SCIENCE CHINA
Information Sciences

• MOOP •

April 2017, Vol. 60 043201:1–043201:8
doi: 10.1007/s11432-016-9010-1

A networked remote sensing system for on-road vehicle emission monitoring

Yu KANG[1,2,3*], Yan DING[4], Zerui LI[2], Yang CAO[2] & Yunbo ZHAO[5]

[1]*State Key Laboratory of Fire Science, University of Science and Technology of China, Hefei* 230027*, China;*
[2]*Department of Automation, University of Science and Technology of China, Hefei* 230027*, China;*
[3]*Institute of Advanced Technology, University of Science and Technology of China, Hefei* 230027*, China;*
[4]*Chinese Research Academy of Environmental Sciences, Beijing* 100012*, China;*
[5]*College of Information Engineering, Zhejiang University of Technology, Hangzhou* 310023*, China*

Received November 19, 2016; accepted January 3, 2017; published online March 6, 2017

Abstract Vehicle emissions are a major source of urban air pollution, and therefore a real-time monitoring system can be very useful in analyzing such emission and consequently assisting the policy making process. In this work we discuss the principle and structure of three different types of remote sensing detectors, and also the key techniques to establish a networked remote sensing monitoring system. We finally conclude this paper with data analysis from some preliminary experiments.

Keywords networked system, remote sensing, vehicle emissions

Citation Kang Y, Ding Y, Li Z R, et al. A networked remote sensing system for on-road vehicle emission monitoring. Sci China Inf Sci, 2017, 60(4): 043201, doi: 10.1007/s11432-016-9010-1

1 Introduction

The number of vehicles has been increasing very fast in most Chinese cities in recent years, due to the dramatically increasing traffic demand caused by urbanization. Consequently and unfortunately, vehicle emissions cause more and more severe air pollution in most areas of China, especially in large cities. It already becomes an urgent task for the government and the society to take serious actions to deal with vehicle emissions, a first step towards which goal would be an efficient and cost-effective approach to measure vehicle emissions, preferably on-road. Conventionally measurement of vehicle emissions is usually done by the chassis dynamometer test, which has to be done on a dedicated platform with specialized equipments. Such a test approach faces two disadvantages. Firstly, although the dedicated platform can ensure accurate measurement, the vehicles to be tested are not in their actual running mode on the road. It is known that vehicle emissions vary with the road conditions, the traffic volume, the driving patterns, etc. Therefore, the accuracy in the chassis dynamometer test may not ensure the required accuracy in practical conditions. Secondly, the dedicated platform used by the chassis dynamometer test means that the test can be cost-ineffective, and is also not convenient nor widely applicable, since the driver has to make his decision to drive the car for the test.

* Corresponding author (email: kangduyu@ustc.edu.cn)

Advanced technologies have been developed to deal with the aforementioned disadvantages, including the portable emission measurement system (PEMS), the remote sensing system (RSS), the on-board diagnostic (OBD) technology, etc. A typical PEMS consists of several gas analysers all mounted on the tested vehicles, to measure CO_2, CO, NO_x and THC in the exhaust emissions. The OBD system is designed to monitor the vehicle emission control system to ensure its normal operation by detecting whether the vehicle exceeds the emission limit or not. The RSS is different from the above two since it is mounted on the roadside but not on the tested vehicle, making it capable of measuring emissions from all passing vehicles. Indeed, the concentrations of CO_2, CO, HC, NO and the opacity of exhaust of a single on-road vehicle can be measured by the RSS in less than one second.

It is known that the 20% highest emitting vehicles are responsible for almost 80% of the total air pollutants, making it vital to screen out the high-emitting vehicles. Remote sensing is quite an efficient tool to make a preliminary screening of thousands of on-road vehicles and recognize high-emitters. The remote sensing technology, i.e., using optical methods to measure vehicle exhaust emissions, has been developed and widely used since the late 1980s. In 1988, scientists from University of Denver applied a long-path IR photometer to detect CO in the tail gas, and in the 1990s, they realized the measurement of CO, CO_2, HC, NO and smoke opacity [1–3]. Remote sensing data has been used to estimate fuel-based emission factors and emission inventories, and the results were compared with those calculated by MVEI model [4–9]. Since the remote sensing measurements respect the vehicle emission under certain conditions, the relationship between remote sensing results and influential factors was also studied [10–12]. Whereas, the remote sensing system which is aimed at monitoring all on-road vehicles has not been considered yet.

In this paper we report the design and implementation of a so-called networked remote sensing system for on-road vehicle emission monitoring, as an essential part of the comprehensive monitoring system. This system is different from conventional RSS, in that it is a networked system rather than an isolated device, and as a whole system it can provide automatic, real-time monitoring of emissions of a large number of vehicles at a low cost through distributed remote sensing detectors on suitable roads across the traffic network. This can be very useful for making pollution-aware policies.

2 Structure and principle of remote sensing detectors

In this section, we introduce the principle and structure of three remote sensing detectors, that is, the horizontal remote sensing detector (HRSD), the vertical remote sensing detector (VRSD) and the transportable remote sensing detector (TRSD).

Figure 1 shows the structure of HRSD. When a car passes by, the infrared and ultraviolet beams with specific wavelength emitted from the light source will be partly absorbed by the exhaust spread to the air from the tailpipe. As the intensity of absorbed light measured increases, the concentration of gases become larger. If the vehicle is equipped with a diesel engine, the laser beam from the light source on one side of the road is received by the receiver on the other side, whose intensity is determined by the shading ability of the exhaust, and then the opacity can be worked out using light transmittance measurement principle. The speed/acceleration sensor uses two light paths to measure speed, acceleration and length of on-road vehicles. There will be a change in the intensity of two parallel infrared beams from two transmitting tubes if a vehicle passes and blocks the beams, so when the receiver on the other roadside detects an intensity change, the controller will send an instruction to the time-base circuit to start timing. The front passing two beams and the rear passing the first beam can be used to calculate the speed, acceleration and length according to the kinematic principles. The video cameras can capture images of lanes on road, analyzing the traffic condition whether there is a passing vehicle on each lane. According to the traffic condition, the optimal time can be determined to detect the intensity of beams and compute concentrations of pollutants. The images captured by the video cameras are vital to the license recognizer which involves projection-based license location, clustering-based characters segment and pattern-matching-based characters recognition. The industrial controller is employed to manage other components and process data.

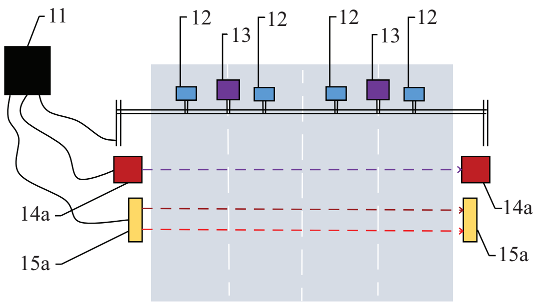

Figure 1 (Color online) An illustration of HRSD. HRSD consists of an industrial controller (11), a speed/acceleration sensor (14), an exhaust gas detector (15), license recognizers (12) and traffic monitors (13).

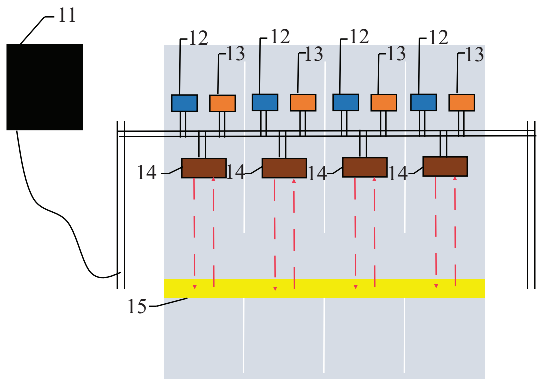

Figure 2 (Color online) An illustration of VRSD. VRSD consists of an industrial controller (11), speed/acceleration sensors (13), exhaust gas detectors (14) and license recognizers (12). The reflection zone (15) is mounted on the ground.

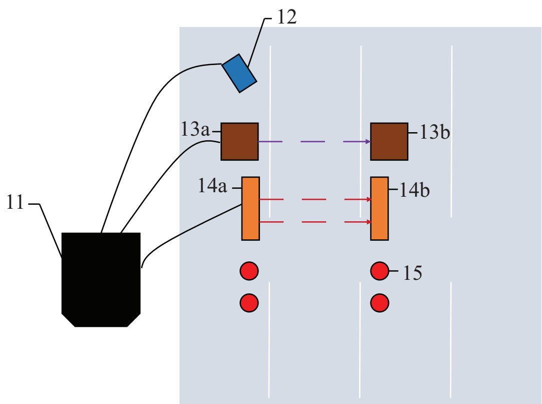

Figure 3 (Color online) An illustration of TRSD. TRSD is composed of a monitoring car (11), an exhaust gas detector (13), a speed/acceleration sensor (14), a license recognizer (12) and barricades (15).

For VRSD which is shown in Figure 2, the traffic monitors are not involved because detection for all lanes is independent. VRSD is different from HRSD in the fact that the former has an integrated laser emitter and receiver which can receive the laser generated by itself to the ground vertically from the reflection area (15). The development of VRSD solves the problem that HRSD may fail to detect several cars passing through the detector in parallel. This drawback limits the application of HRSD to roads with heavy traffic. The TRSD shown in Figure 3 works similarly as HRSD, but is more flexible than HRSD with all the components in the monitoring car, making it easy to move the detector to the roads where vehicles need to be detected temporarily.

3 Establishment of the networked remote sensing system

The networked remote sensing system for on-road vehicle emission monitoring is formed by distributing remote sensing detectors on suitable roads across the traffic network. The reliability of the monitoring system is dependent on the quantity of measurement data. We can collect a comprehensive set of vehicle emissions if we install sufficient detectors in the network, the extreme being at least one detector on any road. Whereas the scale of locating detectors is, to some degree, restricted as a result of the asymmetry between cost and information value. It is therefore critical for the system establishment to detect more vehicles with fewer detectors, and hence the location of the limited detectors is key. The optimal location of the detectors can be affected by many factors (e.g., distribution of vehicles, traffic condition, width

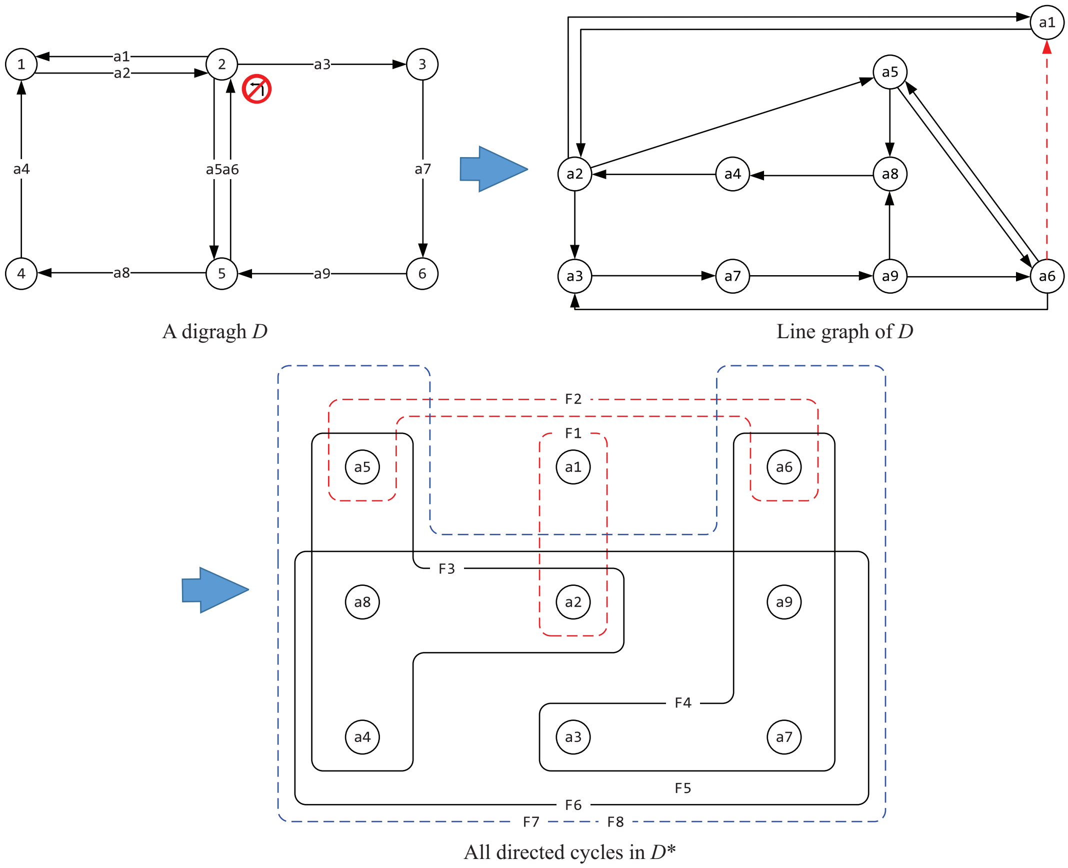

Figure 4 (Color online) Illustration of the location algorithm.

and shape of roads). In this work we introduce a location strategy based only on the topology structure of road network.

We use a digraph $D = (V, A)$ to model the real-world traffic network, where V is the set of vertices representing the junctions and A is the set of arcs representing the roads. The problem of interest is then transformed into a problem to find all the directed circuits in D. We notice that some circuits may not exist due to traffic control regulations like turn limitations. Therefore we design the algorithm for D^*, the line digraph of D. It facilitates the intractable elimination of the nonexistent circuits to delete the corresponding directed cycles in the line digraph of the road-network digraph. Moreover the algorithm of finding all cycles in D^* is much easier to design than that of searching all circuits in D. After all cycles are found, a greedy algorithm should be conducted to determine the minimum set of roads to deploy detectors which intersects all cycles. In Figure 4, a network with 6 vertices and 9 arcs is considered as an example. As illustrated, the number of monitors to be located is 2, and one of the location sites is $\{a_2, a_6\}$.

Since detectors are distributed in the whole traffic network, wireless communication technique instead of wired connection is employed. The data in the networked remote sensing system are of large quantity and various types. According to the real-time characteristic and the large number of data items, the cloud technology is employed to store and manage the dynamic multi-source heterogeneous data, and diverse transmission strategies are adapted to the different types. The item of data type is added to the data packet, according to which transmission strategies can be determined adaptively with the consideration of priorities of different types. In the data transmission protocol, security problems are resolved through security socket layer (SSL). The transmission protocol supports retransmission of data packet, localization of data source and the time synchronization information load, which can help assure the transmission reliability and online correction functioning. An end-to-end middleware is developed to fit the dynamic network changes and is installed to both the remote sensing detectors and the supervision platform. On

Table 1 Statistical results of single-lane HRSD, multi-lane HRSD and TRSD

Detector type	Total data	Valid data	Blue-plate data	Yellow-plate data	White-plate data
single-lane HRSD	109776	87821	79853	7115	853
multi-lane HRSD	156105	102330	97048	4456	826
TRSD	97392	76288	70802	4578	908

the server side, data packets are rearranged as a preprocessing and output using a multi-queue buffer structure to improve the performance of database storage and data access.

In order to improve the reliability of data transfer, a link-performance-sensing based distributed routing is adopted in the application layer. It is deployed on the receiving servers of all detectors and the supervision platform to construct a reliable transmission network. Every node not only has the function of transferring data, but can also detect the link performance automatically and forward route and data according to the link performance. If all the links are detected to be functioning well, the remote sensing detectors will directly transmit data to the server. However if some links are blocked or interrupted, the detectors will transmit data to the equipment that can be connected.

4 Data analysis

In this part, we use the data collected from three detectors throughout a month to analyze vehicle emissions. The detectors are located in Yanqing district, Beijing as a pilot project. The remote sensing detectors are single-lane HRSD, multi-lane HRSD and TRSD, respectively. The collected data are the volume percentage of CO_2, CO, HC and NO through which the ratios of gases, CO/CO_2, HC/CO_2 and NO/CO_2, denoted as Q, Q' and Q'' can be determined. In addition, the opacity of exhaust, speed, acceleration, registration number and meteorological data can also be acquired. Q, Q' and Q'' are constant for a given plume, and many other parameters can be determined based on these ratios by using the knowledge of combustion chemistry, including the grams of gases emitted per liter of gasoline burned and the volume percent of gas compositions which would be read by a tailpipe probe.

Table 1 shows the total amount of data, the amount of valid data and amount of data with different plate colors obtained from three types of the remote sensing detectors. In Table 1, each item of the valid data has an effective measurement, instead of being equal to 0. The single-lane HRSD and TRSD have almost the same amount of data, while multi-lane HRSD have much more. The valid ratios of three detectors are 80.0% for single-lane HRSD, 65.6% for multi-lane HRSD and 78.3% for TRSD, respectively, indicating that multi-lane HRSD has a valid ratio significantly lower than the others. Vehicles with blue plate are the most popular on roads, in percentage, 90.9%, 94.8%, 92.8% of the amount of valid data for three detectors. These ratios for yellow-plate vehicles are 8.1%, 4.4% and 6.0%. For vehicles with white plate, i.e., police cars, the percentages are 1.0%, 0.8% and 1.2%, respectively.

Figures 5 and 6 show the amount of vehicles emitting different concentrations of CO, HC and NO. Here we focus on the blue-plate and yellow-plate vehicles. For CO and HC, the tendency that the amount of vehicles varying with pollutant concentration are similar for blue-plate and yellow-plate vehicles. The overwhelming majority of vehicles emit 0–0.05% CO or 0–3 ppm HC as the volume concentration in the plume. While the situation of NO is different, for which the volume concentration of blue-plate vehicles are almost within the range 0–100 ppm, about half of all blue-plate vehicles emit nearly no NO. It is obvious that yellow-plate vehicles tend to emit much more NO than blue-plate vehicles. About 2500 among the yellow-plate vehicles even emit more than 1000 ppm of NO. Hence, in order to control the pollution of NO, more attention should be paid on the yellow-plate vehicles.

The remote sensing detectors can measure not only the air pollutant of CO, HC and NO, but the speed and the acceleration of the vehicles. It is thus possible to investigate the correlation between the two. 2000 samples are chosen randomly in Figures 7 and 8.

For CO, the volume concentration increases with the acceleration, and the concentration of decelerating is less than that of accelerating. When the speed is within the range of around 20 km/h or around 70 km/h,

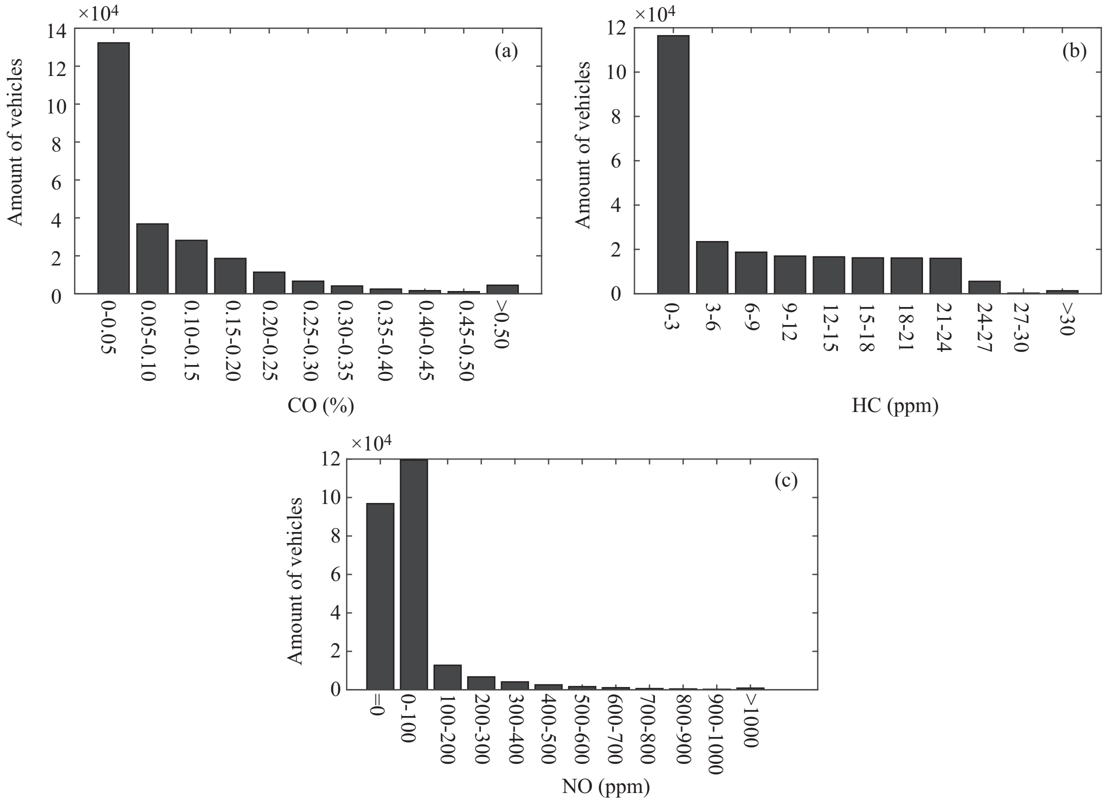

Figure 5 Distribution of (a) CO, (b) HC and (c) NO emission of blue-plate vehicles.

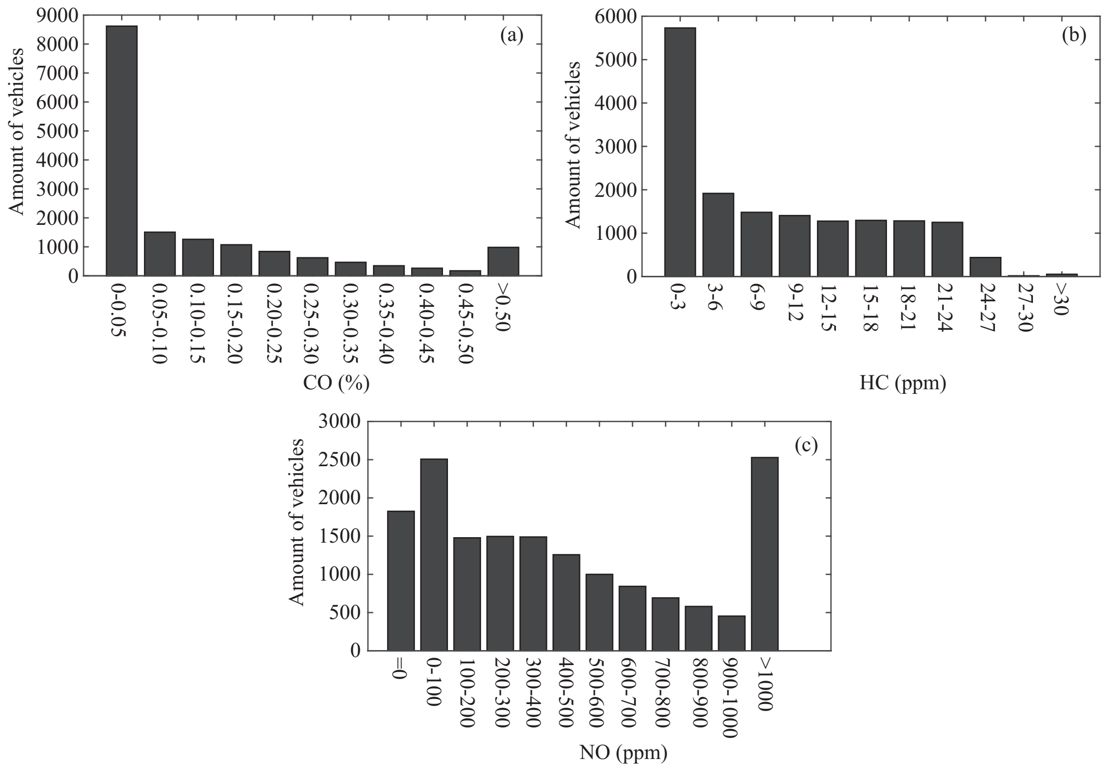

Figure 6 Distribution of (a) CO, (b) HC and (c) NO emission of yellow-plate vehicles.

the emission of CO has an notable increase. While for HC and NO, no straightforward conclusion can

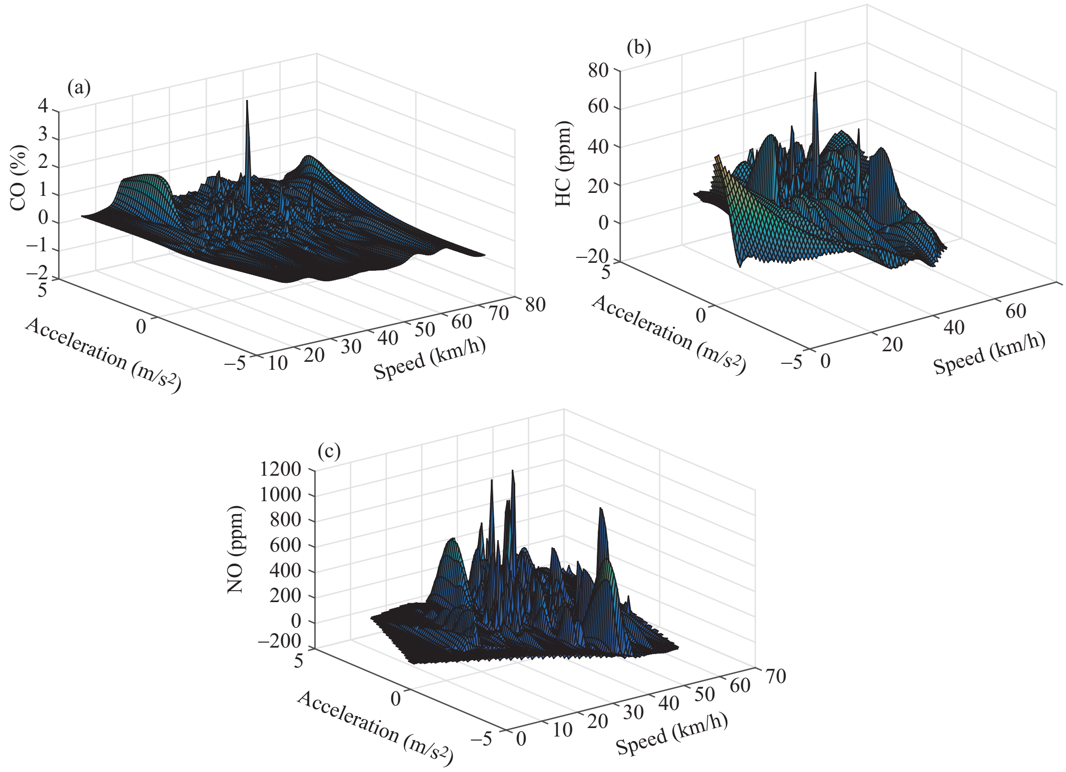

Figure 7 (Color online) (a) CO, (b) HC and (c) NO emission varying with speed and acceleration of blue-plate vehicles.

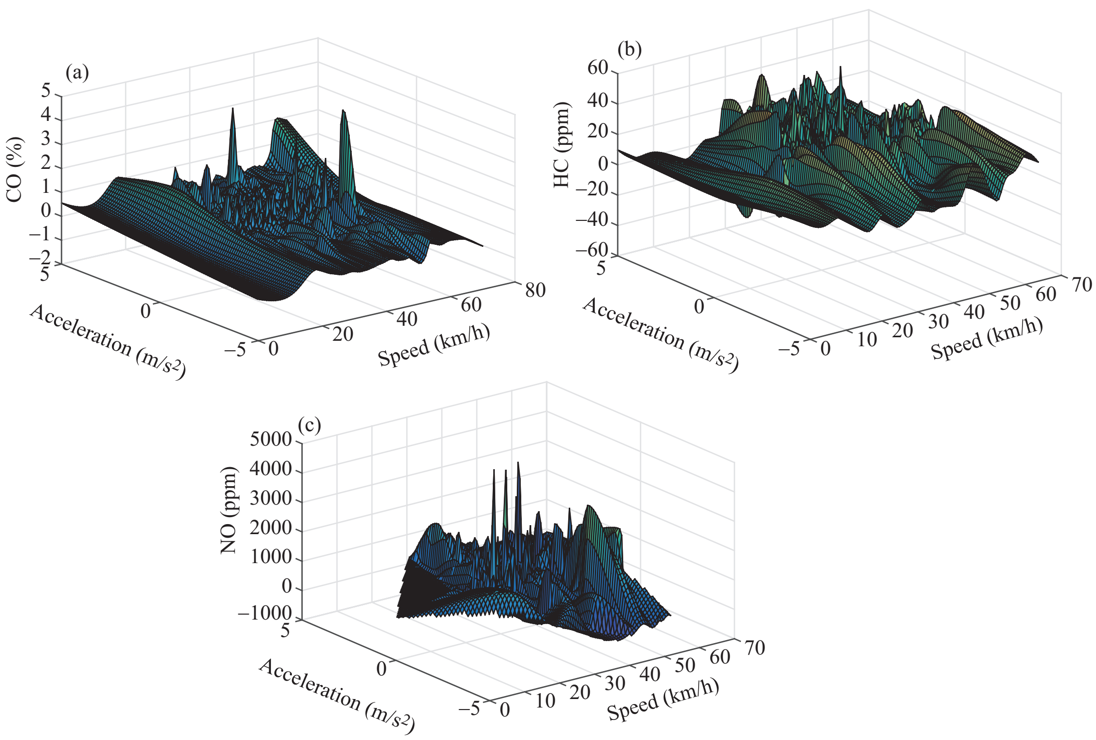

Figure 8 (Color online) (a) CO, (b) HC and (c) NO emission varying with speed and acceleration of yellow-plate vehicles.

be drawn, probably because their correlation with other factors.

5 Conclusion

A networked remote sensing system for on-road vehicle emission monitoring is developed, which can be used for automatic, real-time monitoring of vehicles on road. This is only one possible solution and more improvements are currently undergoing, in order that an efficient and cost-effective solution can be widely deployed in practice.

Acknowledgements This work was supported in part by National Natural Science Foundation of China (Grant Nos. 61422307, 61673350, 61673361, 61472380), Scientific Research Staring Foundation for the Returned Overseas Chinese Scholars and Ministry of Education of China. Authors also gratefully acknowledge supports from the Youth Top-notch Talent Support Program, the 1000-talent Youth Program and the Youth Yangtze River Scholar.

Conflict of interest The authors declare that they have no conflict of interest.

Supporting information The supporting information is available online at info.scichina.com and link.springer.com. The supporting materials are published as submitted, without typesetting or editing. The responsibility for scientific accuracy and content remains entirely with the authors.

References

1 Bishop G A, Starkey J R, Ihlenfeldt A, et al. IR long-path photometry: a remote sensing tool for automobile emissions. Anal Chem, 1989, 61: 671–677
2 Bishop G A, Stedman D H. Measuring the emissions of passing cars. Accounts Chem Res, 1996, 29: 489–495
3 Zhang Y, Stedman D H, Bishop G A, et al. Worldwide on-road vehicle exhaust emissions study by remote sensing. Environ Sci Tech, 1995, 29: 2286–2294
4 Chan T L, Ning Z. On-road remote sensing of diesel vehicle emissions measurement and emission factors estimation in Hong Kong. Atmos Environ, 2005, 39: 6843–6856
5 Guo H, Zhang Q, Shi Y, et al. On-road remote sensing measurements and fuel-based motor vehicle emission inventory in Hangzhou, China. Atmos Environ, 2007, 41: 3095–3107
6 Ning Z, Chan T L. On-road remote sensing of liquefied petroleum gas (LPG) vehicle emissions measurement and emission factors estimation. Atmos Environ, 2007, 41: 9099–9110
7 Pokharel S S, Bishop G A, Stedman D H. An on-road motor vehicle emissions inventory for Denver: an efficient alternative to modeling. Atmos Environ, 2002, 36: 5177–5184
8 Schifter I, Diaz L, Mugica V, et al. Fuel-based motor vehicle emission inventory for the metropolitan area of Mexico city. Atmos Environ, 2005, 39: 931–940
9 Singer B C, Harley R A. A fuel-based motor vehicle emission inventory. J Air Waste Manage Assoc, 1996, 46: 581–593
10 Kuhns H D, Mazzoleni C, Moosmüller H, et al. Remote sensing of PM, NO, CO and HC emission factors for on-road gasoline and diesel engine vehicles in Las Vegas, NV. Sci Total Environ, 2004, 322: 123–137
11 Lau J, Hung W T, Cheung C S. Observation of increases in emission from modern vehicles over time in Hong Kong using remote sensing. Environ Pollut, 2012, 163: 14–23
12 Sjödin Å, Andréasson K. Multi-year remote-sensing measurements of gasoline light-duty vehicle emissions on a freeway ramp. Atmos Environ, 2000, 34: 4657–4665