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The effect of COVID-19 restrictions on particulate matter on different modes of transport in China

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ABSTRACT
Since the COVID-19 pandemic, ventilation on transport has been improved to control the aerosol transmission. We utilized portable monitors to measure real-time concentrations of PM$_{10}$, PM$_{2.5}$, PM$_{1.0}$ and black carbon (BC) on six modes of transport and estimate personal exposures under the epidemic prevention. The mean concentrations of PM$_{10}$, PM$_{2.5}$, PM$_{1.0}$ and BC measured on transport were 18.8 ± 19.4, 16.6 ± 16.5, 12.2 ± 10.8 and 4.1 ± 6.9 μg/m$^3$, respectively. It reduced PM levels on subway to apply the full fresh air mode rather than partial recirculation mode. Airplane had the lowest concentrations and the highest decay rates, implying the most efficient ventilation and filtration. PM were higher on intra-city transport than inter-city, and significantly increased on arrival at stations. BC and BC/PM ratios were higher on road transport than rail transport, indicating the contribution of exhaust emissions. The ventilation mode to exchange air with the outside and the positive association between concentrations and decay rates on high-speed train suggested filtration efficiency should be improved simultaneously with enhancing ventilation. Wearing facemasks on transport further protects passengers against PM exposure, which reduced personal exposure concentrations on four modes of transport lower than 10 μg/m$^3$, the World Health Organization guideline.

1. Introduction

Aerosol transmission of COVID-19 requires an improved and efficient ventilation system in public places to reduce the infection risk (Greenhalgh et al., 2021; Tang et al., 2021). A number of studies have verified that COVID-19 can remain viable and transmit in aerosols for hours (Borak, 2020; van Doremalen et al., 2020). Besides, it presents a significant association between chronic exposure to particulate matters and the incidence and severity of COVID-19 cases (Marques and Domingo, 2021; Setti et al., 2020). Transport, especially public transport, puts crowded people in high densities and increases risk of COVID-19 spread via aerosol particles as well as droplets or by surface deposits (Zhen et al., 2020). Accumulating evidence suggests that improving ventilation system on public transport is an efficient mitigation measure to control COVID-19 spread (Jarvis, 2020). Subway, high-speed train and airplane in China implement ventilation system which constantly exchanges air with the outside environment and equips with filtration system; while cars and buses may be poor in ventilation. Due to the COVID-19 pandemic, many airlines state that a more efficient and improved ventilation and filtration system (i.e. high efficiency particulate air filter, HEPA filter) has been adopted on airplanes to enhance air filtration performance and keep passengers safer (Christopherson et al., 2020).

For urban residents, traffic-related air pollution is one of the primary sources for PM exposures. Personal exposure to air pollutants during commuting accounts for a considerable portion of daily exposure in urban areas (Dons et al., 2011; Fruin et al., 2004). This is mainly because the higher air pollutant exposure concentrations usually appear during commuting, although daily commuting time is merely around 90 min (Yang et al., 2019). In several megalopolises, such as Beijing, Shanghai, and Hong Kong in China, daily commuting time can increase up to 120 min and more. Extra time in transit is linked significantly to the increase of air pollutant exposures (Chen et al., 2018). Different mode and the ventilation (and filtration) efficiency of transport is significantly

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associated with the passengers’ exposure to airborne pollutants, then health problems of relevance (Dons et al., 2012; Zuurbier et al., 2010).

The microenvironment on transport are mainly determined by outdoor air and artificial intervention measurements. PM exposure concentrations of outdoor mode, e.g., walking and cycling, are fully dependent on the outdoor atmospheric environment. Road vehicle mode, with the support of cabin, expose the commuters less to the outdoor environment, affected by meteorological variables (Zheng et al., 2021), traffic time, fuel type (Zuurbier et al., 2010), traffic volume and composition (Kaur and Nieuwenhuijsen, 2009), ventilation, route (Chaney et al., 2017), etc. While, rail transport especially equipped with enclosed carriages is more independent, mainly affected by ventilation system and the station environment, but also influenced by the outdoor air (Zhang et al., 2020). For cabin transport, there’s basically no emission source of particulate matter in the carriage; the primary contributor is the outdoor air pollution. Ventilation mode and efficiency affects the connection between the microenvironment on transport and the external environment, then further influences the PM levels in the cabin (Abbass et al., 2021).

Various studies reported lower outdoor but higher indoor PM levels during the COVID-19 lockdown (Ezani et al., 2021; Mousavi and Wu, 2021). While information regarding PM levels on transport after the COVID-19 pandemic is missing. Therefore, the objectives of this study are to measure concentrations of particulate matter (including black carbon) on different modes of transport, to assess the potential sources and influencing factors, especially the ventilation and filtration efficiency, and to estimate personal exposure concentrations in reasonable scenarios after the pandemic. We hope the result of this study could provide some experience on the success of COVID-19 control in China and be valuable for the countries which are still suffering from the COVID-19 pandemic.

2. Methodology

2.1. Sampling sites and population recruitment

We recruited four volunteers who live in Shanghai and usually travel around China on business by taking different modes of transport. 24 field campaigns were conducted in two seasons (summer: August 7th – 16th, 2020; autumn: September 16th – 28th, 2020). During this period, the sampling cities were free of COVID-19 cases and there were less restrictions on travel; while ventilation on transport has been upgraded and passengers were required to wear face masks. Volunteers carried the PM and BC real-time measurement devices during taking transport and recorded detailed information (see Table 1), regarding transport mode, date/time, site, occupancy, ventilation, etc. Six modes of transport were involved in this study: car, bus, subway (SW), inter-city bus (ICB), high-speed train (HST), and airplane (AP).

2.2. PM and BC measurements

The real-time concentrations of PM and BC were measured using two portable devices. An optical real-time PM monitor (Zefan Technol., China) (Qiu et al., 2019) was used to measure PM$_{10}$, PM$_{2.5}$ and PM$_1$ (particles with aerodynamic diameter equal to or less than 10, 2.5, 1.0 μm, respectively) in μg/m$^3$, as well as temperature (T, °C) and relative humidity (RH, %). A microAeth® MA 200 (Beijing Saark-Mar Environmental Instrument Ltd., Beijing, China) was used to measure BC in ng/m$^3$ simultaneously. Both devices have been used in several previous studies (Chen et al., 2020; Du et al., 2021; Shen et al., 2021a). Before each field campaign, the PM monitor was calibrated against a particulate matter monitor (model 5030 synchronized hybrid ambient real-time particulate monitor, Thermo Scientific) and the BC monitor was calibrated according to the user manual and setting guide. The detection limits for PM and BC were 5 μg/m$^3$ and 0.001 μg/m$^3$, respectively. Values below the detection limits were set as 0 and shown as “ND”.

A smoking event occurred unexpectedly during a sampling campaign in car (see Table 1). Smoking contributed to a remarkable peak of particles, which is an ideal example to calculate the removal efficiency and to explain the importance of particulate matter controlling in a relatively enclosed space, e.g. cabin on transport. Therefore, we analyzed both particle concentrations including and excluding the smoking event’s data, and discussed the contribution of smoking to PM exposure.

Outdoor PM concentrations were obtained from the China Ministry of Ecology and Environment (MEE) national network, which can be downloaded from quotsoft.net/air. We selected the data of same-hour and nearest monitoring sites to represent the outdoor PM concentrations.

### Table 1

| Transport mode | Date | Time period | City            | Occupancy | Ventilation$^1$ | PM$_{10}$ | PM$_{2.5}$ | PM$_{1}$  | BC |
|----------------|------|-------------|-----------------|-----------|-----------------|-----------|------------|-----------|-----|
| Car            | 08/08 | 06:23-06:43 | Shanghai        | 2         | AC, re-circulation | 5.2       | 4.9        | 4.3       | 2.4 |
|                | 08/09 | 11:30-11:46 | Huaian          | 5         | AC, re-circulation | 32.1      | 28.6       | 19.9      | 10.8|
|                | 08/10 | 21:21-21:33 | Shanghai        | 2         | AC, re-circulation | 10.1      | 9.7        | 7.9       | 4.2 |
|                | 08/12 | 08:29-09:17 | Shanghai        | 2         | AC, re-circulation | 2.8       | 2.6        | 2.3       | 1.7 |
|                | 08/14 | 09:36-11:15 | Beijing         | 4         | AC, re-circulation | 9.0       | 8.3        | 6.8       | 1.9 |
|                | 08/14 | 17:12-17:53 | Shanghai        | 4         | AC, re-circulation | 34.2      | 31.9       | 25.1      | 2.5 |
|                | 08/16 | 08:29-23:59 | Shanghai - Nanjing | 4     | AC, re-circulation | 20.7      | 18.7       | 12.8$^b$  | 1.8$^b$|
|                | 09/24 | 14:45-15:34 | Shanghai        | 3         | AC, re-circulation | 11.8      | 11.3       | 9.5       | 5.7 |
|                | 09/24-25 | 22:00-00:55 | Kunming - Chuxiong | 4     | AC, re-circulation | 4.6       | 4.2        | 3.4       | 2.2 |
|                | 09/28 | 18:30-19:38 | Shanghai        | 2         | Windows open      | 13.7      | 13.0       | 10.4      | 5.2 |
| Bus            | 08/09 | 12:34-13:31 | Huaian          | 35-40     | Windows open      | 46.4      | 38.3       | 25.1      | 6.5 |
|                | 09/16 | 12:11-13:55 | Shanghai        | 13-22     | Windows open/closed | 42.4      | 36.2       | 24.8      | 17.3|
|                | 09/16 | 15:19-17:35 | Shanghai        | 3-51      | Windows open/closed | 53.0      | 43.7       | 29.1      | 19.6|
| Subway (SW)    | 08/10 | 20:22-21:08 | Shanghai        | 100       | HVAC             | 20.9      | 17.3       | 10.4      | 3.2 |
|                | 08/12 | 14:29-16:04 | Beijing         | 45        | HVAC             | 56.2      | 45.6       | 29.6      | 8.4 |
| Inter-city bus (ICB) | 08/08 | 06:58-13:09 | Shanghai - Huaian | 25-30    | AC                | 13.2      | 12.4       | 10.0      | 10.4|
|                | 08/10 | 13:27-19:52 | Shanghai - Shanghai | 40-45   | AC                | 19.6      | 18.0       | 13.4      | 5.8 |
|                | 09/16 | 11:15-14:24 | Shanghai - suburb | 40-45   | AC                | 47.0      | 39.3       | 25.6      | 6.9 |
| High-speed train (HST) | 08/07 | 08:05-09:14 | Nanxiong - Chongqing | 50-55   | HVAC             | 31.3      | 28.3       | 20.4      | 3.5 |
|                | 08/07 | 10:15-22:06 | Chongqing - Kunshan | 95-100   | HVAC             | 13.8      | 12.8       | 10.0      | 1.4 |
|                | 08/12 | 09:50-14:29 | Shanghai - Beijing | 95-100   | HVAC             | 30.1      | 26.0       | 18.4      | 1.7 |
|                | 08/14 | 11:48-16:30 | Beijing - Shanghai | 95-100   | HVAC             | 25.3      | 22.6       | 16.5      | 1.3 |
| Airplane (AP)  | 09/24 | 16:45-20:43 | Shanghai - Kunming | 270     | HVAC-HEPA        | ND        | ND         | ND        | 0.4 |
|                | 09/28 | 13:51-17:52 | Kunming - Shanghai | 300     | HVAC-HEPA        | 0.3       | 0.2        | 0.2       | 1.0 |

$^a$ AC: air conditioner; HVAC: Heating Ventilation Air Conditioning; HEPA: high efficiency particulate air filter.

$^b$ Including measurements under smoking conditions.
2.3. Personal exposure concentration assessment

Wearing facemasks is an efficient and low-cost measure for controlling the transmission of COVID-19. During the sampling period, all passengers were asked to follow the requirements to wear masks on transport, especially on public transport, all over the country in China. Wearing masks has been verified to be efficient for both controlling the transmission of COVID-19 and reducing particulate matter exposure concentrations (Shen et al., 2021b). In this study, personal exposure concentrations of particulate matter on transport were calculated assuming 56% removal efficiency of medical facemasks (Shen et al., 2021b), which were used by almost all of the passengers, as shown in eq. (1), where $C_p$ is the exposure concentration ($\mu g/m^3$) of passengers, $C$ is the concentration ($\mu g/m^3$) of PM and BC measured on transport, $RE$ is the removal efficiency of 56% (Shen et al., 2021b).

$$C_p = C \times (100\% - RE)$$

(1)

2.4. Data analysis

Indoor particle removal is due to ventilation, deposition onto indoor surfaces, and indoor air filtration system, which is fitted to a natural decay curve over a portion of the decay period (Kim and Yeo, 2020). Here we used decay rates (DRs) to assess particle’s removal efficiency in the air on transport. The DRs (h$^{-1}$) were estimated for car, inter-city bus, high-speed train, and airplane by fitting the natural decay curves of PM (Kim and Yeo, 2020). We used both PM$_{10}$ and PM$_{2.5}$ for each decay curve, selected curves that had changes as big as possible and that followed (at least roughly) the expected declining exponential trend, as shown in eq. (2):

$$C_t = (C_1 - C_0) \times e^{-DR \times \Delta t} + C_0$$

(2)

where $C_t$ is real-time PM concentration ($\mu g/m^3$), $C_1$ and $C_0$ are the maximum and steady-state PM concentrations over the decay period ($\mu g/m^3$), and $\Delta t$ is decay period (h). DRs were estimated by minimizing residuals (using a nonlinear leastsquares estimator) and then averaging among the estimates for each curve.

Descriptive statistics (e.g., means, standard deviations, medians and ranges) were calculated for each data type. Differences were evaluated using the Mann-Whitney U for two samples and the Kruskal-Wallis H for multiple comparisons. Associations were quantified using Spearman’s correlation analysis. Related parameters including correlation coefficient (R) and significance level (p) were presented. All statistical tests were two-sided with a type-I error rate of 0.05. Data were analyzed using SPSS (SPSS, Inc.) and R version 4.0.1.

3. Results and discussion

3.1. Pollution levels of PM and BC

The concentrations of PM$_{10}$, PM$_{2.5}$, PM$_{1.0}$ and BC measured on all modes of transport ranged ND – 2532, ND – 1936, ND – 315, ND – 76 $\mu g/m^3$, respectively. The large variations result from the variation in outdoor PM levels, ventilation efficiency, passenger densities, and passengers’ activities. It is interesting to find extremely sharp increases of PM and BC when a passenger smoked in a private car, suggesting the necessity to forbid smoking on transport (Figure S1). Excluding the data of smoking, PM$_{10}$, PM$_{2.5}$, PM$_{1.0}$ and BC concentrations measured on different modes of transport are shown in Fig. 1 and Table S1. The detailed PM levels in each single trip are listed in Table 1.

PM levels have been characterized on multiple modes of transport in previous studies. Given the differences among studies, including sampling cities, seasons, ventilation conditions, we only summarized studies under similar conditions in China in Table S2, and listed only Shanghai data in present study. Only car, bus and subway have been studied before the pandemic. The PM$_{2.5}$ levels in carriage of subway presented a significant reduction after the pandemic than before. Northern China (Beijing and Tianjin) during winter before 2020 had the highest PM$_{2.5}$ levels, averaging 62 and 151 $\mu g/m^3$ (Wang et al., 2016a; Yan et al., 2015). The mean level in Nanjing, also located in Yangtze River Delta, was 54 $\mu g/m^3$ (Shen and Gao, 2019). Several studies conducted in Shanghai before the pandemic (in 2013, 2015, 2016 and 2017) reported the average levels from 24 to 84 $\mu g/m^3$, ranging from 7 to 35 $\mu g/m^3$, lower than the observations in the pre-pandemic period. After the pandemic, subway including stations implement the full fresh air mode all through the year to replace partial circulation air mode (Li, 2021; Xiao and Huang, 2019), which introduces full filtered fresh air to subway and stations. While, for car and bus, to open windows is a recommended even required measurement for controlling the pandemic, which may be the reason that no significant decrease of PM levels in the cabin of car and bus in this study was observed (Huang et al., 2012; Peng et al., 2021).

PM and BC on airplane were below the detection limit of the devices, except the beginning minutes, indicating airplane has the lowest concentrations. As stated by multiple airlines, air on plane is exchanged to the outside (almost free of particulate matter at cruising altitude), and filtered by the HEPA filtration (Khatib et al., 2020). The Civil Aviation Administration of China also requires airplane to use the highest ventilation rate during the COVID-19 pandemic. As the COVID-19 is still in pandemic, the adoption of HEPA filtration could be helpful to prevent the aerosol transmission of COVID-19.

The average concentrations of PM$_{10}$, PM$_{2.5}$, PM$_{1.0}$ and BC in car (including smoking values) were 16.6 and 10.0, 15.1 and 9.0 $\mu g/m^3$, which are significantly lower than other modes of transport (except for airplane); even though particulate matter increased dramatically when a passenger smoked in car (see Figure S1). Lower concentrations of particulate matter in car were found when excluding the outlier concentrations during smoking (see Table S1). Vehicle manufacturers install PM$_{2.5}$ filter devices in car. There are two kinds of filter devices: one is assembled with air conditioning system, the other is external integrated in the front row central armrest. For filters in vehicle, the smaller the space, the better the filtration efficiency. Hence, lower particle concentrations in car may be due to the better removal efficiency in such a small space (Cai et al., 2019). PM levels in bus and subway were...
significantly higher than other modes of transport, as shown in Fig. 1. Passengers who take intra-city traffic (e.g. bus and subway) would expose to higher concentrations of particulate matter than ones who take inter-city traffic (e.g. inter-city bus and high-speed train). Inter-city bus and high-speed train go through rural areas more frequently. Various studies found higher levels of airborne pollutants including microorganisms in urban than in rural areas, which could result in a lower exposure when taking inter-city traffic (Liu et al., 2019; Wu et al., 2019).

BC was the highest on bus, which induced BC/PM ratios higher on bus than on subway. Similarly, PM levels on inter-city bus and high-speed train were close, 20.7 and 20.5 μg/m³ for mean PM₁₀, 18.6 and 18.4 μg/m³ for mean PM₂.₅, both 13.7 μg/m³ for mean PM₁.₅, while the mean BC on inter-city bus was 7.9 μg/m³, much higher than 1.5 μg/m³ on high-speed train. The ratios of BC to PM (see Figure S2) were the highest on inter-city bus, while the lowest on high-speed train (excluding airplane). Road transport except car (bus and inter-city bus) had higher BC than rail transport (subway and high-speed train). The main reason for this result is because exhaust emissions from road transport is the main source of BC (Martins et al., 2021), and filter devices in car with a smaller space have higher filtration efficiency than bus, while metallic particulate matter derived from abrasion of rail-wheel-brake interfaces is a main source of PM for rail transport (Martins et al., 2016).

3.2. Outdoor and indoor sources

We found remarkable peaks of PM in high-speed train cabin in 5 min on arrival at stations (Fig. 2). Outdoor PM concentrations were positively associated with the mean concentrations of the PM peaks in cabin when arriving at the corresponding city stations (R² > 0.85, p < 0.05, Fig. 3). This indicated that outdoor environment especially in station is the primary source of PM on transport. Due to the frequent boarding and disembarking of passengers, internal air on public transport are often exchanged with the atmospheric environment in station (Kam et al., 2011). The ventilation mode to exchange air with the outside also makes particle concentrations on transport associated with the outdoor.

We found an extreme peak of PM and BC (up to 2532, 1936, 315, and 75.7 μg/m³ for PM₁₀, PM₂.₅, PM₁.₅, and BC, respectively) in 2 min of smoking in car and declined to the pre-smoking levels in 10 min, with windows open and AC on. This is a remarkable internal source on transport in the present study. Smoking is forbidden on public transport in China, but car especially private car is an exception. Although the PM levels in car were significantly lower than on other modes of transport, our result clearly suggested the very high short-time air pollutants when smoking in car. Only once smoking activity (~15 min) was observed in this study of over 1400-min (about 24-h) measurements; while the mean concentration of PM₂.₅ in car increased 23%, from 12.2 to 15.0 μg/m³. As found in previous studies, frequent or continuous emission (e.g. smoking) in relatively enclosed space (e.g. in a car) will dramatically increase the exposure to particulate matter, which is a health hazard that can induce numerous health problems (Jha and Peto, 2014).

3.3. Temperature, RH and ventilation

Temperatures and RHs were monitored simultaneously with PM (Table S3). Temperatures on all modes of transport ranged from 25 to 44 °C, averaging 31 ± 3 °C. Air conditioners were running on all modes of transport during most of the sampling campaigns, which led to difference from the outside. The association between temperature and airborne pollutants were not consistent on different modes of transport (Table S4). For example, temperature was positively associated with PM₁₀, PM₂.₅, and PM₁.₅ levels on road traffic (car, bus, and intercity bus), but negatively on railway transport (subway and high-speed train), and not significantly on airport. While, BC on all modes of transport was negatively associated with temperature. In various studies, temperature has been reported to be positively and negatively correlated with particle concentrations (Knibbs et al., 2011). Via accelerating the condensation of volatile and semi-volatile compounds, decreasing temperature is more likely to increase ultrafine particles (<100 nm) (Knibbs et al., 2011; Ragettli et al., 2013), which explained the negative association of temperature and BC in present study. RHs were significantly different with the modes of transport. Airplane had the lowest RH, mainly due to the ventilation on airplane exchanging air with the outside while flying, which contains much less humidity. For bus, subway and inter-city bus, due to frequent opening doors for passengers on and off, RHs were all above 50% and close to the outside. We found a positive association between RH and particle concentrations on most modes of transport except inter-city bus (p < 0.05, Table S4). It’s believed that water can enhance secondary organic aerosol (SOA) formation, especially in high humidity atmosphere (Jathar et al., 2016). Summer, the sampling season, usually has higher RHs and is beneficial for the formation of secondary aerosols, which might be more toxic to human health (Zhuo et al., 2017).

Ventilation is an important influencing factor. We found significantly lower concentrations of all PM and BC when windows were closed in car and bus (p < 0.01), same with the previous studies (Abbass et al., 2021), which supported that outdoor air pollution is the routine source. DRs on inter-city bus, high-speed train, and airplane were 13.9 ± 4.3, 9.8 ± 2.8, and 46.9 ± 0.4 h⁻¹ respectively. As reported, the air exchange on plane is around 2 min a time (Khatib et al., 2020), which means the exchange rate is at least 30 h⁻¹. Due to the clean air at cruising altitude, the exchange rate on airplane can be estimated to be the decay rate for particles, which was 47 h⁻¹ in this study. This result verified again that flying travel might be the safest during the COVID-19 pandemic in terms of air quality and ventilation (Khatib et al., 2020). For high-speed train, we found a positive association between PM and DRs (R² = 0.54, p = 0.02, Fig. 4), but the causality cannot be determined. DR estimates included air exchange (e.g. ventilation) efficiency, deposition and filtration efficiency. High-speed train implements air exchange to the outside, which may induce higher particle concentration if enhancing exchange rates. Inversely, the ventilation and filtration efficiency in the

Fig. 2. Particulate matter (PM₁₀, PM₂.₅, PM₁.₅) and black carbon (BC) concentrations measured on high-speed train. Date, city, outdoor PM₁₀ and PM₂.₅ are shown at the corresponding PM peak when arriving at the city station. DRs (decay rates) are shown along the decay curves.
carriage may be automatically improved when increased concentrations of particulate matter are monitored. We may need other measurements for only exchange rate estimates to determine the relationship (Batterman, 2017). While on all accounts, filtration efficiency should be improved along with ventilation for transport.

To exchange air with the outside environment is a better way for ventilation in a carriage, a relatively enclosed space, during the COVID-19 pandemic. PM$_{2.5}$ filtration unit has been assembled with vehicles’ ventilation system, which can significantly block particulate matters intrusion when using the ventilation mode to exchange air to the outside. While, elevated ventilation rate may increase the aerosol particles on transport at the same time (as found above), due to the primary contribution of outdoor air pollution. It is necessary to improve filtration efficiency when increasing ventilation, especially in humid weather, which is a beneficial factor for aerosol formation and growth.

3.4. Personal exposure concentrations on transport

Passengers are required to wear facemasks on transport after the COVID-19 pandemic. According to medical facemasks’ 56% removal efficiency for PM$_{2.5}$ (Shen et al., 2021b), the estimated personal exposure concentrations of PM and BC while taking all modes of transport are lower than the original concentrations measured on transport, as shown in Table 2. Personal exposure concentrations on four modes of transport (car, inter-city bus, high-speed train, and airplane) was even lower than 10 μg/m$^3$, the World Health Organization (WHO) guideline for long-term PM$_{2.5}$ exposure concentration. As discussed above, bus and subway, as intra-city transport and the main ways to commute, might

![Fig. 3. Association between outdoor PM concentrations and mean concentrations of PM peaks on high-speed train when arriving at stations. Dates and city stations are shown.](image1)

![Fig. 4. Association between mean concentrations of the PM peaks when arriving at cities and the decay rates on high-speed train. Dates and cities are shown.](image2)

Table 2

| Transport mode     | PM$_{10}$ | PM$_{2.5}$ | PM$_{1.0}$ | BC  |
|--------------------|-----------|------------|------------|-----|
| Car$^a$            |           |            |            |     |
| Mean               | 5.8       | 5.4        | 4.3        | 0.9 |
| Standard deviation | 5.8       | 5.1        | 3.7        | 1.7 |
| Median             | 4.2       | 4.0        | 3.1        | 0.5 |
| Range              | ND – 51.9 | ND – 50.6  | ND – 38.3  | ND – 33.6 |
| Bus                |           |            |            |     |
| Mean               | 21.2      | 17.6       | 11.8       | 7.1 |
| Standard deviation | 3.4       | 2.3        | 1.4        | 5.6 |
| Median             | 20.7      | 17.2       | 11.9       | 6.1 |
| Range              | 12.8–29.9 | 12.3–24.6  | 8.8–15.8   | ND – 32.2 |
| Subway (SW)        |           |            |            |     |
| Mean               | 20.1      | 16.4       | 10.5       | 3.0 |
| Standard deviation | 11.5      | 9.4        | 6.0        | 2.7 |
| Median             | 22.9      | 18.5       | 12.3       | 2.0 |
| Range              | ND – 33.0 | ND – 29.0  | ND – 18.9  | 0.1–27.3 |
| Inter-city bus (ICB)|         |            |            |     |
| Mean               | 9.1       | 8.2        | 6.0        | 3.5 |
| Standard deviation | 9.8       | 8.7        | 5.4        | 2.4 |
| Median             | 4.8       | 4.6        | 4.0        | 3.0 |
| Range              | ND – 94.6 | ND – 91.5  | ND – 58.1  | 0.1–17.1 |
| High-speed train (HST)|        |            |            |     |
| Mean               | 9.0       | 8.1        | 6.0        | 0.7 |
| Standard deviation | 7.4       | 6.2        | 4.1        | 0.5 |
| Median             | 6.2       | 5.7        | 4.8        | 0.6 |
| Range              | ND – 38.7 | ND – 37.4  | ND – 24.2  | ND – 3.9 |
| Airplane (AP)      |           |            |            |     |
| Mean               | 0.1       | 0.1        | ND         | 0.3 |
| Standard deviation | 0.5       | 0.4        | 0.3        | 0.8 |
| Median             | ND        | ND         | ND         | 0.2 |
| Range              | ND – 6.6  | ND – 5.7   | ND – 4.0   | ND – 13.2 |

$^a$ Car values exclude the measurements under smoking conditions.
expose passengers to higher particulate matter. However, taking most modes of transport may have little effect on particulate matter exposure. Efficient ventilation and filtration system and relatively low concentration in ambient air of the sampling cities is the main reason. Simultaneously, wearing facemasks on transport further protects passengers against particulate matter exposure, which is a side benefit of controlling the transmission of COVID-19. It should be noted that when the ambient air pollution is more severe, the exposure concentrations on transport will be higher, e.g. in winter time. Another note is that some high peaks of air pollutants should also be paid concern since short-time impact on health might also occur, and a dramatic increase even in a short term could induce a big rise of exposure, e.g. smoking in car.

3.5. Implication and limitation

Our study is the first report to focus on the air pollution and personal exposure on transport since the COVID-19 pandemic all over the world, which is expected to provide some helpful information during this special period. Overall, since increasing evidence showed the possibility of aerosol transmission of the COVID-19, the air quality on transport should be concerned and further improved, which leads to the demand of ventilation efficiency. Our findings in China supports that increasing ventilation efficiency to exchange air with the outside may enhance air pollution on transport (Abbass et al., 2021; Azimi et al., 2014). Filtration or other measure should be implemented to improve the air quality simultaneously with the increasing ventilation, which needs immediate attention all over the world. What’s more, wearing masks, a protective measurement for controlling the transmission of COVID-19, could also simultaneously reduce personal exposure to air pollutants.

Some limitations should be noted. The sample size is relatively limited, especially for several modes of transport. Focusing on the southern cities due to high sampling cost may limit our conclusions, although the inter-city travels to Beijing and Kunming are included. Further studies in different cities are expected to address some questions and support our findings. Despite these limitations, the study reveals that PM levels and exposures on transport were significantly influenced by the COVID-19 restrictions. More comprehensive follow-up studies, particularly in other countries, appear warranted.

4. Conclusion

The COVID-19 pandemic has ushered in a new era for ventilation in public places, including on transport. In this study, we measured particulate matter concentration on six modes of transport, and assessed ventilation efficiency, estimated personal exposures during transport to address the questions about air quality on transport after the COVID-19 pandemic. Via using efficient ventilation and HEPA filtration, airplane had the lowest PM levels. Due to applying the full filtered fresh air mode to replace the partial recirculation mode on subway, passengers were exposed to lower PM levels after the pandemic. Outdoor environment especially in station is the primary source of PM on transport. Applying the ventilation mode to exchange air with the outside also introduced air pollutants from the outside to the carriage, especially when enhancing ventilation efficiency. Filtration efficiency could be improved simultaneously with ventilation. Wearing facemasks can further protect passengers against particulate matter exposure, which is a side benefit for controlling the transmission of COVID-19.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envres.2021.112205.

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