Urban air quality, meteorology and traffic linkages: Evidence from a sixteen-day particulate matter pollution event in December 2015, Beijing

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ABSTRACT

A heavy 16-day pollution episode occurred in Beijing from December 19, 2015 to January 3, 2016. The mean daily AQI and PM₂.₅ were 240.44 and 203.6 μg/m³. We analyzed the spatiotemporal characteristics of air pollutants, meteorology and road space speed during this period, then extended to reveal the combined effects of traffic restrictions and meteorology on urban air quality with observational data and a multivariate mutual information model. Results of spatiotemporal analysis showed that five pollution stages were identified with remarkable variation patterns based on evolution of PM₂.₅ concentration and weather conditions. Southern sites (DX, YDM and DS) experienced heavier pollution than northern ones (DL, CP and WL). Stage P2 exhibited combined functions of meteorology and traffic restrictions which were delayed peak-clipping effects on PM₂.₅. Mutual information values of Air quality–Traffic–Meteorology (ATM–MI) revealed that additive functions of traffic restrictions, suitable relative humidity and temperature were more effective on the removal of fine particles and CO than NO₂.

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Introduction

Severe air pollution issues have become 'new normal' in megacities in China since 2013. One of the most serious haze events occurred in December 2015 with 65.5% pollution days over the whole month. This of course attracts considerable concern from both the public and government agencies for adverse effects on human health (Miller et al., 2007; Liu et al., 2016b; Wu et al., 2016; Guo et al., 2016; West et al., 2016), urban air quality (Pleijel et al., 2016; Yassaa, 2016), global climate (Baklanov et al., 2016; Makar et al., 2015) and vital contributions to emission reduction tasks of air pollutants (Thaker and Gokhale, 2016; Kwak et al., 2016). In urban areas of northern China, vehicles and coal combustion are considered to be major emission sources of fine particles in winter (Liu et al., 2016a; Wang et al., 2015; Wang and Hao, 2012). The odd–even traffic restrictions during Olympic games (Wang et al., 2009), APEC (Wang et al., 2016) and Marathon games (Zhao and Yu, 2016) greatly reduce the emissions of Carbon Monoxide (CO), Black Carbon (BC) and Ultrafine Particle (UFP) from vehicles, indicating that large improvements of urban air quality have been occurred by implementing provisional traffic restriction measures (Thaker and Gokhale, 2016; Kwak et al., 2016). Simultaneously, meteorological factors, such as wind direction, wind speed, temperature and relative humidity, are largely responsible for formation, accumulation and dispersion of gaseous pollutants and ambient particles (Kumar et al., 2008;
Wehner and Wiedensohler, 2003; Zhou et al., 2016; Chen et al., 2012). Good air quality is likely to occur with high temperature and low humidity (Zheng et al., 2013), while higher concentrations of particulate matter (PM) occur at low and high wind rather than moderate wind speed (Yin et al., 2016). Particle minima concentration in summer is associated with higher temperature and better mixing (Laakso et al., 2003), and lower concentrations of particles that are less than 2.5 μm in diameter (PM_{2.5}) coincides with pollution transport by south wind (Pasch et al., 2011). NO\textsubscript{2} and O\textsubscript{3} tend to exhibit higher average concentrations with humidity less than 40%, while peak concentrations of PM_{10}, SO\textsubscript{2} and CO accompany with humidity above 80% (Elminir, 2005).

Although an improved understanding of relationships between air quality and synoptic meteorology, air quality and traffic restrictions has been revealed, we still have little knowledge about combined effects of meteorological conditions and traffic patterns, as well as the instant and delayed effects of provisional traffic measures on air pollutants during severe haze events.

Many association rules for two variables have been published with good performance. Of the most relevant studies, maximum information coefficient method was proposed to detect dependence of two-variable relationships (Reshef et al., 2011). Joe (Joe, 1989) tried to use relative entropies to measure the multivariate dependence and conditional dependence. Hosseini et al. (Hosseini et al., 2012b) made traffic speed predictions in 24 hr with mutual information and found it largely reducing the prediction error variance. Therefore, the present study will be the first to combine quantification impacts of traffic restrictions and meteorological conditions based on mutual information theory, detecting multivariate association rules in the field of air quality analysis.

In this study, we present the spatiotemporal characteristics of air pollutants, meteorology and road mean space speed during a 16-day severe pollution episode in Beijing. Then, on basis of classical information theory, we propose an index called Mutual Information of Air quality–Traffic–Meteorology (ATM–MI) to describe combined effects of meteorology and traffic restrictions. An integrated understanding of air pollutants and meteorology, as well as knowledge about traffic restrictions, is beneficial to detect the combined influence on air quality from multi-factors, reduce severe pollution events and decrease their hazardous effects with effective measures.

### 1. Theory and methods

#### 1.1. Data resources

Hourly concentrations of gaseous pollutants and fine particle are derived from the public website of Beijing Municipal Environmental Monitoring Center (http://zx.bjmemc.com.cn/) ranging from December 17, 2015 to February 29, 2016. To correspond to different regional functions, six sites have been selected as follows: YDM (traffic site), DX (industrial site), WL (cultural and educational site), DS (commercial site), CP (residential site) and DL (background site) (Hu et al., 2015). With respect to meteorological data, hourly mean values of temperature, relative humidity, wind direction and wind speed are presented in detail for corresponding district where each monitoring site locates from public information of China Meteorological Administration (http://data.cma.cn). These factors have been reported with significant roles on urban air quality (Xu et al., 2015; Zhang et al., 2015). Simultaneously, from an open source data center (http://www.navinfo.com.cn/news/index.aspx), we collect average vehicle speed on urban roads with a temporal resolution of 5 min. In order to match other two types of data, traffic data have been hourly averaged to create a new data set. All these data are stored in the SQL Server database.

**Fig. 1** – Daily mean concentrations of Air Quality Index (AQI), particulate matter (PM_{2.5}) and trace gases (CO, NO_{2}, O_{3}) from December 17, 2015 to February 29, 2016 in Beijing.
1.2. Air quality–Traffic–Meteorology mutual information

Mutual information, one of many quantities measuring how much one random variable tells about the other, was first introduced in information theory by Shannon in 1948 (Shannon, 2001). High mutual information demonstrates a large reduction of uncertainty, while low value indicates a small one, and zero between two random variables means that the variables are independent. It has been successfully used for prediction (Hosseini et al., 2012a, 2012b), feature selection (Qian and Shu, 2015), image recognition (Pluim et al., 2003) and other fields in recent years.

As to two discrete variables X and Y whose joint probability distribution is \( P_{XY}(x,y) \), we denote \( I(X;Y) \) as their mutual information. It can be calculated by Eq. (1).

\[
I(X;Y) = \sum_{x} \sum_{y} P_{XY}(x,y) \ln \frac{P_{XY}(x,y)}{P_X(x)P_Y(y)} = \sum_{x} \sum_{y} P(x,y) \ln \frac{P(x,y)}{P(x)P(y)} \tag{1}
\]

Here, \( P_X(x) \) and \( P_Y(y) \) are the marginal and can be figured by Eqs. (2) and (3), respectively.

\[
P_X(x) = \sum_y P_{XY}(x,y) \tag{2}
\]

\[
P_Y(y) = \sum_x P_{XY}(x,y) \tag{3}
\]

As to three variables, we calculate the mutual information values among them through multivariate mutual information theory as Eqs. (4) and (5).

\[
I(X;Y;Z) = \sum_{x} \sum_{y} \sum_{z} P_{XYZ}(x,y,z) \ln \frac{P(x,y,z)}{P(x)P(y)P(z)} = \sum_{x} \sum_{y} \sum_{z} P(x,y|z) \ln \frac{P(x,y|z)}{P(x|z)P(y|z)} \tag{4}
\]

\[
I(X;Y|Z) = I(X;Y) - I(X;Y|Z) \tag{5}
\]

where \( I(X;Y|Z) \) is the conditional mutual information of X and Y given Z.

ATM-MI is proposed to evaluate the dependency between air quality and the combined effect of traffic and meteorology. X, Y, and Z express air quality, meteorology, and traffic index, respectively. Specifically, we use X to demonstrate Air Quality Index (AQI), concentration of PM\(_{2.5}\), CO and NO\(_2\); Y is presented by wind speed, temperature and relative humidity; Z is described by road mean speed.

The specific calculation steps are as follows:

1) Define \( X, Y, Z, X=(x_1, x_2, x_3, x_4), Y=(y_5, y_6, y_7), Z=(z_2) \);
2) Extract subsets from original dataset \((X, Y, Z)\) and form a new sample dataset \((X', Y', Z')\);
3) Calculate the mutual information of \((X', Y', Z')\);
4) Repeat step 2) and step 3) for n times and obtain a sequence of mutual information entropy;
5) Rank the sequence, determine the level of significance and calculate the mean mutual information within the range of confidence as the final mutual information;
6) Normalize the mutual information to obtain generalized correlation coefficients by Eq. (6).

\[
\varphi(X;Y;Z) = \sqrt{1-e^{-2I(X;Y;Z)}} \tag{6}
\]

2. Results and discussion

2.1. Spatiotemporal characteristics of air pollutants

Fig. 1 presents a typical air pollution issue from December 17, 2015 to February 29, 2016 in Beijing. The mean AQI was 106.19 during that period, stating a slight pollution stage according to Chinese AQI regulations. However, a continuous heavy pollution stage with the average AQI 240.44 happened from December 19, 2015 to January 3, 2016, bringing hazardous effects on human health, especially for people with heart or breathing diseases (West et al., 2016). During this pretty unhealthy period, average daily concentrations of PM\(_{2.5}\), CO and NO\(_2\) were 203.60, 94.49, 25.94 \(\mu g/m^3\) and 3.63 mg/m\(^3\), respectively. In terms of the thresholds regulated by Chinese National Air Quality Standards II, daily PM\(_{2.5}\), and CO exceed the standard by 2.71 and 1.18 times of thresholds, whereas the highest value of PM\(_{2.5}\) was 6.36 times of that on December 25.

From Fig. 2, we could find a remarkable 16-day pollution episode with high AQI at six different urban function areas. Four typical peaks visibly appeared on December 22, 25, 29 and January 3 with crimson color, but the duration gradually decreased due to different control measures which would be interpreted in the following discussion. From the geographical positions of six sites, the southern sites (DX, YDM, DS)
experienced heavier and longer pollution than the northern sites (DL, CP, WL) via the time thickness and time sequence of purple and brown. Combined effects of wind dispersion and pollution sources could explain this phenomenon. From the perspective of urban functions, traffic-related and industry-related air pollution were much severer than other function areas, which could be known by comparing YDM, DX and other sites.

During this continuous pollution event, hourly variations of PM$_{2.5}$, O$_3$, NO$_2$ and CO over six ambient air stations were presented in Fig. 3a, b, c and d, respectively. Taking the background site DL as the target, five different stages with remarkable variation patterns were divided in Fig. 3a. During the first stage P1, concentrations of PM$_{2.5}$ increased gradually to the peak around 4 pm on December 22, owing to the effects of meteorological factors under stable emission sources. However, there was a sharp decline demonstrated in P2 stage, making a reasonable guess as the result of provisional even–odd traffic restrictions from December 20 to 22. From Fig. 3c and d, effects of traffic restrictions were significantly exhibited from a sudden decrease of traffic-related pollutants once the traffic measures were implemented. Compared with CO and NO$_2$, delayed peak-clipping effects might be performed on PM$_{2.5}$ from the following haze events. On the afternoon of December 24, another round of extreme haze pollution with high PM$_{2.5}$ concentrations came due to stable weather condition, but disappeared quickly with snow falling on the evening of December 26. The snow deposition and the low temperature allowed a short-term pollution with lower peak than the previous two pollution stages. As to Fig. 3d, traffic-related site YDM performed with lower concentrations of CO in stage P2 as a result of traffic restrictions.

2.2. Characteristics of meteorology

Although relationships between synoptic meteorology and air pollution have been investigated for pollutants such as NO$_2$, CO, PM$_{2.5}$ (Xu et al., 2011, 2015; Elminir, 2005; Fast et al., 2007), we still have little information about the combined effects of meteorology and traffic restrictions on air quality. Wind frequency rose diagrams of CP (covering site CP and DL), DC (covering site DS and YDM), DX (site DX), HD (site WL) district were figured in Fig. 4, respectively. For CP, the predominant wind directions were NNW, NW and N, with frequencies of 14.00%, 13.50% and 12.00%, while for DC were ENE (13.65%) and NE (11.18%), for DX were NNE (9.22%) and WSW (7.50%), for HD were NE (22.61%) and ENE (17.83%). From the above analysis,
north winds were dominant during the target period, allowing the pollutants to spread from north to south. To some extent, north wind could end the contamination in northern regions ahead of the southern parts and carry some pollutants to the south. Wind speed less than level 2 occurred frequently in these four districts with frequencies 50.17%, 57.16%, 46.84% and 44.03%, respectively. The top frequency of calm wind appeared at DX, which was one of disadvantages for air pollutants dispersion.

Corresponding to the five pollution stages, hourly variations of temperature and relative humidity were exhibited in Fig. 5. During the first stage P1, the maximum and minimum temperatures gradually decreased, while values of relative humidity sharply increased with mean value 75, accompanying with a gradually serious trend of air pollution. Similar pattern was magnified in the third stage P3, indicating that severe pollution was more likely with higher humidity and lower temperature. During the second stage P2 and late P3, concentrations of pollutants reduced with increasing temperature and decreasing relative humidity, as well as the delayed effects of provisional traffic restrictions argued in the following chapter. From P2 to P3, dramatic variations of AQI accompanied with flagrant contrast of temperature (−6°C–8°C) and humidity (20%–95%), indicating that good AQI was more likely with higher temperature and lower humidity.

2.3. Combined effect of meteorology and traffic restrictions

We take the traffic-related site YDM for example to reveal combined effects of meteorology and traffic restrictions during stage P2. Traffic restrictions were adopted from 0 am, December 20 to 12 am, December 22, and could be identified from variations of road mean speed. Fig. 6 presented the variations of road mean speeds in two directions before (December 19), during (December 20 to 22) and after (December 23) odd–even restrictions at YDM street. The mean speeds during these three periods in S–N direction were 39.34 km/h, 44.63 km/h and 39.89 km/h, respectively. The trend of traffic speed at YDM street first gradually increased, then decreased on the contrary of traffic flow. In the opposite direction, the same trend appeared. Traffic-related pollutants, such as CO and NO₂, were largely affected by traffic count (Shabbir et al., 2016; Noland and Quddus, 2006) seen from Fig. 3c and d.

Based on multivariate mutual information theory, we propose an index 'ATM-MI' to describe combined effects of meteorology and traffic restrictions. The second stage P2 has been selected as the object to calculate mutual information of three variables among air quality, traffic and meteorology.

Fig. 7 shows the test results of mutual information of ATM. The top three values of generalized correlation coefficients $\varphi$
are 0.897, 0.875 and 0.812 in Fig. 7g, k and j, corresponding to speed–temperature–CO, speed–relative humidity–CO and speed–relative humidity–PM$_{2.5}$, respectively. Three bad performance measurements are also selected: speed–wind speed–AQI (0.513), speed–relative humidity–NO$_2$ (0.505) and speed–wind speed–NO$_2$ (0.476). The above comparisons have revealed that combined effects of traffic restrictions and humidity, traffic restrictions and temperature, are more

Fig. 5 – Variations of temperature and relative humidity of six monitoring sites corresponding to five stages.

Fig. 6 – Variations of road mean speed before and after traffic restrictions at YDM street from December 19 to 23, 2015.
effective on the removal of fine particles and CO than NO₂, whose generation and removal may need more evidence from light intensity.

3. Conclusions

Meteorology and traffic emissions play significant roles on urban air quality but relationships among them are complicated. In this paper, we analyze the spatiotemporal characteristics of air pollutants, meteorology and road space speed during a 16-day severe pollution episode in Beijing first; then, we extend to reveal combined effects of traffic restrictions and meteorology on urban air quality based on observational data and a multivariate mutual information method. Results of ATM-MI reveal that additive functions of traffic restrictions, suitable relative humidity and temperature are more effective on the removal of fine particles and CO than NO₂.

Fig. 7 – Test results of Mutual Information of Air quality–Traffic–Meteorology.
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