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Preliminary Estimation of the Transmission Risk of Novel Coronavirus in Hubei Province

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Abstract A novel coronavirus(COVID-19) causes an outbreak of viral pneumonia in Wuhan, Hubei province, China. In this paper, the deterministic compartmental model is given based on the clinical progression of the disease and the intervention measures implemented by the Chinese authorities. Simulations of the model are given to estimate the basic reproduction number for COVID-19 based on the daily reported cases from China CDC. The basic reproduction number of the model is used to assess the transmissibility of COVID-19. The results indicate that COVID-19 will be controlled at the end of March if there are no imported infections people into China. Then the first-level public health emergency response can be adjusted to the second-level or the higher-level response.

Keywords COVID-19, the basic reproduction number, two-stage mathematical model

MSC(2010) 34K20, 37N25, 37N30.

1. Introduction

The World Health Organization (WHO) reported that a novel coronavirus (SARS-CoV-2) was identified as the causative virus by Chinese authorities on January 7th. The first case of the new pneumonia was identified in the city of Wuhan. The virus is related to the SARS coronavirus but is distinct from each of those viruses [6]; the virus causes a range of symptoms including fever, cough, and shortness of breath [6]. The government of China activated the first-level public health emergency response and took a series of measures to contain the outbreak of the epidemic. In order to curb population flow, the government canceled mass gatherings, extended the Chinese New Year holiday, and closed scenic spots, to make fewer trips outside et al. Then most people were quarantined in the cities where they were. Fifty days

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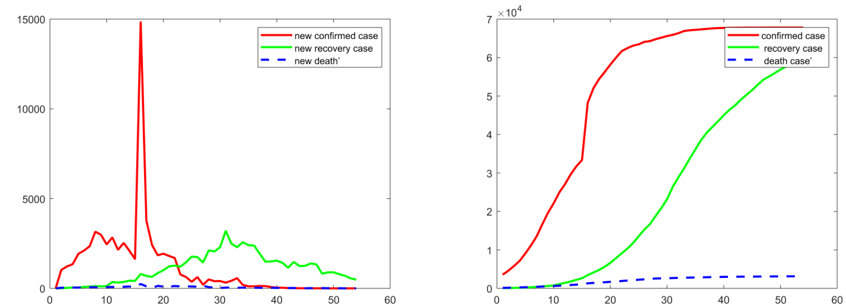


Figure 1. Reported data of the COVID-19 pneumonia in Hubei Province(2020.1.16-2020.3.19).

later, the number of confirmed cases of the novel coronavirus had increased to more than 80000. There were 67800 confirmed cases in Hubei Province in late March.

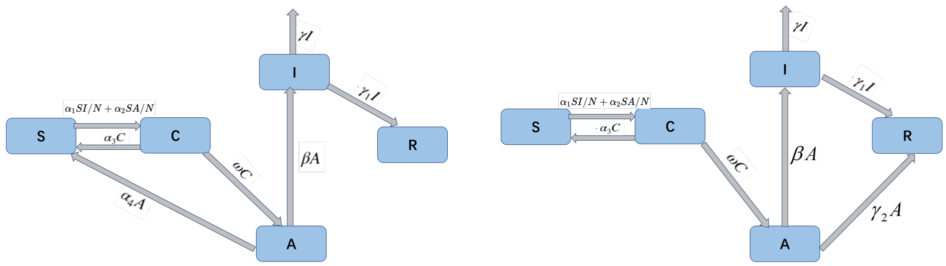
There are many works about this object [3,9,10]. In this paper, we try to analyze the case in the origin of infectious disease. That is the deterministic compartmental models are given based on the clinical progression of the epidemic and the intervention measures of Hubei Province. Simulations are used to show the potential transmission from the infection source to humans. The basic reproduction number has also been computed from our model, with which the transmission ability of COVID-19 can be estimated. We aim to find the transmitted regulation of the epidemic and predict the number of infectious people in Hubei Province. Then the appropriate suggestions will be given to Hubei authorities for the duration of the quarantine.

2. The two stages SCIAR model

Scientists have tried their best to expose the origins [7, 8, 11], the spread of the virus [1, 2, 5], and to find the treatments [4]. More information about COVID-19 has been obtained than the early detection of disease. In the following three months, people have been quarantined. They reduce the contact with others unless urgent cases. In our model, we will not consider the impact of the bat population, and the other hosts (probably be wild animals), only the health of the people here. From the daily reported cases from China CDC, we can see the reported data of the 2019-nCoV directly from the following Figure 1.

Hubei Province reported zero new confirmed cases of COVID-19 for three days, the minimum number of confirmed case since March 27th. Only 3 cases were reported outside Hubei province. But more than 210,000 cases have now been reported to WHO, and more than 9,000 people have lost their lives. The countries include Korea, Italy, Iran, Japan, and so on. Individuals, families, and communities still should follow the advice provided by local health authorities. All researchers and scientists need to try their best to prohibit the transmission of the virus.

In fact, at the beginning of the first several days, all people did not pay attention to the transmission of COVID-19 and they lived in their own way. Then the virus spread very quickly. On Jan 23rd, the lockdown of the city Wuhan was initiated on. Later, the Chinese authorities activated the first-level public health emergency response and implemented a series of measures to curb the transmission of the



(a) Stage I (b) Stage II

Figure 2. Flowchart of a two-stage COVID-19 model

virus, such as suspending inter-province coach service, offering full refunds without surcharges, an extension of the holiday, and prolonging winter break et al. Then the COVID-19 was controlled step by step. From Figure 1, we can also note that the new confirmed cases increased quickly in the first twenty days (2020.1.16-2020.2.10), and then the increased rate slowed down twenty days later. Then we made the mathematical model of two-stage ordinary differential equations system.

In this paper, we propose a deterministic SCAIR compartmental model based on the daily reported cases and the daily news. We also simulate and estimate the parameters of the model using data obtained from the confirmed cases of COVID-19 in Hubei Province, then the basic reproduction number of the disease transmission is given. We classify the populations as susceptible population(S) , close contact population (C), suspected population(A, distinguished from susceptible population), infectious population(I) and recovered population(R), where close contacts refer to the people who live, study, work or have close contact with the infectious. The flowchart of the two-stage model adopted in the study of the COVID-19 infection is given in Fig. 2.

When the quarantined close contact population has any symptom, they will be conveyed to suspected population. Hence we assume there is no transition from the close contact cases to the infectious cases. In the first stage, there were many suspected populations, who were not infectious cases indeed because of the shortage of personal protective equipment and medical resources. Perhaps, some of them just had a fever. Once they were cleared, they would be a susceptible cases again. In the second stage, more and more experts, doctors, nurses, and many staff were engaged in fighting against the COVID-19. More medical supplies and protective equipment are supplied to the hospital. Then the infectious could be tested and diagnosed as soon as possible. On the other hand, the transmission from the susceptible population to the suspected population is checked accurately, since enough pneumonia test kits were used to test for infection. What's more, the clinical patients were computed into the confirmed cases, then the transmission rate from the suspected population to the susceptible solution was zero, that is $\alpha_4 = 0$. Hence the two-stage compartment model can be given in the following system:

$$\begin{cases} S' = -\alpha_1 \frac{SI}{N} - \alpha_2 \frac{SA}{N} + \alpha_3 C + \alpha_4 A, & 0 < t \leq 21, \\ C' = \alpha_1 \frac{SI}{N} + \alpha_2 \frac{SA}{N} - \alpha_3 C - \omega C, & 0 < t \leq 21, \\ I' = -\gamma I - \gamma_1 I + \beta A, & 0 < t \leq 21, \\ A' = \omega C - \alpha_4 A - \beta A, & 0 < t \leq 21, \\ R' = \gamma_1 I, & 0 < t \leq 21, \\ S' = -\alpha_1 \frac{SI}{N} - \alpha_2 \frac{SA}{N} + \alpha_3 C & t > 21, \\ C' = \alpha_1 \frac{SI}{N} + \alpha_2 \frac{SA}{N} - \alpha_3 C - \omega C, & t > 21, \\ I' = -\gamma I - \gamma_1 I + \beta A, & t > 21, \\ A' = \omega C - \beta A - \gamma_2 A, & t > 21, \\ R' = \gamma_1 I + \gamma_2 A, & t > 21, \end{cases} \tag{2.1}$$

where all parameters are positive, and the meaning of the parameters can be seen in the following Table 1.

Parameters	Definitions
α_1	Contact rate of infectious cases to susceptible cases
α_2	Contact rate of suspected cases to susceptible cases
α_3	Transition rate of close contact cases to susceptible cases
α_4	Transition rate of suspected cases to susceptible cases
ω	Transition rate of close contact cases to suspected cases
β	Transition rate of suspected cases to infectious cases
γ_1	Recovery rate of infectious cases
γ_2	Transition rate of suspected cases to recovered cases
γ	Disease-induced death rate

Table 1: Parameters of the two stages model for 2019-nCoV in Hubei Province.

In this paper, we will use the basic reproduction number R_0 to assess the transmissibility of the virus (COVID-19). R_0 is defined as the expected number of secondary infections that result from introducing a single infected individual into the susceptible population. With the help of the next generation matrix , we can get an expression of R_0 for model (2.1) as follows:

$$R_{01} = \frac{\alpha_1 \beta \omega + \alpha_2 (d + \gamma_1) \omega}{(\omega + \alpha_3)(d + \gamma_1)(\beta + \alpha_4)}, \qquad R_{02} = \frac{\alpha_1 \beta \omega + \alpha_2 (d + \gamma_1) \omega}{(\omega + \alpha_3)(d + \gamma_1)(\beta - \alpha_4)},$$

where R_{01} and R_{02} are the basic reproduction numbers of the first and second stages, respectively. In order to give an accurate estimation of the R_0, we need to estimate all parameters in R_0. Here, we use the reported data to estimate the parameters in model (2.1) with the Markov Chain Monte Carlo (MCMC) method. The estimation of all parameters can be seen in Table 2.

Para.	Estimated mean value (first stage)	Std(first stage)	95%CI	Source	Estimated mean value (second stage)	Std (secend stage)	95%CI	Source
α_1	6.1185	0.1623	(6.0024, 6.2345)	MCMC	0.1	0.05	(0.0975, 0.125)	mean value
α_2	4.1324	0.0632	(4.0872, 4.1776)	MCMC	1.4426	0.0009	(1.4420, 1.4432)	MCMC
α_3	0.8438	0.0228	(0.8275, 0.8601)	MCMC	0.1463	0.0001	(0.1462, 0.1463)	MCMC
α_4	0.2572	0.0640	(0.2114, 0.3029)	MCMC	0	0	(0.0000, 0.0000)	*
β	0.1787	0.0001	(0.1787, 0.1787)	MCMC	0.3452	0.0001	(0.3451, 0.3453)	MCMC
ω	0.1311	0.0097	(0.1286, 0.1136)	MCMC	0.0126	0.0000	(0.0126 0.0126)	MCMC
γ_1	0.031	0.005	(0.0295, 0.0335)	LM	0.0245	0.0001	(0.0244, 0.0245)	MCMC
γ	0.03	0.005	(0.0275, 0.0325)	LM	0.012	0.005	(0.0995, 0.0145)	mean value

Table2: Parameters estimates for COVID-19 in Hubei Province.

All the 'median (95%CI)$'$ parameters in the last table are obtained with the method of MCMC. In fact, we use twelve days' data to estimate the parameters in the first stage, and the other nine days' data are used to check the feasibility and effectiveness of the model. In the second stage, the data of the first fifteen days (2020.2.10-2020.2.24) are used to estimate the parameters in the mathematical model, and the other five days' data are used to check the feasibility and effectiveness. Then the prediction of the virus is given. With all parameters in the two stages, we can compute the basic reproduction numbers of the two stages as $R_{01} = 6.8948$ (95%CI(6.68, 6.6583)) and $R_{02} = 0.4556$ (95%CI(0.4554 , 0.4558)), respectively.

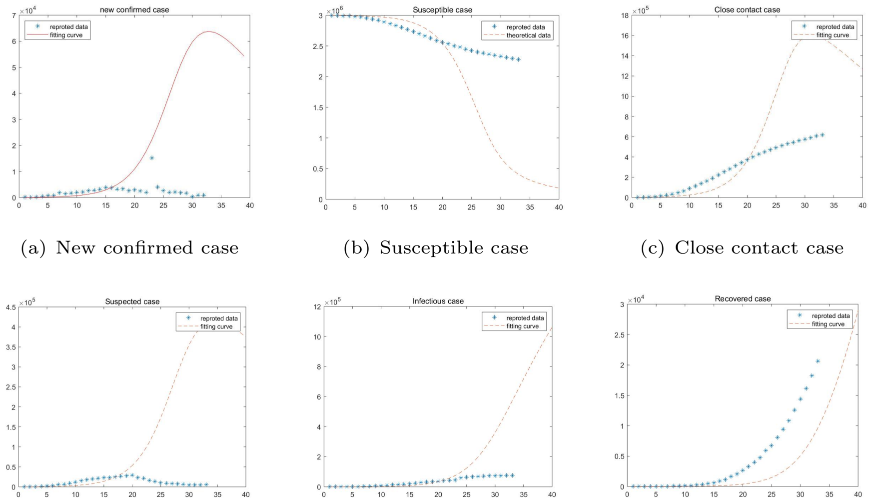
With the help of all parameters in Table 2, we can predict efficiently the new confirmed cases, the change of susceptible populations, close contact populations, suspected populations, infectious populations, and recovered populations to time t(days) in the following Figure 3, which shows the necessity of self-monitored quarantine. To control the transmission of the virtues, it is better to receive the treatment in isolation.

The first stage is the past. In the rest of the paper, we will concentrate on analyzing the basic reproduction number of the second stage as follows. In fact, R_{02} can be written as

$$R_{02} = \frac{\alpha_1\beta\omega+\alpha_2(\gamma+\gamma_1)\omega}{(\omega+\alpha_3)(\gamma+\gamma)(\beta-\alpha_4)} = \frac{\alpha_1\beta\omega}{(\omega+\alpha_3)(\gamma+\gamma_1)(\beta-\alpha_4)} + \frac{\alpha_2\omega}{(\omega+\alpha_3)(\beta-\alpha_4)}. \tag{2.2}$$

It is easy to obtain the inequalities

$$\frac{\partial R_{02}}{\partial \beta} = \frac{-\alpha_1\omega\alpha_4 - \alpha_2\omega(\gamma+\gamma_1)}{(\omega+\alpha_3)(\gamma+\gamma_1)(\beta-\alpha_4)^2} < 0 \tag{2.3}$$



(a) New confirmed case (b) Susceptible case (c) Close contact case

(d) Suspected case (e) Infectious case (f) Recovered case

Figure 3. Comparatione of the prediction and the daily reported cases.

and

$$\frac{\partial R_{02}}{\partial \omega} = \frac{\alpha_1 \beta \alpha_3 + \alpha_2 \alpha_3 (\gamma + \gamma_1)}{(\omega + \alpha_3)^2 (\gamma + \gamma_1)(\beta - \alpha_4)} > 0. \tag{2.4}$$

From equations (2.2), (2.3) and (2.4), we can get the following result:

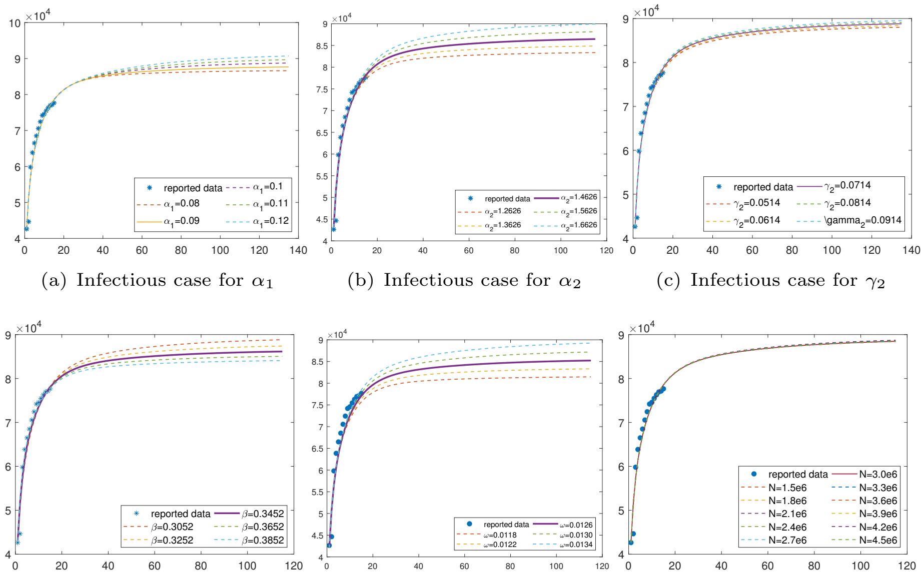
Theorem 2.1. *To control the basic reproduction number to be less than one is to control the parameters $\alpha_1, \alpha_2, \alpha_4, \omega$ or increase the parameters α_3, γ_1 and β.*

Remark 2.1. From the above result, we can see the china government has implemented a series of effective measures, which can be explained as follows:

- People try to make fewer trips and reduce the times of going outside unless it is necessary, which is aimed to decreasing the contact rates α_1 and α_2;
- Early detection and early isolation is to decrease the transition rate of ω, α_4 and β;
- Make-shift hospitals, such as Huoshenshan and Leishenshan, and more medical personnel going to the frontline are to increase the recovery rate of infectious cases γ_1;
- To present yourself to medical observation such as nucleic acid testing (NAT) and serodiagnosis is to increase the transition rate α_3.

That is to see the China government has given effective measures to control the COVID-19. Hence all individuals, families, and communities should follow the advice provided by health institutions and medical institutions. The first thing we can do is to stay at home as far as possible until the end of the epidemic situation.

From the analysis of the above, we can also see that R_0 will change with the change of the parameters. These parameters are extremely important for the transmission of COVID-19. In our model, the contact rates α_1 and α_2, the transition



(a) Infectious case for α_1 (b) Infectious case for α_2 (c) Infectious case for γ_2

(d) Infectious case for β (e) Infectious case for ω (f) Infectious case for N

Figure 4. Sensitivity analyses with respect to parameters.

rates ω_1, β and α_4 are important for the transmission of the virus. These parameters determine when the novel coronavirus will end up. That is, the efficiency of the parameters will affect the accuracy of the perdition. Hence we will give the sensitivity analyses with respect to these parameters, which can be seen in Figure 3. Figure 3 shows that our parameters are stable, and the prediction is efficient. That is, the system will be steady with a small change of the critical parameters. In our model, there is also a critical implicit parameter N. N is the number of people who have activities outside and have the chance to contact with the infectious populations and suspected populations, especially the workforce, community workers, and relatives et al. are included. A small change in N has little effect on the change of the infectious population in stage II; see Figure 4(f) and the following Table 3.

N	2E+06	3E+07	1E+07	5E+07	1E+08	5E+08	1E+09
R_{02}	0.4716	0.4556	0.4352	0.4287	0.4281	0.4272	0.4270

Table 3: The base reproduction number R_0 to the number of the population N in stage II.

However, the number N has a great effect on the basic reproduction number R_0, and then on the number of infectious population in stage I, which can be seen in the following Figure 5. Then quarantine is an effective measure for the transmission of COVID-19.

From Figure 5 and Table 3, it is evident that the total population size, N(t), serves as a pivotal parameter in virtus control. The earlier the control measures are implemented, specifically the commencement of the second stage, the lower the ultimate total number of infected individuals will be, which can be seen in Figure 6 (1). Additionally, the number of cured cases would decrease significantly, as shown

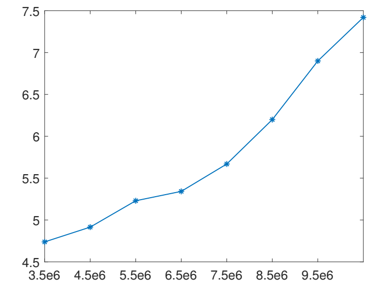


Figure 5. The basic reproduction number R_0 to the number of the population N in stage I.

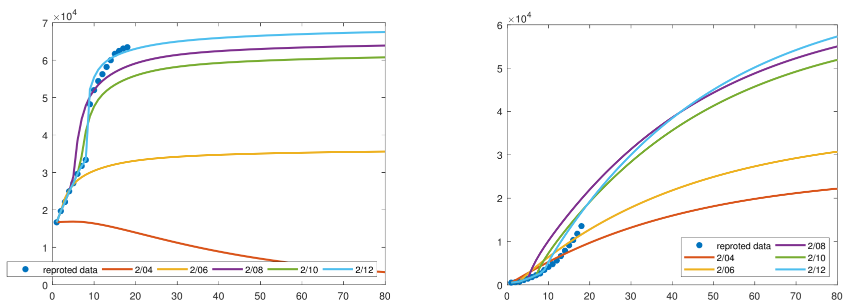


Figure 6. The number of infectious and recovered cases with the different start time of the second stage

in Figure 6 (2). Then the Figure 6 conclusively demonstrates the effectiveness of early control.

3. Conclusion

The quarantine is the best measure to prohibit the transmission of COVID-19. If the close contact population can engage in self-monitored quarantine, and the suspected population can receive treatment in isolation, while the infectious population is early detection and early isolation. Then the contact rates α_1 and α_2 can be controlled to as small as possible, hence the COVID-19 can be controlled on March 20th or so. Before the first-level public health emergency response can be adjusted to a lower-level response, four things must be done:

1. All limited infections must receive treatment in isolation and the new confirmed cases will not appear in the next fourteen days.

2. All close contact population and suspected population must be isolated for 14 days.

3. There must be no imported infectious people from other countries.

4. Figure 6 shows all the policies and measures that the government implemented are effective. If the second stage began from February fourth, the COVID-19 will be completely eradicated in fifty days. On the contrary, if the second stage begins later, all the people will be quarantined at home for more time.

If all the above three things are finished by the end of March, the first-level public health emergency response can be adjusted to the second-level or the thirdlevel response. Then all students can go to school, and all people can go out to work in late April 2020.

If one of the above is not satisfied, people should be isolated as much as possible, and students must study at home. Because all the number of students is more than 200 million. If one is infected, the transition rate will increase quickly, which can be seen in Figure 5. That is, the basic reproduction number R_0 will increase multiply, then the COVID-19 may break out. In order to ensure the safety of all people, the government should make a careful decision before everything is ready.

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