire city. The video cameras were installed on
25 typical roads to gather video identification data. The data collection points are shown

1 in Fig. 2. The traffic survey data were collected from a video field survey of more than
2 300 minutes on typical roads.

3 **2.2.1 Average running speed based on floating car data**

4 Floating car data technology is recently believed to be an advanced technological
5 method to collect traffic information in intelligent transport systems (ITS). Based on
6 GPS devices, floating cars periodically record information such as time, speed, latitude
7 and longitude while moving and send those data back to an information centre via on-
8 board wireless transmission equipment. In this research, the floating car data were
9 processed to calculate the average speed following the steps below: 1) the unqualified
10 data of each transfer interval longer than 150 seconds at speeds over 120 km/h were
11 filtered; 2) the position data from floating car within the road segment was fixed by the
12 map algorithm by matching and route estimation; 3) the single vehicle speed was
13 calculated by the travel length divided by the travel time, 4) the single vehicle speed on
14 the same road segment within an hour were averaged to find the average running speed
15 value. Therefore, the hourly average running speed on each road segment is obtained
16 from the floating car data collection and processing. The average vehicle running speed
17 is one of the important parameters of traffic data, which is utilized to estimate traffic
18 flow.

19 **2.2.2 Traffic flow from speed**

20 The traffic volume was estimated by the average speed based on the relationship
21 between the traffic speed and volume. The relationship between the traffic speed and
22 volume and the same speed-flow model was established using models such as the
23 Greenshields model, the Greenberg model and the Underwood model (Wang, 2013;
24 Hooper, 2014).

25 According to the traffic volume observed by the video identification data and traffic
26 speed estimated by floating car data, the speed-flow model for the traffic in Beijing was

1 designed on every road segment and was grouped into three road types including the
2 urban freeway, artery roads and local roads. In this study, Greenshields, Greenberg, and
3 Underwood models was fitted respectively for three road types. The Underwood model
4 was used because of the best goodness of fit (R2) among these models.

$$5 \quad V = k_m u \ln \frac{u_f}{u} \quad (2)$$

6 where V is the traffic volume at speed u , veh/h; u is the traffic speed, km/h; k_m is
7 the best fitting traffic density, veh/km; u_f is the free-speed, km/h. k_m and u_f were
8 determined by fitting the Underwood model based on the video identification data and
9 the floating car data from the different road types.

10 **2.2.3 Vehicle fleet composition**

11 Considering the significant emission differences between different vehicles, more
12 attention should be paid to emission control technologies (Heeb et al., 2003; Karlsson,
13 2004). The fleet composition of driving vehicles is estimated to calculate emissions
14 based on vehicle information and the video data from typical roads in Beijing.

15 **3. Results and Discussions**

16 **3.1 Traffic characteristics in Beijing**

17 Traffic speed, traffic volume and fleet composition show the main characteristics of
18 vehicle activities that quantify vehicle emissions in Beijing. According to the floating
19 GPS car data, the hourly average traffic speed fluctuates at different times throughout
20 the day but shows similarity for the different road types. The daily average traffic speed
21 on weekdays is close to the weekend speeds, as illustrated in Fig. 3; however, the trends
22 of hourly traffic speed on the urban freeway and the artery roads changes significantly
23 from weekdays to weekends. There are two low-speed valleys on weekdays during the
24 early and afternoon peak hours at approximately 8 a.m. and 6 p.m. (GMT +8),
25 respectively. On weekends, the early valley period appears two hours later, and the late

1 valley period appears one hour early than on weekdays. The traffic speed is lower than
2 that on weekdays during the off-peak hours. For the local road, the variation of traffic
3 speed is similar between weekdays and weekends.

4 The traffic volume of vehicles contributes significantly to influence pollutant emissions.
5 As shown in Fig. 4, the average daily traffic volume on weekdays is close to the traffic
6 volume on weekends. However, the variation tendencies display a different picture
7 during different moments between weekdays and weekends. The overall traffic volume
8 changes dramatically at different times during a day, and two obvious peaks of traffic
9 volume appear at 8 a.m. and 6 p.m. On weekends, the early peak period appears two
10 hours later, and the late peak period appears one hour early than on weekdays: the
11 variation extent around the traffic volume peak is significantly lower than on weekdays.

12 The contributions to emission vary significantly based on different types of vehicles.
13 Therefore, the fleet composition is a major factor affecting the release of emissions, as
14 showed in Table 1.

15 **3.2 Vehicle emission inventory**

16 **3.2.1. Emission inventory**

17 Using the methodology described above, a high temporal-spatial resolution vehicle
18 emission inventory (HTSVE) was established in this study. The total daily emissions
19 of each road, which is a sum of emissions during a 24 hour period, is shown in Table 2.

20 The daily total emissions of the urban freeway, the artery roads and local roads are
21 288.71 Mg of NO_x, 58.29 Mg of HC, 116.58 Mg of CO and 11.24 Mg of PM,
22 respectively. It is clear that the emissions of each pollutant display a descending order
23 for the urban freeway, the artery road and the local road. High emission intensity and
24 the long length of artery road (approximately 33% of total length of roads in Beijing)
25 contribute to the highest emissions. Although the urban freeway length is 2169 km
26 accounting for 22% of total length of roads in Beijing, the emissions of the urban

1 freeway account for more than 38% of the total emissions, which is a little lower than
2 the artery roads for each type of pollutant. The local road emissions are lower than those
3 on the urban freeways and artery roads; although, the length of local roads is the longest
4 in Beijing (approximately 38% of the total length of roads).

5 The spatial distributions of emissions among the night, off-peak hours, morning and
6 afternoon peak hours are illustrated in Fig. 5. With the assistance of ArcGIS, vehicle
7 emissions are estimated at a 1 km × 1 km resolution for the Beijing urban area. The
8 emission intensity of vehicles decreases from the centre to the periphery of the city with
9 a radiating structure during the night, off-peak, morning and afternoon peak hours. The
10 reason for the high emissions at the city centre is mainly caused by the high traffic
11 volume and low vehicle speed. In the surrounding areas of Beijing, the high emissions
12 are mostly distributed in the areas including the urban freeways and the major
13 intersections.

14 As illustrated as Fig. 5, the northern areas have the highest emission intensities, the
15 southern areas have the lowest emission intensities, and the emission intensities of
16 eastern areas are slightly higher than the western areas. The difference of emissions
17 among the various areas is mainly caused by the different degrees of prosperity. More
18 business activities and human activities occur in the northern areas than other areas,
19 leading to more intensive traffic activities in the northern areas.

20 The emission intensity of 8 to 9 a.m. and 5 to 6 p.m. is much higher than for the rest of
21 day because of high traffic volume during those times. Due to serious traffic congestion,
22 vehicles emit more pollutants when they operate at low speed with frequent
23 accelerations, decelerations and in idle mode.

24 **3.2.2 Temporal variation in emissions**

25 According to the emission factors and vehicle activities, the vehicle emission
26 inventories model mentioned above was used to calculate the pollutant emissions rate.

1 The emissions of NO_x, HC, CO and PM show similar trends within a day. For example,
2 the emissions of NO_x vary throughout the day but reach agreement among the urban
3 freeway, artery roads and local roads, as shown in Fig. 6. However, there is an obvious
4 difference in the vehicle emissions scenario between emissions on weekdays and
5 weekends. For all road types, the temporal variations of vehicle emissions are much
6 closer to the traffic flow, occurring separately at two emission peaks in the morning and
7 afternoon. The daytime emissions account for approximately 70% of the daily total
8 emissions because most private and business activities are conducted during the
9 daytime.

10 **3.2.3 Spatial variation in emissions**

11 As a result of the vehicle emission inventories model, the spatial distribution of
12 emissions has a strong correlation with the location of Beijing. Table 3 summarize the
13 emission intensities in different areas of Beijing on weekdays and weekends. For both
14 weekdays and weekends, vehicle emission intensities in the centre area of the city are
15 higher than in the outside areas. The area between the second and third ring has the
16 strongest emission intensity because of its intensive road system and intense traffic
17 activities (show as higher volume and lower traffic speed). Although the urban centre
18 (within the second ring) has the highest traffic density and the lowest traffic speed, the
19 high density of freeways and artery roads in the area between the second and third ring
20 cause the highest vehicle emission intensities, which is consistent with the forecast in
21 2004 that the emission intensities in the areas between the second and fourth rings could
22 be as high as those in the urban centre, caused by rapid construction on the outside of
23 the city centre (Huo, 2009).

24 **3.2.4 Contribution of vehicle classification**

25 Each vehicle on road is used for the estimation of the bottom-up vehicle emissions. The
26 contribution of different vehicle types is shown in Fig. 7. Although the number of LDV

1 is highest, its NO_x and PM emission contributions are lower than HDT and Bus; its PM
2 emission is even lower HDV. The HC and CO emission contributions of LDV and HDT
3 account for the largest proportion. As shown in Fig. 8, the vehicles with lower emission
4 control levels have the higher emission contributions.

5 **3.2.5 Comparison between fuel consumption and fuel sales**

6 Based on the fuel consumption factors and vehicle activities, the fuel consumption of
7 on-road vehicles was calculated by this model. The gasoline and diesel consumption
8 was 429.63×10^4 Mg and 141.02×10^4 Mg, respectively, for the Beijing urban core area
9 in 2013. According to the data from the petroleum sale company, the retail sales of
10 gasoline and diesel fuel for the area in 2013 were 364×10^4 Mg and 121×10^4 Mg,
11 respectively. However, the consumption of gasoline and diesel was 18% and 16.5%
12 higher than the sales of gasoline and diesel, respectively, because out-of-town vehicles
13 driving into Beijing commonly refuelled outside of the city.

14 In order to estimate the effects of out-of-town vehicles on fuel consumption calculation,
15 the number of permissions to permit out-of-town vehicles enter to Beijing collected
16 from Beijing Vehicle Emission Management Centre, the travel distance and time
17 investigated from some drivers of out-of-town vehicles. The statistics results shows that
18 there were 80 million out-of-town vehicles driving into Beijing, and each vehicle
19 travelled two days in Beijing with the distance of 100 km per day. According to the
20 above statistics, the VKT of out-of-town vehicles accounts for 12.6% of the total VKT.
21 If the fuel consumption of the out-of-town vehicles is added, the total fuel consumption
22 values are closer to the fuel sale values.

23 **3.3 Comparison with other inventories**

24 **Table 4** illustrates some uncertainties that exist in HTSVE after a comparison with
25 vehicle emission inventory of Chinese Unified Atmospheric Chemistry Environment
26 (hereafter refer to VECU) developed by China Meteorological Administration (He et

1 al., 2015) and inventory of China Vehicle Emission Control Annual Report (Ministry
2 of Environmental Protection of the People's Republic of China, 2013). By comparing
3 vehicle emissions between HTSVE and VECU, it is clear that NO_x and HC vehicle
4 emissions in HTSVE are higher than in VECU, and CO and PM vehicle emissions in
5 HTSVE is slightly lower than in VECU, as shown in Table 4. The vehicle emissions of
6 NO_x and PM in the China Vehicle Emission Control Annual Report are in an agreement
7 with the emissions in HTSVE, whereas the emissions of HC and CO show significant
8 differences. Moreover, the HC emissions in HTSVE are larger than the HC emissions
9 in VECU, but smaller than the HC emission in the China Vehicle Emission Control
10 Annual Report. The spatial distributions of vehicle emissions for Beijing urban area in
11 HTSVE and VECU are shown in Fig. 9. This figure shows that the high temporal-spatial
12 resolution in HTSVE would be helpful to accurately produce a numerical simulation of
13 the air quality of the city.

14 In conclusion, HTSVE established in this paper was closed to VECU and inventory of
15 China Vehicle Emission Control Annual Report on the order of magnitude. However,
16 HTSVE was indirectly evaluated by the comparison of fuel consumption and fuel sale
17 values, and showed that HTSVE could be closed with the actual emissions of on-road
18 vehicles. Meanwhile, HTSVE had advantage on air quality numerical simulation
19 compared with VECU (He et al. 2015), which indicates HTSVE can better depicts
20 vehicle emission in temporal and spatial trends

21 **4. Conclusions**

22 A bottom-up methodology using local emission factors and NRT traffic data are applied
23 to estimate the emissions of on-road vehicles in the Beijing urban core area. The total
24 vehicle emissions of NO_x, CO, HC and PM were 10.54×10^4 , 42.51×10^4 , 2.13×10^4 and
25 0.41×10^4 Mg, respectively, for the Beijing urban area in 2013. In this paper, HTSVE
26 shows high temporal-spatial resolution. The pollutant emissions from on-road vehicles
27 show consistent temporal and spatial variation trends with the activity trends of people.

1 HTSVE established in this study can be extended in various ways. For example, it can
2 be used to evaluate the impact of urban land plans on traffic emissions, and the effect
3 of traffic management measures on vehicle emissions reduction. Meanwhile, HTSVE
4 can be transformed into arbitrary scale grid according to different demands of
5 researcher. It can also be used to provide accurate vehicle emission source inventory
6 for air quality numerical simulation. And the result shows that the accuracy of air
7 quality simulation has been improved by using HTSVE in Part 2 of this project.

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13

1 Tables

2 Table 1 Fleet composition in Beijing

Vehicle types	Stage 0	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5	Total
LDV	2.32%	2.34%	8.71%	11.10%	46.39%	3.72%	74.58%
MDV	1.44%	0.33%	0.36%	0.29%	0.20%	0.00%	2.63%
HDV	0.23%	0.09%	0.40%	0.93%	0.56%	0.00%	2.21%
LDT	0.40%	0.36%	0.44%	0.71%	2.61%	0.00%	4.53%
MDT	0.18%	0.07%	0.09%	0.42%	0.65%	0.00%	1.40%
HDT	0.21%	0.28%	0.14%	1.15%	1.76%	0.00%	3.54%
Taxi	0.00%	0.00%	1.68%	3.06%	3.76%	0.35%	8.84%
Bus	0.02%	0.10%	0.53%	0.99%	0.63%	0.00%	2.27%

3

1 Table 2. Daily vehicle emission on different road types of Beijing (unit: Mg day⁻¹)

Date	Road type	Length(km)	NOx	CO	HC	PM
Weekdays	Urban freeway	2169.49	111.09	447.12	22.40	4.33
	Artery road	3786.94	124.53	502.89	25.16	4.85
	Local road	4586.06	56.49	228.36	11.42	2.20
Weekends	Urban freeway	2169.49	95.39	383.79	19.21	3.71
	Artery road	3786.94	110.81	446.98	22.36	4.31
	Local road	4586.06	74.04	299.36	14.97	2.88

2

1 Table 3. Daily vehicle emission intensities within different areas of Beijing (unit: 10^4 Mg km⁻²)

Date	Ring	NO _x	CO	HC	PM
Weekdays	Within the second ring	0.377	1.520	0.076	0.015
	Between the second and third ring	0.411	1.656	0.083	0.016
	Between the third and fourth ring	0.366	1.477	0.074	0.014
	Between the fourth and fifth ring	0.201	0.810	0.041	0.008
	Between the fifth and sixth ring	0.058	0.234	0.012	0.002
Weekends	Within the second ring	0.368	1.483	0.074	0.014
	Between the second and third ring	0.389	1.567	0.078	0.015
	Between the third and fourth ring	0.347	1.398	0.070	0.013
	Between the fourth and fifth ring	0.186	0.749	0.037	0.007
	Between the fifth and sixth ring	0.057	0.230	0.012	0.002

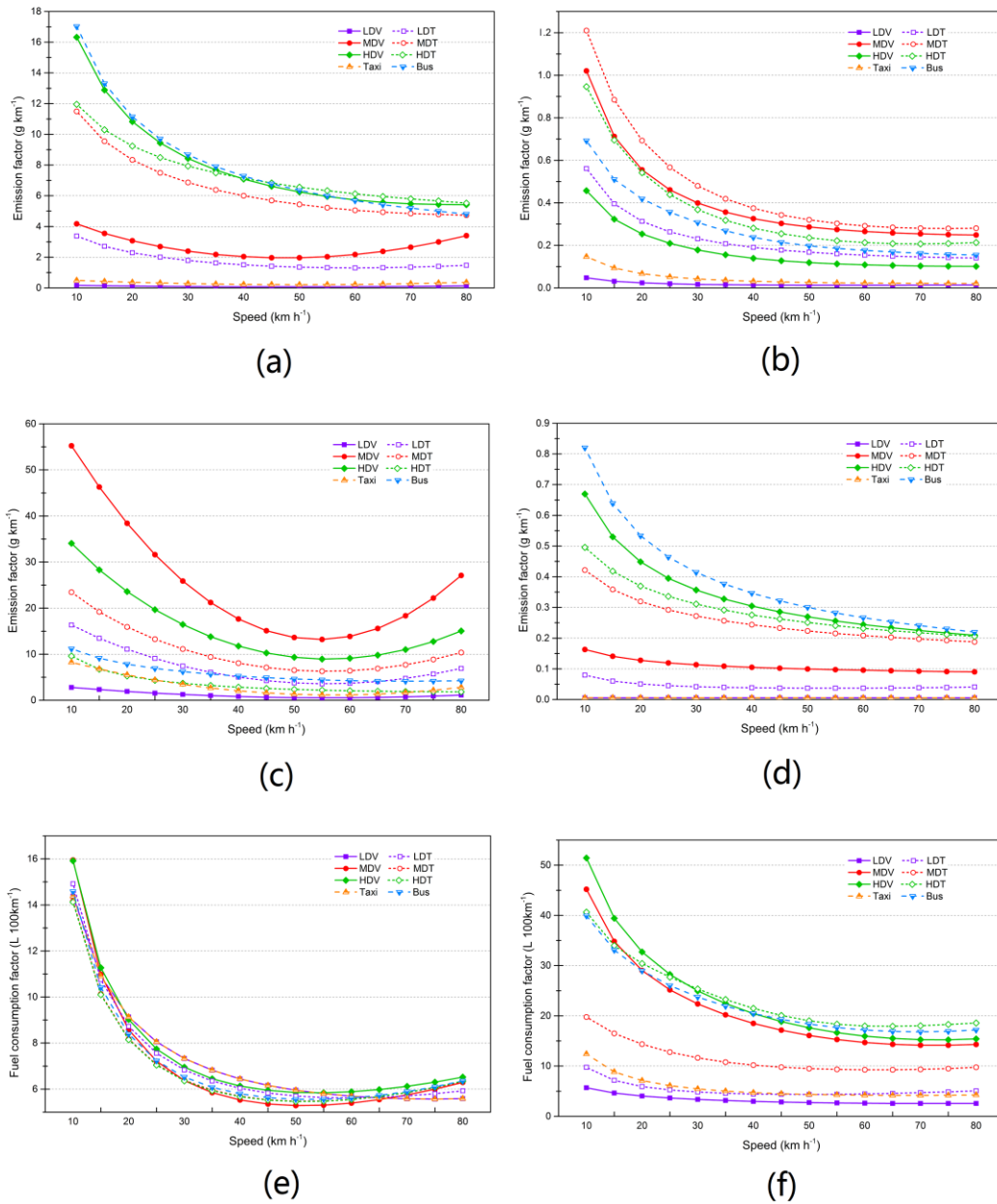
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1 Table 4. Annual vehicle emissions in different reports (unit: 10^4 Mg yr⁻¹)

Species	Region	NOx	HC	CO	PM
HSTVE	Beijing	10.54	2.13	42.51	0.41
VECU (He et al., 2015)	Beijing	5.85	1.62	64.29	0.48
China Vehicle Emission Control Annual Report (2012)	Beijing	8.69	8.61	78.11	0.41

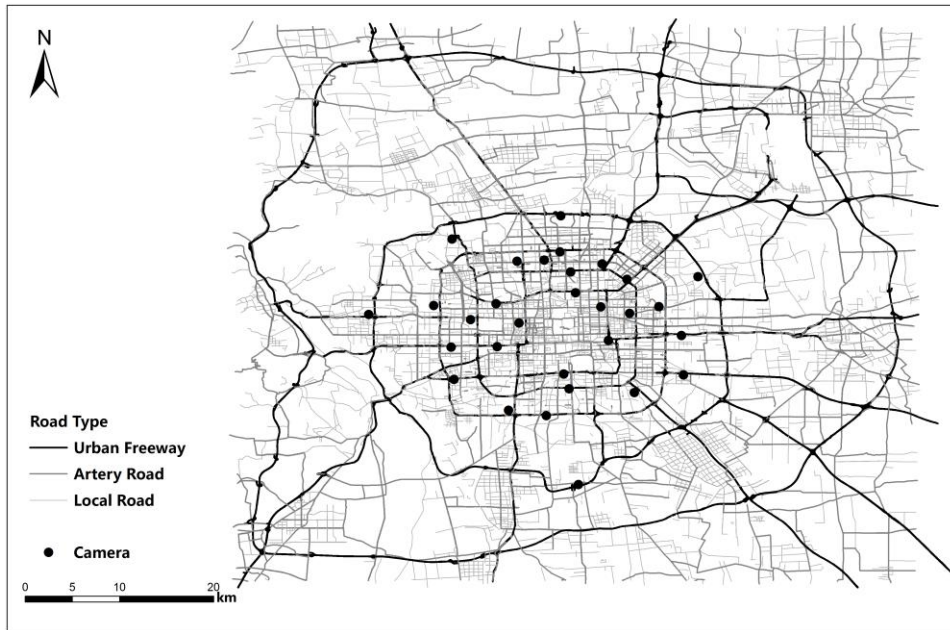
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1 Figures



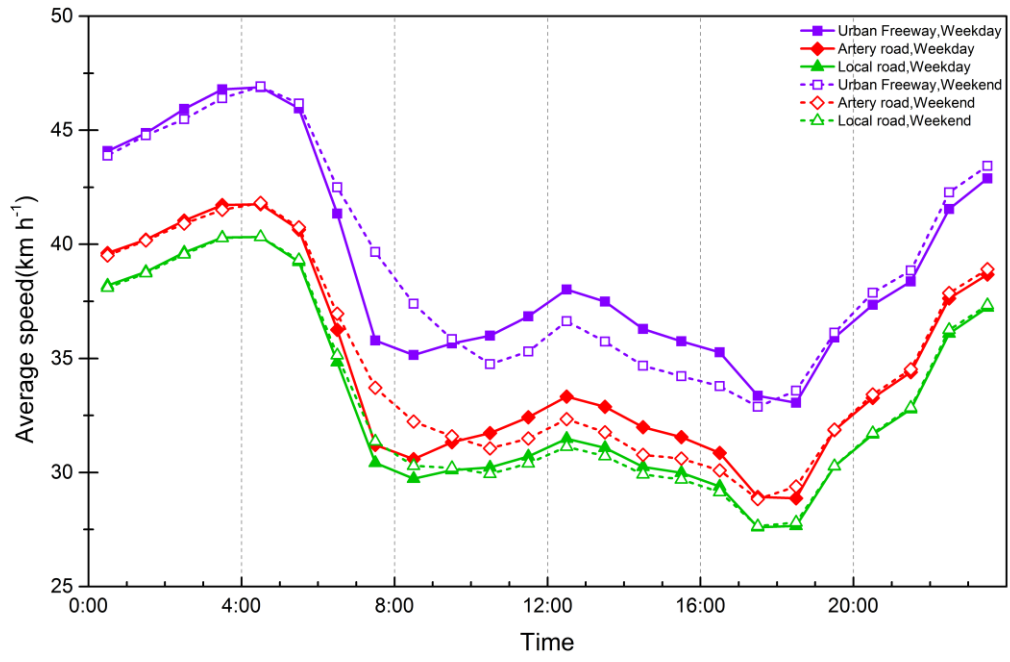
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3 Fig. 1. Emission factors of NO_x, HC, CO, PM and fuel consumption factors of gasoline and diesel
 4 (Huo, 2009; Hu et al., 2012; Wu et al., 2012; Wang et al., 2013): (a) emission factors of NO_x, (b)
 5 emission factors of HC, (c) emission factors of CO, (d) emission factors of PM, (e) fuel consumption
 6 of gasoline, (f) fuel consumption factors of diesel.



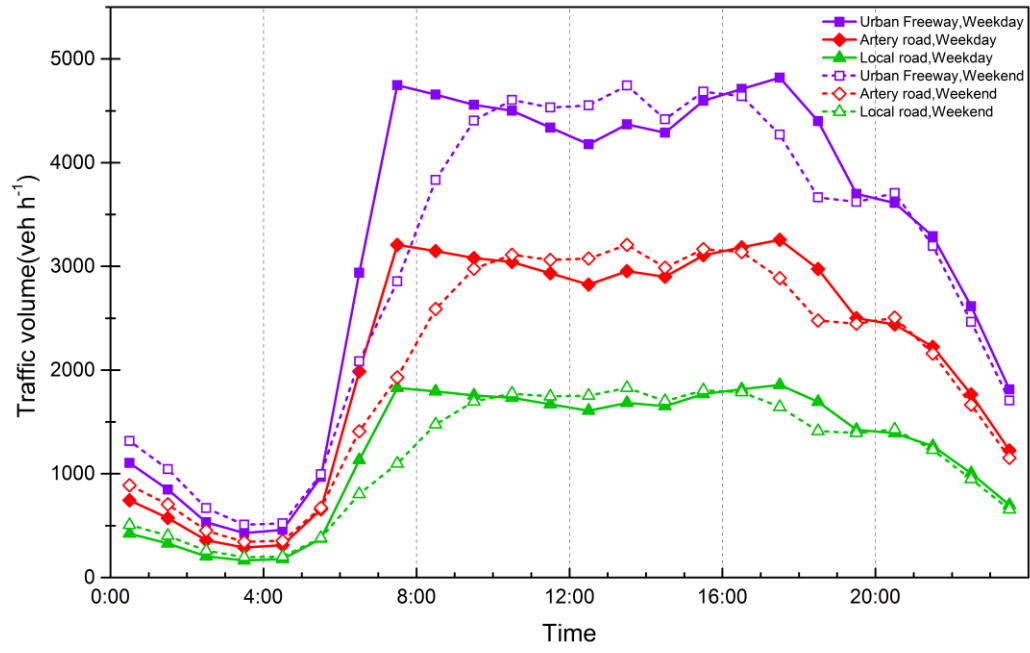
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2 Fig. 2. Point location of video cameras



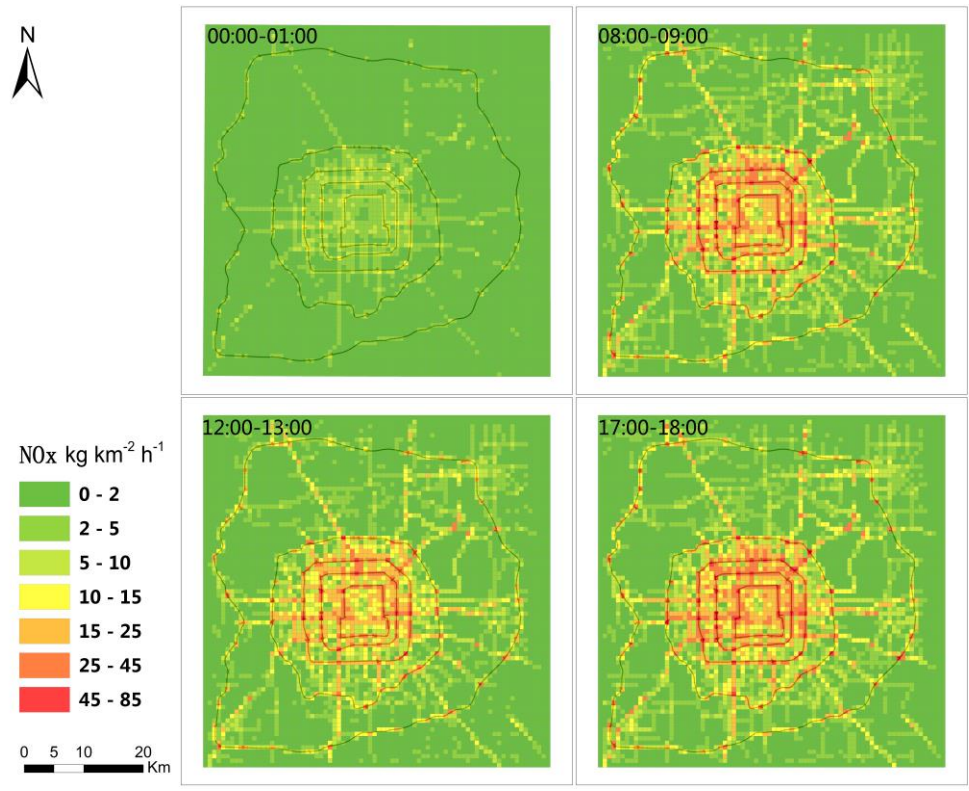
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2 Fig. 3. Hourly traffic average speed on different road types in Beijing

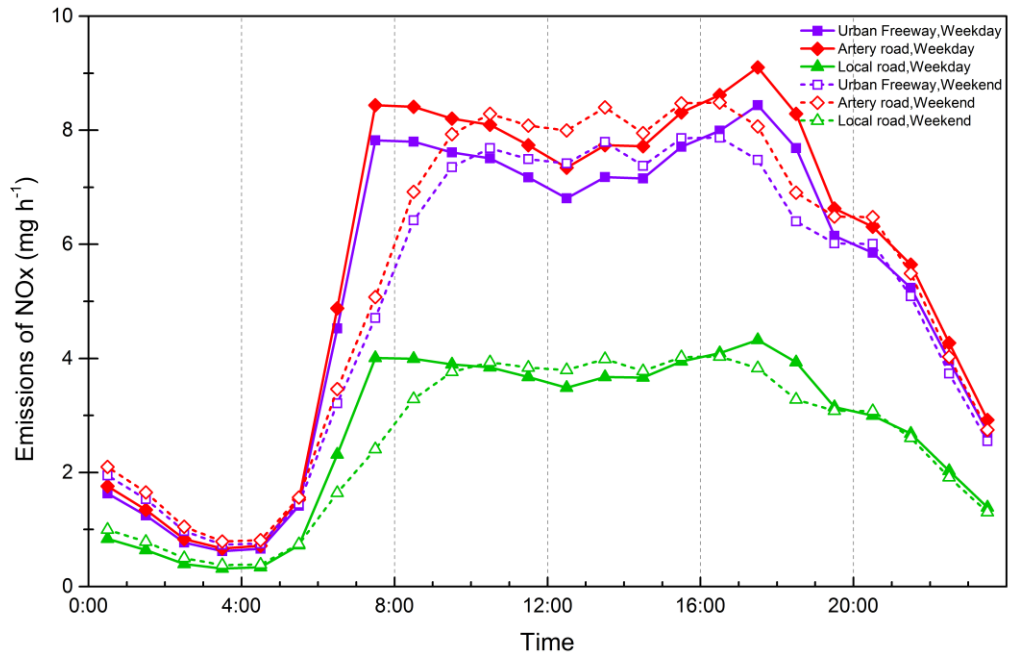


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2 Fig. 4. Hourly traffic volume on different road types in Beijing

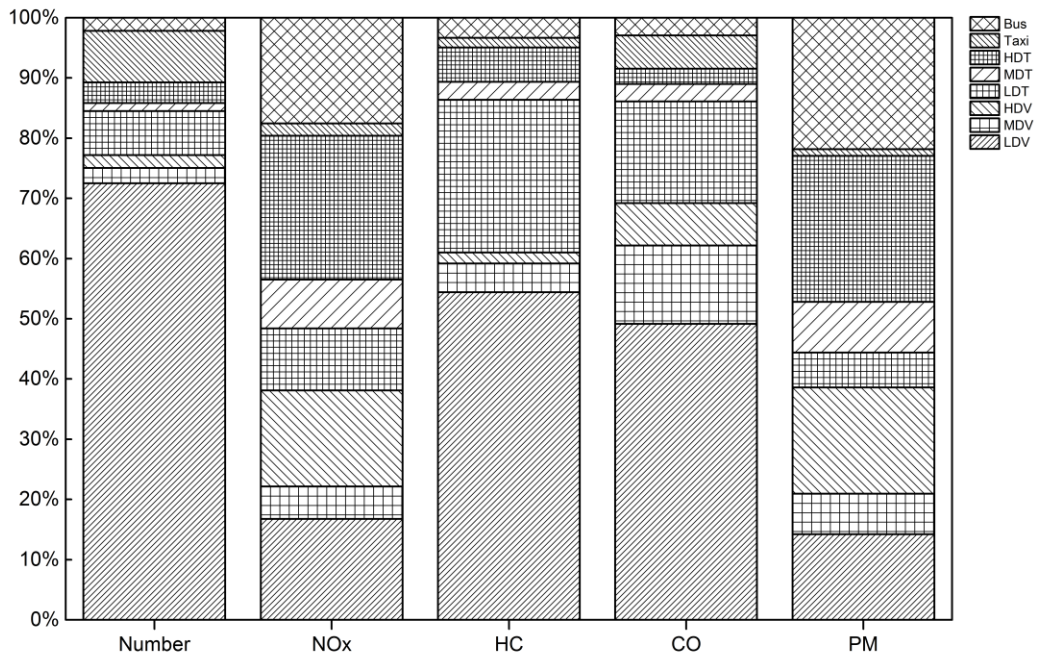


2 Fig. 5. Grid-based vehicle emission inventory of NOx in Beijing



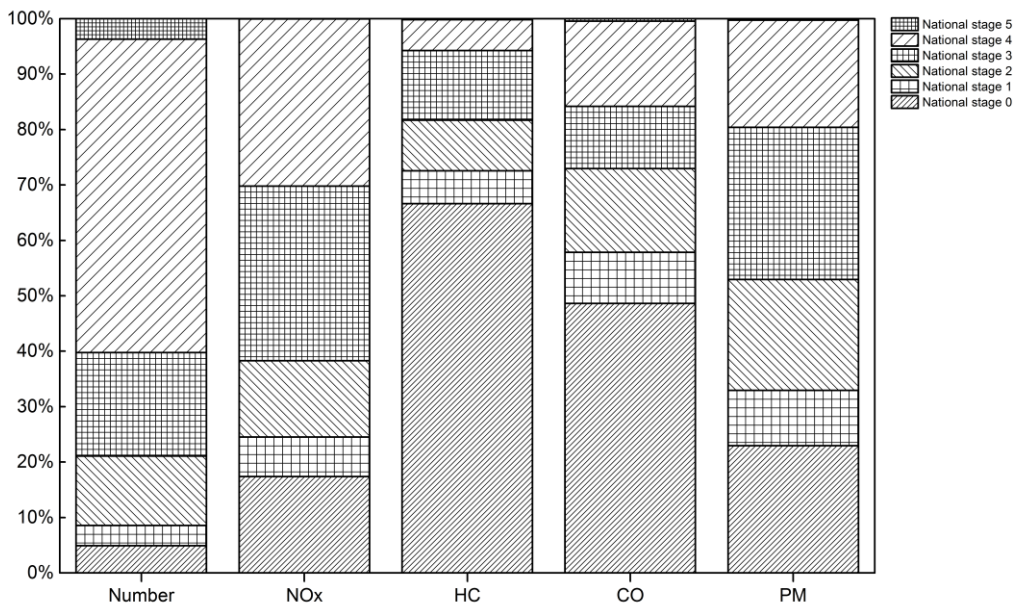
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2 Fig. 6. Hourly variation of vehicle emissions by road type on weekdays and weekends



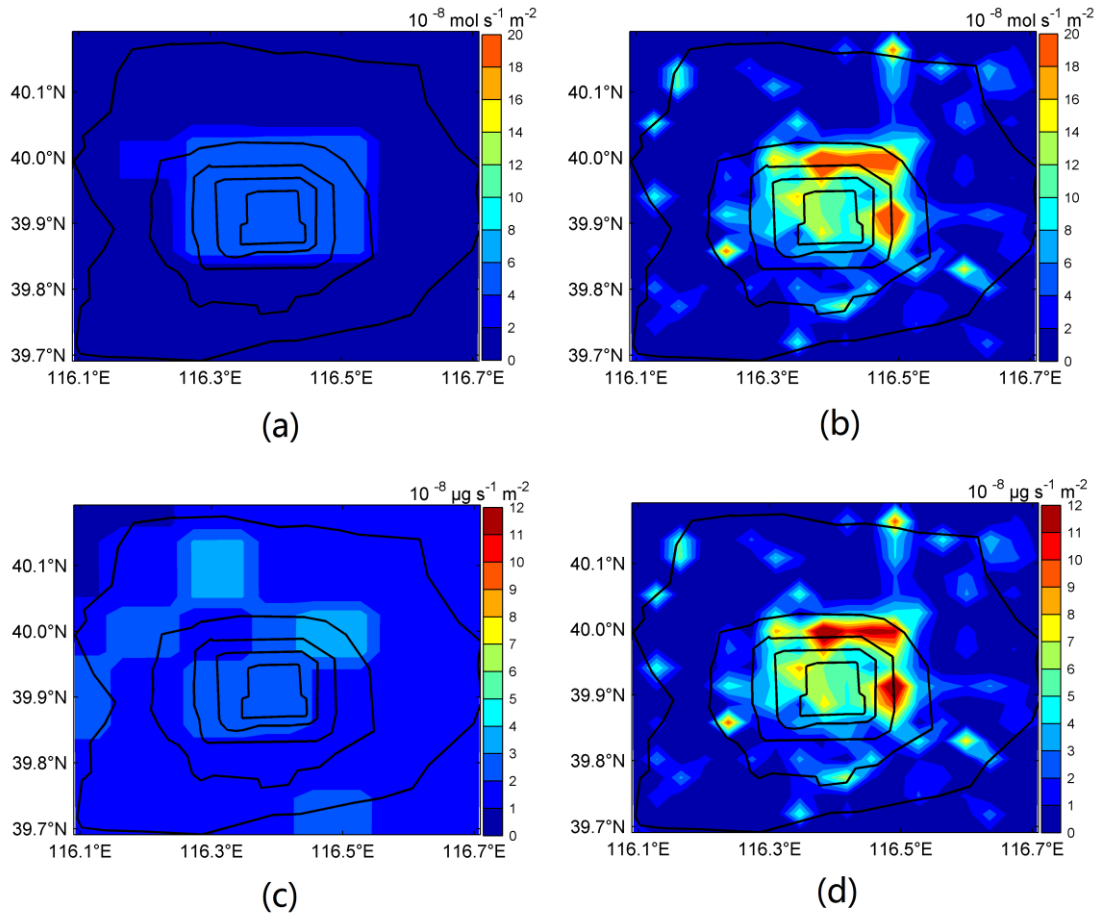
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2 Fig. 7 The vehicle emission contribution of different vehicle types



1

2 Fig. 8 The vehicle emission contribution of different emission control level



1

2 Fig. 9 Spatial distributions of vehicle emissions in Beijing urban core area: (a) NO_x emissions in

3 VECU, (b) NO_x emissions in HTSVE, (c) PM emissions in VECU, (d) PM emissions in HTSVE.