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Research Paper

Close contact behavior-based COVID-19 transmission and interventions in a subway system

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HIGHLIGHTS

• Average interpersonal distance is 0.8 m during rush hours in subway.
• Close contact rate in subway is 56.1 % and face-to-back is the main pattern.
• Short-range inhalation exposure is 3.2 times higher than deposition exposure.
• Virus exposure could be reduced by 74.1–98.5 % if all passengers stand in order.
• Virus exposure could be reduced by 82.0 % if all passengers wear surgical masks.

ABSTRACT

During COVID-19 pandemic, analysis on virus exposure and intervention efficiency in public transports based on real passenger’s close contact behaviors is critical to curb infectious disease transmission. A monitoring device was developed to gather a total of 145,821 close contact data in subways based on semi-supervision learning. A virus transmission model considering both short- and long-range inhalation and deposition was established to calculate the virus exposure. During rush-hour, short-range inhalation exposure is 3.2 times higher than deposition exposure and 7.5 times higher than long-range inhalation exposure of all passengers in the subway. The close contact rate was 56.1 % and the average interpersonal distance was 0.8 m. Face-to-back was the main pattern during close contact. Comparing with random distribution, if all passengers stand facing in the same direction, personal virus exposure through inhalation (deposition) can be reduced by 74.1 % (98.5 %). If the talk rate was decreased from 20 % to 5 %, the inhalation (deposition) exposure can be reduced by 69.3 % (73.8 %). In addition, we found that virus exposure could be reduced by 82.0 % if all passengers wear surgical masks. This study provides scientific support for COVID-19 prevention and control in subways based on real human close contact behaviors.

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1. Introduction

By the end of 2021, more than 280 million people had been infected by the SARS-CoV-2 virus (https://covid19.who.int/). Close contact, mainly via short-range airborne and large droplet routes, is considered to be the main route for COVID-19 transmission (Chen et al., 2022; Nguyen et al., 2021). Public transport is commonly used by many people's daily travel (Wen et al., 2020). Where available, subways are the most popular public transport methods, but during the COVID-19 pandemic, the subway became a high-risk indoor environment for SARS-CoV-2 transmission because of high population density, complicated and frequent population flow, and possible insufficient ventilation (Goscée and Johansson, 2018). In the pandemic, subways connected people from different geographical locations (Cooley et al., 2011).

In January 2020, a confirmed COVID-19 case took a bus, and in one hour had infected 10 passengers in Hunan Province, China (Cheng et al., 2022; Ou et al., 2022). In February 2020, there was an outbreak on the Diamond Princess Cruise ship, resulting in 20 % (712) of the passengers being infected (Tokuda et al., 2020). Population taking public transports had a strong association with the severity of COVID-19 transmission (Venugopal et al., 2021). In many cities such as New York, Seoul, and Hong Kong, subway ridership dropped by 40–90 % due to the pandemic (Harris, 2020; Zhang et al., 2021a; Lee et al., 2020). In Wuhan, China, all public transports were suspended during the serious COVID-19 period in January 2020 (Hinjoy et al., 2020). Beijing is one of the longest-commute cities in China, with the average commute time being 119.1 min in 2016 (Beijing Transport Institute, 2016). Understanding close-contact behaviors on public transport in general, and in subways in particular, is essential to recommend effective interventions to prevent the spread of disease.

When an infected passenger in the subway exhales SARS-CoV-2 by talking or breathing, other passengers would be exposed through both short-range inhalation (inhalation via short-range airborne) and deposition (droplets on oral, ocular, and nasal mucosa). Except for close contact, many outbreaks such as Diamond Princess cruise ship (Azimi et al., 2021), a restaurant in Guangzhou (Li et al., 2021), and a choir in Washington (Buonanno et al., 2020) showed that long-range airborne is also an important route for transmission, especially in the poorly ventilated indoor environment (Moraw ska et al., 2009; Zhang et al., 2020a; Ding et al., 2021). If ventilation is not enough, the infection risk of long-range inhalation would be greater, and it is easy to cause a large-scale outbreak of COVID-19 (Dai and Zhao, 2020).

Currently, there are only a few studies that focus on close contact behaviors. Interpersonal distance is usually considered for analysis of COVID-19 transmission via the close contact route. Many studies obtained interpersonal distance via questionnaires (Sorokowska et al., 2017), Radio Frequency Identification (RFID) (Vanhems et al., 2013), or indoor positioning (Zhang et al., 2020b). However, data collected through the questionnaires are subjective and prone to memory bias and omission, the RFID-based sensor measurement with insufficient spatial (1.5 m) and time (20 s) resolution needs to arrange the scene in advance (Isella et al., 2011). Devices based on indoor positioning can record all close contact-related behaviors, however, all participants have to wear the device, and many base stations need to be installed in all experimental rooms (Zhang et al., 2020b).

We developed a wearable device for close contact behavior detection. We conducted a field trial in the Beijing subway system, gathering a total of 20 h of recordings of close contact behaviors during both rush-hour and non-rush-hour times. All depth images were processed by semi-supervised learning, and data on close contact behaviors were obtained automatically. This data provided: the interpersonal distance, face orientation, relative position (horizontal and vertical), close contact rate, and number of people per close contact. We analyzed virus exposure of passengers under different conditions based on real human close contact behaviors, and based on these findings we propose interventions for epidemic prevention and control.

2. Method

Taking the Beijing subway (Table 1) as an example, a carriage has a symmetrical structure with a group of six single-sided seats and a total of four groups.

2.1. Close contact behaviors

Since the main transmission route of COVID-19 is close contact, we estimated the exposure to COVID-19 through inhalation (inhalation via short-range airborne and inhalation via long-range airborne) and deposition in subway carriages, based on the real, observed, close contact behaviors. Close contact, which could also be called close proximity, is defined as a contact between an interpersonal distance shorter than 1.5 m (WHO, 2020; CDC, 2022; Liu et al., 2017). It mainly includes communication and non-communication behaviors within short distance, which have the potential infection risk via short-range airborne and large droplets. The face touch behaviors such as hand shaking are excluded. Close contact behaviors include interpersonal distance, face orientation, relative position (horizontal and vertical), close contact rate, and number of people per close contact (Table 1, Fig. 1).

The virus exposure decreases with increasing interpersonal distance, termed distance decay. For face orientation, we defined 5 categories: face-to-face (F-F), face-to-side (F-S), face-to-back (F-B), side of the infected (S-I), and back of the infected (B-I). When the target person stands in front of the wearer (the infected) (within 90°), F-F, F-S, and F-B were defined based on the relative face orientation between the wearer and the target person (Fig. 2). When the target person is within 90° of the side or back of the wearer, it is defined as side (S-) or back (B-) of the infected, the effect of the face orientation in these two areas was not considered because the virus exposure was very small. The reduction of exposure because of the face orientation is called orientation decay.

Fig. 3 describes the three transmission routes for COVID-19 in a carriage. In this study, particles with size smaller than 5 μm were regarded as fine aerosols, while those size no less than 5 μm were regarded as large droplets (Coleman et al., 2021; Milton et al., 2013; WHO, 2020; Yan et al., 2018). Fine aerosols with the size of 5 μm have a terminal settling velocity of 0.74 mm/s, and are able to stay airborne for hours in the indoor environment (Wei and Li, 2015). Fine aerosols are mainly transmitted via short-range inhalation. However, from the CFD simulation, we found that when the infected release SARS-CoV-2 by talking or breathing, fine aerosols may be deposited on mucous when they hit the mucous membranes although the probability is not high. Large droplets exhaled by the infected have a high probability to be deposited on mucous membranes of the susceptible. In addition, they could also enter the respiratory tract, and be transmitted via short-range inhalation. Some smaller large droplets with the size between 5 and 10 μm after evaporation could suspend in the air for hours, it may be transmitted via long-range inhalation. However, this route was not considered in this study because it difficult to calculate.

| Table 1 | Definitions of close contact behaviors. |
| --- | --- |
| **Close contact behavior** | **Definition** |
| Interpersonal distance | Distance from the wearer’s forehead to the nose of the target person |
| Face orientation | Face orientation of the target person |
| Relative position | Relative horizontal and vertical angles of the target person (horizontal view is 91.2°; vertical view is 65.6°) |
| Close contact rate | Ratio of the close contact time (interpersonal distance ≤1.5 m) to the total recording time |
| Number of people per close contact | Average number of passengers who had close contacts with the wearer during each close contact |
2.2. Data collection

We developed a device for close contact behavior detection. The device comprises a depth sensor, a portable power source, and a microcomputer (Fig. 4). The device was made of a depth sensor, a portable power source, and a microcomputer. The frame rate of the device is 1/6 s and the resolution of distance detection is 1 mm. The resolution of the depth image captured by the device is 640 × 480. The horizontal angle of view is −45.6° to 45.6° with the accuracy of 0.142°/pixel and the vertical angle of view is −32.6° to 32.6° with the accuracy of 0.136°/pixel. The device was supplied by a power source with 10,000 mA and 64 G memory card. It could continually detect human close contact behaviors for at least 12 h. This device is worn on the head as shown, and the location and interpersonal distance between experimenter and target can be determined.

The experimenter was assumed to be an infected person in a carriage, and wore this close contact behavior detection device during rush hour (7:00–9:00 and 17:00–19:00 on weekdays) and non-rush hour periods for a total of 10 h each day. The device only needs to be worn by the experimenter and does not require any arrangement of the experimental scene in advance. Since all the recorded images are depth images, which do not involve facial information, the target’s personal privacy is protected. This experiment was approved by the Ethics Committee of Zhejiang University (No. IIT20220116B).

Of the 20 h of recorded images from rush-hour and non-rush-hour periods, we first manually processed 3 h of subway images and then labeled the location and face orientation of all observed human heads. Finally, we obtained more than 3000 depth images for semi-supervised machine learning (the detailed steps for machine learning are described in Appendix A). After this processing, the locations and face orientation of human heads could be automatically recognized. Therefore, all 20 h of recorded close contact behaviors, including interpersonal distance, face orientation, relative position (horizontal and vertical), close contact rate, and number of people per close contact, could be obtained and calculated. After the semi-supervised learning, the accuracy of head recognition was close to 93%.

2.3. Exposure calculation

Only one infected passenger in the carriage was assumed. Two respiratory activities were considered in our simulations: breathing and talking. Coughing and sneezing were not considered in this study because few people cough or sneeze face to other people without covering their mouth. In the simulation, for the infected, virus was assumed to be generated via nasal breathing (only via nose) and talking (only via mouth). For the susceptible, only nasal inhalation was considered.

Many researchers measured the size distribution of exhaled particles (Cortellessa et al., 2021; Johnson et al., 2011; Morawska et al., 2009) and got the different results. The virus exposure influenced by the size distributions because of different movement path of particles. In this study, a well-known article (Duguid, 1946) in the field was used for size distribution of exhaled aerosols. The size distribution of exhaled aerosols by a single exhalation, or when talking (counting from “1” to “100”) were obtained from a previous study (Duguid, 1946; Chen et al., 2020). According to the size distribution of exhaled particles, the particle generation rate in volume of fine aerosols released by breathing, fine aerosols released by talk, and large droplets released by talk were calculated as 1.73 × 10⁻⁶ µL/s, 1.95 × 10⁻⁸ µL/s, 2.39 × 10⁻³ µL/s, respectively. The total virus RNA loads in fine (≤5 µm) and large droplets (≥5 µm) generated by COVID-19 patients was collected by G-II exhalation collector, and the virus concentration of SARS-CoV-2 in fine aerosols generated by breathing were 2.6 × 10⁶ viral RNA loads/µL, in fine and large droplets generated by talking were 5.2 × 10³ viral RNA loads/µL and 3.1 × 10¹ viral RNA loads/µL, respectively (Coleman et al., 2021). Then the virus generation velocity by breathing and talking in fine aerosols by breathing, fine aerosols by talking, and large droplets by talking were 4.5 × 10⁻² viral RNA loads/s, 1.0 viral RNA loads/s, 7.4 × 10⁻² viral RNA loads/s, respectively. Then, based on exposure reduction with distance and face orientation (Wei and Li, 2015), we can obtain the inhalation and deposition exposure during close contact at different distances and with different face orientations. The face orientation coefficient ηf was defined as the ratio of exposure for different face orientations to the exposure in the case of face-to-face close contact. ηf can be calculated using Eq. (1). The distance coefficient ηd was defined as the ratio of exposure for different interpersonal distances to the viral load generated by the infected.

\[
η_f = \frac{1}{4} \left[ t_f \eta_t^1 + t_s \eta_s^t + t_p \eta_p + t_p \eta_p \right] + \frac{1}{2} \left[ η_s^f + \frac{1}{4} η_s^b \right] \tag{1}
\]

where, \(t_f\), \(t_s\), and \(t_p\) are the probability of face-to-face, face-to-side and face-to-back close contact detected by the device, respectively; \(η_f^t\), \(η_s^t\), \(η_p\), \(η_f^b\), \(η_s^b\), \(η_p\) are the orientation coefficients of face-to-face, face-to-side, and face-to-back, side of the infected and back of the infected, respectively; Because the horizontal view of the depth camera is 91.2°, the close contact circle (D ≤ 1.5 m) of the device’s wearer is divided into four parts uniformly. The front and rear sector of 90° account for 1/4 of the circle each, and the side sectors account for 1/2 (Fig. 2).

Virus exposure velocity (viral RNA load/s) per person via inhalation (\(e_i\)) and deposition (\(e_d\)) for a close contact at different interpersonal distances (d) and face orientations can be calculated by Eq. (2) based on the talking rate.

\[
\begin{align*}
\{ e_i(s,d) &= g_t(s) \eta_t(s) P_I \eta_I(s) g_f(s) \eta_f(d) (1 - P_I) \eta_{I,b}(d) \\
  e_f(s,d) &= g_f(s) \eta_f(s) P_I \eta_I(s) g_s(s) \eta_s(d) (1 - P_I) \eta_{I,b}(d) \\
  e_d(s,d) &= g_d(s) \eta_d(s) P_I \eta_I(s) g_p(s) \eta_p(d) (1 - P_I) \eta_{I,b}(d) \\
\end{align*}
\]

(2)

where \(s\) is the aerosol particle size, categorized as either fine (<5 µm) or coarse (≥5 µm); \(d\) is the interpersonal distance; \(P_I\) and \(T\) represent breathing and talking; \(I\) and \(D\) represent inhalation and deposition; \(g_t\) and \(g_f\) are the virus generation velocities (viral RNA load/s) by breathing and talking by the infected, respectively; \(P_I\) is the talking rate which is defined as the ratio of the time a person spends talking, to the
The relationship between personal virus exposure velocity and the effect of interpersonal distance and face orientation on virus exposure is shown in Fig. 6. Face-to-face position resulted in the highest personal virus exposure, followed by face-to-side, face-to-back, side of the infected, and back of the infected. The virus exposure is highest through short-range inhalation, which is 3.2 and 7.5 times higher than deposition and long-range inhalation during the rush hour, respectively, and 5.6 and 3.7 times higher than deposition and long-range inhalation during the non-rush hour, respectively. The personal virus exposure through short-range inhalation, long-range inhalation, and deposition during the rush hour were 1.7, 0.9, and 2.6 times higher than during the non-rush hour, respectively. The number of people per close contact was 3.2 during rush hour and 1.6 during non-rush hour. For all close contacts, during rush hour, face-to-face (F-F), face-to-side (F-S), and face-to-back (F-B) patterns accounted for 16.4 %, 15.1 %, and 68.5 %, respectively; during non-rush hour, F-F, F-S, and F-B accounted for 52.8 %, 20.3 %, and 26.9 %, respectively. All close contact behavior data are shown in Table S1. (Table 2).

3.2. Virus exposure via three transmission routes

3. Results

3.1. Close contact behaviors

A total of 53,487 data points of close contact behavior during non-rush hour, and 92,334 during rush hour, were obtained. We calculated the probability distribution of interpersonal distance and face orientation based on all the obtained data (Fig. 5). The average interpersonal distance was 0.8 m and 1.1 m during rush and non-rush hours, respectively. The close contact rate during rush and non-rush hours were 56.1 % and 41.9 %, respectively. The number of people per close contact was 3.2 during rush hour and 1.6 during non-rush hour. For all close contacts, during rush hour, face-to-face (F-F), face-to-side (F-S), and face-to-back (F-B) patterns accounted for 16.4 %, 15.1 %, and 68.5 %, respectively; during non-rush hour, F-F, F-S, and F-B accounted for 52.8 %, 20.3 %, and 26.9 %, respectively. All close contact behavior data are shown in Table S1. (Table 2).
inhalation, and deposition were 7.1, 3.5 and 12.4 times higher than during the non-rush hour.

In this study, we analyzed the relationships between personal inhalation/deposition virus exposure velocity, number of passengers, and talk rate (Fig. 7). Total virus exposure velocity is shown in Fig. S3. During rush hour, when the talk rate is 50%, the personal virus exposure for short-range inhalation and deposition was 31.6 and 159.8 times higher than those when the talk rate is 0%, respectively. For long-range inhalation, the personal virus velocity during rush hour was 10.2 times higher than that during non-rush hour. Compared to the no-talk condition, when the talk rate is 20%, the personal virus exposure and total exposure for short-range inhalation, long-range inhalation, and deposition were 1.7, 0.9, 2.7 times during rush hour, and 8.0, 3.4, 12.6 times during non-rush hour, respectively.

3.3. Interventions to reduce virus exposure

3.3.1. Mask

Fig. 8 shows the personal virus exposure velocity when the infected and the susceptible wore masks with different filtration efficiencies for fine aerosols. During the rush hour with a talk rate of 20%, personal exposure was reduced by 99.5%, 82.0% and 41.5% times if all passengers wore N95 respirators, surgical masks, and cloth masks (without filtration layer), respectively, when compared to no-masking. The short-range inhalation exposure could be reduced by 95.0% and 90.0% if the infected and the susceptible wore N95 respirators, respectively. The infected alone wearing a surgical mask was more effective than the susceptible alone wearing a mask, and the personal exposure could be reduced by 60.0% if the infected person was the only one wearing a mask. Due to better inhalation protection, a cloth mask worn by the susceptible only was more effective than if only worn by the infected, with personal exposure being reduced by 65%.

In Fig. 9, we assumed that both the infected and the susceptible wore the same type of masks with different inward and outward protection for fine aerosols and large droplets. When the talk rate was 20% and all passengers wore surgical masks (the filtration efficiency of large droplets was assumed to be 95% and for fine aerosols to be 60%), compared to rush hour, the short-range inhalation and deposition exposure during non-rush hour was reduced by 42.0% and 63.4%, respectively. During rush hour and with all passengers wearing surgical masks, if the talk rate was 5% and not 20% of talk rate, the short-range inhalation, deposition and long-range inhalation exposure could be reduced by 69.3%, 75.0%, and 78.8%, respectively.

3.3.2. Passenger position

Four positions were considered for passengers in the carriage (Fig. 10, Fig. S4), namely random (RD), same direction (SD), face-to-face (FF), and face-to-side (FS).

The personal short-range inhalation and deposition exposure was the lowest for SD positions, followed by FS, RD, and FF during both rush hour and non-rush hour times. When the talk rate was 10%, the personal short-range inhalation and deposition exposure in the FF position was 3.5 and 32 times higher, respectively, than for passengers in the SD position. During rush hour and RD positions, short-range inhalation exposure was the most sensitive to talk rate, and the personal short-range inhalation exposure reduced by 86.0% when the talk rate decreased from 10% to 0%, for the FS position. Deposition exposure was the most sensitive to talk rate, and the personal deposition exposure decreased by 96.3% when the talk rate decreased from 10% to 0%. Changes in passenger’s relative position influences the deposition exposure the most and the long-range inhalation exposure the least. Although the long-range inhalation exposure was the highest for the FF position, the difference between the four positions was not significant.

4. Discussion

We monitored close contact behaviors of subway users by deploying
wearable depth detection devices during both rush hour and non-rush hour periods. We used machine semi-supervised learning to automatically process the data collected recording close contact behaviors. A model for COVID-19 transmission by short-range inhalation, long-range inhalation, and deposition in a subway carriage was established to analyze virus exposure for different interventions.

Controlling social distancing is one of the most effective ways to reduce the infection risk via close contact. During a face-to-face close contact, the infection risk when the interpersonal distance is 2 m is one thousandth of that when the interpersonal distance is 0.4 m (Chen et al., 2020). The average interpersonal distance in offices is 0.8 m (Zhang et al., 2020b). The social distance between close friends and acquaintances in shopping malls is 0.5–1.2 m (Ozdemir, 2008). The social distances between doctors and doctors, doctors and nurses, and nurses and nurses in hospitals were 0.9 m, 1.1 m, and 1.0 m, respectively (Kerr, 1986). The average social distance in China is 1.2 m, ranked 10th lowest out of the 42 countries studied (Sorokowska et al., 2017). We found that the average interpersonal distance in the subway during rush hour is 0.8 m, which is smaller than in most other indoor environments. In addition, it is difficult to maintain a comfortable social distance during the rush hour, so, the infection risk of COVID-19 in the subway is higher. Many cities have reduced or even closed subway operations during outbreaks to prevent widespread infection (Krietschlits and Cats, 2021; Zhou et al., 2020).

Virus exposure was determined by the face orientation of passengers (Wei et al., 2022). When the interpersonal distance is 0.8 m, the personal virus exposure for the face-to-face position is 0.9 and 2.3 times higher than it for face-to-side and face-to-back position, respectively (Nielsen et al., 2020). However, on a subway train, where almost all passengers are strangers, passengers preferred to maintain a maximum social distance and avoid face-to-face contact with strangers (Gokmen et al., 2020). This study found that the face-to-face position was adopted only 11.8% of the time of recorded close contacts with an interpersonal distance of less than 1.0 m during rush hour, and that the face-to-back position was the position with the highest probability. And passengers generally choose to sit in seats located at both sides of the aisle during non-rush hours, the distance between the two rows of seats is between 1.3 m and 1.5 m, and the passengers’ face orientation are usually face-to-face when sitting on seats. However, familiar people preferred to talk face-to-face, random distribution of the face orientation in this study would bring some errors. The most effective way to reduce the infection risk of COVID-19 on a subway, is to optimize passenger positioning, by maximizing the interpersonal distance and avoiding face-to-face close contact. During the rush hour with a 10 % talk rate, the SD position resulted in short-range inhalation and deposition exposures being reduced by 74.1 % and 98.5 %, respectively compared to the RD position.

The velocity of virus generation during talking is 19.7 times greater than for breathing (Coleman et al., 2021), and talking for 5 min can generate the same number of droplets as a single cough (Xie et al., 2007). In offices, the close contact rate was found to be 10.0 %, and workers talked for 70.0 % of this close contact time (Zhang et al., 2020b). In restaurants, diners and staff on average spent 20 % of their indoor time talking (Zhang et al., 2021b). Reducing the talk rate is a very effective way to reduce infection risk via close contact on the subway. We found that during rush hour, the short-range inhalation and deposition exposure when the talk rate was 20 % were 3.3 times and 3.8 times higher than when the talk rate was 5 %, respectively.

Since it is difficult to control human behavior (e.g. reducing talk rate), wearing a mask is effective for reducing infection risk (D’Orazio et al., 2021). When passengers wears masks, the exhaled virus would be blocked by the mask and the direction and speed of the exhaled airflow would be changed (Tang et al., 2009). In this study, only protection rate including both filtration efficiency and leakage was considered and used for simulation, while effect of mask on exhaled jet was ignored, Therefore, the efficiency of the mask in this study is lower than it in the real situation. Wearing a surgical mask or an N95 respirator for daily travel via subways has a protection rate of 54.0 % and 92.8 %, respectively (Koh et al., 2022). However, in the case of a highly transmissible virus such as the Omicron variant, whose R0 could be as high as 10 (Burki, 2021), it may be necessary to wear N95 respirators to achieve effective prevention and control.

In general, if we want to reduce 70 % of personal short-range inhalation (or deposition) exposure during rush hour when the talk rate is 20 %, the following interventions should be considered: First, reduce the talk rate to 4.9 % (13.9 %). Second, encourage at least 70.4 % of passengers to wear N95 respirators or 85.4 % of passengers to wear surgical masks. Third, all passengers should adopt the SD (F8) position relative to other passengers when maximizing interpersonal distances.

Many researchers used dose-response model to analyze the risk of infection based on the virus exposure via different transmission routes (Zhang and Wang., 2021; Watanabe et al., 2010; Zhang et al., 2020c). The ratio of dose-response parameters between inhalation and deposition is roughly 1:100 (Ji et al., 2022). Considering that there was no accurate dose-response parameter for each route, we did a sensitivity analysis for the parameter to analyze the relative contribution of different dose-response parameters. Fig. 11 shows that when the ratio of
Fig. 6. Virus exposure velocity per person via: (a) inhalation and (b) deposition, and (c) total virus exposure by number of passengers.

Fig. 7. Virus exposure velocity per person via: (a) short-range inhalation; (b) long-range inhalation; (c) deposition by rate of talking during close contact.
The virus concentration in particles is fundamental for virus exposure, however, it can vary by several orders of magnitude. Therefore, we did a sensitivity analysis on virus concentration (viral RNA loads/µL) of SARS-CoV-2 in fine aerosols generated by breathing and fine aerosols and large droplets generated by talking (Fig. S5). The detailed results could be referred to Appendix C.

Fig. 8. Virus exposure velocity via inhalation (short-range and long-range) and deposition per person by inward and outward protection worn by the susceptible and the infected during rush hour (160 passengers per carriage) and non-rush hour (40 passengers per carriage) for different talk rates (filtration rate for large droplets for all masks and respirators were assumed to be 95%).

Fig. 9. Personal virus exposure velocity by mask protection for fine aerosols and large droplets during rush and non-rush hour times, for different talk rates (both the infected and the susceptible were assumed to wear masks). (a) Short-range inhalation; (b) deposition; (c) long-range inhalation.

dose-response parameters between inhalation and deposition is 100, short-range inhalation was the main transmission route, which contribute to the 98.6% of infection risk. If dose-response parameters of both inhalation and deposition is the same (1:1), short-range inhalation, deposition, and long-range inhalation contribute to the total infection risk of 75.4%, 23.7%, and 0.9%, respectively. Talk rate strongly deter-

First, there may be some error because the device worn on the headband may influence the behaviors of other passengers. Second, the device can only detect the front area with the horizontal angle of $91^\circ$ and vertical angle of $65^\circ$, which means the passengers cannot be detected out of the target zone. However, the errors would be small because the exposure for those who located at the side or of the infected person is extremely small. In the future, we should run some experiments using a pseudo-virus or tracing gas to verify the simulation results of this study, but this study can still provide scientific support for COVID-19 prevention and control in subways based on real human close contact behaviors.
Data Availability

The data and the code developed for this study may be accessed by contacting the corresponding author.

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Environmental implication

From a novel perspective on real human behaviors, our study focused on COVID-19 prevention and control in public transports. A monitoring device was developed to gather a total of 145,821 close contact data in subways during both rush-hour and non-rush-hour times based on machine learning. SARS-CoV-2 was a serious hazardous material. As one of the most important indoor environments, public transports (e.g. subway) connected people from different geographical locations during the pandemic. Many COVID-19 outbreaks started from the spread on public transports.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.jhazmat.2022.129233.

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