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Forecast of peak infection and estimate of excess deaths in COVID-19 transmission and prevalence in Taiyuan City, 2022 to 2023

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ABSTRACT

In this paper, with the method of epidemic dynamics, we assess the spread and prevalence of COVID-19 after the policy adjustment of prevention and control measure in December 2022 in Taiyuan City in China, and estimate the excess population deaths caused by COVID-19. Based on the transmission mechanism of COVID-19 among individuals, a dynamic model with heterogeneous contacts is established to describe the change of control measures and the population's social behavior in Taiyuan city. The model is verified and simulated by basing on reported case data from November 8th to December 5th, 2022 in Taiyuan city and the statistical data of the questionnaire survey from December 1st to 23rd, 2022 in Neijiang city. Combining with reported numbers of permanent residents and deaths from 2017 to 2021 in Taiyuan city, we apply the dynamic model to estimate theoretical population of 2022 under the assumption that there is no effect of COVID-19. In addition, we carry out sensitivity analysis to determine the propagation character of the Omicron strain and the effect of the control measures. As a result of the study, it is concluded that after adjusting the epidemic policy on December 6th, 2022, three peaks of infection in Taiyuan are estimated to be from December 22nd to 31st, 2022, from May 10th to June 1st, 2023, and from September 5th to October 13th, 2023, and the corresponding daily peaks of new cases can reach 400 000, 44 000 and 22 000, respectively. By the end of 2022, excess deaths can range from 887 to 4887, and excess mortality rate can range from 3.06% to 14.82%. The threshold of the infectivity of the COVID-19 variant is estimated 0.0353, that is if the strain infectivity is above it, the epidemic cannot be control with the previous normalization measures.

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1. Introduction

From the end of 2019 to November 2022, there appeared three outbreaks of COVID-19 in Taiyuan City, Shanxi Province in China: February 2020, April to May 2022, and November 2022 to December 2023. In response to each outbreak, Taiyuan Municipal government promoted a series of epidemic prevention and control work, such as regular nucleic acid testing, timely tracking and isolation of close contacts and sub-close contacts, and management measures of crowd gathering in high-risk areas, which effectively contained the spread of the epidemic. In the second half of 2022, Taiyuan city experienced an unprecedented impact of imported epidemic, which was the largest epidemic in scale, and had the most complex transmission chain. After evaluating the spread progress of COVID-19 epidemic and the characteristics of Omicron variant of COVID-19, the government in Taiyuan had fully optimized prevention and control measures, and no longer required regular nucleic acid testing. Against this background, the actual number of infections, infection peaks and other related data after December 6th, 2022 cannot be obtained. In this case, what is the propagation character of the Omicron strain without any control measures? How many people will be infected? Are people's self-protection measures effective, such as refraining from going outdoors? When can we return to normal life? Whether the spread of the Omicron strain can be contained with previous normalization control measures? All these require further quantitative study of mechanism model in the absence of epidemic monitoring information. Thus, it is necessary to adopt mathematical model to theorize and evaluate the epidemic situation, excavate propagation characteristics of the Omicron strain and assess the effect of control measures, which further not only provide theoretical basis for the allocation of medical resources and the decision-making of relevant departments, but also provide reference basis for the prevent and control of emerging infectious diseases in the future.

The dynamic method is based on the infection and transmission mechanism of COVID-19 to establish mathematical models to describe the transmission process of the virus in the population, and to evolve the dynamic transmission trend of infectious diseases (Gu & Yin, 2022; Mamis & Farazmand, 2022, p. 479; Metcalf et al., 2020; Vespignani et al., 2020). Dynamic modeling is widely used in human infectious diseases and animal infectious diseases (Chang et al., 2022; Ma et al., 2022; Sun et al., 2022). In view of COVID-19 epidemic in Shanxi Province in 2020, Chen Lin (Chen & Wang, 2021), Li Yang (Li & Liu, 2022), Cui Jin (Cui et al., 2021) and other research teams constructed ordinary differential equations to describe the epidemic process, simulated the development trend of COVID-19 epidemic, and evaluated the effectiveness of epidemic prevention and control measures, respectively. According to the chain of virus transmission, Zhang Juan et al. (Zhang et al., 2022) established an integral model with infection generations to describe the epidemic mechanism under the prevention and control measures in Shanxi Province, and evaluated the epidemic situation after the resumption of work and production. For the epidemic in Shanxi Province in 2022, Zhang Xiaoqin (Zhang et al., 2021), Li Mingtao (Li et al., 2020) and others constructed different dynamical models to simulate the development trend of the epidemic, respectively. These results provided theoretical basis for epidemic prevention and control and management in Shanxi Province. For more information on the dynamic transmission model of COVID-19, please see Reference (Chang et al., 2020; Huo et al., 2021; López & Rodó, 2020; Maier & Brockmann, 2020; Siegenfeld & Bar-Yam, 2020; Dehning, Zierenberg, & Spitzner, 2020; Song et al., 2020; Tang et al., 2020; Tang et al., 2022; Vespignani et al., 2020; Wang et al., 2020; Yuan et al., 2022).

Based on the transmission of COVID-19 Omicron virus in November 2022 in Taiyuan City, Shanxi Province, in this paper we predict the peak time, peak value, prevalence time, case growth rate, final scale of first infection, and secondary and tertiary infection peaks in Taiyuan City after the epidemic policy adjustment on December 6th, 2022 with the help of dynamic method. In addition, the excess population mortality related with COVID-19 in Taiyuan in 2022 is estimated. Finally, we apply the model to determine the propagation character of the Omicron strain and the effect of the control measures.

2. Materials and methods

2.1. Materials

The data adopted in this paper are given as follows.

(1) The number of permanent residents and the average family size in Taiyuan City are all derived from the 7th census of Taiyuan City, Shanxi Province (The People's Government of Taiyuan Municipalitya).
(2) The region area of Taiyuan is derived from the official website of Taiyuan Bureau of Statistics of Shanxi Province (The People's Government of Taiyuan Municipalityb).
(3) The data of COVID-19 cases reported in Taiyuan in the second half of 2022 are from the official website of Taiyuan Municipal Health and Construction Commission.
(4) The key time points of COVID-19 prevention and control policy adjustment in Taiyuan are November 8th, November 15th, December 6th, 2022. On November 8th, two asymptomatic cases of COVID-19 were reported in Taiyuan, one of which had close contact with an infectious individual from Shijiazhuang (The People's Government of Shanxi Province, 2022). On November 15th, Taiyuan began to take strict epidemic prevention and control measures. From December 6th, Taiyuan has further optimized the implementation of COVID-19 prevention and control measures and no longer required regular nucleic acid testing.

2.2. Assumptions

The model in this paper is based on the following assumptions.

(1) The time unit of the model is days, and the initial time is November 8th, 2022.
(2) The individuals in the region are regarded as homogenous, that is, each person has the same characteristics and is evenly distributed in the region.
(3) The total number of people in the area in time t is denoted as $N(t)$. According to the infection process and control measures of COVID-19, the whole population in the region can be divided into susceptible individuals ($S(t)$), individuals in the latent period with no infec tivity ($E(t)$), infectious individuals but not detected ($I(t)$), tested positive patients ($P(t)$), hospital patients ($H(t)$), and recovered individuals ($R(t)$). Where

$$N(t) = S(t) + E(t) + I(t) + P(t) + H(t) + R(t).$$

(4) Individual contacts are divided into three categories: intra-family members, colleagues/classmates, and other social close contacts. And the numbers of three categories of people that each individual contact with in unit time are recorded as c_h, c_d, and c_s respectively. For the social contact population, the close contact is defined as the people with the contact distance of 2 m, and contact time of more than 5 min.

2.3. Dynamical model

According to the transmission mechanism of the novel coronavirus in the population, the transfer diagram is shown in Fig. 1, and the corresponding dynamic model is constructed as Model (1), where the meanings of variables and parameters are shown in Table 1.

$$\begin{cases} \dfrac{dS}{dt} = -f(S,I,P) + \theta R, \\ \dfrac{dE}{dt} = f(S,I,P) - \omega E, \\ \dfrac{dI}{dt} = \omega E - \delta I - \sigma_i I, \\ \dfrac{dP}{dt} = \delta I - \gamma P - \sigma_p P, \\ \dfrac{dH}{dt} = \gamma P - \sigma_h H - \mu H, \\ \dfrac{dR}{dt} = \sigma_i I + \sigma_p P + \sigma_h H - \theta R. \end{cases} \tag{1}$$

Where, $f(S,I,P) = (\lambda_h c_h + \lambda_d c_d + \lambda_s c_s)\frac{I}{N}S + \lambda_h c_h \frac{P}{N}S$, $c_s = \varphi \frac{N}{Q} h$.

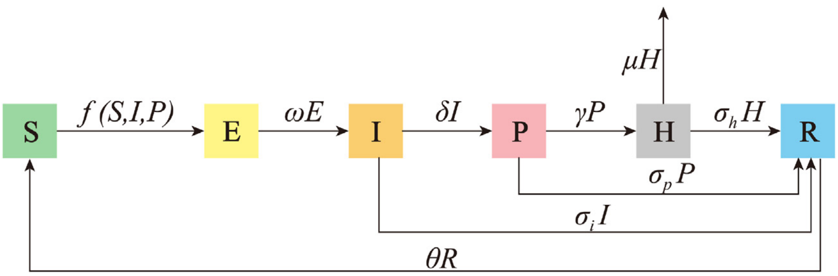

Fig. 1. Transfer diagram of COVID-19 transmission in the population.

Table 1
Description of variables and parameters of Model (1).

Variable/Parameter	Description
$S(t)$	Number of susceptible individuals at time t
$E(t)$	Number of latent individuals at time t
$I(t)$	Number of infectious individuals but not test at time t
$P(t)$	Tested positive patients at time t
$H(t)$	Hospital patients at time t
$R(t)$	Recovered individuals at time t
$N(t)$	Total population at time t
λ_h	Probability of transmission among family members
λ_d	Probability of transmission among colleagues or classmates
λ_s	Probability of transmission among rand contact
ω	Inverse of latent period
δ	The detection rate of nucleic acid test for each infectious individual
γ	Hospitalization rate
Q	Region area
h	The range of activity for each individual per day
φ	The proportion of close contacts in the total contacts
c_h	The average size of family
c_d	Number of close colleagues/classmates each individual has per day
c_s	Number of close other contacts each individual has per day
σ_i	Recovery rate of I
σ_p	Recovery rate of P
σ_h	Recovery rate of H
θ	The decay rate of antibody
μ	The diseased death rate

2.4. Basic reproduction number

According to Model (1), the basic reproduction number R_0, which measures the average number of secondary infections caused by a single infectious individual in an entirely susceptible population during the mean infectious period (Li, 2018), can be expressed as follows:

$$R_0 = \frac{\left[\lambda_h c_h \left(1 + \frac{\delta}{\gamma+\sigma_p}\right) + \lambda_d c_d + \lambda_s c_s\right]}{(\delta + \sigma_i)}. \tag{2}$$

Furthermore, the effective reproduction number R_t is obtained, which is the average number of secondary infections produced by the infected individual at time t during the infection period.

$$R_t = \frac{\left[\lambda_h c_h \left(1 + \frac{\delta}{\gamma+\sigma_p}\right) + \lambda_d c_d + \lambda_s c_s\right] S(t)}{(\delta + \sigma_i) N(t)}. \tag{3}$$

In addition, two important indicators for assessing the level of transmission and control of infectious diseases are defined: transmission rate and removal rate (Wei et al., 2023). The transmission rate v_t is the number of new cases per unit time. Removal rate v_r refers to the number of infected individuals who withdraw from the transmission process per unit time, that is, the sum of hospitalization rate and self-recovery rate in Model (1). Hospitalization rate v_h refers to the number of infected persons who are hospitalized or centrally isolated for medical treatment. Self-recovery v_d rate refers to the number of infections who are not hospitalized or isolated, and recover themselves. Based on Model (1), the mathematical expressions of these rate are given as follows.

$$v_t = f(S, I, P),$$

$$v_h = \gamma P, v_d = \sigma_i I + \sigma_p P,$$

$$v_r = v_h + v_d = \gamma P + \sigma_i I + \sigma_p P.$$

3. Result

According to the timeline of prevention and control measures in November and December 2022 in Taiyuan, the epidemic after November 8th, 2022 can be divided into four stages: concealed free transmission(November 8th to November 15th, 2022, called as the stage I), epidemic prevention and control(November 15th to December 5th, 2022, called as the stage II), optimized prevention and control(December 6th, 2022 to December 31st, 2022, called as the stage III), and post-epidemic(from January 1st, 2023 to December 31st, 2023, called as the stage IV).

The epidemic trend of COVID-19 in Taiyuan after the adjustment of epidemic prevention policy is related to the following factors: (1) The total number of existing infected individuals on November 15th, which is unknown. (2) The behavior changes of the crowd. (3) The population density in public place. Therefore, in this paper we first apply the model to fit the epidemic data from November 8th to 15th, to calculate the number of existing infectious individuals when the policy was adjusted on November 15th. Then, based on the theoretical number of infected individuals on November 15th and the reported number in the following days, and considering the changes in population behavior, we apply the model to continue to evolve the epidemic tend.

3.1. Data fitting

The actual reported case data in Model (1) are mainly from the website of Taiyuan Municipal People's Government. The coefficients of infection, λ_h, λ_d, λ_s, are derived from the least squares parameter estimation, and some parameters values are assigned according to the actual situation. The average number of close contacts of colleagues or classmates per person per day (c_d) is assumed to be 5 in the stage of hidden free transmission, and reduced to 2 in the stage of epidemic prevention and control. According to the total population and geographical area of Taiyuan City, the proportion of close contacts in the total number of social contacts per person per day (φ) is set to be 0.01. The latent period of the novel Omicron coronavirus is about 2 days, so ω is 0.5. During the free transmission stage, residents take nucleic acid detection every 3 days, so the detection rate of positive nucleic acid detection (δ) at this stage is 1/3. During the strict prevention and control stage, the nucleic acid detection frequency of residents is once a day, and laboratory detection need take half a day, so the detection rate of positive nucleic acid detection (δ) is 1/1.5. For people with positive nucleic acid test, reexamination and traceability investigation should be conducted, which takes about 1.5 days, so the isolation rate after test (γ) is 1/1.5. In the actual situation, the isolated patients recover within about a week, so the recovery time of I, P, and H is taken as 10, 8.5 and 7 days, respectively, that is σ_i, σ_p and σ_h are taken as 1/10, 1/8.5 and 1/7, respectively. In the first two stages, due to the short time span and small number of infections, it is assumed that the recovery individuals are not transformed into susceptible individuals again, and antibody decay rate θ is set to 0.

By means of least squares estimation, the cumulative number of positive cases reported in Taiyuan City from November 8th to December 5th is fitted with Model (1) to estimate the epidemic situation on December 6th when the strict prevention policy is began to carry out. The number of reported positive cases includes confirmed cases and asymptomatic cases that are tasted to be positive. The actual cumulative number of reported cases is recorded as $\tilde{Y}$, corresponding to variable Y in the model, satisfying $\frac{dY}{dt} = \delta I$. The values of model parameters are shown in Table 2. It can be seen from Fig. 2 that simulated result of the model is in good agreement with the real data, indicating that the model (1) in this paper is reasonable to a certain extent. According to the simulation results, on December 6th, the number of undetected infected people is estimated to be 501.

Table 2
The initial values of variables and parameter values of Model (1) in Fig. 2.

Variable/Parameter	Value	Source
$S(0)$	5304061	Actual data (The People's Government of Taiyuan Municipalitya)
$E(0)$	20	Assumed based on actual situation
$I(0)$	10	Assumed based on actual situation
$P(0)$	2	Actual data (Website of Taiyuan Municipal Health Commission)
λ_h	0.2	Parameter Estimation
λ_d	0.07 0.035	Parameter Estimation
λ_s	0.01 0.005	Parameter Estimation
σ_i	1/10	Assumed based on actual situation
σ_p	1/8.5	Assumed based on actual situation
σ_h	1/7	Assumed based on actual situation
ω	0.5	Assumed based on actual situation
δ	1/3 1/1.5	Assumed based on actual situation
γ	1/1.5	Assumed based on actual situation
Q	6988	Actual data (The People's Government of Taiyuan Municipalityb)
h	5 2	Assumed based on actual situation
φ	0.01	Assumed based on actual situation
c_h	2.45	Actual data (The People's Government of Taiyuan Municipalitya)
c_d	5 2	Assumed based on actual situation
θ	0	Assumed based on actual situation
μ	/	/

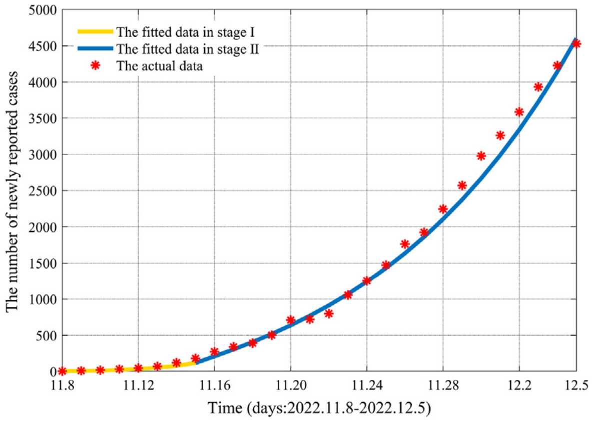

Fig. 2. Fitted curve of cumulative reported cases. The red dots are the actual cumulative reported positive case data in Taiyuan from November 8th to December 5th, 2022. The yellow line is the model simulation result at the stage I (November 8th to November 15th). The blue line is the model simulation result at the stage II (November 15th to December 5th).

3.2. Basic reproduction number

Using Eq. (2), the change of effective reproduction number R_t with time t is shown in Fig. 3. In the free spread stage of the epidemic, R_t in Taiyuan exceeds 1, and stabilizes around 3.279. In the strict prevention and control stage, under the case that Taiyuan Municipal government further promotes a series of epidemic prevention and control work, the value of R_t is smaller significantly than the stage I, and shows a decreasing trend over time. Because the Omicron strain is highly contagious, the effective reproduction number R_t in the stage II is still greater than 1. Therefore, it can be concluded that in the stage II, due to the high transmission capacity of Omicron, the epidemic has been controlled to a certain extent, but the intervention effect is limited, and dynamic zero-COVID case cannot be achieved.

In order to compare the spread speed of COVID-19 with the control speed of government, the changes of transmission rate v_t and removal rate v_r in Section 2.4 with time are defined (Fig. 4). From November 8th to December 5th, 2022, the spread rate of the novel coronavirus increases with time. The v_t value in the stage I (from November 8th to November 15th) is significantly higher than that in the stage II, and the slope of v_r curve is lower than that in the stage II, indicating that Taiyuan Municipal government effectively slows down the spread of the epidemic by promoting a series of epidemic prevention and control work timely.

3.3. Peak prediction

Based on the simulation results in Section 3.1, we continue to evolve model by taking December 6th as the initial time.

3.3.1. The optimization phase of the prevention and control

In the stage III (from December 6th to December 31st), some parameter values need to be adjusted according to policy change, as shown in Table 3. Among them, it is assumed that λ_h, λ_d, h and c_d obey normal distribution, and the values of other parameters are shown in Table 2.

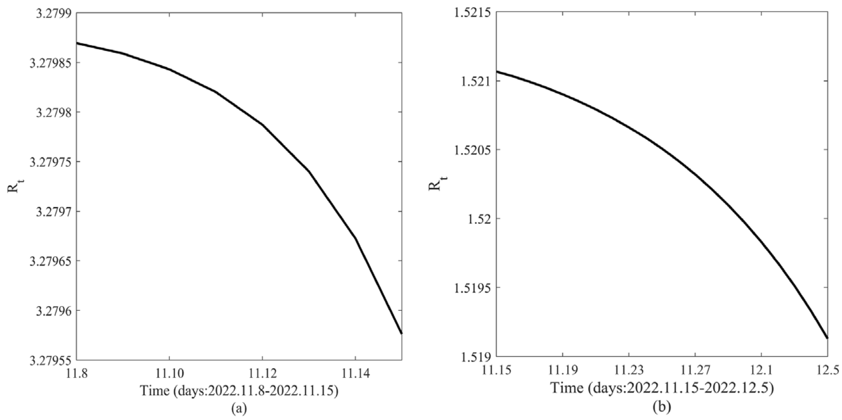

Fig. 3. The graph of effective reproduction number. (a) In the stage I. (b) In the stage II.

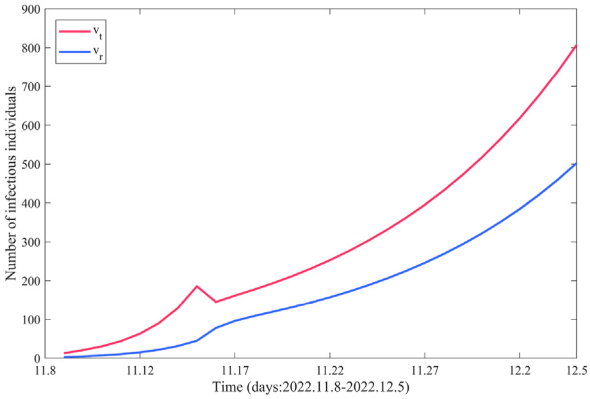

Fig. 4. The change of transmission rate and removal rate with time. Where the red line represents v_t, the blue line represents v_r.

Table 3
In the stage III, some parameter values of Model (1).

Parameter	Value
λ_h	$N(0.3, [0.2/6]^2)$
λ_d	$N(0.05, [0.06/6]^2)$
σ_i	1/7
σ_p	$1/5 \times 0.965$
σ_h	$1/5 \times (1 - 0.03688)$
h	$N(5, [4/6]^2)$
c_d	$N(10, [6/6]^2)$
δ	1
γ	$1/1.5 \times 0.035$

The prediction results of the stage III are shown in Fig. 5 and Table 4. As can be seen from Fig. 5, in the stage III, the peak number of infected individuals $I(t)$ is between 300 000 and 500 000, and the corresponding peak period is from December 22nd to December 31st, 2022. Therefore, the number of infected people in Taiyuan can reach the peak on December 26th, about 400 000 people.

Meanwhile, the cumulative infection rate of Taiyuan City is given, as shown in Fig. 5, and it is satisfied

$$i_{cum}(t_2) = i_{cum}(t_1)e^{r(t_2-t_1)},$$

where $i_{cum}(t_2)$ represents the cumulative infection rate at time t_2, $i_{cum}(t_1)$ represents the cumulative infection rate at time t_1, and r represents the growth rate of infection rate. The average cumulative infection rate and growth rate from December 15th to December 28th are presented in Table 4. Up to December 28th, the cumulative infection rate has reached 85%.

3.3.2. Post-epidemic phase

In the stage IV (post-epidemic phase: from January 1st, 2023 to December 31st, 2023), the classification of COVID-19 has been downgraded from the highest level of Class A to Class B for infectious disease control. Since the peak of the first infection has passed, the range of activities of the population and the proportion of social contacts have changed. Therefore, the values of the corresponding parameters will be changed. Due to the decay of antibodies in the body after infection, part of the population whose antibody level are lower than the threshold level of protection can be reinfected. So at this stage we introduce the antibodies decay rate θ. Baidu index of search keyword “Second Positive + Secondary Infection”, shows a growing tend, as shown in Fig. 6. It can be considered that COVID-19 epidemic has increased again during this period. Combined the dynamic model with search trends of Baidu index, the antibodies decay rate θ is set to be 0.004. Corresponding adjustments of the values of some parameters are shown in Table 5, where it is assumed that φ and h follow normal distribution. Table 3 lists the values of σ_i, σ_p, σ_h, δ, and γ. The values of other parameters can be seen in Table 2.

The prediction of the peak of the stage IV of COVID-19, including the peak of secondary and tertiary infections, is shown in Fig. 7. It can be seen from Fig. 7 that the peak time of the second wave is from May 10th to June 1st, 2023, and the peak number of infectious individuals during this period is about 44 000. The third wave of the epidemic will peak from September 5th to October 13th, 2023, and the peak number of infectious individuals in this period will be about 22 000. In Taiyuan, the interval time between the peak of the first wave and the second wave is about 146 (135 ~157) days, and the interval time between the first wave and the third wave is about 272 (253 ~291) days. The peak of infectious individuals in the second wave and the third wave is 1/9 and 1/18 (5.5%) of the first wave, respectively, and the epidemic time is longer than that of the first wave. The

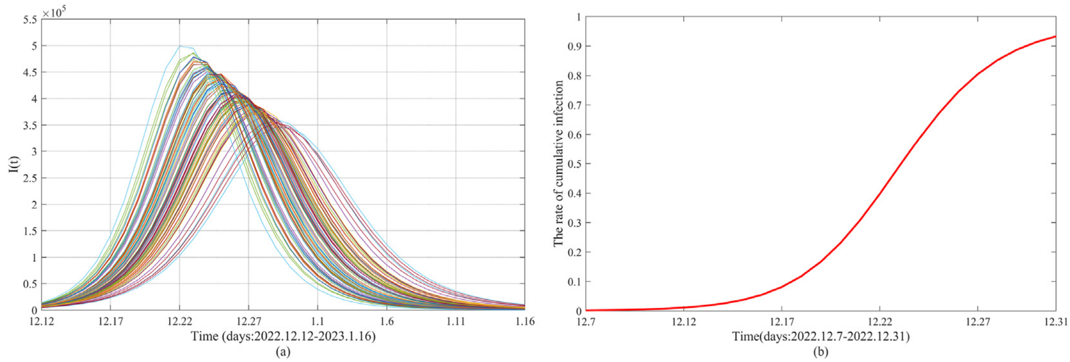

Fig. 5. Prediction of Model (1) in the stage III. (a) 100 times of numerical simulations of the COVID-19 outbreak in Taiyuan from December 6th, 2022 to January 16th, 2023. The parameter values are given in Tables 2 and 3 (b) The average cumulative infection rate after December 6th in Taiyuan city.

Table 4
Prediction results of cumulative infection rate.

Time	Average cumulative infection rate	Growth rate *r*
December 15	0.0373	–
December 16	0.0553	0.1710
December 17	0.0813	0.1674
December 18	0.1179	0.1614
December 19	0.1673	0.1520
December 20	0.2311	0.1403
December 21	0.3087	0.1257
December 22	0.3973	0.1096
December 23	0.4915	0.0924
December 24	0.5846	0.0753
December 25	0.6704	0.0595
December 26	0.7445	0.0455
December 27	0.8049	0.0339
December 28	0.8521	0.0247

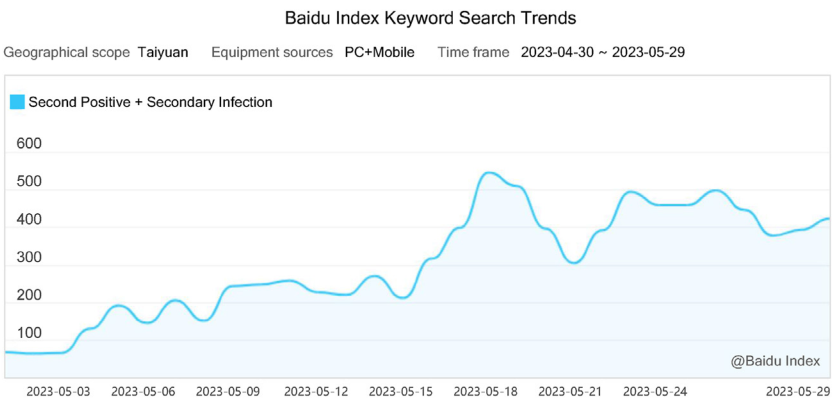

Fig. 6. The trend of Baidu index of keyword “Second Positive + Secondary Infection” (Baidu Index).

Table 5
In the stage IV, part of parameter values of Model (1).

Parameter	Value
λ_h	0.3
λ_d	0.05
φ	$N(0.01, [0.01/5.16]^2)$
c_d	10
h	$N(10, [5/2.58]^2)$
θ	0.004

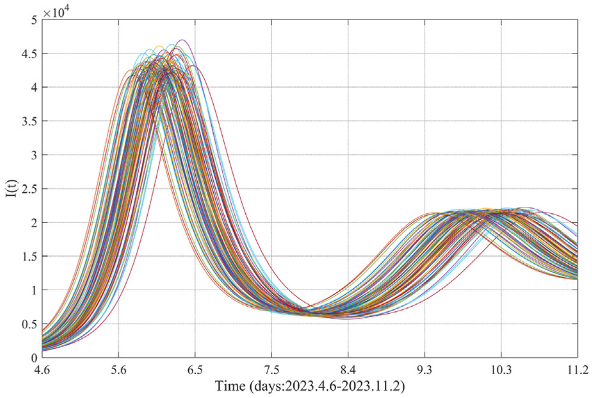

Fig. 7. 100 numerical simulations of COVID-19 epidemic in Taiyuan from April to November 2023. Parameter values are shown in Tables 2 and 5.

results is similar to the results of the "pre-planned study" published in CDC weekly which examines the second wave of infections in different regions and populations around the world (Niu et al., 2023; Zhang et al., 2023).

3.4. Excess death

Excess death is the difference between the number of deaths that actually occurred with the disease outbreak and the estimated number of deaths without the disease outbreak and includes those directly caused by the epidemic and those indirectly related to the impact of the pandemic on health systems and society (Xinhuanet). The excess mortality rate is the ratio of the excess death number to the estimated number of deaths. Since December 6th, 2022, the intensity of the new coronavirus epidemic in Taiyuan is very different from the previous epidemic, and the production and lifestyle of residents have undergone major changes.

Based on annual resident population of Taiyuan from 2017 to 2021, we calculate the expected total population in 2022. Taking 2017 as the initial year, the total permanent population of Taiyuan in year t is dented as $N(t)$, and Logistic population model is applied to describe its change with time:

$$\frac{dN}{dt} = \rho N\left(1 - \frac{N}{K}\right),$$

where ρ stands for the net population growth rate of Taiyuan, and K stands for the environmental capacity of the permanent population of Taiyuan. Applying the least squares, we fit the model with the actual reported number of human population from 2017 to 2021 to estimate parameter values $\rho = 0.2443$, $K = 5671502$. With the parameter values, and the fitting result is given in Fig. 8, the expected permanent population of Taiyuan in 2022 without the impact of COVID-19 is estimated to be 5 449 890.

The death population of Taiyuan City in year t is recorded as $D(t)$, then $D(t)$ satisfies the linear expression

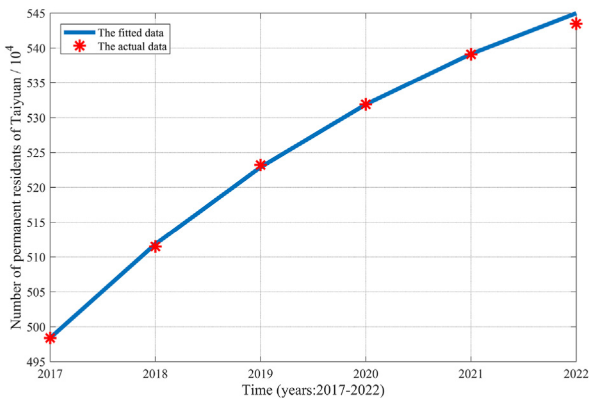

Fig. 8. The fitting curve of permanent resident population from 2017 to 2022 in Taiyuan. The red dots are the reported permanent population data. The blue line is model simulation result.

$$D(t) = dN(t) + c.$$

Similarly, we fit $D(t)$ with the actual death number from 2017 to 2019, and 2021 to obtain $d = 0.0326$, $c = -146690$. According to the fitting results (see Fig. 9), it can be seen that the expected death number in 2022 in Taiyuan without the impact of the epidemic is between 28 976 and 32 976.

It is known that the actual number of deaths in Taiyuan City in 2022 is 33 863, and the number of excess deaths in 2022 is calculated to be 887 ~4887, and the excess mortality rate is estimated to be 3.06% and 14.82%.

3.5. Parameter sensitivity analysis

We conduct sensitivity analysis of the effective reproduction number in the first two stages of the epidemic transmission process (see Fig. 10), and calculate partial rank correlation coefficient (PRCC) to determine the key parameters affecting the disease transmission. Assuming that the parameters λ_h and λ_d are normally distributed and λ_s, c_d, φ and h are uniformly distributed, the PRCC of the effective regeneration number R_t in term of parameters changes with time. By observing Fig. 10, it can be concluded that.

(1) In the stage I, the correlation coefficients between parameters λ_h, λ_d, φ, λ_s and the effective regeneration number remaine above 0.5, and the correlation between parameter λ_h and the effective regeneration number is as high as 0.9. The correlation coefficient between the parameter c_d and the effective regeneration number is between 0.4 and 0.5. The correlation coefficient between the parameter h and the effective regeneration number ranges from 0.25 to 0.35, and the correlation decreases with time. The correlation coefficient between the parameter φ and the effective regeneration number is about 0.7, indicating that intra-family contact and social contact have a greater impact on the spread of the disease during the free transmission of the epidemic. This is consistent with the fact that, due to social contact, the import of external infected persons leads to the spread of the disease.

(2) In the stage II, the correlation between the parameter λ_h and the effective regeneration number is still greater than 0.9, and is getting stronger and closer to 1. The correlations between the other parameters and the effective regeneration number decrease than them in the stage I. Compared with the stage I, the correlation between λ_d and the effective regeneration number decreased to below 0.8, but the correlation coefficient is still greater than 0.5. The correlation coefficients between parameters φ, λ_s, c_d, h and the effective regeneration number are between 0.1 and 0.4. The results show that is taken by Taiyuan Municipal government work to some extent a series of epidemic prevention and control work, so that the stage II of disease transmission mainly occurred in the family.

4. DISSION

4.1. Application of the model

In this section, we apply the Model (1) and the parameter values to Neijiang city in Sichuan province. The government in Neijiang city adjusted and optimized COVID-19 epidemic prevention and control measures from December 9th, 2022 (Neijiang). Taking December 1st as the initial time, the existing reported number of infections as initial value of variable and considering changes in population behavior, we used Model (1) to predict the infection rate of Neijiang citizens during the optimization phase of prevention and control.

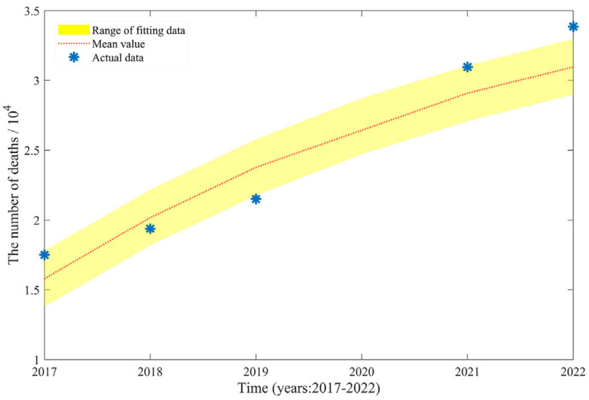

Fig. 9. The fitting curve of the death number from 2017 to 2022 in Taiyuan City. The blue dots are the death data. The yellow area represents the range of simulation result of $D(t)$. The dashed line is the mean of the fitting results.

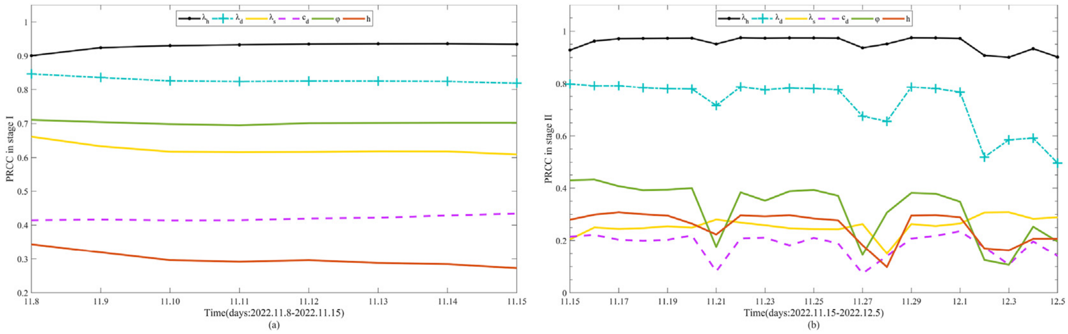

Fig. 10. Parameter sensitivity analysis. (a) In the stage I. (b) In the stage II.

In addition, in order to get a timely grasp of the situation of COVID-19 infection among the citizens of Neijiang City and assess the spreading speed of the epidemic, the Center for Disease Control and Prevention of Neijiang City organized and carried out a special survey on the situation of COVID-19 infection from December 23rd to 25th, 2022. The survey found that of the 37 114 survey respondents, 25 642 stated that they were infected with the new coronavirus, and the infection rate reached up to 69.09%. The number of new coronavirus infection in term of the infection time in Neijiang City is shown in Fig. 11.

According to the population of Neijiang City, in the Model (1), the initial values variables and some parameter values are shown in Table 6, the parameters λ_h and λ_d are the corresponding means in Table 3, and the others are taken from Table 1. We show to the solution of $\frac{\tilde{Y}}{N}$ as the infection rate, where $\tilde{Y}$ is the cumulative number of infected cases, and make a comparison with the questionnaire data, see Fig. 12. It is found that when the parameter values obtained from the data of Taiyuan City are taken into Neijiang City, the theoretical results are relatively in line with the actual situation, thus it is concluded that the Model (1) and the parameter values have a certain degree of reasonableness.

4.2. Estimation of the threshold

The basic reproduction number R_0 is an important indicator to determine the ability of an epidemic to spread. If $R_0 < 1$, then an epidemic will not outbreak; If $R_0 > 1$, an epidemic will outbreak and spread. Denoting the probability of transmission of Omicron viruses in different populations as λ, R_0 for Eq. (2) becomes:

$$R_0 = \frac{\lambda\left[c_h\left(1+\frac{\delta}{\gamma+\sigma_p}\right)+c_d+c_s\right]}{(\delta+\sigma_i)}. \tag{4}$$

Let $R_0 = 1$, we obtain

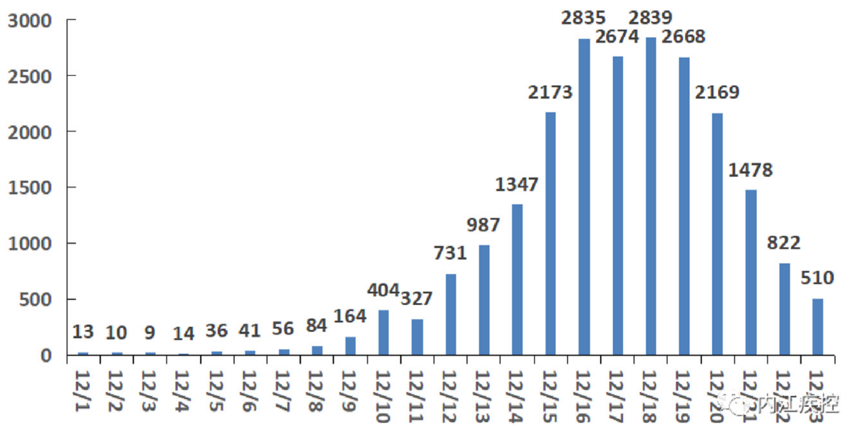

Fig. 11. The distribution of the time of new coronavirus infection in Neijiang City. The vertical axis represents the number of positive detections per day in the questionnaire data.

Table 6
The initial values of variables and some parameter values of Model (1) in Neijiang City.

Variable/Parameter	Value	Source
$S(0)$	3139578	Estimated based on actual situation
$E(0)$	1100	Estimated based on actual situation
$I(0)$	0	Estimated based on actual situation
$P(0)$	0	Estimated based on actual situation
N	3140678	Actual data (The People's Government of Neijiang Municipality)
Q	5385	Actual data (The People's Government of Neijiang Municipalityb)
h	8	Assumed based on actual situation
c_h	2.39	Actual data (The People's Government of Neijiang Municipality)

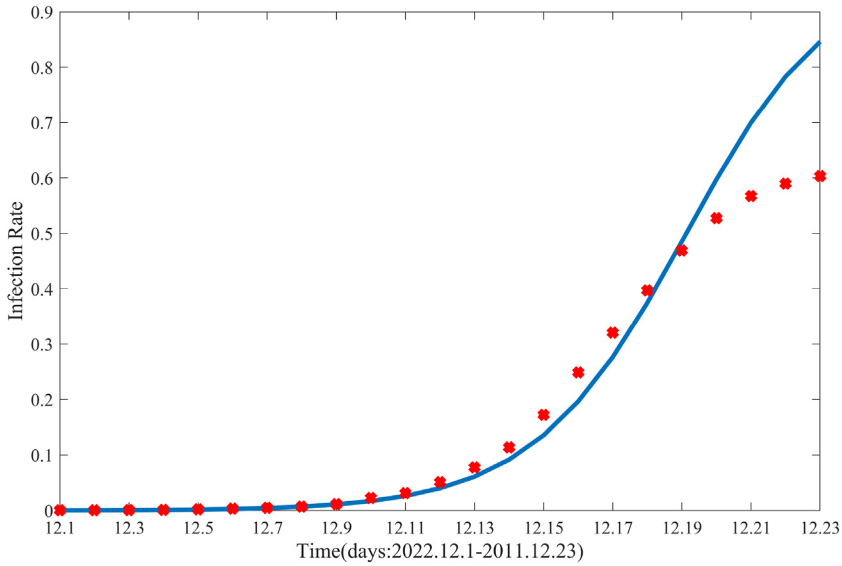

Fig. 12. The infection rate of the citizens of Neijiang City from December 1st to 23rd. Red dots are questionnaire survey data in Neijiang from December 1st to 23rd, 2022. The blue line is the model theoretical result.

$$\lambda = \frac{(\delta + \sigma_i)}{\left[c_h\left(1 + \frac{\delta}{\gamma+\sigma_p}\right) + c_d + c_s\right]}. \tag{5}$$

Different thresholds of transmission can be obtained by solving the value of λ at different stages of Taiyuan City by using $R_0 = 1$, and the calculated thresholds with different stages of transmission probabilities are compared in Table 7. It is concluded that when there is no any control measure, the threshold of λ is 0.0093, and when there is normalized prevention and control measure, the threshold of λ is 0.0353. In other words, under China's normalized prevention and control, if the infection probability of the virus strain is less than 0.0353, then the disease can be controlled, and if it is higher than 0.0353, then the disease can't be controlled, and can't be dynamically zeroed out. In COVID-19 propagation prediction and assessment for Shanxi Province by Zhang Juan et al. (Zhang et al., 2022), it gives that the original strain transmission probability λ is 0.0149, which is less than the threshold. In evaluating the effectiveness of interventions and interventions in China by Wei Xiaomeng et al. (Wei et al., 2023), it gives that the Delta strain transmission probability λ is $\frac{0.7465}{c_h+c_d+c_s}$, the result is 0.0164 and less than the threshold.

Table 7
The threshold of the infectivity of the COVID-19 virus strain.

cases	λ_h	λ_d	λ_s	λ
without control measures	0.2	0.07	0.01	0.0093
with control measures	0.2	0.035	0.005	0.0353

5. Conclusion

In this paper, by taking into account the epidemic prevention and control policies at different stages of the epidemic and different types of contacts among individuals in Taiyuan, we establish a dynamic model to simulate the spread of COVID-19 in Taiyuan in the second half of 2022, and predict that after the adjustment of epidemic policy on December 6th, 2022, the peak time of the first wave of the epidemic in Taiyuan may be between December 22nd and 31st, 2022, and the peak number of new cases per day will be about 400 000. Combing with Baidu Index, it is predicted that the peak time of the second wave may be between May 10th and June 1st, 2023, and the daily peak number of new cases is about 44 000. The third wave may peak between September 5th to October 13th, 2023, with the peak value of about 22 000 cases, and the latter two waves will last longer than the first wave. Furthermore, by fitting the 5-year resident population data and death data before 2022, and it is estimated that the number of excess deaths in 2022 may be 887 ~4887, and the excess mortality rate is between 3.06% and 14.82%. In addition, it is found that the effective reproduction number of disease transmission is greatly related to the transmission coefficient and the number of contacts between individuals. During the free transmission stage of the epidemic, intra-family contact and social contact have greater impact on the spread of the disease. From December 6th, 2022, Taiyuan municipal government promoted a series of efficient epidemic prevention and control measures, so that the second stage of the disease transmission mainly occurred within the family. After estimating the transmission probability threshold, it is found that the threshold for λ is 0.0353 under the case with the normalized control measures. For the original and Delta strains of COVID-19, the transmissibility is less than the threshold and dynamic zero-COVID policy can realize with the implementation of normalized control measures. However, for Omicron strain, its transmission is higher than the threshold, so the epidemic cannot be controlled easily. In addition, considering lower ratio of serious cases for Omicron virus, the control and prevention strategy was adjusted by the Chinese government in December 2022. These results can provide theoretical basis for the allocation of medical resources and the decision-making of relevant departments for the prevent and control of emerging infectious diseases in the future.

In this paper, the model is a deterministic model, therefore the conclusions obtained are the mean case without taking into account the effect of random factors. Furthermore, in the model estimated in this paper, we consider the recovery of individuals, but not consider different individual's vaccination state, since individuals who receive different doses of vaccine may have different risks of infection, transmission capacity, and resilience. In the future, strain variation will be considered in model to assess the prevalence and spread of COVID-19.

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Authors contributions

J.W., X.X., F.Z., X.P., M.T., J.Z., J.Z. and G.S. determined the research theme, conceived and designed the research methods. J.W. X.X., F.Z., X.P., M.T., and J.Z. investigated and analyzed the data. J.Z. and G.S. supervised and validated the paper. J.W. and J.Z. programmed and wrote the paper. J.W., J.Z. and G.S. reviewed and edited the paper. All authors gave final approval for publication.

CRediT authorship contribution statement

Jia-Lin Wang: Data curation, Investigation, Methodology, Writing – original draft, Writing – review & editing. **Xin-Long Xiao:** Data curation, Methodology, Software. **Fen-Fen Zhang:** Methodology, Validation. **Xin Pei:** Funding acquisition, Investigation, Validation. **Ming-Tao Li:** Investigation, Methodology, Software. **Ju-Ping Zhang:** Funding acquisition, Methodology, Validation. **Juan Zhang:** Funding acquisition, Investigation, Project administration, Validation, Writing – original draft, Writing – review & editing. **Gui-Quan Sun:** Investigation, Methodology, Project administration, Validation, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no competing interests.

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