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Research article

Finding travel proportion under COVID-19

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Abstract: Travel restrictions have become an important epidemic preventive measure, but there are few relevant quantitative studies. In this paper, travel proportion is introduced into a four-compartment model to quantify the spread of COVID-19 in Wuhan. It is found that decreasing the travel proportion can reduce the peak of infections and delay the peak time. When the travel proportion is less than 35%, transmission can be prevented. This method provides reference for other places.

Keywords: COVID-19; travel restrictions; travel proportion; epidemic model

1. Introduction

The COVID-19 pandemic raging around the world has severely impacted daily life, work, education and travel [1–5]. Numerous measures are taken in various regions [6–9] (case isolation, travel restrictions, social distancing, closure of public places, etc.) to prevent the spread of the outbreak. Multiple studies [10–14] show that travel restrictions, which fall into two categories, domestic travel restrictions [10–12] and international travel restrictions [13, 14], can be among the most effective and commonly used measures against early outbreak. In the Netherlands [10], simulation results showed domestic travel restrictions could reduce the average number of clinical COVID-19 cases. If no action is taken, there is a significant risk of a large-scale outbreak. By imposing international travel restrictions in Australia [13], COVID-19 imports were reduced by 79%, and the outbreak was delayed by approximately one month. However, research on travel restrictions, whether domestic or international, remains in the period of qualitative description. This paper attempts to quantify the effect of travel restrictions on the spread of COVID-19 in Wuhan. We introduce the travel proportion in an epidemic model to measure the level of travel restrictions. The importance of this concept is that it builds a bridge between travel restrictions and clinical cases. The numbers of clinical cases corresponding to different travel proportions can be obtained by simulations.

In today's global economy, travel restrictions are undoubtedly a fatal blow to economic development [15–19]. If travel restrictions lead to a major economic downturn, the impact may outweigh the pandemic itself [20, 21]. It's crucial to find the appropriate travel proportion that will control the epidemic without causing a serious economic slowdown. When formulating epidemic prevention measures, local governments generally weigh three important indicators: infected persons, medical resources and economic development. The travel proportion provides a valuable reference for the government to formulate policies.

In an epidemic model with incubation period, the incidence rate can be expressed as $f(S, I_a, I_s)$, where S, I_a and I_s respectively represent the susceptible population, the asymptomatic population and the symptomatic population. This study chooses the bilinear incidence rate that is denoted as $f(S, I_a, I_s) = \alpha_a S I_a + \alpha_s S I_s$, where α_a and α_s represent infection rates of asymptomatic and symptomatic patients. In the predator-prey model, if p is the proportion of prey with refuge, the probability of the meeting becomes $1 - p$ of the original [22–25]. Whether predation or infection, they are all encounters that occur in flat space. If the uninfected and infected populations are simultaneously reduced to p of the original, then the probability of the encounter becomes p^2 of the original. The incidence rate with the travel proportion of p can be expressed as $f(S, I_a, I_s) = \alpha_a p^2 S I_a + \alpha_s p^2 S I_s$.

2. Methods

2.1. Modeling

So far, scholars have constructed various models based on the propagation characteristics of COVID-19 [26–30]. This paper divides the population into four parts, susceptible ($S(t)$), asymptomatic infected ($I_a(t)$), symptomatic infected ($I_s(t)$) and recovered ($R(t)$) populations.

Susceptible population ($S(t)$): It is assumed that the input of the population is a constant (Λ), and the natural mortality of the population is μ. Both symptomatic patients and asymptomatic patients have the ability to infect, and the transmission ability of symptomatic patients is stronger than that of asymptomatic patients ($\alpha_a < \alpha_s$). If the allowable travel proportion is p, the incidence rate is $\alpha_a S p I_a p + \alpha_s S p I_s p$. There is no vertical transmission of the disease. The change rate of the susceptible population is

$$\dot{S} = \Lambda - \alpha_a p^2 S I_a - \alpha_s p^2 S I_s - \mu S.$$

Asymptomatic infected population ($I_a(t)$): It is assumed that all infected persons will experience an incubation period, and the infected persons in the incubation period will be transformed into symptomatic patients in a fixed proportion of β. The change rate of the asymptomatic population is

$$\dot{I}_a = \alpha_a p^2 S I_a + \alpha_s p^2 S I_s - \beta I_a - \mu I_a.$$

Symptomatic infected population ($I_s(t)$): The recovery and mortality rates of symptomatic infected patients are δ_1 and $\mu_1 + \mu$. Then, the change rate of the symptomatic population is

$$\dot{I}_s = \beta I_a - \delta_1 I_s - \mu_1 I_s - \mu I_s.$$

Recovered population ($R(t)$): The recovered population comes from the symptomatic population with a proportion of δ_1. Then, we get

$$\dot{R} = \delta_1 I_s - \mu R.$$

Integrating the above four dimensions, we obtain

$$\begin{cases} \dot{S} = \Lambda - \alpha_a p^2 S I_a - \alpha_s p^2 S I_s - \mu S, \\ \dot{I}_a = \alpha_a p^2 S I_a + \alpha_s p^2 S I_s - \beta I_a - \mu I_a, \\ \dot{I}_s = \beta I_a - \delta_1 I_s - \mu_1 I_s - \mu I_s, \\ \dot{R} = \delta_1 I_s - \mu R. \end{cases} \tag{2.1}$$

The next generation matrix method is used to solve for the basic reproductive number [31]. Rewrite system (2.1) to $X = [I_a, I_s, S, R]^T$. The disease-free equilibrium is $x_0 = (0, 0, \frac{\Lambda}{\mu}, 0)$. Then, we get

$$r_i(x) = \begin{bmatrix} \alpha_s p^2 S I_s + \alpha_a p^2 S I_a \\ 0 \\ 0 \\ 0 \end{bmatrix},$$

$$h_i(x) = \begin{bmatrix} \beta I_a + \mu I_a \\ -\beta I_a + \delta_1 I_s + \mu_1 I_s + \mu I_s \\ -\Lambda + \alpha_s p^2 S I_s + \alpha_a p^2 S I_a + \mu S \\ -\delta_1 I_s + \mu R \end{bmatrix},$$

$i = 1, 2, 3, 4$. We calculate the Jacobian matrix of $r(x_i)$ and $h(x_i)$ on disease-free equilibrium

$$F(x_0) = \frac{\partial r(x_i)}{\partial x_j}(x_0) = \begin{bmatrix} \alpha_a p^2 \frac{\Lambda}{\mu} & \alpha_s p^2 \frac{\Lambda}{\mu} & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix},$$

$$V(x_0) = \frac{\partial h(x_i)}{\partial x_j}(x_0) = \begin{bmatrix} \beta + \mu & 0 & 0 & 0 \\ -\beta & \delta_1 + \mu_1 + \mu & 0 & 0 \\ \alpha_a p^2 \frac{\Lambda}{\mu} & \alpha_s p^2 \frac{\Lambda}{\mu} & \mu & 0 \\ 0 & -\delta_1 & 0 & \mu \end{bmatrix},$$

$i, j = 1, 2, 3, 4$. Hence, the basic reproductive number is

$$R_0 = \rho(FV^{-1}) = p^2 \frac{\Lambda}{\mu} \alpha_a \frac{1}{\beta + \mu} + p^2 \frac{\Lambda}{\mu} \alpha_s \frac{\beta}{\beta + \mu} \frac{1}{\delta_1 + \mu_1 + \mu}.$$

$p^2 \frac{\Lambda}{\mu} \alpha_a$ and $p^2 \frac{\Lambda}{\mu} \alpha_s$ can be regarded as the numbers of asymptomatic and symptomatic patients. $\frac{1}{\beta+\mu}$ and $\frac{1}{\delta_1+\mu_1+\mu}$ represent the mean times to removal for asymptomatic and symptomatic patients. $\frac{\beta}{\beta+\mu}$ is the ratio of asymptomatic patients to symptomatic patients.

2.2. Parameters and initial values

According to the data released by the Wuhan Bureau of Statistics, the resident population of Wuhan is 11,081,000, and the natural mortality rate is 1.6×10^{-5} per day [32]. When the incubation period of COVID-19 is 7 days [34], β is 1/7. Tab. 1 shows the values of all parameters for model (2.1). The initial value is $(11081000, 105, 27.6, 2)$ [33].

Table 1. Parameters estimation of model (2.1).

Parameter	Definition	Value (day^{-1})	Source
Λ	Population input	177.3	[32]
α_a	Transmission rate of asymptomatic infection	2.1×10^{-8}	[33]
α_s	Transmission rate of symptomatic infection	1.9×10^{-7}	[33]
β	Transformation rate from asymptomatic infection to symptomatic infection	$1/7$	[34]
μ	Mortality	1.6×10^{-5}	[32]
δ_1	Self healing rate	0.33	[33]
μ_1	Disease-related mortality	0.004	[33]

Table 2. Six indicators changing with travel proportion.

p	R_0	S_∞	R_∞	Peak of I_a	Peak of I_s	Death toll
100%	7.9313	0	10931571	5388809	1983606	149429
80%	5.0760	82213	10866920	4149796	1620546	131867
75%	4.4613	145070	10804322	3759753	1491238	131608
70%	3.8863	256939	10691817	3341702	1342614	129127
65%	3.3510	452921	10488069	2877590	1171388	126806
60%	2.8553	796997	10160953	2371781	978389	123050
55%	2.3992	1360211	9603985	1825794	761952	116804
50%	1.9828	2325476	8650783	1252105	527788	104741
45%	1.6061	3952237	7043474	683415	290356	85289
40%	1.2690	6761179	4268123	200913	85801	51698
35%	0.9716	11076820	4271	105	40	-91

3. Results

Six important indicators are considered, namely, basic reproductive number (R_0), final susceptible population (S_∞), final recovered population (R_∞), peak of asymptomatic infected population, peak of symptomatic infected population and death toll. Tab. 2 shows the values of the six indicators corresponding to their travel proportions. Fig. 1, 2, 3 show the changes of S, I_a, I_s and R with time when the travel proportion ranges from 35% to 100%.

In the absence of travel restrictions, the peak number of symptomatic cases is about 2 million. This number is a quarter of the simulation results in [35]. It can be found that the model developed in [35] contains $Q(t)$, which represents quarantine. There is no doubt that quarantine has a very good effect on reducing the number of infections. In this paper, the peak of infection occurs roughly 30 days later. For [35], that was 40 days, because quarantine has the effect of delaying the time of peak infection [36–39]. As can be seen from the brown curve in Fig. 1, the epidemic lasts for about 60 days. The simulation result in [35] was that the outbreak lasted for about 100 days. Quarantine lengthens the cycle of infection. Tab. 2 shows that although there is a large number of people infected with

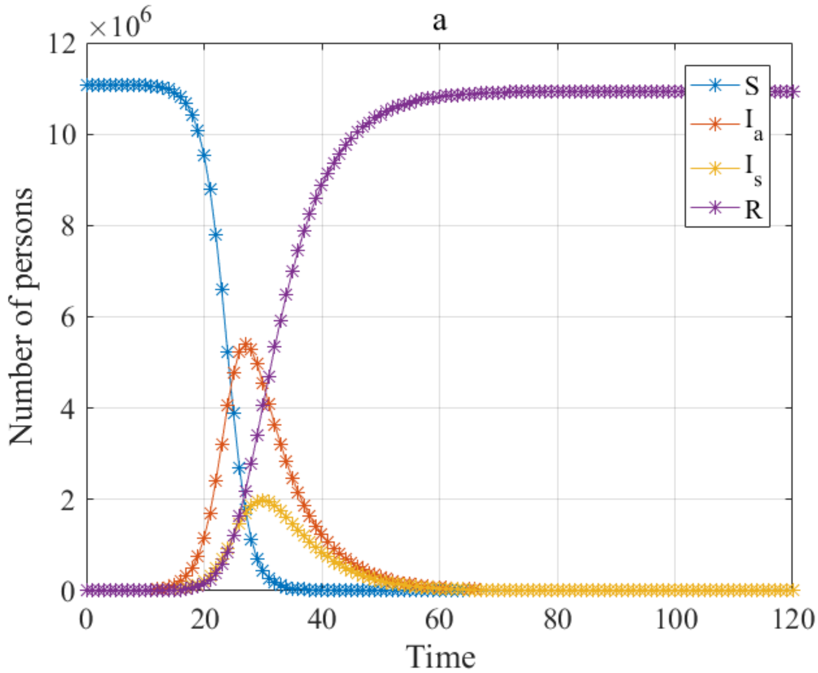

Figure 1. Sequence diagrams of S, I_a, I_s, R. **a** with $p = 100\%$.

COVID-19, the final number of deaths is not very high.

Fig. 2 shows the changes of S, I_a, I_s and R with time when travel proportion drops from 80% to 40%. As the travel proportion decreases, the number of susceptible people rises, which means the number of infections decreases. The infections peak and death toll both decline. Another very interesting finding is that the lower the travel proportion, the later the peak time of infection and the longer the duration of infection. In fact most of the preventive measures such as social distance, quarantine, isolation, etc. have the effect of reducing the peak of infections and delaying the peak time [40–43].

When the travel proportion is reduced from 40% to 35%, the basic reproductive number is reduced to less than 1, and COVID-19 spreads no more widely, which is shown in Fig. 3. Therefore, the key to whether travel restrictions can completely prevent the spread of the epidemic is that the travel proportion exceeds the threshold. It can be seen that the spread is very sensitive to the travel proportion near the threshold.

4. Discussion

How to formulate corresponding policies according to the travel proportion is an issue worth discussing. For example, when the travel proportion is one third, it should be applied to every unit. One third of a town can go out to shop, work and study at the same time. One third of a town's community is allowed to go out at the same time. One third of the people in a building of the community from the town can go out at the same time. Only one person is allowed to go out in a family of three people at the same time.

Severe epidemic prevention measures, such as suspending public transport, closing entertainment places and banning public gatherings, can produce good results in a short time [44, 45]. However,

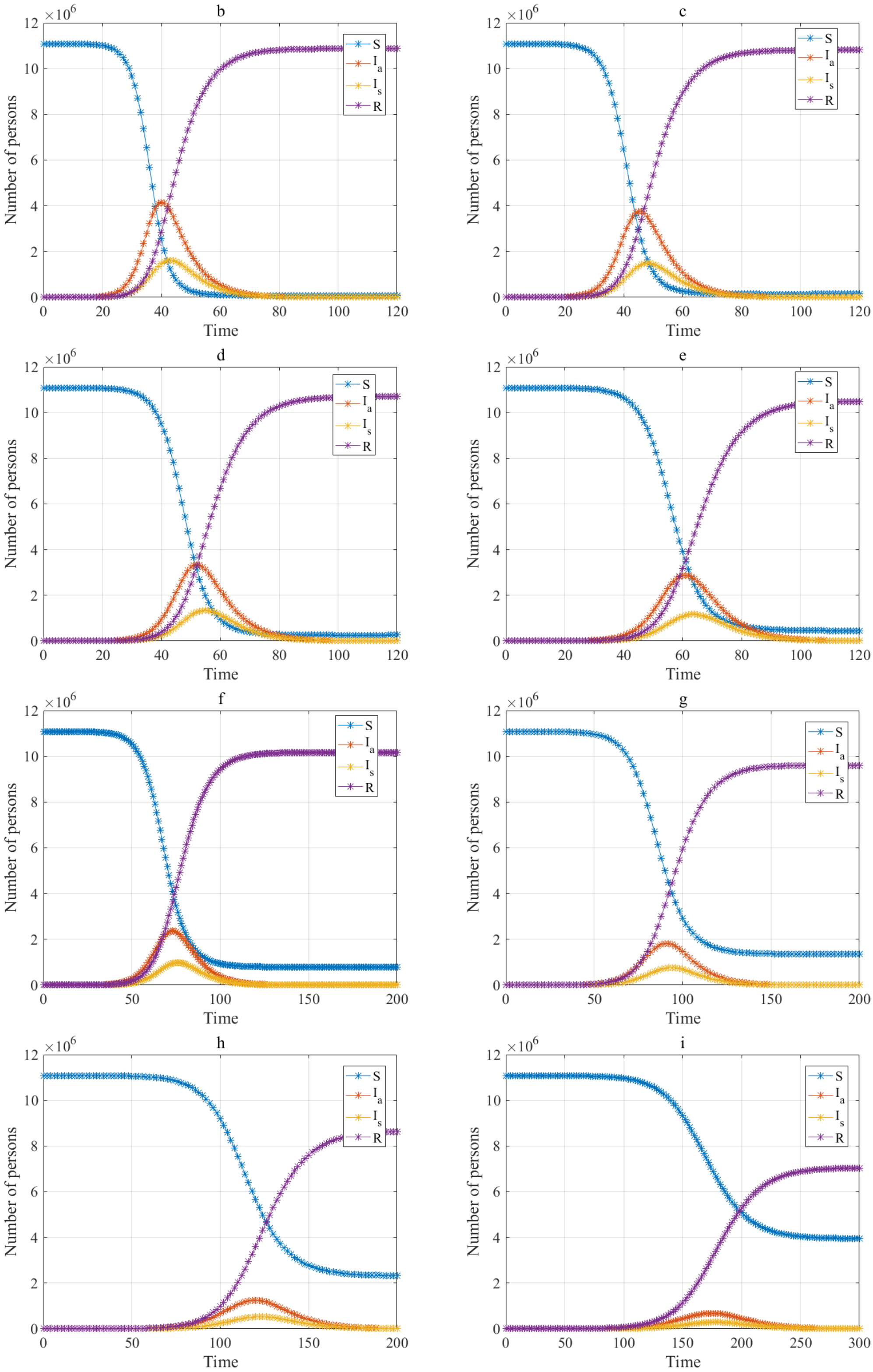

Figure 2. Sequence diagrams of S, I_a, I_s, R. **b** with $p = 80\%$; **c** with $p = 75\%$; **d** with $p = 70\%$; **e** with $p = 65\%$; **f** with $p = 60\%$; **g** with $p = 55\%$; **h** with $p = 50\%$; **i** with $p = 45\%$.

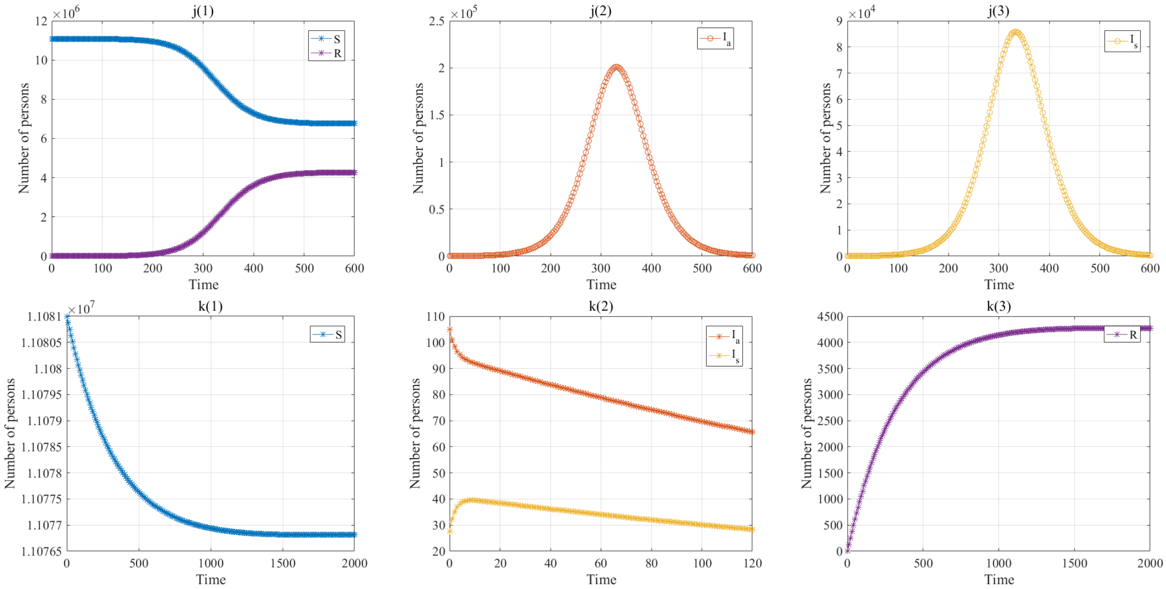

Figure 3. Sequence diagrams of S, I_a, I_s, R. **j(1)**, **j(2)** and **j(3)** with $p = 40\%$; **k(1)**, **k(2)** and **k(3)** with $p = 35\%$.

the long-term travel restrictions will definitely bring serious harm to life, study and work [46–48]. The pandemic even triggered people's travel fear [49]. The use of travel restrictions, quarantines, and other measures to control epidemics has been controversial because these strategies raise political, ethical, and socioeconomic issues [50,51]. Finding a balance between the public interest and individual rights is a very challenging matter. Normally, the cost-effectiveness and the travel restrictions are combined to comprehensively evaluate the effect of epidemic prevention measures [52]. Appropriate travel proportion can not only meet the needs of people's lives, work and tourism, but it also will not cause large-scale infection.

5. Conclusions

Travel proportion is introduced into the epidemic model to quantify the trend of COVID-19 transmission in Wuhan. The basic reproductive number can be obtained by the next generation matrix method. When the travel proportion is less than 35%, COVID-19 will not spread on a large scale. Simulation experiments find that the lower the travel proportion, the smaller the peak infections and the later the peak time. The appropriate travel proportion can maintain the normal operation of society without causing outbreaks.

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Conflict of interest

The authors declare no competing interest.

Author contributions

Yong Zhou: model, software and original draft preparation. **Yiming Ding**: conceptualization, validation, analysis and revision.

Data availability statements

The datasets analyzed during the current study are available from the corresponding author on reasonable request.

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