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LETTER

Methane emissions from on-road vehicles in China: a case study in an urban tunnel

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Abstract

Reducing emissions of methane (CH4) in developed regions and urban areas is a practical way to curb the unexpected surge in global CH4 levels in recent decades. Traffic emissions are among the important anthropogenic CH4 emission sources in megacities, yet CH4 emissions from on-road vehicles are less characterized and not well addressed. Based on tunnel tests in an urban tunnel in south China, a real-world emission factor (EF) of CH4 was measured to be 0.26 ± 0.03 g·km−1 (mean ±95% C.I.) for on-road vehicle fleet which including gasoline vehicles, diesel vehicles, and liquefied petroleum gas vehicles, with an average CH4/CO2 mass ratio of 40.6±5 g·g−1, and CH4 could account for 1.3% of vehicle CO2-equivalent emissions. Using the measured CH4/CO2 ratio and available automobile CO2 emission estimates, traffic CH4 emissions in 2014 could have reached 333 Gg and represented 0.6% of total anthropogenic CH4 emissions in China, approximately four times the previous reported value of 79 Gg. Our results indicate that improving energy efficiency would have co-benefits for reducing traffic emissions of CH4, as observed EFs of CH4 are positively correlated with that of CO2, and over 90% of traffic CH4 emissions in China could be avoided if the traffic CH4/CO2 ratio can be an order of magnitude lower as previously observed in a tunnel in Switzerland.

Introduction

Methane (CH4) is the second-largest contributor to anthropogenic greenhouse forcing after carbon dioxide (CO2) [1, 2]. Apart from trapping the infrared energy emitted by the Earth and its atmosphere, CH4 has extra warming effects affecting the abundance of other greenhouse gases, such as ozone (O3), water vapor (H2O), and CO2 [3]; becoming involved in gas-aerosol interactions [4]; and absorbing energy from the Sun at shorter wavelengths [5]. The radiative forcing attributed to methane emissions is very likely to be almost twice as large as that from its change in concentration [1]. Data from NOAA observation stations show that global mean atmospheric CH4 started to rise in 2007 after a near-zero growth from 2000–2006 [6], with a sharper increase beginning in 2014 [7]. As a result, the global level of atmospheric methane climbed to 1.87 ppm in March, 2019 [8] from 1.78 ppm in 2006 [7]. Because CH4 is a potent greenhouse gas with a 20-year Global Warming Potential (GWP20) of 84 and a 100-year Global Warming Potential (GWP100) of 28–32 [1, 2, 5], this unexpected surge in global methane levels presents a major challenge, and eliminating emissions of CH4 would quickly provide a benefit for achieving the goals set out in the Paris Agreement to limit temperature increases to 2 °C or, if possible,
to 1.5 °C above preindustrial levels [9, 10]. In the near term, a weakening of aerosol cooling by a reduction in sulfur dioxide emissions would add to future warming, but can be tempered by reductions in methane emissions [1].

Anthropogenic methane emissions have dominated global methane growth since 1999 [11–13]. Although the drivers behind the surge in atmospheric methane in the recent decades are less well understood and hotly debated, there are limited opportunities to address agricultural emissions or natural emissions, and reducing methane emissions in the energy sector is the most practical option available to control global methane levels. In fact, the fractions of CH4 emissions from the energy sector reached 44.6% in China in 2014 and 26.5% in the world in 2012 [14, 15]. Considering ethics, social justice and equity issues, developed regions and urban areas should take on more responsibilities in emissions reduction efforts. Non-CO2 forcers such as methane are emitted alongside CO2, particularly in the energy and transport sectors, and thus, reducing emissions of CO2 and CH4 in urban areas can be largely addressed as co-benefits of curbing emissions of air pollutants from the energy and transport sectors. In fact, CH4 emissions from fossil fuel industries were found to be 20%–60% higher than previously estimated, implying a greater potential for energy efficiency improvements to mitigate anthropogenic climate forcing [16]. Transport is an important sector in fossil fuel consumption. Anthropogenic CH4 emissions from mobile sources are estimated to contribute only 0.2%–0.5% to the global CH4 budget [17, 18], and this sector ranked 12th among all sources in 2017 in the US [19]. However, Nakagawa et al. [20] revealed that up to 30% of CH4 could come from automobile exhaust in Nagoya, Japan, suggesting substantial opportunities for reducing CH4 from traffic emissions in megacities.

China has become the world’s largest manufacturer and consumption market of motor vehicles; thus traffic emissions of CH4 are of great concern, particularly in urban areas. However, as CH4 is an unregulated pollutant, there are few studies concern its emissions from vehicle exhausts [21]. Emission factors (EFs) along with traffic statistics are needed to estimate traffic emissions of CH4 [22], yet EFs of specific vehicle types are mainly derived from European or US vehicle emission databases for compiling China’s CH4 emission inventory using mobile source emission models such as the Computer Programme to Calculate Emissions from Road Transport (COPERT) [21, 23–26], MOBILE [27, 28], International Vehicle Emissions (IVE) [29] and MOtor Vehicle Emission Simulator (MOVES) [30]. Due to differences in technological levels, emission control standards and driving conditions, simply borrowing EFs from developed countries will lead to significant uncertainty when estimating emissions in China [31, 32]. There are only a few tests that are available that provide EFs for light-duty gasoline vehicles, gasoline vehicles, compressed natural gas vehicles, natural gas vehicles and passenger cars, respectively [33–35], or obtain the CH4/CO2 ratio for a whole fleet [22, 36–39].

Tunnel tests have proven to be a useful method to estimate real-world fleet–wide EFs [22, 40]. In this study, we conducted tests in 2014 in the underwater Zhujiang Tunnel with a daily traffic flow of approximately 40,000 vehicles in urban Guangzhou, South China, to provide a real-world EF of CH4 for an on-road fleet for the first time, to recheck the status of traffic CH4 emissions in China and to assess the potential of reducing CH4 emissions in the transport sector.

Methods

Field work

Zhujiang Tunnel is an underwater tunnel crossing the Pearl River in west-central Guangzhou. Located in a relatively populated area, the traffic load in the tunnel reaches ~40,000 vehicles per day. The tunnel is 1238.5 m long with a 721 m flat underwater section. It has two bores with two lanes in each bore. A schematic diagram of the tunnel was given by Liu et al. [41] and Zhang et al. [42]. During our test, the ventilation system of the tunnel was not operated. Zhujiang Tunnel has a speed limit of 50 km h\(^{-1}\), and the traffic speed during our sampling (data from Guangzhou Transportation Administration Bureau, personal communication) ranged from 20 km h\(^{-1}\) to 47 km h\(^{-1}\), averaging 35 ± 5 km h\(^{-1}\) (95% confidence intervals, 95% C.I.). Detailed descriptions of the Zhujiang Tunnel can be found in the supporting information text S1 is available online at stacks.iop.org/ERC/2/061005/mmedia.

Sampling was conducted from June 25th to July 1st in 2014. We placed the two sampling stations (outlet station and inlet station) 50 m from the ends of the 721–meter flat underwater section. Determined emission factors for air pollutants and halocarbons based on tunnel tests are reported elsewhere [41–45]. CO2 and CH4 in this study were measured using the same batch of air samples collected by canisters for the analysis of volatile organic compounds (VOCs). The VOC samples were collected during intervals of 02:00–3:00, 07:00–8:00, 08:00–9:00, 09:00–10:00, 10:30–11:30, 14:00–15:00, 17:00–18:00, 18:00–19:00, and 19:00–20:00 on June 25th, 26th, 28th and 29th. Two more samples were collected on June 27th (02:00–3:00) and June 30th (4:00–5:00) as supplements. The air samples were collected into pre-evacuated 2-liter electro-polished stainless steel canisters using a Model 910 pressurized canister sampler (Xontec, Inc., Fremont, CA, USA). The sampler was set at a
constant flow rate of 66.7 ml min\(^{-1}\) to guarantee that the air pressure of each canister was approximately 2 atm after sampling for 60 min. More details about quality control and quality assurance of canister samples were offered in Zhang et al [42].

An IRGASON eddy covariance system (Campbell, Inc., USA) with an integrated CO\(_2\) and H\(_2\)O open-path gas analyzer and a 3D sonic anemometer was used to measure in situ CO\(_2\), wind speed/direction and temperature. During the sampling period, the air temperature recorded by the IRGASON at the outlet station ranged from 27.9°C to 41.5°C with an average of 34.4 ± 0.3°C (mean ± 95% C.I.).

**Laboratory analysis**

CH\(_4\) was analyzed by an Agilent Model 6890 GC equipped with an FID and a packed column (5 A Molecular Sieve 60/80 mesh, 3 m × 1/8 inch). CO\(_2\) was analyzed by the same equipment with a different packed column (10 Ft 1/8.2 mm HayeSep Q 80/100 SS). CO\(_2\) was first converted by a Ni-based catalyst to CH\(_4\) and then detected by the FID after separation by the packed column [42]. Both CH\(_4\) and CO\(_2\) were quantified by an external calibration method. Working calibration curves were obtained by diluting ultra-pure CO\(_2\) or CH\(_4\) (>99.999%) to working standards with an Entech Model 4700 high-precision static dilution standards preparation system (Entech Instruments Inc., USA), running each of the working standard for three times and then plotting the average responses against the mixing ratios by linear regression. Re-calibration is needed: (1) if the R\(^2\) for the linear dose-response correlation was below 0.99; and (2) the calibration curve is challenged with a NIST traceable standard (Spectra Gases, 398 ppm for CO\(_2\) and 1.01 ppm for CH\(_4\)) each day before the analysis of air samples. If the determined mixing ratio is beyond ±0.5% the labelled value of the NIST traceable standard. The method detection limits (MDLs) of the analysis system for CH\(_4\) and CO\(_2\) are 20 ppb and 3 ppm, respectively.

**Results and discussion**

**Emission factor (EF)**

The average EF for vehicles traveling through the tunnel during a time interval T can be calculated in the same way as in previous studies [46, 47]:

\[
EF_{\text{avg}} = \frac{\Delta c \times V_{\text{air}} \times T \times A}{N \times l}
\]

where \( EF_{\text{avg}} \) (mg km\(^{-1}\)) is the mean emission factor of CH\(_4\), \( \Delta c \) (mg m\(^{-3}\)) is the concentration difference between the inlet and outlet sampling stations inside the tunnel, \( V_{\text{air}} \) (m s\(^{-1}\)) is the air speed velocity parallel to the tunnel sensed by the 3D sonic anemometer with an average of 3.54 m s\(^{-1}\), \( A \) (m\(^2\)) is the tunnel cross section with value of 58.2 m\(^2\), \( N \) is the monitored traffic count passing the tunnel during the time interval \( T \) (s) (3600 s in this study), and \( l \) (m) is the distance between the two sampling points which is 0.621 km.

The results showed that the EFs of CH\(_4\) measured in the tunnel ranged from 0.048 g km\(^{-1}\) to 0.40 g km\(^{-1}\), with an average of 0.26 ± 0.03 g km\(^{-1}\) (mean ± 95% C.I.). The time series of EFs of CH\(_4\), as well as those of numbers of three fuel-type vehicles travelling through the tunnel, are shown in figure 1. During the time intervals of 2:00–3:00 or 3:00–4:00, the EFs of CH\(_4\) became significantly lower, corresponding to a relatively lower amount (approximately 40%) of gasoline vehicles. The number of gasoline vehicles in these hours decreased by approximately 80% relative to that in rush hours. A highly significant \( p < 0.01 \) correlation was observed between the observed EFs of CH\(_4\) and the percentages of gasoline vehicles (figure S1), implying that gasoline vehicles may dominate CH\(_4\) emissions in the traffic fleet. Chassis dynamometer results from Koike and Odaka [33] have also showed that diesel vehicles have significantly lower emissions of CH\(_4\) than gasoline vehicles. Even though there were fewer diesel vehicles on the weekends, no significant difference in the EFs of CH\(_4\) was found on the workdays and weekends.

Figure 2 shows a comparison of the EFs of CH\(_4\) for vehicles measured in this study with those previously reported. The average EF of 0.26 ± 0.03 g km\(^{-1}\) from our study is approximately 50 times that of 0.0052 g km\(^{-1}\) for gasoline vehicles measured using chassis dynamometer under New European Driving Cycle (NEDC) conditions [34] and over 20 times higher than that of 0.012 ± 0.003 g km\(^{-1}\) estimated for the US on-road fleet under the Federal Test Procedure – 75 (FTP-75) conditions [17]. These large gaps cannot solely be explained by differences in vehicle operating conditions since NEDC and FTP-75 conditions include acceleration and idling modes during which more emissions would typically occur than during the cruising mode for vehicles in the tunnel; instead, they reflect the large gaps in fuel quality, engine performance, exhaust control and vehicle maintenance as well. As an example, during our study on-road vehicles in Guangzhou were mostly composed of Euro 3 (which equals to China 3) (39.4%) and Euro 4 (36.2%), and Euro 1 and Euro 2 still shared a notable proportion of 21.7%. Previous studies demonstrated that CH\(_4\) emissions increase with the age of catalytic convertors [48–51]. Additionally, cars using premium grade gasoline fuel with higher aromatic hydrocarbon content and lower content of saturated hydrocarbons and olefins are found to have lower CH\(_4\) emissions [48],
and the notoriously higher amount of olefins in China’s gasoline (a limit of 24% v/v even in the China 6 grade gasoline oil) would probably give rise to the CH₄ emissions from China’s gasoline vehicles.

As shown in figure 2 and table S2, our measured EFs of CH₄ for the urban vehicle fleet were also substantially higher than those derived from the COPERT and MOBILE models [17, 21, 23–27, 30], but comparable to those derived from the IVE model [28, 29], which was designed for mobile source emissions of developing countries by researchers at the International Sustainable Systems Research Center and the University of California at Riverside. In contrast to other models that use average speed to represent a driving cycle, the IVE model introduces parameters such as vehicle specific power and engine size to better represent driving conditions [28, 52], making it more suitable for estimating vehicle CH₄ emissions in developing countries.

The CH₄/CO₂ ratio
The CH₄/CO₂ ratio is proven to be a simple and practical way to estimate traffic emissions of CH₄ [17]. In order to better represent the emissions of CH₄ from on-road vehicles, the slope for the correlation of EFs between CH₄ and CO₂ was used as the average CH₄/CO₂ ratio in this study. A significant (P < 0.01) positive linear relationship was observed between the EFs of CH₄ and CO₂ measured in the time intervals in the Zhujiang Tunnel (figure 3), with an average CH₄/CO₂ mass ratio of 40.61E-5 ± 7.21E-5 g g⁻¹.
The CH\textsubscript{4}/CO\textsubscript{2} ratio in this study is consistent with that of 17.09E-5 to 50.91E-5 obtained in the Nanjing Yangtze River Tunnel in 2014 \cite{39} by using a portable greenhouse gas analyzer to measure the concentration gradient between the inlet and outlet of the tunnel. It is worth noting that gasoline vehicles dominated the traffic composition in the Yangtze River Tunnel during their sampling time. However, tests in the Islisberg Tunnel in Switzerland in 2011 revealed a CH\textsubscript{4}/CO\textsubscript{2} ratio of 1.67E-5 ± 0.07E-5 g·g\textsuperscript{-1} \cite{22}, which is approximately 25 times lower than the average ratio from this study. Nam \textit{et al} \cite{17} reported a ratio of 15E-5 ± 4E-5 g·g\textsuperscript{-1} for the on-road fleet in the US in 2003 based on chassis dynamometer tests, while Herndon \textit{et al} \cite{36} used a ‘Bus Chase’ method to obtain a CH\textsubscript{4}/CO\textsubscript{2} (g·g\textsuperscript{-1}) ratio of 21.82E-5 ± 7.27E-5 for diesel vehicles and 443.64E-5 ± 65.45E-5 for compressed natural gas (CNG) vehicles. Except for the difference in vehicle size (bus to light-duty vehicle), the equipped oxidation catalyst in cars for emission control may be the main reason for the differences in EFs \cite{36}. Hu \textit{et al} \cite{37} also reported a relatively higher CH\textsubscript{4}/CO\textsubscript{2} (g·g\textsuperscript{-1}) ratio of 254.55E-5 ± 130.91E-5 for natural gas vehicles (NGV) in China in 2015.

**Vehicle CH\textsubscript{4} emissions estimate in China**

In 2014, annual traffic CO\textsubscript{2} emissions in China were 820 Tg while annual traffic CH\textsubscript{4} emissions were estimated to be 79 Gg, and annual anthropogenic CH\textsubscript{4} emissions were 5357 Gg \cite{14}. However, using the CH\textsubscript{4}/CO\textsubscript{2} mass ratio of 40.61E-5 ± 7.21E-5 from this study and China’s traffic CO\textsubscript{2} emissions of 820 Tg yr\textsuperscript{-1} in 2014, we could roughly obtain an estimate of 333 Gg yr\textsuperscript{-1} for traffic CH\textsubscript{4} emissions in China in 2014, which is approximately 4 times that reported value of 79 Gg and accounts for approximately 0.6% of the total anthropogenic CH\textsubscript{4} emissions (5357.2 Gg) in China. This percentage is above the upper limit of <0.5% estimated by Metz \cite{18}, and comparatively higher than the values of <0.2% estimated by Nam \textit{et al} \cite{17} and 0.20% compiled for America in 2014 \cite{19}. With a GWP100 of 32 \cite{5} and a CH\textsubscript{4}/CO\textsubscript{2} ratio of (40.61E-5 ± 7.21E-5) g·g\textsuperscript{-1} for the on-road fleet, CH\textsubscript{4} can account for approximately 1.3% of traffic CO\textsubscript{2}-equivalent emissions from our study in China, which is significantly higher than the range of 0.3%–0.4% estimated by Nam \textit{et al} \cite{17} for global CH\textsubscript{4} emissions and the value of 0.08% estimated for the U.S. on-road fleet in 2014 \cite{19}. In upcoming decades, such as in a 20-year horizon, the global warming potential of CH\textsubscript{4} is 84 times that of CO\textsubscript{2} \cite{1}, indicating an even greater contribution to climate warming.

**Conclusion**

As the CH\textsubscript{4}/CO\textsubscript{2} mass ratios measured for an urban on-road fleet in this study in the Pearl River Delta were consistent with those obtained in the Yangtze River Delta in 2014 \cite{39}, so the much higher CH\textsubscript{4}/CO\textsubscript{2} mass ratios might be common for vehicle emissions in China. Using the CH\textsubscript{4}/CO\textsubscript{2} mass ratios obtained in this study, we can roughly estimate that on-road vehicles in China might have contributed ∼330 Gg CH\textsubscript{4} (∼1 Tg CO\textsubscript{2}-equivalent) in 2014, or 0.6% of China’s total anthropogenic CH\textsubscript{4} emissions. Our results indicate that improving energy...
efficiency would have co-benefits for reducing traffic emissions of CH₄, as the observed EFs of CH₄ are positively correlated with those of CO₂. On the other hand, if the traffic CH₄/CO₂ ratio can be lowered to the level of 1.67E-5, as observed in the Islisberg Tunnel [22], over 90% of traffic CH₄ emissions in China could be tempered, suggesting a large potential or space to reduce China’s CH₄ emissions in the transport sector.

Why were the EFs of CH₄ or CH₄/CO₂ mass ratios so high for on-road vehicle fleet in China? The answer is not clear. However, fuel quality, engine performance, exhaust after treatment facilities and/or maintenance might be among the factors inducing more CH₄ emissions. Our previous study in the same tunnel revealed that the global warming potentials associated with refrigerant leakage from on-road vehicles are equal to 1.4% of that of the directly emitted CO₂ [44], and now, we have demonstrated that the emissions of CH₄ from on-road vehicles are equal to 1.3% of the directly emitted CO₂ in terms of the global warming potentials. These findings raises concerns about whether we need to consider overall environmental and climatic effects of traffic emissions in formulating emission control policies, such as the emissions of greenhouse gases (CO₂, CH₄ and halocarbons) or secondary formation of ozone, which is also a greenhouse gas that can be formed from photochemical ageing of traffic-emitted VOCs and NOₓ.

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Competing interests

The authors declare that they have no competing interests related to the study performed and presented in this paper.

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References

[1] Intergovernmental Panel on Climate Change 2014 Climate Change 2014– Synthesis Report: Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (Geneva, Switzerland) https://www.ipcc.ch/report/ar5/syr/
[2] Allen M R, Shine K P, Foglestvedt J S, Millar R J, Michelle C, Frame D J and Macey A H 2018 A solution to the misrepresentations of CO₂ equivalent emissions of short-lived climate pollutants under ambitious mitigation npj Clin. Atmos. Sci. 1 116
[3] Shindell D T, Faluvegi G, Bell N and Schmidt G A 2005 An emissions-based view of climate forcing by methane and tropospheric ozone Geophys. Res. Lett. 32 L04803
[4] Shindell D T, Faluvegi G, Koch D M, Schmidt G A, Unger N and Bauer S 2009 Improved attribution of climate forcing to emissions of global atmospheric ethane concentrations and implications for methane Climate Change 2014- Synthesis Report: Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (Geneva, Switzerland) [Ar5]–SYR
[5] Nisbet E G et al 2016 Rising atmospheric methane: 2007-2014 growth and isotopic shift Global Biogeochem. Cycles 30 318
[6] Nisbet E G et al 2018 Very strong atmospheric methane growth in the 4 years 2014-2017: implications for the Paris agreement Global Biogeochem. Cycles 33 318–42
[7] NOAA/ESRL https://esrl.noaa.gov/gmd/ccgg/trends_ch4/
[8] Rogelj J, Meinshausen M, Schaeffer M, Knutti R and Riahi K 2015 Impact of short-lived non-CO₂ mitigation on carbon budgets for stabilizing global warming Environ. Res. Lett. 10 075001
[9] Collins W J et al 2018 Increased importance of methane reduction for a 1.5 degree target Environ. Res. Lett. 13 1054003
[10] Bouquet P et al 2006 Contribution of anthropogenic and natural sources to atmospheric methane variability Nature 443 439–43
[11] Simpson I J, Sulbaek Andersen M P, Meinardi S, Bruhwiler L, Blake N J, Helmig D, Röckmann T and Blake D R 2012 Long-term decline of global atmospheric ethane concentrations and implications for methane Nature 488 490–4
[12] Alvarez R A et al 2018 Assessment of methane emissions from the US oil and gas supply chain Science 361 186–8
[13] UNFCCC The People’s Republic of China Second Biennial Update Report on Climate Change https://unfccc.int/documents/197666
[14] Saunois M et al 2016 The global methane budget: 2000-2012 Earth Syst. Sci. Data 8 697–751
[15] Schwietzke S et al 2016 Upward revision of global fossil fuel methane emissions based on isotope database Nature 538 88–91
[16] Niki E K, Jensen T E and Wallington T J 2004 Methane emissions from vehicles Environ. Sci. Technol. 38 2005–10
[17] Metz N 2001 Contribution of passenger cars and trucks to CO₂, CH₄, N₂O, CFC and HFC emissions SAE Technical Paper 01 3578-89
Environ. Res. Commun. 2 (2020) 061003

[19] US Environmental Protection Agency 2019 Inventory of US Greenhouse Gas Emissions and Sinks: 1990–2017 (Washington DC: US EPA 430-R-19-001)
[20] Nakagawa F, Tsunogai U, Komatsu D D, Yamada K, Yoshida N, Morizumi J, Nagamine K, lida T and Ikebe Y 2005 Automobile exhaust as a source of $^{13}$C- and D-enriched atmospheric methane in urban areas Org. Geochem. 36 727–38
[21] Lang J, Zhou Y, Cheng S, Zhang Y, Dong M, Li S, Wang G and Zhang Y 2016 Unregulated pollutant emissions from on-road vehicles in China, 1999–2014 Sci. Total Environ. 573 97–84
[22] Popa M E, Vollmer M K, Jordan A, Brand W A, Pathirana S L, Rothe M and Rockmann T 2014 Vehicle emissions of greenhouse gases and related tracers from a tunnel study: CO, CO$_2$, N$_2$O, CO$_2$, CH$_4$, CO, O$_2$, CO$_2$ ratios, and the stable isotopes $^{13}$C and $^{18}$O in CO$_2$ and CO Atmos. Chem. Phys. 14 2105–23
[23] D’Angiola A, Davidowski L E, Gomez D R and Oses M 2010 On-road traffic emissions in a megacity Atmos. Environ. 44 483–93
[24] Cai H and Xie S 2010 Determination of emission factors from motor vehicles under different emission standards in China Acta Sci. Nat. Univ. Pekin. 46 319–26
[25] Ho B Q and Clappier A 2011 Road traffic emission inventory for air quality modelling and to evaluate the abatement strategies: a case of Ho Chi Minh City, Vietnam Atmos. Environ. 45 3584–93
[26] Zeng X, Li H, Cheng X, Xu W, Liu Y and Huang J 2013 Study on traffic exhaust emissions and characteristics of Foshan city Environmental Pollution & Control 35 51–5
[27] Li W, Hao J, Ma H, Li S and Hu W 2016 Emission inventory of 10 kinds of air pollutants for road traffic vehicles in China Urban Environment and Urban Ecology 16 36–8
[28] Yao Z L, Wang Q D, Wang X T, Zhang Y Z, Shen B Y, Yin H and He K B 2011 Emission inventory of no-regulated pollutants for motor vehicles in typical cities Environmental Pollution & Control 33 96–101
[29] Tang W, He P, Yang Q, Lu Q, Zheng S, Xiao Y, Jing B, Lu B, Huang C and Lu J 2018 Study on greenhouse gas emission inventory of road source in Hangzhou based on IVE model and large data analysis Acta Scientiae Circumstantiae 38 1368–86
[30] Tao S, Deng S, Hao Y, Gao S, Xiong X and Kong Y 2019 Vehicle emission characteristics of gaseous pollutants in Guanzhong urban agglomeration China Environmental Science 39 542–53
[31] Shen X, Yao Z, Zhang Q, Wagner D V, Huo H, Zhang Y, Zheng B and He K 2015 Development of database of real-world diesel vehicle emission factors for China J. Environ. Sci. (China) 31 209–20
[32] Heo H, Zhang Q, He K, Wang Q, Yao Z and Streets D G 2009 High-resolution vehicular emission inventory using a link-based method: a case study of light-duty vehicles in Beijing Environ. Sci. Technol. 43 2394–9
[33] Koike N and Odaka M 1996 Methane and nitrous oxide (N$_2$O) emission characteristics from automobiles SAE Technical Paper 01 61–71
[34] Zervas E and Panousi E 2010 Exhaust methane emissions from passenger cars SAE Technical Paper 01 2234–32
[35] He L Q, Song J H, Hu J N, Xie S X and Zu L 2014 An investigation of the CH$_4$ and N$_2$O emission factors of light-duty gasoline vehicles Environmental Science 35 4489–94
[36] Herndon S C, Shorter J H, Zahnisner M S, Wormhoudt J, Nelson D D, Demerjian K L and Kolb C E 2005 Real-time measurements of SO$_2$, H$_2$CO, and CH$_4$ emissions from in-use curbside passenger buses in New York City using a chase vehicle Environ. Sci. Technol. 39 7984–90
[37] Hu N, Liu S, Gao Y, Xu J, Zhang X, Zhang Z and Lee X 2018 Large methane emissions from natural gas vehicles in Chinese cities Atmos. Environ. 187 374–80
[38] Li X, Gao M G, Tong J J, Wei X L, Cheng S Y and Feng M C 2011 Monitoring of transport gases CO/CO$_2$/N$_2$O and CH$_4$ emissions in urban area by OP-FTIR Infrared Technology 33 473–76
[39] Zhang X, Hu N, Liu S, Wang S, Gao Y, Zhao J, Zhang Z, Hu Y, Lee X and Zhang G 2017 Characteristics of methane emission from urban traffic in Nanjing China Environmental Science 38 469–75
[40] Ropkins K, Beebe J, Li H, Daham B, Tate J, Bell M and Andrews G 2009 Real-world vehicle exhaust emissions monitoring: review and critical discussion Critical Reviews in Environ. Sci. Technol. 39 79–152
[41] Liu T, Wang X, Wang B, Ding X, Deng W, Li S and Zhang Y 2014 Emission factor of ammonia (NH$_3$) from on-road vehicles in China: tunnel tests in urban Guangzhou Environ. Res. Lett. 9 064027
[42] Zhang Y et al 2015 Emission factors of fine particles, carbonaceous aerosols and traces gases from road vehicles: recent tests in urban a typical urban area in the Pearl River Delta, China Atmos. Environ. 122 876–84
[43] Zhang Y, Wang X, Wen S, Herrmann H, Yang W, Huang X, Zhang Z, Huang Z, He Q and George C 2016 On-road vehicle emissions of glyoxal and methylglyoxal from tunnel tests in urban Guangzhou, China Atmos. Environ. 127 55–60
[44] Zhang Y L, Yang W Q, Huang Z H, Liu D, Simpson L, Blake D, George C and Wang X M 2017 Leakage rates of refrigerants CFC-12, HCFC-22, and HFC-134a from operating mobile air conditioning systems in Guangzhou, China: Tests inside a busy urban tunnel under hot and humid weather conditions Environ. Sci. Technol. Lett. 4 481–6
[45] Zhang Y L et al 2018 Decadal changes in emissions of volatile organic compounds (VOCs) from on-road vehicles with intensified automobile pollution control: case study in a busy urban tunnel in south China Environ. Pollut. 233 806–19
[46] Pierson W R and Brachacek W W 1983 Emissions of ammonia and amines from vehicles on the road Environ. Sci. Technol. 17 757–60
[47] Pierson W R, Gerlert A W, Robinson N F, Sagebiel J C, Zielinska B, Bishop G A, Stedman D H, Zweidinger R B and Ray W D 1996 Real-world automotive emissions—summary of studies in the Fort McHenry and Tuscarora mountain tunnels Atmos. Environ. 30 2233–56
[48] Takigawa A, Matsunami A and Arai N 2005 Methane emission from automobile equipped with three-way catalytic converter while driving Energy 30 461–73
[49] Lipman T E and Delucchi M A 2002 Emissions of nitrous oxide and methane from conventional and alternative fuel motor vehicles Clim. Change 53 477–516
[50] Winkler A, Dimopoulos P, Hauert R, Bach C and Aguirre M 2008 Catalytic activity and aging phenomena of three-way catalysts in a compressed natural gas/gasoline powered passenger car Appl. Catal., B: Environmental 84 162–9
[51] Winkler A, Ferré D and Hauert R 2010 Influence of aging effects on the conversion efficiency of automotive exhaust gas catalysts Catal. Today 155 140–6
[52] Davis N, Lents J, Oses M, Nikkila N and Barth M 2005 Development and application of an international vehicle emissions model Transportation Research Record-Series 1939 157–65