Response to Referee #1

The authors developed a high-resolution vehicle emission inventory of air pollutants in China for the year 2008. The emission inventory is essential and important data for atmospheric science community as well as policymaker and the topic certainly is suitable for ACP. The manuscript presents the sophisticated methodology based on activity data and emission factors at county-level. The author's inventory has some advantages in the spatial distribution and in the input data.

Reliability and accuracy of an emission inventory rely on data certainties of activities and emission factors. In this paper, the authors have established new database on the activity data, emission factors, and spatial allocation factors to reflect the regional situation. Especially, they have developed a new method for China to assess vehicle emissions based on regional information of county-level vehicle population estimated by city-level functions and province-level technology distribution calculated by provincial vehicle stock and survival functions. In terms of emission factors, they determined monthly county-level emission factors simulated by the vehicle emission model using China's on-road vehicle emission corrections and county-level meteorological corrections. Also, the authors developed the gridded inventory with high-resolution of 0.05 degree based on allocation weights for the vehicle kilometers traveled and the finer road-network map. Such efforts have made this new emission inventory study more reliable and complete compared to others previously reported.

Consequently, the contents of this manuscript are suitable for the publication of ACP. However, there are some questions and problems in methodology and data. I am recommending the acceptance of this paper after major revisions.

Response: We thank the reviewer for the constructive comments. We address the comments as below.

(Major comments)

(1)Page 32010, Eq. (1): Eq. (1), which is a vehicle population-based approach, doesn't take account of inter-county traffic. On the other hand, the inter-county traffic has an important role of vehicle emissions as described in lines 10-11 of page 32017 ("Heavy duty trucks run more frequently on inter-county than on county roads"). The authors should analysis and discuss the influences on spatial allocation of emissions. Additionally, the assumption in lines 20-21 of page 32017 ("all use of passenger vehicles occurred within the city boundary and the use of trucks within the province boundary") is unclear in the relation to Eq. (1).

Response: Eq. (1) is used to calculate emissions for vehicles registered in a given county. We have clarified this in the revised manuscript. Actually, we do consider inter-county traffic when allocating emissions to different road types. We allocated the county-level emissions calculated by Eq. (1) to different road types (highways, national, provincial, and county roads, as defined in Table 1) on the basis of VKT weighting factors that take into account the inter-county traffic, as documented in Sect. 2.5.

(2)Page 32012, Eq. (3): The left hand is proportional to the city-level per-capita GDP with slope of [beta]. Fig.1b shows that the slope [beta] is in inverse proportional to the GDP. Consequently, the left hand of Eq. (3) is independent on GDP. This is very curious. The

authors should analyze and discuss about this point more carefully.

Response: The Eq. (3) is used to simulate the β value of each individual city from the historical time series data. For a specific city, β is a fixed value which regressed from GDP and vehicle population during 2001-2010. While Fig. 1b is used to illustrate the relationship between per-capita GDP and β values of different cities in the same province for a given year. For the cities in the same province, city-level β is inversely proportional to city-level per-capita GDP of the same year, representing that the growth rate of vehicle ownership are driven by GDP per-capita. The Eq. (3) and Fig. 1b are used to present two different concepts and we cannot simply multiply them together. In the revised manuscript, we have rewritten the Sect. 2.2 and change the title of Fig. 1b, to make it more straightforward.

(3)Page 32016, lines 10-11: It is considered that the driving pattern strongly depends on traffic characteristics of each county. The assumption of "same driving pattern for all counties" is too rough. At least, the authors should analysis and discuss about the uncertainty caused by this assumption.

Response: We agree with the reviewer that driving pattern varies by county. However, it is very difficult to take into account driving patterns for individual counties due to the lack of data.

The national average driving patterns used in this work are calculated on the basis of measurements in about 20 cities in China. In the discussion section of the revised manuscript, we conducted a sensitivity analysis to evaluate the effect of driving patterns on CO emission factors of LDBs for Beijing and Changchun, one megacity with frequent traffic congestions and one midsize city with less traffic congestions. We found that using local driven cycles will lead to 6% increase of CO emission factor in Beijing and 18% decrease in Changchun respectively, comparing with national average driving cycles.

(4)Page 32016, lines 24-28: The authors need to explain in detail how to set the correction factor and demonstrate their values.

Response: The correction factor is the ratio of measured emission factors to modeled emission factors from the IVE model using the same parameters (driving patterns, meteorological parameters, and accumulated mileage) as the measurement conditions. Measured emission factors are collected in 12 Chinese cites using the portable emissions measurement system (PEMS) during the past ten years (Wang et al., 2005; Yao et al., 2007, 2011; Liu et al., 2009; Huo et al., 2012a, b). We explained this method in detail in the Sect. 2.4 of the revised manuscript and demonstrated their values.

(5)Page 32017, lines 2-4: The author's method of VKT allocation weights on different types of roads to split vehicle activity is an interesting method for spatial allocation. However, the driving pattern (and emission factors) varied largely between road types. The variation of emission factors due to road types should be reflected in estimation of county-level emissions.

Response: We agree with the reviewer that driving pattern varies by road types (and in different cities). However, as we stated above, it is very difficult to take into account the spatial variation of driving patterns in this work due to the lack of data. Resolving this would require large scale investigation of driving patterns across China. We conducted a sensitivity analysis to evaluate the effect of driving patterns on emission factors and found that the

differences of emission factors due to the variation of driving cycles are likely within 20%. We hope the reviewer can acknowledge this.

(Minor comments)

(1)Title: The new method of this work has great advantages in the spatial distribution characteristics. On the other hand, the author's effort in high temporal resolution is relatively small and only is development of monthly emission factors corrected by monthly variation of meteorological parameters. For higher temporal resolution of vehicle emissions, not only monthly variation (including VKT) but also daily and weekly variations should be considered. As a result, the title "A new vehicle emission inventory for China with high spatial resolution" may be more suitable for author's work.

Response: We agree. We changed the title to "High-resolution mapping of vehicle emissions in China in 2008" to make it more specific.

(2)Page 32008, line 3: REAS inventory uses road density as a surrogate for grid allocation.(Ref.) Page 4422 of Ohara et al. (2007)

Response: Thank the reviewer for pointing it out. It is corrected in the revised manuscript.

(3)Page 32008, line 20: It is better that "Therefore" is replaced by "Consequently" or other term.

Response: Corrected.

(4)Page 32010, lines 3-5: Why is motor cycle excluded in this work?

Response: We didn't include motorcycle in this work mainly because the growth pattern of motorcycle stock doesn't follow the GDP-related Gompertz function (Wang et al., 2006). Therefore the method of refining spatial resolution of activities from province to county developed in this manuscript is not applicable to motorcycles.

(5)Page 32026, lines 19-25: The reviewer can't find from Fig. 14b and c that M1 and M2 methods causes "significant bias". Fig.14b and c or Fig.14d and e seem to demonstrate that M1 is closer to "this work" than M2. It is suggested that the authors add some discussions about this reason.

Response: Fig. 14 suggests that M1 is closer to "this work" than M2 for large urban areas (>200,000 population per grid). This is because using population as spatial proxy tends to allocate more emissions in urban area. However, M2 was not able to identify emission hotspots in big cities, because city roads are not included in DCW and few emissions could be allocated to urban areas. We have removed the statement of "significant bias" and added some discussions in the revised manuscript.

References:

Huo, H., Yao, Z., Zhang, Y., Shen, X., Zhang, Q., Ding, Y., and He, K.: On-board measurements of emissions from light-duty gasoline vehicles in three mega-cities of China, Atmos. Environ., 49, 371-377, doi: 10.1016/j.atmosenv.2011.11.005, 2012a.

Huo, H., Yao, Z., Zhang, Y., Shen, X., Zhang, Q., and He, K.: On-board measurements of emissions from diesel trucks in five cities in China, Atmos. Environ., 54, 159-167, doi: 10.1016/j.atmosenv.2012.01.068, 2012b.

Liu, H., He, K., Lents, J. M., Wang, Q., and Tolvett, S.: Characteristics of Diesel Truck Emission in China Based on Portable Emissions Measurement Systems, Environ. Sci. Technol., 43, 9507-9511, doi: 10.1021/es902044x, 2009.

Wang, Q. D., He, K. B., Huo, H., and Lents, J.: Real-world vehicle emission factors in Chinese metropolis city - Beijing, J. Environ. Sci-China., 17, 319-326, 2005.

Wang M., Huo, H., Johnson, L., and He, D.Q.: Projection of Chinese Motor Vehicle Growth, Oil Demand, and CO2 Emissions Through 2050. ANL/ESD/06-6, Argonne National Laboratory, Argonne, Illinois, 2006

Yao, Z.,Wang, Q., He, K., Huo, H., Ma, Y., and Zhang, Q.: Characteristics of real-world vehicular emissions in Chinese cities, J. Air & Waste Manage. Assoc., 57, 1379–1386, doi:10.3155/1047-3289.57.11.1379, 2007.

Yao, Z., Huo, H., Zhang, Q., Streets, D. G., and He, K.: Gaseous and particulate emissions from rural vehicles in China, Atmos. Environ., 45, 3055-3061, doi: 10.1016/j.atmosenv.2011.03.012, 2011.

Response to Referee #2

General comments

This manuscript develops a vehicle emission inventory by estimating vehicle stock and monthly emission factors at county-level, and technology distribution at provincial level. The emissions are then allocated to 0.05x0.05 grids based on China Digital Roadnetwork Map. This manuscript presents improvements in bottom-up emission estimates by increasing the spatial resolution of input parameters, and emission gridding by applying more vehicle activity related surrogates. These improvements will benefit climate and air quality modeling. The paper is well written and clearly structured.

My major concern of this manuscript is that some assumptions are not clearly explained (see specific comments). Therefore, I would like to recommend major revisions.

Response: We thank the reviewer the constructive comments. We address the comments as below.

1. Line 15 on page 32007, what is the reference for vehicle emission contributions in Beijing?

Response: The reference is as follow:

Zhang, Q., Streets, D. G., Carmichael, G. R., He, K. B., Huo, H., Kannari, A., Klimont, Z., Park, I. S., Reddy, S., Fu, J. S., Chen, D., Duan, L., Lei, Y., Wang, L. T., and Yao, Z. L.: Asian emissions in 2006 for the NASA INTEX-B mission, Atmos. Chem. Phys., 9, 5131-5153, 10.5194/acp-9-5131-2009, 2009.

We add this reference in the revised manuscript.

2. Lines 4-6 on page 32009, explain why use road map in 2010 to allocate emissions in 2008.

Response: We used the road map in 2010 because it is the only data close to 2008 that we can get. Spatial proxy data are not always updated and time-consecutive. This is the situation that the emission inventory community has to deal with. For example, The Digital Chart of the World (DCW) database compiled in the 1990s is still used in current emission inventories (Kurokawa et al., 2013).

3. Line 11 on page 32009, be consistent in the whole manuscript, whether VOC,NMHC, or HC.

Response: It is NMHC and we make them consistent in the revised manuscript.

4. Equation (1) on page 32010, it includes emissions from buses and trucks. Authors should explain whether these buses are for commercial use only or not. It is not quite clear whether cars for private use and motorcycles are included. In the latter discussion, "passenger vehicles" and "passenger cars" are used sometimes. Authors should clarify the grouping of vehicle types. Besides, authors did not distinguish emission factors by road types. The symbol E was used twice in Equation (1) and (3) to represent emissions and per-capita GDP. It is better to use different ones.

Response: The definition of vehicle types in this manuscript is consistent with the statistics of vehicle activity data in National Bureau of Statistics. Private cars are included in the "light duty buses (LDBs)" category. Motorcycles are not included in this work. We have clarified this in the revised manuscript.

It is very difficult to take into account the spatial variation of driving patterns in this work due to the lack of data. Resolving this would require large scale investigation of driving patterns across China. We conducted a sensitivity analysis to evaluate the effect of driving patterns on emission factors and found that the differences of emission factors due to the variation of driving cycles are likely within 20%. We hope the reviewer can acknowledge this.

We replaced "E" in Equation (1) with "Emis" to avoid confusion.

5. Equation (2) on page 32011 and lines 19-21 on page 21013, authors first used Gompertz function to estimate the total vehicle ownership on county level and then broke it down to different vehicle types based on provincial shares of vehicle type. There are several gaps here: whether the shares of vehicle type is the same for county level and provincial level, whether passenger cars, buses, and trucks have the same relationship with GDP per cap, and whether all vehicle types share the same value of V. Authors should provide more information about their assumptions.*

Response: Counties have the same share of vehicle types as the province they belong to. We make this assumption because the statistics for shares of different vehicle types are only available at provincial level, which makes it difficult to construct different Gompertz functions for all vehicle types at county level. We first use the Gompertz function to estimate total vehicle population for each county, then the population of different vehicle types are split by the provincial shares. We have clarified this in the revised manuscript.

6. Equation (3) on page 32012 and lines 1-2 on page 32013, α and β are derived from linearly relationship, and they should be independent on E. But the discussion about Fig. 1b finds inverse correlation between β and E. it seems conflict. Authors are suggested to have an explanation here.

Response:

The Eq. (3) is used to simulate the β value of each individual city from the historical time series data. For a specific city, β is a fixed value which regressed from GDP and vehicle population during 2001-2010. While Fig. 1b is used to illustrate the relationship between per-capita GDP and β values of different cities in the same province for a given year. For the cities in the same province, city-level β is inversely proportional to city-level per-capita GDP of the same year (see response below), representing that the growth rate of vehicle ownership are driven by GDP per-capita. In the revised manuscript, we have rewritten the Sect. 2.2 and change the title and legend of Fig. 1b.

7. Equation (4) on page 32013, it is not quite straightforward how authors use the discussion on page 32012 and 32013 to conclude the adjustment of β from city to county level in Equation (4). It is better that authors provide more explanation.

If I understand it correctly, $E_{i,min}$ and $E_{i,max}$ are min and max of 10 observations of E in city i, then what is the definition of E_j? Does it represent GDP per cap of county j in 10 years, on average, or in single model year (e.g., 2008)?

Response: β represents the growth rate of vehicle ownership driven by GDP per-capita. Cites with more GDP per-capita tend to have lower vehicle growth rates (and smaller β value) than those cities with less GDP per-capita. Fig. 1 illustrated the inverse relationship between β and GDP per-capita. Figure 1(a) compares the β values of Hebei and its three cities. As shown in the figure, the three cities had different β values from the provincial one. Of the three cities,

the richer city tended to have a lower vehicle growth rate because the Gompertz function is S-shaped and the vehicle growth rate slowed down close to the saturation level. Figure 1(b) further shows that the β values of the Hebei province and all its cities had a strong inverse correlation with their per-capita GDP. When applying β derived from each city to counties, it needs to be adjusted because the GDP per-capita in each county varies from the city they belong to. We then use Eq. (4) to determine the adjustment factors. In the revised manuscript, we have rewritten the Sect. 2.2 to make it more straightforward.

$E_{i,min}$ and $E_{i,\ max}$ are min and max of 10 observations of E in city i, and E_j represents GDP per cap of county j in 2008.

8. Equation (9) on page 32014, authors used T and b values determined in Huo and Wang (2012), which provides survival rate of light-duty vehicles in Beijing from Yang et al. (2003). Authors should clarify their assumptions about survival rates for different vehicle types in different provinces. It is better to show T and b values for each province if it is possible.

Response:

National average T and b of different vehicle types were first derived based on our previous estimate (Huo and Wang, 2012) as the default for each province. We then use successive approximation approach to adjust T and b for each province to match the registered vehicles numbers calculated by Eq. 9 with the numbers derived from Eq. 8. We have clarified this in the revised manuscript and presented T and b values of each province in the supplementary information.

9. Lines 21-28 on page 32016, how many and which cities with measurements are used to determine φ values? How are φ values determined? For which vehicle types, φ is set as 1? Are φ values distinguished by county or city? Please clarify.

Response: Measurements conducted in 12 Chinese cities are used to determine the correction factors. These cities include Beijing, Jilin, Changchun, Shanghai, Ningbo, Chengdu, Chongqing, Xi'an, Guangzhou, Shenzhen, Jinan and Yichang (Wang et al., 2005; Yao et al., 2007, 2011; Liu et al., 2009; Huo et al., 2012a,b). The correction factor is the ratio of measured emission factors to modeled emission factors from the IVE model using the same parameters (driving patterns, meteorological parameters, and accumulated mileage) as the measurement conditions. We explained this method in detail in the Sect. 2.4 of the revised manuscript. The correction factors remain same across counties.

10. Lines 25-28 on page 32017, clarify whether all provinces use the same VKT levels, as shown in Table 2.

Response: Yes, we used the same VKT levels for all provinces, as shown in Table 2. We clarify it in the revised manuscript.

11. Lines 6-9 on page 32023, the statement that NOx running emissions are not dependent on temperature is not consistent with Fig. 7c and discussion in line 1 on page 32021. Authors should have a careful discussion about little latitude variations of NOx monthly emissions.

Response:

The statement that NO_x running emissions are not dependent on temperature is not correct. We thank the reviewer for pointing it out. We have corrected this in the revised manuscript.

12. Line 22 on page 32026, define what is "significant bias"

Response: In the revised manuscript, we removed the terms "significant bias" and use quantitative statements to clarify specific differences between inventories derived from different methods.

Editorial Comments 13. Table 1, suggest to show the VKT allocation of other vehicles types, though they are based on assumptions

Response: Revised as suggested.

14. Table 2, suggest to show which year and which level (national, provincial or others) in the title

Response: Revised as suggested.

15. Fig. 1, suggest to give more details about the x label in Fig. 1b. Is it the average per-cap GDP or the one in 2008?

Response: It is the per-cap GDP in 2008 for x label in Fig. 1b. We clarify it in the title of Fig. 1 in the revised manuscript.

16. Fig. 4b, define the growth rate. Is it the average growth rate between 2002 and 2010, or the growth rate for a specific year?

Response: The growth rate in Fig. 4b is defined as the average growth rate between 2002 and 2010. We clarify it in the title of Fig. 4 in the revised manuscript.

17. Fig. 8, is the spatial distribution by county or grid (0.05x0.05)?

Response: The spatial distribution in Fig. 8 is by county. We clarify it in the title of Fig. 8 in the revised manuscript.

18. Fig. 9, the second element of legend in (d) should be "PM2.5_Running" instead of "PM2.5_Emission"

Response: Corrected.

19. Line 8 on page 32024, "constrain "instead of "contain"

Response: Corrected.

References:

Huo, H., and Wang, M.: Modeling future vehicle sales and stock in China, Energ. Policy., 43, 17-29, doi: 10.1016/j.enpol.2011.09.063, 2012.

Huo, H., Yao, Z., Zhang, Y., Shen, X., Zhang, Q., Ding, Y., and He, K.: On-board measurements of emissions from light-duty gasoline vehicles in three mega-cities of China, Atmos. Environ., 49, 371-377, doi: 10.1016/j.atmosenv.2011.11.005, 2012a.

Huo, H., Yao, Z., Zhang, Y., Shen, X., Zhang, Q., and He, K.: On-board measurements of emissions from diesel trucks in five cities in China, Atmos. Environ., 54, 159-167, doi:

10.1016/j.atmosenv.2012.01.068, 2012b.

Liu, H., He, K., Lents, J. M., Wang, Q., and Tolvett, S.: Characteristics of Diesel Truck Emission in China Based on Portable Emissions Measurement Systems, Environ. Sci. Technol., 43, 9507-9511, doi: 10.1021/es902044x, 2009.

Wang, Q. D., He, K. B., Huo, H., and Lents, J.: Real-world vehicle emission factors in Chinese metropolis city - Beijing, J. Environ. Sci-China., 17, 319-326, 2005.

Yao, Z.,Wang, Q., He, K., Huo, H., Ma, Y., and Zhang, Q.: Characteristics of real-world vehicular emissions in Chinese cities, J. Air & Waste Manage. Assoc., 57, 1379–1386, doi:10.3155/1047-3289.57.11.1379, 2007.

Yao, Z., Huo, H., Zhang, Q., Streets, D. G., and He, K.: Gaseous and particulate emissions from rural vehicles in China, Atmos. Environ., 45, 3055-3061, doi: 10.1016/j.atmosenv.2011.03.012, 2011.

Zhang, Q., Streets, D. G., Carmichael, G. R., He, K. B., Huo, H., Kannari, A., Klimont, Z., Park, I. S., Reddy, S., Fu, J. S., Chen, D., Duan, L., Lei, Y., Wang, L. T., and Yao, Z. L.: Asian emissions in 2006 for the NASA INTEX-B mission, Atmos. Chem. Phys., 9, 5131-5153, doi: 10.5194/acp-9-5131-2009, 2009.