Import and Export Risk of Urban Public Transportation System Under COVID Scenario

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ABSTRACT {in approximately 800 words}:

This study proposed an import and export risk evaluation method of public transportation system under COVID. The vulnerability of public transportation system under COVID period has attracted considerable attention after the outbreak of COVID. Commuters enter into and exit from public transportation system all the time, and some of these commuters may be infectors. Hence different bus station possesses different import risk or export risk levels. The evaluation of the two risks levels is crucial for the transportation management design to reduce the infection risk of the whole society. Import risk and export risk evaluation models are developed considering the cumulative contact durations among commuters. The sensitivity analysis is implemented by considering the bus service frequencies and the demand levels. Both micro and macro prevention and control strategies are proposed to reduce infection risk in public transportation system: these control strategies include the adjusting of servicing frequency and the stop closure. The SEIR model is introduced into the public network to describe the propagation process of each station, and the result shows infection risk of public transportation is reducing significantly. It is found that quantitatively evaluate the risk can accurately guide to design of public transportation epidemic prevention and control strategies.

Keywords: COVID; Import risk and export risk; sensitivity analysis; prevention and control strategy; public transportation network; SEIR model.

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0. Introduction

Urban operations rely on public transportation systems. Under COVID period, the virus propagates easily through public transportation systems, as it is the major travel option in urban areas. Therefore, how to balance bus access limitations and the normal operation of public transportation system is an important issue for managers (Tian et al., 2020).

After the outbreak of the COVID-19 epidemic, researchers have been more interested in the operational analysis and management design of public transportation system under the COVID scenario. Compared to the normal control strategy, such as using a one-size-fits-all method to restrict travel for specific people, more flexible service design methods are proposed, such as bus timetable optimization (Luo et al., 2021), customized bus route optimization (Ma et al., 2020), and halting a limited number of bus lines (Ru et al., 2020). However, most researches have concentrated on transmission risk in public transportations. The import and export risk, on the other hand, receives less attention. The import risk of certain station refers to the possibility that the on-board passengers gets infected and enter the public transportation system, while the export risk of certain station refers to the possibility that the off-board passengers are infected and influence the communities around that station. Both risks can be measured by the cumulative contact duration among travellers. As a result of the lacking of import and export risk model, it is difficult to evaluate the influence of existing infection cases on communities along the bus line.

This research proposes two risk indexes, i.e. import and export risk, to quantitatively evaluate the risk of public transportation system. The import risk describes the influence level of different bus stations on the whole public transportation system. On the other hand, the export risk evaluates the risk imposed on neighbouring communities by each bus station. Both risk indexes are influenced by many factors, such as bus schedules, demand levels. We analyze the sensitivity of the bus schedules. The results can be used in the optimization of bus frequencies or bus line schedules. It is found that the import risk increase with the bus intervals, and the import risk and export risk of a bus station increase in rush hours, compared with off-peak periods. The certain bus stop can be closed after the specified risk threshold is exceeded, achieving the purpose of propagation control and guide both public transmission epidemic prevention and control strategies design.

To prove the effectiveness of our proposed strategies (adjustment of servicing frequency and the stop closure), we propose using a complex network and the SEIR model to simulate and compare the changes in the risk of infection in the public transportation system before and after the strategies are adopted.

The rest of this paper is structured as follows: we describe the main idea of our research in Section 1. The notions and models of import and export risk are introduced in Section 2. Then sensitivity analysis to different factors is analyzed in Section 3. The SEIR model is introduced into the public traffic network to describe the propagation process of each station, and a comparison of the results of epidemic spread after adopting control measures is given in Section 4 and Section 5. We conclude the manuscript in Section 6.

1. Framework overview

As shown in Fig. 1, the model development is divided into two phases: model development and case study.

Phase1 (Model development):

Model development based on IC card data and GPS data. The main idea of establishing the import and export risk model is to: (1) quantitatively evaluate infection level based on the number of passengers in the public transportation system and the cumulative time of contact with other passengers; (2) introduce contact rate and infection rate to convert risk into probabilistic form; (3) take into account the different types of stops to introduce adjustment parameters to adjust the import risk.

Phrase2 (Case study):

In this phase, we propose two strategies, i.e. adjusting of servicing frequency and the stop closure to reduce the infection risk of the public transportation system. The detailed introduction as the following:

(1) Strategy1 (Adjusting of servicing frequency): Under different scenarios, adjusting departure interval, travel time, demand to observe the changing trend of the import and export risk, and providing a micro prevention and control approach to reduce import risk by optimization of bus frequencies or bus line schedules.

(2) Strategy2 (The stop closure): For each station, we set a risk threshold. Once the import and export risk exceeds the threshold, the bus skips the station to prevent risk from spreading throughout the public transportation system.

Establishing a complex network using geographical data of the public transportation data and changing the complex network through strategy2. The SEIR model is introduced to simulate and analyze the epidemic transmission process and prevention strategy. The result demonstrates strategy1 and strategy2 were successful in reducing the risk.

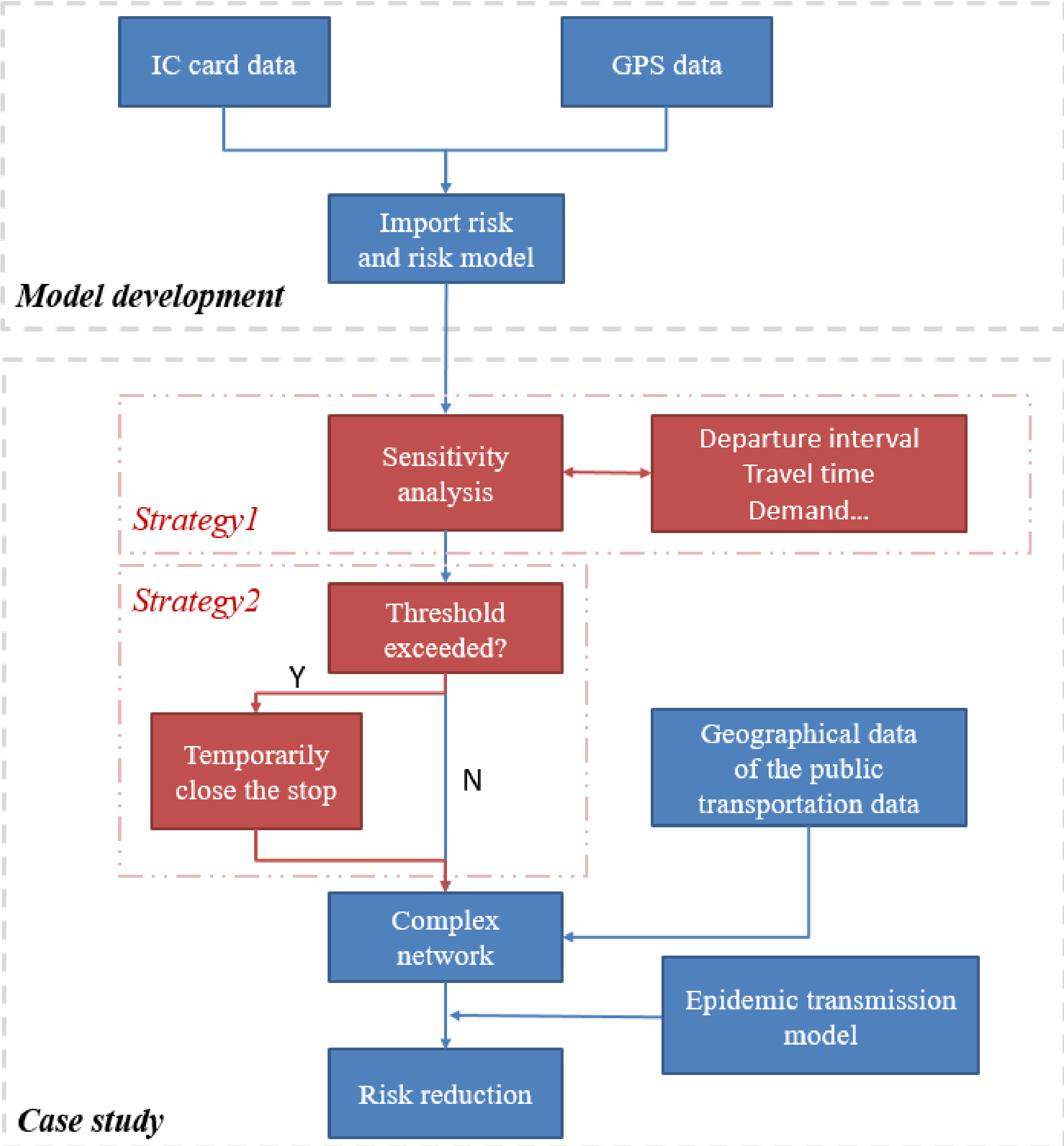


Fig. 1 The main idea of this paper

2. Model development

In this section, import risk and export risk are introduced. Passengers in the public transportation system include two processes, i.e., waiting and taking a bus. We propose that passengers enter the public transportation system when they get on a bus, and exit the public transportation system when they get off a bus without changing routes. With more time and individuals in touch in public transportation networks, the risk of passengers being infected increases, as does the risk of self-carrying. Import risk refers to the per person carried by passengers when they get on the bus from the bus stop after the process of waiting for the bus, while export risk refers to the per person carried by passengers when they get off from the bus stop after the process of waiting and taking a bus. We also introduce in-bus risk to support us in model construction. Detailed risk scenarios are shown in Fig. 2. The export risk is composed of import risk and in-bus risk.

It is worth mentioning that a bus station generally has multiple bus lines connecting to it. We propose that the sum of all connected routes in the same temporal dimension is the import and export risk of a bus stop.

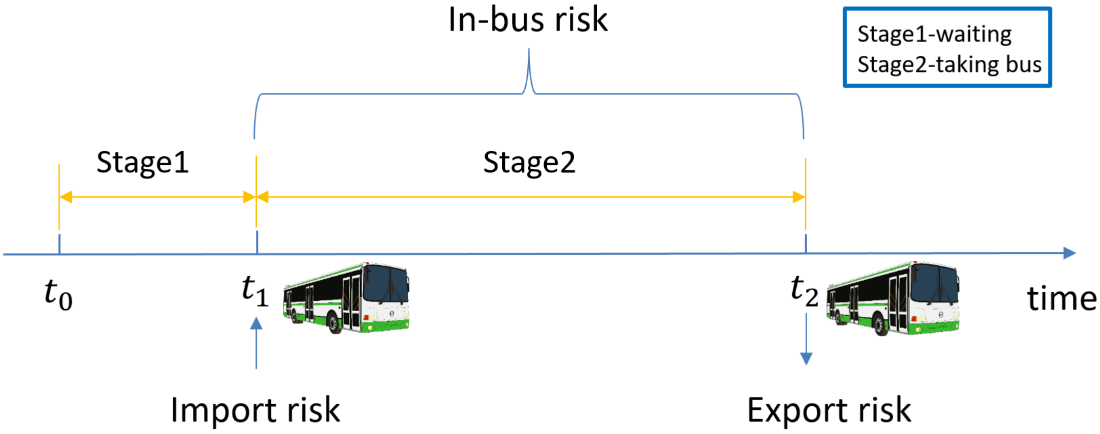


Fig. 2 Illustration of the import and export risk

2.1. Notations and assumptions

For easy reference, we list the notations of the manuscript:

- l_c: the ID of one of the bus lines, and l_c has m stops;
- s_j: bus stops in the bus line l_c, and $j = \{1,2,\dots,m\}$;
- $period_i$: one hour of operation time (5:00-22:00), and $i = \{1,2,\dots,17\}$;
- f_i: the departure interval between two continuously buses in the $period_i$ (min);
- $a_{x,y}$: the number of passengers from s_x to s_y, and $1 \le x < y \le m$;
- $\tau_{j,j+1}$: the travel time between s_j and s_{j+1} (min);
- g_j: the stopping time at s_j (min);
- $d_{j,j+1}$: the delay from s_j to s_{j+1} (min);
- n_{O_j}: the number of passengers getting on one bus in s_j (passenger);
- n_{D_j}: the number of passengers getting off one bus in s_j (passenger);
- n_j: the number of passengers in the bus before the bus arrives at s_j, namely $n_j = \begin{cases} 0, j = 1 \\ \sum_{k=1}^{j-1}(n_{O_k} - n_{D_k}), j = 2,3,\dots,m \end{cases}$ (passenger);
- λ_j: the inter-arrival time between two passengers (min/passenger);
- $R_{import,i,j}$: the import risk of s_j in $period_i$ (min*passenger);
- $R_{export,i,j}$: the export risk of s_j in $period_i$ (min*passenger);
- $R_{inbus,i,(j,j+1)}$: the in-bus risk from s_j to s_{j+1} (min*passenger);
- $P_{import,i,j}$: import risk converted into probability (%);
- $P_{export,i,j}$: export risk converted into probability (%);
- $P_{inbus,i,(j,j+1)}$: in-bus risk converted into probability (%);
- θ_j: the threshold of s_j (%);
- α_1, α_2: a constant exposure rate (1= waiting for a bus; 2= on a bus);
- β_1, β_2: a constant infection rate (1= waiting for a bus; 2= on a bus);

- δ_j: adjustment parameters affecting import risk.

The following assumptions are used:

- The temporal horizon is divided into several time intervals. The interval step can be adjusted, for instance, half an hour;
- Within each time interval, departure frequency f_i of the same bus line is a constant, and n_{O_j} and n_{D_j} at a certain stop is also the same;
- The bus always keeps the speed v at a constant speed while diving;
- All buses on the same route are of the same model, and the standard passenger capacity of each bus is the same;
- Passengers arriving at the station obey uniform distribution, and when the buses pass by, all passengers on the station can board;
- The import or export risk of a stop is the cumulative import or export risk of each line passing through the stop.

2.2. Model development with deterministic demand

In the $period_i$, the information of l_c is shown in Fig. 3. In $period_i$, the departure interval is f_i. n_{O_j} passengers getting on one bus and n_{D_j} passengers getting off one bus in s_j. $\lambda_j = \frac{f_i}{n_{O_j}}$ because passengers arriving at the station obey uniform distribution.

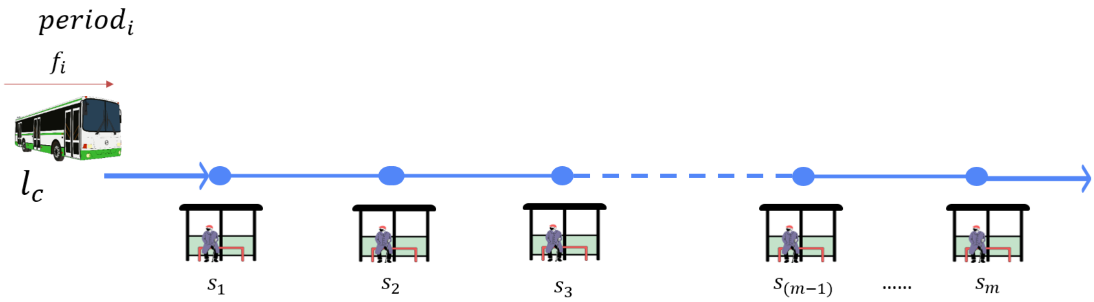


Fig. 3. The information of l_c

2.2.1.Import risk

The import risk relies on the number of passengers waiting at the stop and the cumulative amount of time that they have contact with other passengers. Assuming the cumulative arrivals at the stop is k when certain passenger Y arrives (i.e. Y is the $k^{th}(1 \leq k \leq n_{O_j})$ passenger at the station $s_j(j \neq m)$. The infection risk (which is represented by the cumulative contact duration) for those arriving before Y and those arriving after Y are different. Therefore, we divide the infection risk into two parts, i.e. part A (arriving before Y) and part B (arriving after Y), as illustrated in Fig. 4.

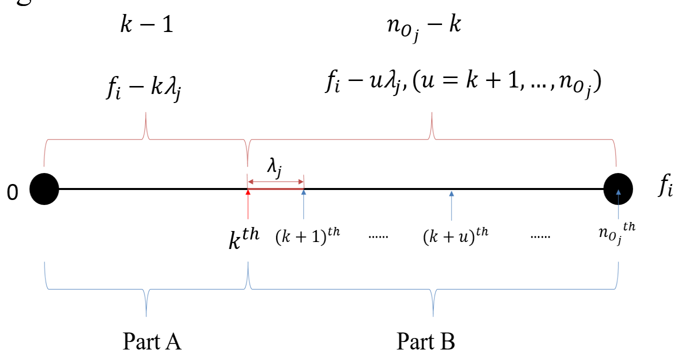


Fig. 4 Illustration of the import risk

- Part A: the number of passengers arriving before Y is $k-1$, and the contact duration with $k-1$ passengers is $Y's$ waiting time $f_i - k\lambda_j$, therefore, the infection risk of Part A is $(k-1)(f_i - k\lambda_j)$;
- Part B: the number of passengers arriving after Y is $n_{O_j} - k$, the contact duration depends on the waiting time for each passenger arriving later than Y. For example, the contact duration between Y and $(k+u)^{th}$ passenger is $f_i - u\lambda_j, (u = k+1, \dots, n_{O_j})$. Therefore, the infection risk of Part B is $\sum_{u=k+1}^{n_{O_j}} (f_i - u\lambda_j) = \left(n_{O_j} - k\right)((f_i - k\lambda_j) - \frac{\left(n_{O_j} - k + 1\right)}{2}\lambda_j)$.

The cumulative infection risk of passenger Y is shown in Eq. (1) by combining Part A and Part B. The cumulative infection risk of n_{O_j} passengers is shown in Eq. (2). Therefore, $R_{import,i,j}$ is shown in Eq. (3).

$$\begin{aligned} &(k-1)(f_i - k\lambda_j) + \left(n_{O_j} - k\right)((f_i - k\lambda_j) - \frac{\left(n_{O_j} - k + 1\right)}{2}\lambda_j) \\ &= (k-1)(f_i - k\frac{f_i}{n_{O_j}}) + \left(n_{O_j} - k\right)(\left(f_i - k\frac{f_i}{n_{O_j}}\right) - \frac{\left(n_{O_j} - k + 1\right)}{2}\frac{f_i}{n_{O_j}}) \\ &= \frac{f_i(n_{O_j} - k)(n_{O_j} + k - 3)}{2n_{O_j}} \end{aligned} \tag{1}$$

$$\sum_{k=1}^{n_{O_j}} \left(\frac{f_i \left(n_{O_j} - k\right)\left(n_{O_j} + k - 3\right)}{2n_{O_j}} \right) = \frac{f_i \sum_{k=1}^{n_{O_j}} (n_{O_j} - k)(n_{O_j} + k - 3)}{2n_{O_j}} \tag{2}$$

$$\begin{aligned} &R_{import,i,j} = \begin{cases} \frac{f_i \sum_{k=1}^{n_{O_j}} \left(n_{O_j} - k\right)\left(n_{O_j} + k - 3\right)}{2{n_{O_j}}^2}, j = \{1,2,\dots,m-1\} \\ 0, \quad j = m \end{cases} \\ &\xRightarrow{d_{j-1,j}} R_{import,i,j} = \begin{cases} \frac{(f_i + d_{j-1,j}) \sum_{k=1}^{n_{O_j}} (n_{O_j} - k)(n_{O_j} + k - 3)}{2{n_{O_j}}^2}, j = \{1,2,\dots,m-1\} \\ 0, \quad j = m \end{cases} \end{aligned} \tag{3}$$

The above model is developed when the arrival rate is uniform and deterministic. It can be extended to the case when arrives are not uniform and stochastic, which is omitted here.

2.2.2.In-bus risk

We define the risk that passengers increase when taking a bus as the in-bus risk. In this paper, in-bus risk depends on the number of passengers in the bus and the contact duration (which includes travel time and stop time). In Fig. 5, $R_{inbus,i,(x,x+1)} = (\sum_{j=1}^{(x+1)-1} n_{O_j} - n_{D_j})\left(\tau_{x,x+1} + g_x + d_{x,x+1}\right) = n_{x+1}\left(\tau_{x,x+1} + g_x + d_{x,x+1}\right)$. However, since each passenger has its origin and destination, the in-bus risk of non-adjacent stations should be concerned with the origins and destinations of passengers and the interpersonal exchanges between stations.

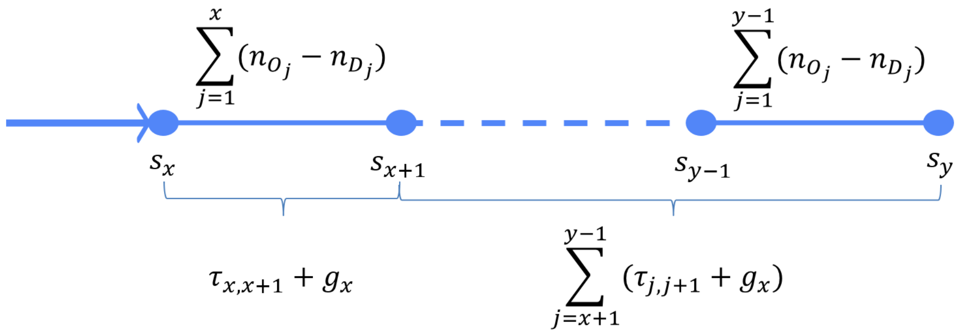


Fig. 5 The example of in-bus risk

For example, if $s_x < s_{x+1} < \cdots < s_{y-1} < s_y$, $R_{inbus,i,(x,y)}$ is shown in Eq. (4). It is worth mentioning that if $y = x + 1$, Eq. (4) is also applicable.

$$R_{inbus,i,(x,y)} = n_{x+1}(\tau_{x,x+1} + g_x + d_{x,x+1}) + \cdots + n_y(\tau_{y-1,y} + g_{y-1} + d_{y-1,y}) \\ = \sum_{k=x}^{y-1} n_{k+1}(\tau_{k,k+1} + g_k) = \sum_{k=x}^{y-1}(\sum_{j=1}^{k} n_{O_j} - n_{D_j})(\tau_{k,k+1} + g_k + d_{k,k+1}), \{1 \le x < y \le m\} \quad (4)$$

2.2.3.Export risk

The export risk is composed of import risk and in-bus risk. When calculating $R_{export,i,j}(j \neq 1)$, we cannot ignore the station of the passengers getting off the bus and the transfers of passengers at each station. Take the export risk $R_{export,i,3}$ of s_3 (Fig. 6) as an example, the origin of passengers who get off at the s_3 maybe either s_1 or s_2. Therefore, we calculate the risk by weighing between the two cases, i.e. $R_{export,i,3} = \frac{a_{1,3}R_{export,i,(1,3)}+a_{2,3}R_{export,i,(2,3)}}{n_{D_3}}$ as shown in Fig. 6 and Eq. (7). Therefore, $R_{export,i,j}$ as shown in Eq. (8).

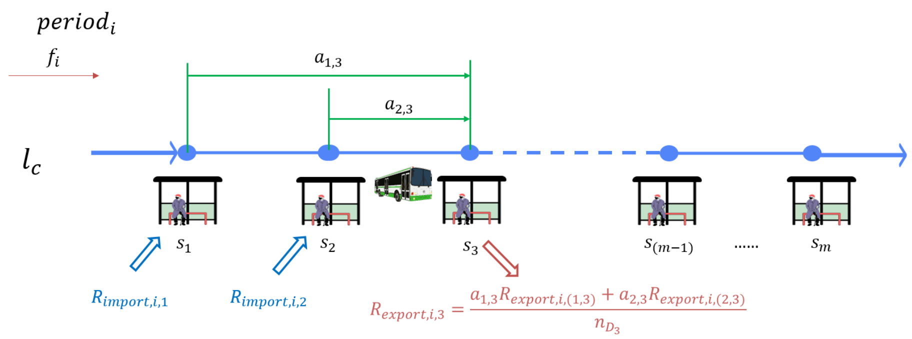


Fig. 6 An example of $R_{export,i,3}$

$$R_{export,i,(2,3)} = R_{import,i,2} + R_{inbus,i,(2,3)} \\ = R_{import,i,2} + \sum_{k=2}^{3-1}(\sum_{j=1}^{k} n_{O_j} - n_{D_j})(\tau_{k,k+1} + g_k + d_{k,k+1}) \\ = R_{import,i,2} + \sum_{k=2}^{3-1} n_{k+1}(\tau_{k,k+1} + g_k + d_{k,k+1}) \\ = R_{import,i,2} + n_3(\tau_{2,3} + g_2 + d_{2,3}) \quad (5)$$

$$R_{export,i,(1,3)} = R_{import,i,1} + R_{inbus,i,(1,3)} \\ = R_{import,i,1} + \sum_{k=1}^{3-1}(\sum_{j=1}^{k} n_{O_j} - n_{D_j})(\tau_{k,k+1} + g_k + d_{k,k+1}) \\ = R_{import,i,1} + \sum_{k=1}^{3-1} n_{k+1}(\tau_{k,k+1} + g_k + d_{k,k+1}) \quad (6)$$

$$R_{export,i,3} = \frac{a_{1,3}R_{export,i,(1,3)} + a_{2,3}R_{export,i,(2,3)}}{n_{D_3}} \quad (7)$$

$$= \frac{\sum_{v=1}^{3-1} a_{v,3}\left(R_{import,i,v} + R_{inbus,i,(v,3)}\right)}{n_{D_3}}$$

$$R_{export,i,j} = \begin{cases} 0, & j = 1 \\ \dfrac{\sum_{v=1}^{j-1} a_{v,j}\left(R_{import,i,v} + R_{inbus,i,(v,j)}\right)}{n_{D_j}}, & j = \{2, \dots, m\} \end{cases}$$

$$= \begin{cases} 0, & j = 1 \\ \dfrac{\sum_{v=1}^{j-1} a_{v,j}\left(\dfrac{(f_i + d_{v-1,v})\sum_{k=1}^{n_{O_v}}(n_{O_v} - k)(n_{O_v} + k - 3)}{2{n_{O_v}}^2} + \sum_{k=v}^{j-1} n_{k+1}\left(\tau_{k,k+1} + g_k + d_{k,k+1}\right)\right)}{n_{D_j}}, & j = \{2, \dots, m\} \end{cases} \quad (8)$$

2.3. *Probabilistic risk conversion*

2.3.1. Exposure rate and infection rate

To make our model easier to understand, more intuitive and more realistic, we introduce exposure rate (α_1, α_2) and infection rate (β_1, β_2) to convert risk into probability. Now Eq. (3), Eq. (4) and Eq. (8) become Eq. (9), Eq. (10) and Eq. (11).

$$P_{import,i,j} = \frac{(f_i + d_{v-1,v})\sum_{k=1}^{n_{O_j}}(n_{O_j} - k)(n_{O_j} + k - 3)}{2{n_{O_j}}^2} * \alpha_1 * \beta_1 \quad (9)$$

$$P_{inbus,i,(x,y)} = \left(\sum_{k=x}^{y-1}\left(\sum_{j=1}^{k} n_{O_j} - n_{D_j}\right)\left(\tau_{k,k+1} + g_k + d_{k,k+1}\right)\right) * \alpha_2 * \beta_2 \quad (10)$$

$$P_{export,i,j} = \frac{\sum_{v=1}^{j-1} a_{v,j}\left(R_{import,i,v} * \alpha_1 * \beta_1 + R_{inbus,i,(v,j)} * \alpha_2 * \beta_2\right)}{n_{D_j}} \quad (11)$$

2.3.2. Other adjust parameters

Different bus stations have different import risks. There are many methods for bus stop classification because different bus station has different features, such as the number of connected lines, the condition of station location, average daily passenger volume distribution and so on (Qiao and Guo, 2017). Therefore, we introduce parameter δ_j to adjust $P_{import,i,j}$, Eq. (9) and Eq. (10) further becomes Eq. (12) and Eq. (13).

$$P_{import,i,j} = \frac{(f_i + d_{v-1,v})\sum_{k=1}^{n_{O_j}}(n_{O_j} - k)(n_{O_j} + k - 3)}{2{n_{O_j}}^2} * \alpha_1 * \beta_1 * \delta_j \quad (12)$$

$$P_{export,i,j} = \frac{\sum_{v=1}^{j-1} a_{v,j}\left(R_{import,i,v} * \alpha_1 * \beta_1 * \delta_j + R_{inbus,i,(v,j)} * \alpha_2 * \beta_2\right)}{n_{D_j}} \quad (13)$$

We analyze the travel trajectories of stochastic 100 infected persons, of which 60 were recorded by bus rides. We paid attention to the origin and destination of these 60 infected people, and classified statistics according to the location of station, the number of connected lines, etc. We just need to find the eligible values in Table 1 and add them. For example, if s_j is an integrated hub in commercial district (connected to 7 lines), therefore, $\delta_j = 0.3 + 0.3 + 0.4 = 1.0$.

Table 1 The factors affecting the value of δ_j

What kind of s_j?			
Bus terminals	0.2	Commercial district	Commercial district
Transfer Hub	0.3	Residential area	Residential area
Ordinary station	0.1	Other area	Other area
How many connected lines?			
≤5		0.2	
>5		0.4	

3. Sensitivity analysis

3.1. Case description

In this section, we explore the case with import risk and export risk. We chose a typical bus line in the urban area of Suzhou, China for analysis. The basic information of the line is shown in Table 2.

Table 2 The information of a single line named No.1

Bus line name	No.1 (West-East)
Service hours	5:00-22:00
Bus ticket price	2 yuan
Number of stops	23
Departure interval	12min (5:00-7:00; 20:00-22:00); 10min (10:00-17:00); 6min (7:00-9:00; 17:00-20:00)
Physical length	11km

For convenience, we selected 9:00-10:00 in this case, and hence departure interval $f_5 = 8$ (min). Learning from the COVID-19 virus transmission experience and taking into account many factors impacting the contact rate and the COVID-19 virus infection rate, such as virus effectivity, personnel mobility, and protection awareness of bus companies and passengers (Zhang et al., 2020), we set $\alpha_1 = 0.3$, $\alpha_2 = 0.1$, $\beta_1 = 0.5$, $\beta_2 = 0.7$. Combining IC card data and bus GPS data, we can easily calculate import risk (converted into probability) and export risk (converted into probability). In Fig. 7, we visualized the import risk and export risk of the bus stops of the No.1 bus line.

Fig. 7 Import and export risk of the stations of No.1 bus line in 9:00-10:00

3.2. Influencing factors of import and export model risk

According to our models for import risk and export risk, we discovered that import risk and export risk are related to departure interval, travel time (delay) and resident demand. We will discuss how import risk and export risk are changing as a result of different situations.

Situation 1: Varying departure interval

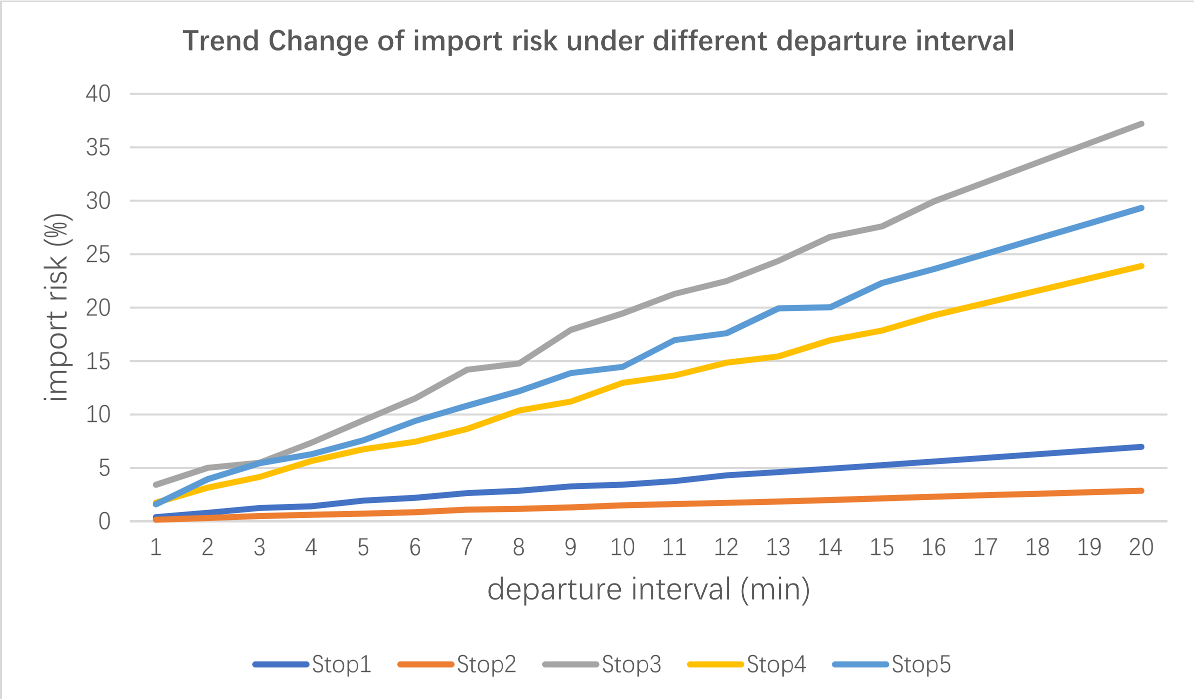


Fig. 8 Trend Change of import risk under different departure interval

In Fig. 8, the import risk rises with the bus interval, and the growth rate of different stations is different, which mainly depends on the number of people on the station. Therefore, the departure interval can be shortened as much as possible to lower the import risk under constrained conditions such as the full-load ratio and the operating cost of the bus company.

Compared with import risk, the export risk does not show a clear upward tendency as the interval increases. Therefore, adjusting the departure interval is not the best choice to reduce export risk.

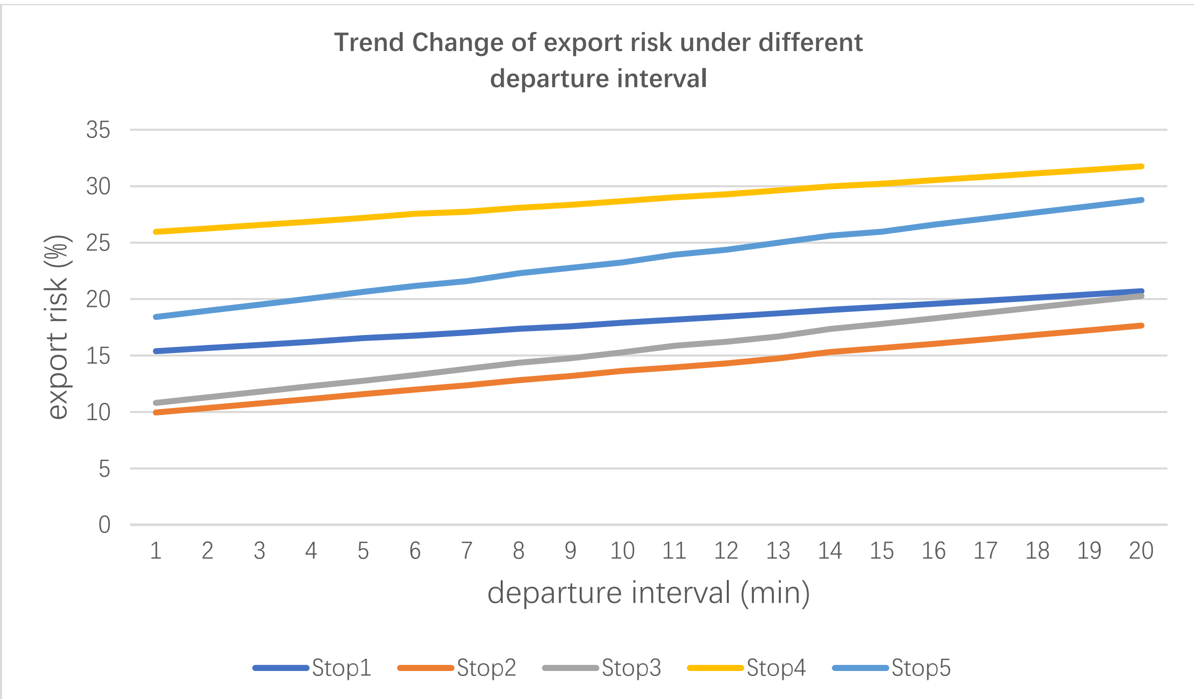


Fig. 9 Trend Change of export risk under different departure interval

Situation 2: Rush hours *vs.* off-peak periods

Increased travel demand during peak periods can easily cause traffic congestion and delays, affecting both import risk and export risk. Comparing import risk and export risk of s_j, we found that the risk during peak periods is higher than during off-peak periods generally.

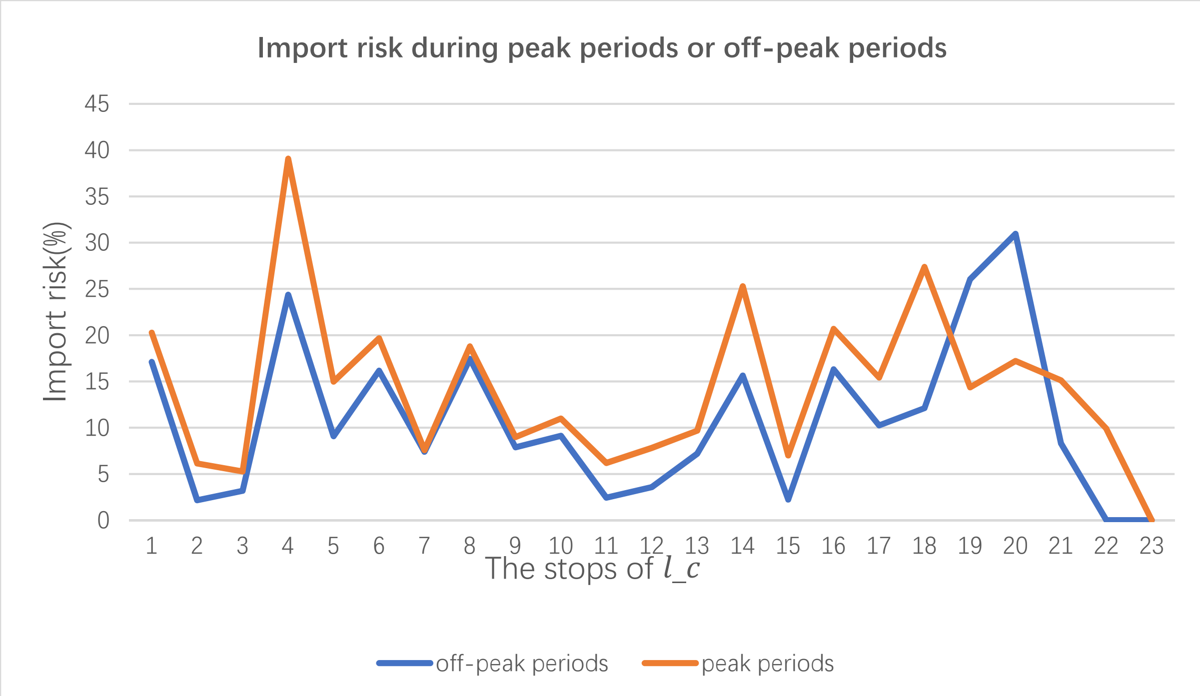


Fig. 10 Import risk during peak periods or off-peak periods

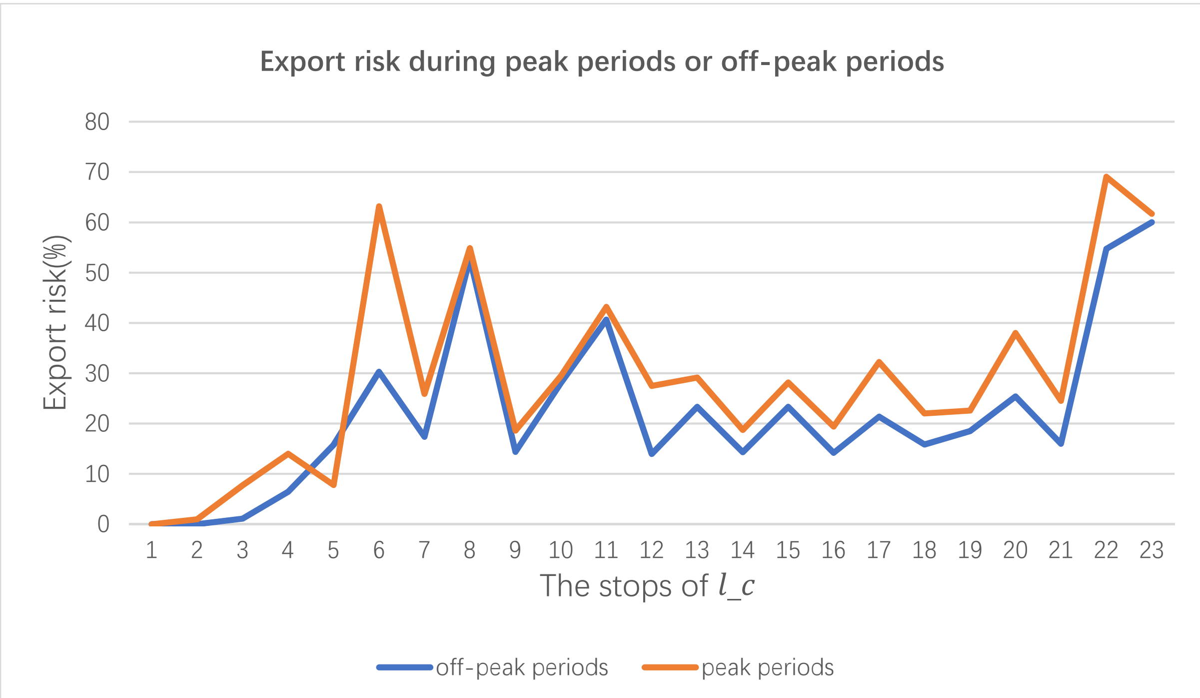


Fig. 11 Export risk during peak periods or off-peak periods

4. Public transportation network propagation model

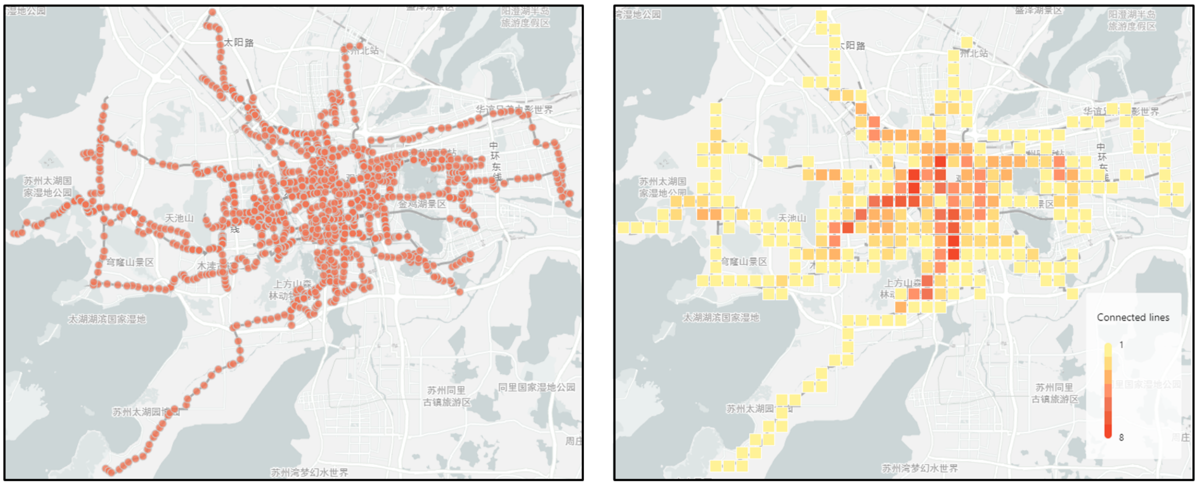
4.1. Public transportation network

The public transportation network is a collection of lines and stops. For the public traffic network, bus stops can be divided into three categories, i.e., bus terminals, transfer hubs and ordinary stations. The topological relationship of a complex system can be reflected through a network. Nodes are used to characterize individual stations, and connected lines are used to characterize certain interrelationships between stations. Therefore, public traffic network is a kind of complex network.

The graph is being used to represent the topology of a complex network, denoted as $G(V, E, W)$, where V is a collection of network nodes, E is a collection of network edges, and W is a collection of network edges weights. Part of the public traffic network in Suzhou, China is shown in Fig. 12(a), which can be further expressed in the form of a network. In our research, the network is changing rather than fixed as a few stations in the public transportation may be closed.

The degree refers to the number of edges connecting the node, which is an important statistical indicator in the complex network. In this paper, the degree is used to describe the intensity of a bus station. The greater the intensity, the stronger the transmission capacity of the station. On the contrary, the weaker transmission capacity of the station. Fig. 12(b) shows the heat map of different degrees of bus stops in a part of Suzhou public traffic network.

We know, different stops have different transmission capabilities, which depend on the degree of the stop. Because the degree of a hub is higher than a general station's, the transmission capacities of hubs are often greater than that of general stations. As we mentioned in Section 1, the ultimate goal of our threshold is to cut off the risk of transmission in the public transportation system. Therefore, the threshold θ_j depends on the degree of s_j.



(a) Part of the public traffic network in Suzhou (b) Different degree of a bus stop

Fig. 12 Part of Suzhou public traffic network and heat map of degree

4.2. Epidemic transmission model

Many researchers have proposed to establish a Susceptible-Exposed-Infectious-Recovered (SEIR) model (Fig. 13) to simulate the spread of COVID-19 in public transportation system. For example, Zhang et al. (Zhang et al., 2020) established a traffic route propagation model by improving the SEIR model to explore the propagation mechanism of the new crown epidemic along the bus route; based on complex network theory, Fan et al. (Fan et al., 2020) established the SEIR model to predict and analyze the spread and inflexion points of COVID-19 epidemic;

Feng et al. (Feng et al., 2021) proposed the SEIR model to analyze the epidemic trend in Wuhan. Therefore, the SEIR model is effective to analyze the spread of COVID-19 in the public transport network, and it can be well integrated with the complex network.

In Fig. 13, β is the probability of a susceptible person becoming an exposed person, which depends on the export of the station where the susceptible person gets off. We assume the number of infected people in s_j is $n_{o_j} * P_{import,i,j}$ during $period_i$. t_I is time for exposed person to become an infected person (assuming that the exposed people must become infected duration a period), and t_R is time for infected person to become a removed person. The SEIR model is introduced into the public traffic network to describe the propagation process of each node and simulate the spread of COVID-19 in the public transportation system.

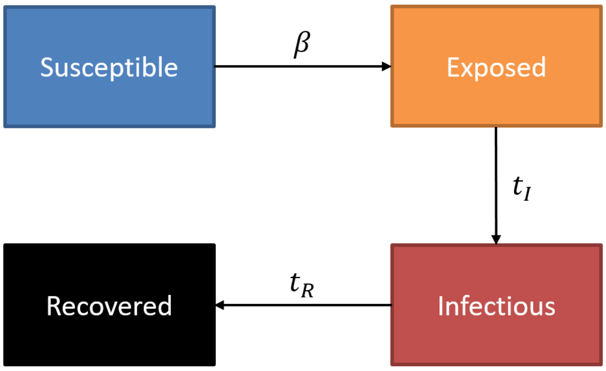


Fig. 13 SEIR model

5. Effectiveness analysis of control strategies

This paper proposed two control strategies, i.e. the adjusting of servicing frequency and the stop closure, to reduce the risk in the public transportation system.

A comparison of the results of epidemic spread after adopting control measures is shown in Fig. 14. In Fig. 14, blue lines are bus lines. Dots are bus stops and the colour and size of the Dots are proportional to the cumulative number of infected people at the station. Our observation duration is 1 month. Before control (Fig. 5 (a)), there are four infected areas, where are concentrated many bus stops with a large cumulative amount of infection. Although there are infections on lines, most stations have not experienced serious infections as shown in Fig. 14 (a). The prevention and control strategies proposed in this paper not only guarantees the normal travel of residents but also effectively controls the spread of COVID.

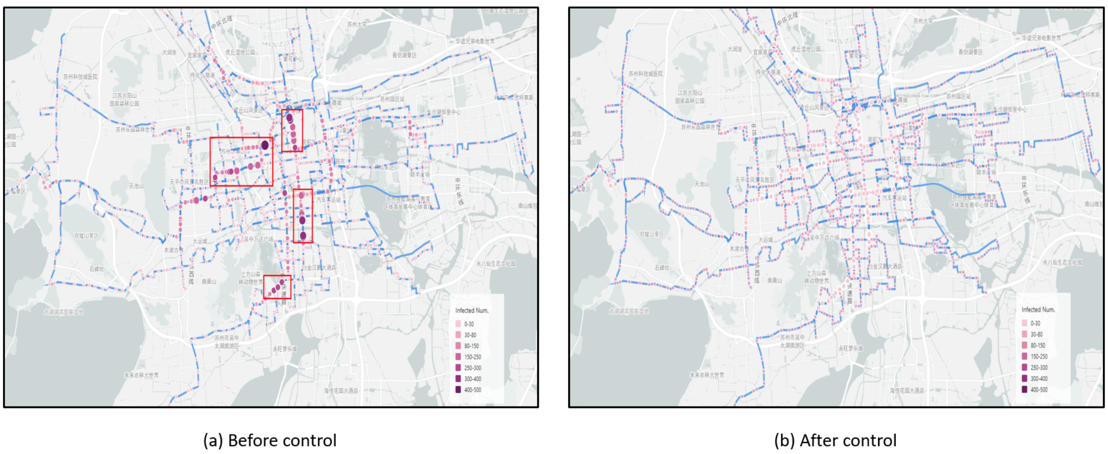


Fig. 14 Comparison of the results of epidemic spread after adopting control measures

6. Conclusions and further research

This paper proposes import and export risk to quantitatively evaluate the risk of public transportation system under COVID scenario. Based on import and export risk models, methods that adjusting the influencing parameters to achieve the goal of reducing import and export risk as much as possible is developed under constrained conditions through sensitivity analysis. A risk threshold is set for each station to decide whether to temporarily close the stop to achieve the purpose of cutting off virus transmission. Finally, the complex network and the SEIR model are employed to simulate the spread of COVID-19 in public transportation system. The result shows that the proposed import and export risk can quantitatively evaluate infection risk and guide both public transmission epidemic prevention and control strategies design.

In further work, more attention should be paid to the increase in passenger accessibility caused by the closure of the stop, as well as the fluctuation of demand because passengers choose other modes or transfer to other stops caused by the station is temporarily closed or the departure interval is relatively large.

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