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Prediction for Spread of COVID-19 in India using SIR Model

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Abstract

The outbreak of the coronavirus (Covid-19) disease has resulted in a worldwide crisis. To control the transmission of the virus, Standard Operating Procedures (SOP) during the pandemic, such as movement control orders, have been implemented. This project aims to study the transmission of the Covid-19 virus in India using the SIR model. The SIR model is used to derive differential equations using Covid-19 data from January 2020. The maximum number of infectious individuals with different contact ratios was also analyzed. As a result, using MATLAB software, it can be concluded that as the reproduction number of Covid-19 transmission (R_0) increases, the wave speed will also increase. To minimize the wave speed, the contact ratio must be controlled. It is also proven that the number of infectious individuals can be reduced by lowering the contact ratio.

Keywords: SIR Model, Differential Equation, Covid-19, Matlab

Introduction

In December 2019, a numerous cases of pneumonia caused by novel coronavirus have been reported in Wuhan city, China and subsequently causing major outbreak worldwide. This virus was identified as SARS-CoV-2 and the disease is referred as Coronavirus disease (COVID-

19). According to World Health Organization (WHO), most people infected by Covid-19 had mild to moderate respiratory illness. However people in high risk categories like elderly and those with chronic medical conditions such as diabetes, cancer, heart disease and chronic respiratory disease are more likely to develop serious illness.
According to current evidence, COVID-19 virus is primarily transmitted through respiratory droplets from coughing or sneezing when person is in close contact (within 2 metres) with symptomatic individuals. In addition, the virus also can be detected in faeces, urine and blood however there have been no reports of faeco-oral transmission of the virus to date. According to a research by Public Health England (2020), this virus also spread in health care setting through medical procedure involving aerosol use. Staying in space with poor indoor ventilation system also increase human to human transmission of Covid-19.
Research done by Public Health England (2020) stated that people infected with Covid-19 may presented with multifarious symptoms in various stages of severity. Some may be assymptomatic. Common symptoms are fever, cough, breathlessness, reduced appetite, loss of smell (anosmia), loss of taste (ageusia) and fatigue. Some of the non-specific symptoms include the sore throat, diarrhoea, myalgia, nasal congestion, fatigue, headache, vomiting and nausea. Research also has shown some statistics of those people that develop the symptoms, whereby 40% experience mild symptoms without pneumonia or hypoxia (lack of oxygen level in blood), 40% with moderate symptoms and mild pneumonia, 15% having significant disease like severe pneumonia and 5% have critical disease with life-threatening problem. The critical disease includes sepsis, heart disease, septic shock, acute respiratory distress syndrome (ARDS) and thromboembolic events, for example multi-organ failure and pulmonary embolism. It is suggested that those who suffered from mild and severe Coronavirus can develop long-term health complications.

Research Problem

According to the World Health Organization (2020), the total reported cases of Covid-19 continue to increase globally. This trend may cause the downfall of healthcare systems due to limitations in facilities such as treatment space, respiratory aids, inadequate manpower, and more. Based on research [15], a deterministic model, the Susceptible-Infectious-Recovered (SIR) model, was used to predict and analyze the maximum number of infected people and the speed of disease transmission. In this study, the differential equation of the SIR mathematical model with the assumption of no migration cases was discussed using the initial value of Covid-19 cases in India. The equation was also derived to calculate the speed of disease spread based on several values of the reproduction number , with 1.55, 1.36, and 1.13. Various initial conditions and parameters were used to run the MATLAB software to produce the SIR model graph. Lastly, the maximum number of infectious people was calculated using the derived equation.

This project will use SIR model equations to analyze Covid-19 cases in India in terms of the spread of the disease, the maximum number of infectious individuals, the size of the disease spread, and the speed of the disease spread in migration scenarios. The derivation of the model will be conducted by assuming that society is migrating and not migrating. The parameter variations applied in the model are the contact ratio and reproduction number. By generating the SIR equations with all of the assumptions and parameter variations, the effects of Covid-19 cases can be analyzed. To lower the number of Covid-19 cases, the value of the contact ratio has been controlled to reduce the number of infectious individuals. The value of has been determined by implementing social distancing and other standard operating procedures with ratios of 50% and 20%.

Method

Construction of SIR Model

SIR model was invented by Kermack and McKendrick in 1927 (Brauer, 2005). It is a foundational model commonly used in disease transmission analysis. Susceptible, Infectious, and Recovered stand for S,I,R are the three elements was consider of this model. The population that is not infected is considered susceptible, and because there is no vaccine for COVID-19, the entire population could spread the infection. When a person in the susceptible group be in close contact to a Covid-19 patient, that person will go into infectious level. Because the disease is transmissible, the number of infected persons grows with time, causing persons in the susceptible stage more likely to be infected and evolve to the infected stage. Person who are no longer infectious are represented by recovered level. SIR model was generated by this equation referred from the journal of systematic approach for COVID-19 predictions and parameter estimation, Srivasta et.al [7] :

$$\frac{dS}{dt}+\frac{dI}{dt}+\frac{dR}{dt}=0 \quad (1)$$

$$\frac{dS}{dt}=-rIS \quad (2)$$

$$\frac{dI}{dt}=rIS-aI \quad (3)$$

$$\frac{dR}{dt}=aI \quad (4)$$

r = Rate of contact between susceptible and infectious

a = Rate of recovery

With the initial conditions given as :

$$S=S_0,\ I=I_0,\ R=0$$

This model is for no migration case in which the generated SIR model followed by these assumptions :

1. The population remains constant.
2. The rate of infection is directly proportional to contacts.
3. A constant rate of infectious persons will recover or die.

Deriving the Equation for the Speed of Disease Spread

In this step, the SIR model is further analysed by considering it with migration condition. As the individuals in the population are travelling and migrating, the number of infected cases will spike and lead to epidemic. According to [7], these are the following presumptions to take into account in the following SIR model :

1. The susceptible population does not move around in space.
2. The infectious population migrates randomly at a constant rate.
3. The recovered population does not move in space.

A migrating population requires a partial derivative analysis as it is a time and space dependent. The SIR equation will be :

$$\frac{\partial S}{\partial t} = -rIS \quad (5)$$

$$\frac{\partial I}{\partial t} = rIS - aI + D\frac{\partial^2 I}{\partial x^2} \quad (6)$$

Where,

D = constant rate of diffusion

x = space in which the individuals are migrating

$$\frac{\partial R}{\partial t} = aI \quad (7)$$

Then, a new variables y is created as this model is a function of time and space

$$y = x - Ct \quad (8)$$

Where,

C = travelling speed

Differentiating the equation (8) with respect to time :

$$\frac{dy}{dt} = -C \quad (9)$$

Dividing the equation (5) and (6) by (9) and rearrange space x to y using the non-dimensionalize analysis, another equation is obtained :

$$0 = C\frac{dS}{dy} - rIS \quad (10)$$

$$0 = \frac{d^2 I}{dy^2} + C\frac{dI}{dy} + I(rS - a) \quad (11)$$

With **r**, rate of susceptible and **a**, rate of recovery, the equation (11) can be modified to :

$r = \frac{1}{S}$ and $a = \frac{1}{R}$

$$0 = \frac{d^2 I}{dy^2} + C\frac{dI}{dy} + I(S - \frac{1}{R_0}) \quad (12)$$

Analysis of COVID-19 using SIR model

The spread of the disease

According to Srivastava et al. (2020), the reproductive ratio is

$$R_0 = r\frac{S_0}{a} \quad (13)$$

Where, R_0 number of secondary infections in population caused by initial primary infection.

In which the contact ratio is shown by

$$\frac{a}{r} = \frac{1}{q} \quad (14)$$

Therefore, q is the contact ratio. If $S_0 > \frac{a}{r}$, thus the disease will spread. The equality of initial susceptible was gained
from the equation below by substituting the given condition in (3),

$$\frac{dI}{dt} = I(rS_0 - a) \tag{15}$$

Where the given conditions are r, I and S must be positive and $S > S_0$ in order for $\frac{ds}{dt}$ to be negative.

Maximum number of infectious individuals and size of the disease spread

The number of infected individuals is important to be determine in order to plan and distribute health resources. The equation of maximum number of infectious is

$$I_{\max} = I_0 + S_0 \tag{16}$$

The equation (19) was gained by dividing (3) and (2) :

$$\frac{dI}{dS} = \frac{rIS - aI}{-rIS} \tag{17}$$

$$\frac{dI}{dS} = -1 + \frac{a}{rS} \tag{18}$$

$$\frac{dI}{dS} = -1 + \frac{a}{qS} \tag{19}$$

After integrating (19) and substitute the initial values,

$$I + S - \frac{1}{q}\ln S = I_0 + S_0 - \frac{1}{q}\ln S_0 \tag{20}$$

From (20), (21) and (22) were achieved,

$$\frac{dI}{dS} = 0 \tag{21}$$

$$S = \frac{1}{q} \tag{22}$$

By putting the above values into (20), then the maximum number of infectious as,

$$I_{\max} = I_0 + S_0 - \frac{1}{q}\left(1 + \ln(qS_0)\right)$$

Next, Substituting $R_0 = qS_0$, and equation (23) and (24) was achieved,

$$I_{\max} = I_0 + S_0 - \frac{1}{q}\left(1 + \ln(R_0)\right) \tag{23}$$

$$I_{\max} = I_0 + S_0 - f(x) \tag{24}$$

Where,

$$f(x) = \frac{1}{q}\left(1 + \ln(R_0)\right) \tag{25}$$

From (25), $f(x)$ is subtracted from the entire population as $f(x)$ is a logarithmic function. When the symptoms might not be observed as the contact ratio, q is very high, $f(x)$ will be very low and maximum number of infectious can be written as shown in (17). The equation for the final value of R is

$$Rend = 2(I_0 + S_0) + \frac{1}{q}\ln Send - S_0 \tag{26}$$

When the number of infected individual become zero, it means that the spread of the disease is stopped. By substituting $I = 0$ into (20), then

$$Rend = I_0 + S_0 - Send \tag{27}$$

$$Send - \frac{1}{q}\ln Send = I_0 + S_0 - \frac{1}{q}\ln S_0 \tag{28}$$

Where $Rend$ and $Send$ are the final value of R and S respectively.

Analysis

Initial Conditions for Sir Model

Based on the first case COVID-19 reported in India on January 30, 2020 there was only a single case on that day and a total population in India was 1.38 billion. Then, according to Srivastava et al. [7],

$$I_0 = 1 \tag{29}$$

$$\begin{aligned} S_0 &= N - I_0 \\ &= 1380000000 - 1 \\ &= 1379999999 \end{aligned} \tag{30}$$

$$R = 0 \tag{31}$$

In the beginning of the COVID-19 cases in India, the R_0 and a are as follow

$$R_0 = 2.28 \tag{32}$$

$$a = \frac{1}{7} \tag{33}$$

The value of r can be determine using the formula (13) and rewrite it as

$$r = \frac{aR_0}{S_0} \tag{34}$$

$$r = 2.3602 \, x \, 10^{-10}$$

Derive Equation of The Speed of Disease Spread

Next, the spatiotemporal spread of the disease will be determined. From equation (5) and (6) the non- dimentionalization method has been used. By rearranging equation (4), and (5), equations below were obtained:

$$\frac{\partial S^* S_0}{\partial \frac{t^*}{rS_0}} = -r\left(I^* S_0\right)\left(S^* S_0\right)$$

On the left hand side, taking out r and S_0 as they are constant,

$$\left(rS_0\right)\left(S_0\right)\frac{\partial S}{\partial t} = -r\left(I^* S_0\right)\left(S^* S_0\right)$$

Dividing both sides with rS_0 and then by dropping the asterisks for notational simplicity, the equation below was obtained

$$\frac{\partial S}{\partial t} = -IS \tag{35}$$

Next, substituting the assumptions into (6), and simplify

$$S_0\left(rS_0\right)\frac{\partial I^*}{\partial t^*} = r\left(I^* S_0\right)\left(S^* S_0\right) - \lambda r S_0\left(I^* S_0\right) + D\frac{\partial^2\left(I^* S_0\right)}{\partial\left(x^*\right)^2}.\left(\frac{rS_0}{D}\right)$$

To make the equation dimensionless, all the terms were divided with the coefficient of the highest order derivative. In this case, the highest order derivative is second derivative with the coefficient of $r\left(S_0\right)^2$ then, dropping the asterisks notation for simplicity

$$\frac{\partial I^*}{\partial t^*} = \left(I^* S^*\right) - \lambda\left(I^*\right) + \frac{\partial^2\left(I^*\right)}{\partial\left(x^*\right)^2}$$

$$\frac{\partial I}{\partial t} = (IS) - \lambda(I) + \frac{\partial^2 I}{\partial x^2}$$

Now, the parameter r, a and D from the dimensional model have been reduced to one dimensionless grouping, λ. According to Murray (2003), $\frac{1}{\lambda}$ can be referred as the number of secondary infections caused by the primary infective in a susceptible population, or can be describe as basic reproduction number, R_0. By changing the λ terms into R_0,

$$\frac{\partial I}{\partial t} = I\left(S - \frac{1}{R_0}\right) + \frac{\partial^2 I}{\partial x^2} \tag{36}$$

Then, to determine the speed of the disease spread in the population, a new variable y has been introduced as (8). Deriving (8) with respect to time while assuming x as a constant,

$$\frac{dy}{dt} = -C(1)$$

Dividing this equation with the equation of $\frac{\partial S}{\partial t}, \frac{\partial I}{\partial t}$. To divide to equation, the partial derivatives have been converted into the full derivatives in terms of single variables y as it is now dimensionless.

$$\frac{dS}{dt}.\frac{dt}{dy} = \frac{IS}{C}$$

$$C\frac{dS}{dy} - IS = 0$$

(37)

And,

$$\frac{dI}{dt}\cdot\frac{dt}{dy} = \left(I\left(S - \frac{1}{R_0}\right) + \frac{\partial^2 I}{\partial x^2}\right)\cdot\left(-\frac{1}{C}\right)$$

$$0 = I\left(S - \frac{1}{R_0}\right) + \frac{d^2 I}{dx^2} + C$$

(38)

To analyse these equations, consider some initial values of t from (8), which are $t = -\infty$ (past) and $t = \infty$ (future), substituting the value into (8),

For $t = -\infty$,

$$y = x - (-\infty)$$
$$y = \infty$$

(39)

As t approaches negative infinity, which is going back to the past, it means the disease does not exist yet so I → 0 and S → 1 which is the full proportion of susceptible.

For $t = -\infty$,

$$y = x - (\infty)$$
$$y = -\infty$$

(40)

As t is approaching infinity, it means the future value, the infection will eventually going to be zero as the disease gone by time.

To further analyse the equation, linearization method is used with the aid of the value of S from the past which is 1, to make an approximation, thus equation as below is obtained

$$S = 1 - P$$

(41)

Where P is a constant with a small value. Differentiate the equation with respect to y

$$\frac{dS}{dy} = -\frac{dP}{dy}$$

(42)

Substitute the value from (41) and (42) into (37) and (38), then equations below are obtained

$$-C\frac{dP}{dy} - I = 0$$

(43)

$$\frac{d^2 I}{dy^2} + C\frac{dI}{dy} + I\left(1 - \frac{1}{R_0}\right) = 0$$

(44)

Using the phase plane analysis on (43) and (44), then, for the travelling waves solution to exist (Crawford, 2020),

$$C \geq 2\sqrt{1 - \frac{1}{R_0}}$$

(45)

Which refers to the minimum possible wave speed for a travelling waves solution to exist for the entire problem. Then, the wave speed (speed of the travelling waves/speed of the spread of the disease as it is
transmitted through the population) is

$$C = 2\sqrt{1 - \frac{1}{R_0}} \tag{46}$$

Then, using three values of R_0 taken from Srivastava et al. [7], the values of C were calculated, which are presented in Table 3.1 below. The higher the Ro value, the greater the spread of the COVID-19 virus.

Table 3.1
Speed of Disease Spread

R_0	C
1.55	1.191366794
1.36	1.028991511
1.13	0.6783634654

Maximum Number of Infectious Individuals
The spread of the disease
By integrating equation (19) directly,

$$\int \frac{dI}{dS} dS = \int \left(-1 + \frac{1}{qS}\right) dS$$

$$I = -S + \frac{1}{q}\ln S$$

$$I + S - \frac{1}{q}\ln S = 0$$

Hence, by substituting initial values of S_0 and I_0, new equation achieved as

$$I_0 + S_0 - \frac{1}{q}\ln S_0 = 0 \tag{47}$$

Maximum number of infectious individuals and size of the disease spread
According to journal Srivastava et al. [7], parameter value given by Table 3.2 .
Table 3.2
List of Parameter Value

Parameter	Description	Constant Value
a	Rate of recovery	1/7
r	Rate of contact between susceptible and infectious	$2.3602e^{-10}$
q	Contact ratio	$1.65214e^{-9}$

Basic reproduction number, $R_0 = qS_0 = 1.65214e^{-9}(1379999999)$

$$I_{max} = N - \frac{1}{q}(1 + \ln R_0)$$

$$I_{\max} = 275871147.1$$

From (28) and (26) :

$Send$ = Number of susceptible left in pandemic

$\mathrm{Re}\,nd$ = Number of people catch the disease

$$Send - \frac{1}{q}\ln Send = -1.158e^{10}$$

$$\mathrm{Re}\,nd = 16843464777$$

The values stated for q and R_0 are taken from Srivastava et al. [7] after calculated, the number of each $I_{\max}$, $Send$ and $\mathrm{Re}\,nd$ are given in the following table 3.3:

Table 3.3

Number of Maximum Infectious Individuals

q	R_0	I_{max}	S_{end}	R_{end}
20%	1.55	1379999993	1379999895	2760000023
50%	1.55	1379999997	1379999958	2760000007
20%	1.36	1379999993	1379999895	2760000023
50%	1.36	1379999997	1379999958	2760000007
20%	1.13	1379999994	1379999895	2760000023
50%	1.13	1379999998	1379999958	2760000007

When the percentage of the contact ratio increases, it is found that the R_0 number also increases. Therefore, we can conclude that to manage and prevent the spread of the COVID-19 epidemic, emphasis must be placed on limiting the contact ratio. Table 3.3 shows the maximum number of infected based on R_0 and contact ratio percentage.

Result

Predicted Spread of Covid-19 in India before Lockdown

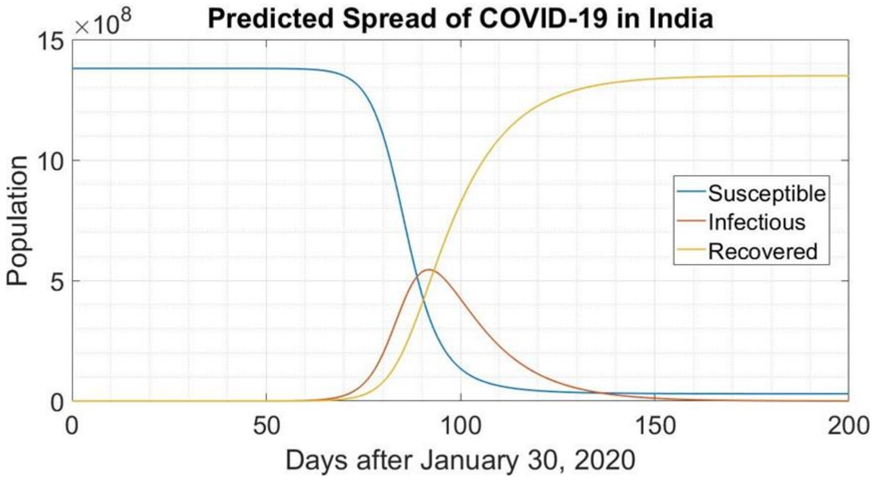

Figure 4.1: SIR Model Prediction for Spread of COVID-19 in India

Figure 4.1 above shows the spread of COVID-19 virus starting from the first case reported in India which is on January 30, 2020. The initial reproduction value, R_0 is 2.28. Initially, the population of susceptible is increasing and on the 70th day, it starts to decrease drastically. After that, it only decreases slightly until the value approaching 0. For recovered population, as days goes by, the population keep increasing until it approaching the total population in India. Infectious population is highest on 92nd day. From this, it clearly shows that the number of infectious group could be very high if there is no action taken to limit the disease spread. It could infect other people in a big scale such as through community transmission that will lead to very serious problem.

From the calculation of the maximum number of infected patients and the percentage of the population size, it is found that the contact ratio size plays an important role in the spread of the COVID-19 epidemic. As we know, if the number $R_0 > 1$, the spread of the COVID-19 virus will increase. When the contact ratio increases, the number of COVID-19 patients will also increase.

Discussion on the Speed of the Disease Spread

From the results obtained in Figure 4.1, it can be concluded that as the R_0 is increasing then the C will also increase. Besides, based on (12) and (13), it can be said that $R_0 = S_0 q$ where S_0 and q are both initial susceptible and contact ratio respectively. The value of S_0 is clearly a fixed number while the value of q is changed by time. Hence, it can be concluded that to minimize the wave speed, the contact ratio must be controlled.

Predicted Number of Infectious Individuals

Table 4.1
Number of Maximum Infectious Individuals

q	R_0	I_{max}	S_{end}	R_{end}
$1.65214e^{10}$	2.28	275871147.1	$-1.1358e^{10}$	16843464770
20%	1.55	1379999993	1379999895	2760000023
50%	1.55	1379999997	1379999958	2760000007
20%	1.36	1379999993	1379999895	2760000023
50%	1.36	1379999997	1379999958	2760000007
20%	1.13	1379999994	1379999895	2760000023
50%	1.13	1379999998	1379999958	2760000007

From the table 4.1 above, generally, in the current outbreak of COVID-19, the initial number of contact ratio produced was very high because the disease is easily transmitted and lots of people coming into contact with the infected people. Hence, the initial values of contact ratio, q and reproduction number, R_0 were **$1.65214e^{10}$** and **2.28** respectively were high. Then, I_{max} and $Rend$ that has been calculated by the given values has been produced such a big number but value of $Send$ was too small. In order to lower the number of infectious individuals, the contact ratio, q need to be minimized. To minimize the contact ratio, strict social distancing has been implemented to the society. From the table, it can be seen clearly that 20% of contact ratio will produce less number of infectious individuals while 50% of contact ratio will produce high number of infectious individuals. Thus, it can be concluded that to reduce the number of infectious individuals, the value of contact ratio, q need to be reduce too.

Conclusion

In this paper, a mathematical model for COVID-19 pandemic is constructed with two assumptions which are no migration and with migration. The SIR model yields three outcomes, which are predicted spread of COVID-19 in India before lockdown, speed of disease for coronavirus and prediction for number of infectious individuals by using the different value of q and R_0. These analysis can lead to an improved utilization of health-care resources.From the result, it can be concluded that R_0 is very important to determine the spreading of the disease. The lower the value of R_0, the lower the spread of virus will be. Furthermore, from the analysis of disease spread, we may conclude that when R_0 increases, so the potential of virus spread high and by controlling the contact ratio will reduce wave speed virus. Next, contact ratio also affecting the maximum number of infectious individuals. If we reduce the contact ratio, the maximum number of infectious individuals will drop as well. So, to limit this COVID-19 from spreading widely, the government need to use a lockdown policy to reduce the contact ratio beside enforcing the strict social distancing rule. With the developed of COVID-19 vaccine in 2021, it is also helping us to lower the number of infected people and the death cases due to the virus. As a consequence, the healthcare system still can cope with the COVID-19's situation even though it may take some time to reach the endemic equilibria, where the spread of the disease will finally stop and the infected population reduced to zero.

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Conflict of Interest Statement
I agree that this research was conducted in the absence of any self-benefits, commercial or financial conflicts and declare the absence of conflicting interests with the funders.

Authors' Contributions
Noor Azreen Rosedee, Nurulain Afiqah Abd Razak, Wan Nur Aisyah wan Roslan : Conceptualisation, methodology, formal analysis, investigation and writing-original draft; Mohd Rahimie Md Noor, Mohd Azry Abd Malek: Conceptualisation, methodology, and formal analysis; Mohd Zainurri, Amri: Conceptualisation, formal analysis, and validation; Mohd Rahimie, Sharifah Athirah Syed Adnan: Conceptualisation, supervision, writing- review and editing.

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