STUDY OF THE EBOLA VIRUS CONTROL

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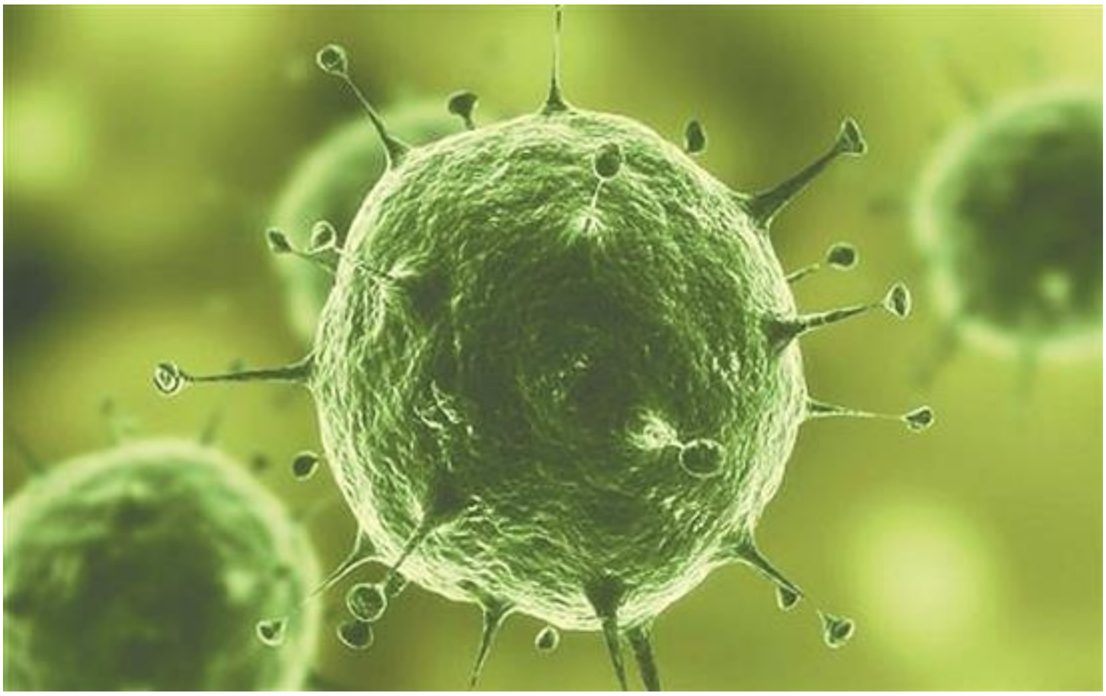

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In this paper, we established two different mathematic models in order to know the spread law of Ebola virus disease and forecast the climactic moment and give corresponding preventive and control measures. Meanwhile, an efficient delivery system has been found to minimize the transportation cost and time cost.

Firstly, we establish a mathematic model named S-I model to analyze the infection spread of Ebola virus disease in the crowd without considering the mortality of the death rate of infected people. We can come to a conclusion that when the daily contact rate increase, the maximum of percentage of people infected will become larger and the time approaching the peak of the max infected rate will become shorter.

Secondly, we establish a new model named S-I-D model by taking the dead people into account. We get the same result in S-I model with higher accuracy.

Thirdly, by the comparison between numerical results of S-I model and S-I-D model, we find that S-I-D model is more suitable for simulating the reality.

Finally, optimization of delivery system is carried out between thirty affected areas by K-means clustering method. As a consequence, we meet the target that control the spreading of Ebola virus disease in a short time with the least cost.

In a few words, based on our strong theoretical knowledge and appropriate assumption, we obtain the conclusion about the spread law of Ebola virus disease and an efficiency delivery system to minimize the cost. By combining our S-I-D model and K-means clustering method with more statistics will maximize the accuracy of our work.

I am very glad that you can read my research report. If there is any shortage in my report, I hope you can make some valuable suggestions for improvement!

Sincerely,

Kailin Tang

Kailin Tang

Contents

I. Introduction

Ebola virus disease (Ebola hemorrhagic fever) is a disease of humans and other primates caused by Ebola virus disease. Signs and symptoms typically start between two days and three weeks after contracting the virus with a fever, sore throat, muscle pain, and headaches. Then, vomiting, diarrhea and rash usually follow, along with decreased function of the liver and kidneys. At this time some people begin to bleed both internally and externally. The disease has a high risk of death, killing between 25 and 90 percent of those infected with an average of about 50 percent. This is often due to low blood pressure from fluid loss, and typically follows six to sixteen days after symptoms appear.

However, the existing data shows that the virus can spread in a short period of time. We can learn from the data that there are 602 people infected in Sudan, among which 431 people are dead. Since Ebola virus disease broke out in West Africa in August, Ebola virus disease has killed a large number of people and makes a lot of people become infected, which has aroused growing panic around the world.

Therefore, in order to know the spread law of Ebola virus disease, this paper has established two mathematical models in view of the present data of Ebola virus disease. There are a few problems need to be solved.

1. Try to collect the present data of Ebola virus disease and establish a mathematical model describing the spread law of Ebola virus disease. Moreover, try to forecast the climactic moments and give corresponding preventive and control measures.

2. Analyze the robustness and the sensitivity of model mentioned earlier.

3. Determine a possible feasible delivery systems to control the spread of Ebola virus disease with the least amount of days.

4. Provide the government and related departments meaningful and preventive measures according to the conclusion from problem 1 to problem 3.

II. The Description of the Problem

2.1 How do we establish the mathematical model?

Before the release of drugs and vaccine, Ebola virus disease cannot be cured. Therefore, we establish two different mathematical models based on the present data of Ebola virus disease.

First of all, we divide people of certain area into two parts, which is infected people and uninfected people who is likely to be infected. At the same time, we analyze the infection spread of Ebola virus disease in the crowd. We establish a based mathematic model without considering the mortality of the death rate, which is called S-I model. S is the initial of susceptible while I is the initial of infected. We use the Matlab to solve differential equations, and finally we get the law of the amount of infected people and the percentage of infected people with spreading time. And at the same time, the curve of daily average growth is acquired.

Then, we establish a new mathematical model by modifying the simple S-I model. The new model mainly aimed at the shortage of the simple S-I model that it does not take dead people into account. When a patient dies, the dead patients are unable to contact with other people, which we should pay more attention to. Therefore, the new model can better reflect the real infection spread of Ebola virus disease. By analyzing the modified model, we can also get the law of the amount of infected people and the percentage of infected people with spreading time, and the curve of daily average growth can also be obtained.

2.2 How do we evaluate the model mentioned earlier?

We collect the present data of Ebola virus disease and establish a mathematical model describing the spread law of Ebola virus disease. Meanwhile, in order to evaluate the robustness and the sensitivity of model mentioned earlier, we analyze the model by changing different parameters. By comparing the numerical results of different models with the actual data, we can know the error of our mathematical models, which is with great guiding significance.

2.3 How to determine a possible feasible delivery system?

Based on the modified model, we use K-means clustering method to determine the distribution plan according to the quantity demand of emergency medical supplies of every regions. Our target is to minimize the transport cost and to minimize the amount of delivery process at the same time.

2.4 What is the significance of this paper?

We can get a lot of conclusions after analyzing problem 1 to problem3, according to which we can provide the government and related departments meaningful and preventive measures. Therefore, people can firm their confidence to stop the spread of Ebola virus disease, and the phenomenon that growing panic around the world will not happen again.

III. Models

3.1 Assumptions

- We divide people of certain areas into two parts, which are infected people and uninfected people who are likely to be infected;
- The effective probability of each infections contact people is called daily contact rate, the uninfected people will be infected after an effective contact;
- After death of an Ebola infected patient, he will no longer participate in the transmission system;
- Do not take natural birth rate and natural death rate into account;
- Affected areas are isolated from each other without population mobility when an epidemic strikes, which is to say the amount of population in a certain region keeps a constant value;
- The locations of the distribution centers are previously known;
- There are enough vehicles to deliver the vaccine without loss;

3.2 Terms, Definitions and Symbols

- N is the total number of population;
- S is the number of susceptible people who are likely to be infected;
- I is the number of infected people;
- D is the number of infected people who are dead;
- t is time;
- λ is daily contact rate;
- μ is the death rate of infected people;

3.3 Basic S-I Model

Before the release of drugs and vaccine, Ebola virus disease can be not cured. When only consider spread process without considering the number of dead patient, as the time increases Δt, the number of increasing patient has the following relationship:

$$N \cdot [i(t+\Delta t) - i(t)] = [\lambda \cdot s(t)] \cdot N \cdot i(t) \cdot \Delta t \tag{3-1}$$

$$\frac{i(t+\Delta t) - i(t)}{\Delta t} = [\lambda \cdot s(t)] \cdot i(t) \tag{3-2}$$

It is assumed that the transmission is continuous and differentiable. The above differential equation (3-2) can change into equation as shown below:

$$\frac{di}{dt} = \lambda \cdot s(t) \cdot i(t) \tag{3-3}$$

Where,

s(t) is the percentage of susceptible people who are likely to be infected;

i(t) is the percentage of infected people;

λ is the daily contact rate;

The summation of percentage of susceptible people and the percentage of infected people keeps a constant value:

$$s(t) + i(t) = 1 \tag{3-4}$$

Putting equation (3-4) into equation (3-3), we can get the final expression of S-I model as shown below:

$$\frac{di}{dt} = \lambda \cdot (1 - i(t)) \cdot i(t) \tag{3-5}$$

3.4 Modified S-I-D Model

Basic S-I model does not take dead people into account. So in allusion to this disadvantage, we establish a new mathematic model based on basic S-I model by considering the dead people. That is to say, after death of an Ebola infected patient, he will no longer participate in the transmission system.

As the time increases Δt, the number of increasing infected people and decrease of susceptible people has the following relationship:

- Increasing number of infected people:

$$N \cdot [i(t+\Delta t) - i(t)] = [\lambda \cdot s(t)] \cdot N \cdot i(t) \cdot \Delta t - \mu \cdot N \cdot i(t) \cdot \Delta t \tag{3-6}$$

$$\frac{i(t+\Delta t) - i(t)}{\Delta t} = [\lambda \cdot s(t)] \cdot i(t) - \mu \cdot i(t) \tag{3-7}$$

It is assumed that the transmission is continuous and differentiable. The above differential equation (3-7) can change into equation as shown below:

$$\frac{di}{dt} = \lambda \cdot s(t) \cdot i(t) - \mu \cdot i(t) \tag{3-8}$$

- Decreasing number of susceptible people:

$$N \cdot [s(t+\Delta t) - s(t)] = [-\lambda \cdot N \cdot s(t) \cdot i(t) \cdot \Delta t \tag{3-9}$$

$$\frac{s(t+\Delta t) - s(t)}{\Delta t} = -\lambda \cdot s(t) \cdot i(t) \tag{3-10}$$

It is assumed that the transmission is continuous and differentiable. The above differential equation (3-10) can change into equation as shown below:

$$\frac{ds}{dt} = -\lambda \cdot s(t) \cdot i(t) \tag{3-11}$$

Synthesizes the final differential expression of increasing number of infected people and decreasing number of susceptible people, we can get the final expression of S-I –D model as shown below:

$$\begin{aligned} &\frac{di}{dt} = \lambda \cdot s(t) \cdot i(t) - \mu \cdot i(t) \\ &\frac{ds}{dt} = -\lambda \cdot s(t) \cdot i(t) \\ &s(t) + i(t) + d(t) = 1 \end{aligned} \tag{3-12}$$

Where,

s(t) is the percentage of susceptible people who are likely to be infected;

i(t) is the percentage of infected people;

d(t) is the percentage of infected people who are dead;

λ is the daily contact rate;

μ is the death rate of infected people;

3.5 Solution of basic S-I model

We use Matlab to solve differential equations of S-I model. The result of are obtained as below:

$$i(t) = \frac{1}{1+(\frac{1}{i_0}-1)\cdot e^{-\lambda t}} \tag{3-13}$$

By taking the derivative of the equation (3-13) and getting the maximum of it, we can get the time cost to reach the point of biggest growth rate as the following form:

$$t_{\max} = \frac{1}{\lambda}\ln(\frac{1}{i_0}-1) \tag{3-14}$$

Due to the value of effective contact every day is not determined. Therefore, we set up qualitative analysis of the S-I model.

We simulate the spread of Ebola virus disease in two months. The range of daily contact rate is [0.2, 1.2], the initial percentage of infected people $i_0 = 0.0178$. Solving the S-I model, we can get the percentage of infected people $i(t)$ and daily rate of change of percentage of infected people di/dt as shown below:

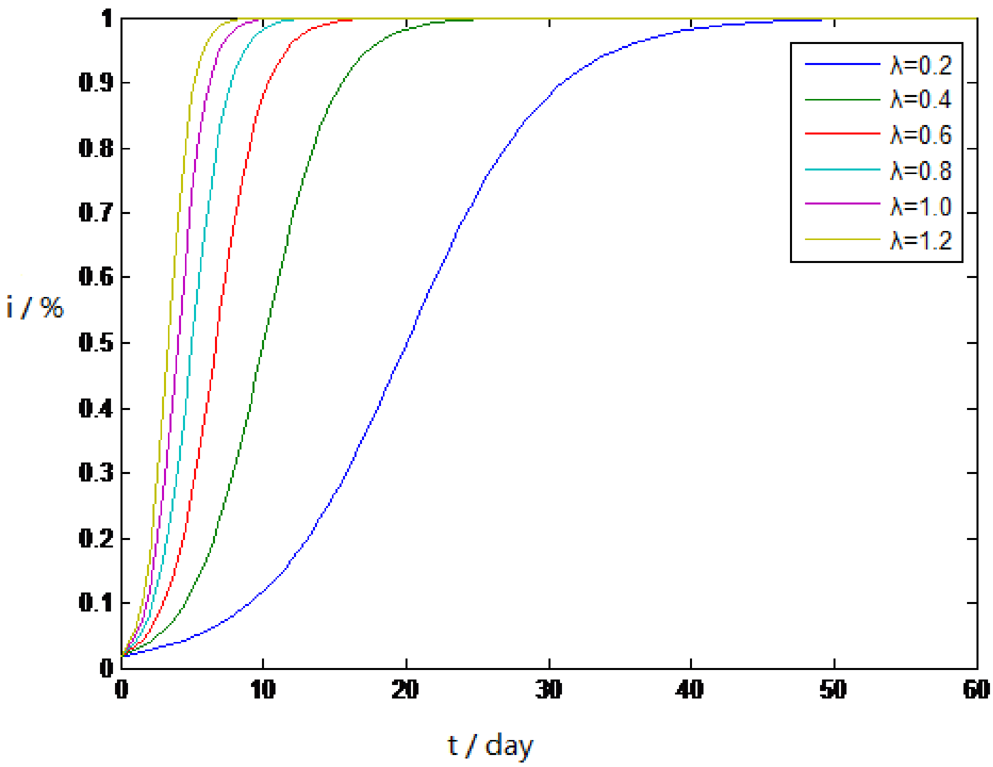


Figure 6.1 Daily change of *i* corresponding to different daily contact rate

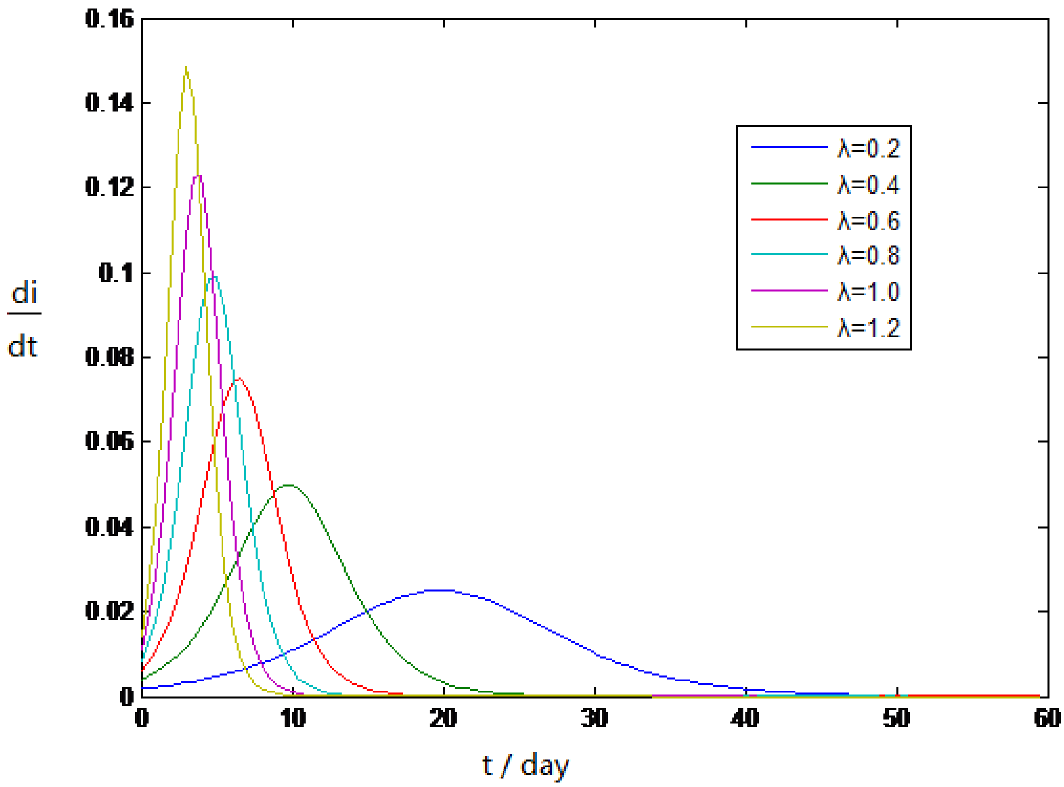


Figure 6.2 Percentage of infected people corresponding to different daily contact rate

We can draw conclusion from results above:

- The results of figure 6.1 indicate that the spreading speed of Ebola virus disease increased when the daily contact rate increase. What's more, most people will be infected in a short time;
- As we can see from figure 6.2, when the daily contact rate increase, the maximum of percentage of people infected will become larger and the time approaching the peak will become shorter. The maximum of percentage of people infected corresponding with different daily contact rate is shown in table 6.1;

Table 6.1 Results corresponding to different daily contact rate

Daily contact rate λ	0.2	0.4	0.6	0.8	1.0	1.2
t_{max} / day	20	10	6.5	5	4	3
Maximum of i / %	0.025	0.049	0.074	0.098	0.122	0.148

Therefore, in view of the spread law of Ebola virus disease, we should make sure the daily contact rate is small enough to reduce the percentage of infected people. That is to say, the infected people should be isolated so that they will be unable to effectively contact with susceptible people. It can make the maximum growth of percentage of infected people delay as possible, and the smaller the percentage of the infected people will be.

3.6 Solution of S-I-D model

The S-I-D model contains two differential equations of percentage of infected people and percentage of susceptible people. Therefore, we should carry on the numerical solution respectively. The relationship in Matlab is shown as below:

$$\frac{di}{dt} = \lambda \cdot s(t) \cdot i(t) - \mu \cdot i(t) \rightarrow y(1) = [\mathrm{a} * \mathrm{x}(2) * \mathrm{x}(1) \text{ - } \mathrm{b} * \mathrm{x}(1)] \tag{3-15}$$

$$\frac{ds}{dt} = -\lambda \cdot s(t) \cdot i(t) \rightarrow y(2) = [\text{-}\mathrm{a} * \mathrm{x}(2) * \mathrm{x}(1)] \tag{3-16}$$

Where,

x(1) is the percentage of infected people;

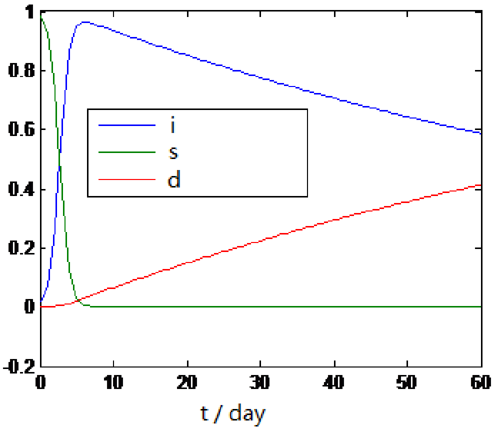
x(2) is the percentage of susceptible people;

a is the daily contact rate;

b is the daily death rate of infected people;

Due to the value of effective contact every day and daily death rate is not determined. Therefore, we set up qualitative analysis of the S-I-D model.

We simulate the spread of Ebola virus disease in two months. The range of daily contact is determined as 0.5, 1.0 and 1.5, the initial percentage of infected people $i_0 = 0.0178$, and the daily death rate μ =0.0093. Solving the S-I-D model, we can get the percentage of infected people $i(t)$ and daily rate of change of percentage of infected people di/dt as shown below:



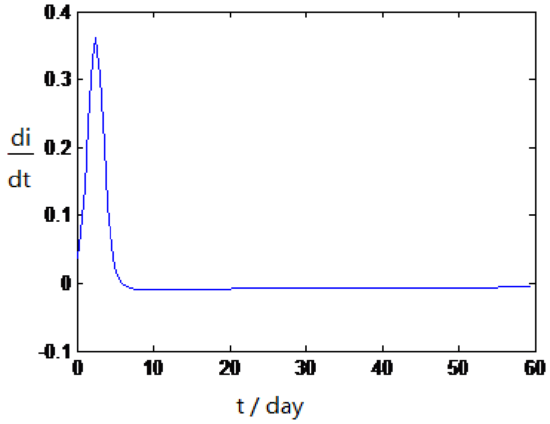


Figure 6.3 Curve of spreading when λ =1.5

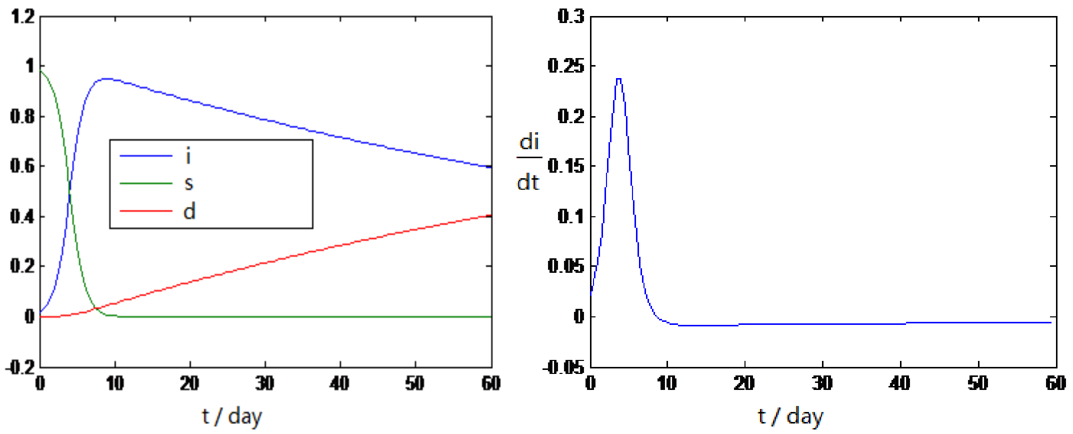


Figure 6.4 Curve of spreading when λ =1.0

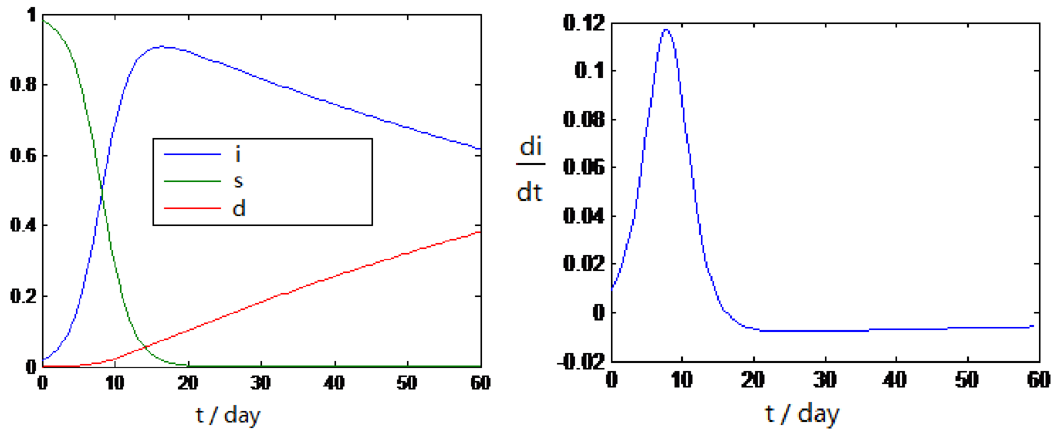


Figure 6.5 Curve of spreading when λ =0.5

We can draw conclusions from the results above:

- The results of figure 6.1, figure 6.2 and figure 6.3 indicate that the spreading speed of Ebola virus disease increased when the daily contact rate increase. What's more, most people will be infected in a short time;
- As we can see from figure 6.1, figure 6.2 and figure 6.3, when the daily contact rate increase, the maximum of percentage of people infected will become larger and the time approaching the peak will become shorter. The maximum of percentage of people infected corresponding with different daily contact rate is shown in table 6.2:

Table 6.2 Results corresponding to different daily contact rate

Daily contact rate λ	0.5	1.0	1.5

t_{max} / day	8	4	2.5
Maximum of i / %	0.1168	0.2375	0.3617

3.7 Validation of Basic S-I Model

Firstly, we use basic S-I model to simulate the spread of Ebola virus disease. Following is the data of Ebola virus disease within a period of time by official statics.

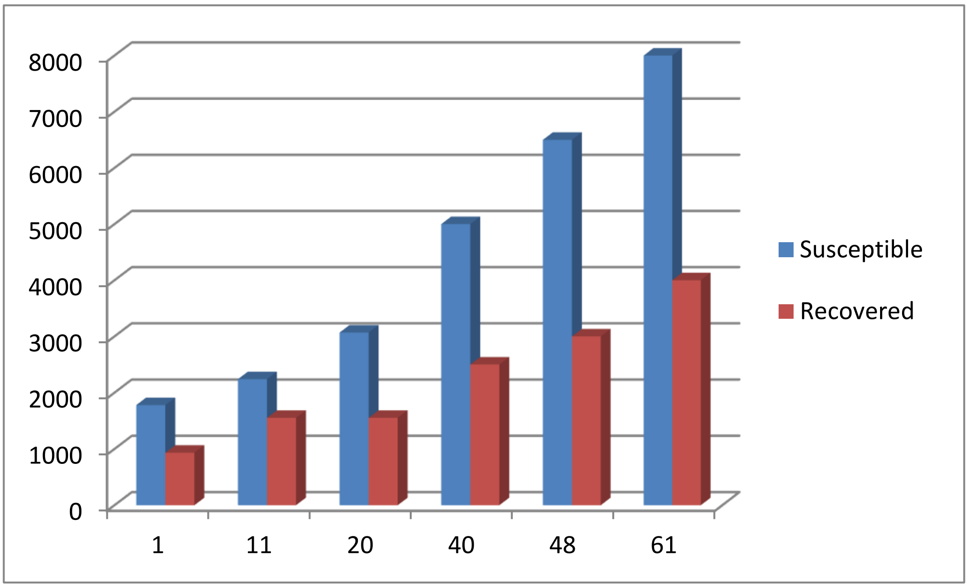


Figure 7.1 Real data of Ebola virus disease

In the simulation of Ebola virus disease, we set parameters of model as following:

The daily contact rate λ=0.026;

The initial percentage of infected people $i_0 = 0.0178$;

The summation of population N=100000.

Result of simulation is shown as following:

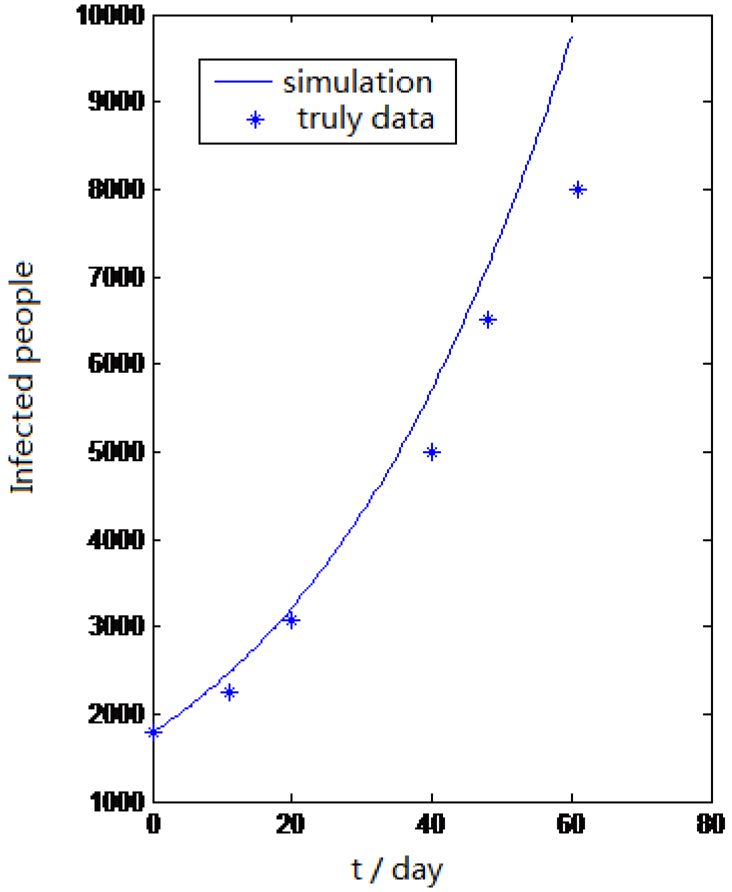


Figure 7.2 Numerical results of S-I model and real data

After the comparison of numerical results and actual statistical data, we can draw a conclusion that the basic S-I model is quite accurate with small error. The basic S-I model has a good stability.

3.8 Validation of S-I-D Model

Then, we use S-I-D model to simulate the spread of Ebola virus disease. In the simulation of Ebola virus disease, we set parameters of model as following:

The daily contact rate λ=0.04;

The initial percentage of infected people $i_0 = 0.0178$;

The daily death rate μ=0.0093;

The summation of population N=100000.

Result of simulation is shown as following:

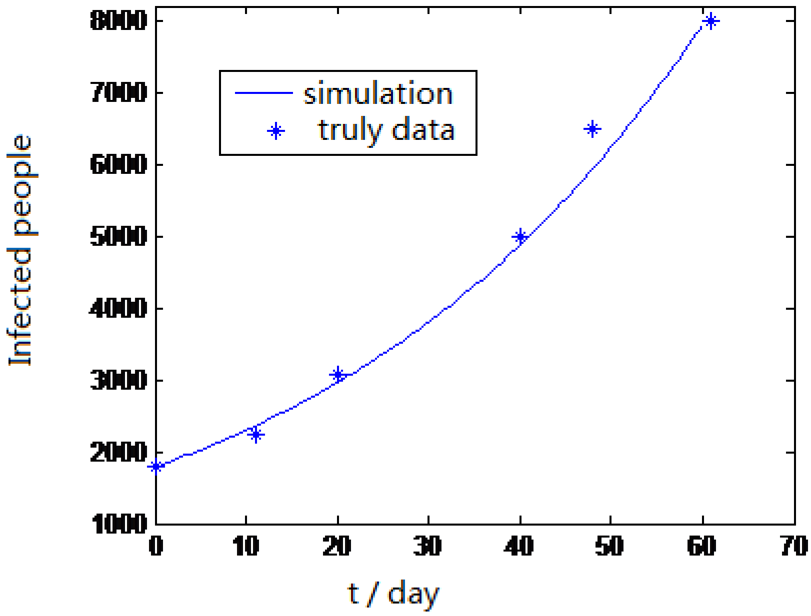


Figure 7.3 Numerical results of S-I-D model and real data

After the comparison between results of S-I model and S-I-D model, we can draw a conclusion that the basic S-I-D model is more accurate with smaller error. The S-I-D model is more suitable for simulating the reality.

3.9 Delivery systems

Based on the modified model, we use K-means clustering method to determine the distribution plan according to the quantity demand of emergency medical supplies of every regions. Our target is to minimize the transport cost and to minimize the amount of delivery process at the same time. Therein, $F_j^{1k}(t)$ and $F_j^{2k}(t)$ are given by

$$\min F_j^{1k}(t) = \sum_{\forall k}\sum_{\forall j}\sum_{i=1}^{n}(c_{ij}x_{ij}^{k}(t) + \beta_j \max\{0, t_{ij} - T^k\}) \qquad (3\text{-}17)$$

$$\min F_j^{2k}(t) = \sum_{\forall k}\sum_{\forall j} DM_j^k(t) - \sum_{\forall k}\sum_{\forall j}\sum_{i=1}^{n} x_{ij}(t) \qquad (3\text{-}18)$$

$$\forall(k, j); t = k\tau$$

Where,

c_{ij} is the unit transportation cost from distribution center i to affected area j;

t_{ij} is the time needed from distribution center i to affected area j;

T^k is the time threshold(Penalty should be given if exceeding T);

β_{j} is the penalty coefficient (the cost is increased if punished);

DM_j^k is the amount of demand vaccine distributed to the affected area;

$x_{ij}{}^k(t)$ is the decision variable denoting planned amount from distribution center I to affected area j.

Considering different priorities and effects of the two objectives mentioned above, the weight is introduced to integrate the two objective functions into a composite optimization problem. The composite objective function $F_j{}^k(t)$ is given by:

$$\min F_j{}^k(t) = \mu_1 \left\| F_j{}^{1k}(t) \right\| + \mu_2 \left\| F_j{}^{2k}(t) \right\| \tag{3-19}$$

$$\forall (k, j); t = k\tau; \quad \mu_1 + \mu_2 = 1 \tag{3-20}$$

Where,

$\left\| F_j{}^{1k}(t) \right\|$ and $\left\| F_j{}^{2k}(t) \right\|$ are normalized objectives.

In order to simulate the truly delivery system, there list the initial conditions of 30 affected areas:

Table 8.1 Initial data of the affected areas

Affected area	Total population	Susceptible people	Infected people
1	1442	1327	115
2	867	834	33
3	1686	1550	136
4	1796	1615	181
5	1107	1041	65
6	2119	1976	143
7	2138	1976	163
8	1505	1485	20
9	1659	1631	28
10	1698	1570	129
11	1505	1425	80
12	1925	1790	134
13	1406	1265	141
14	2509	2373	136
15	1610	1455	165
16	1679	1546	133
17	2086	1927	160

18	1564	1524	40
19	1561	1462	99
20	1259	1157	72
21	2535	1425	88
22	2925	2792	137
23	1408	1264	146
24	2505	2178	236
25	1515	1255	145
26	1681	1346	154
27	2112	1708	154
28	1624	1527	38
29	1333	1211	80
30	1247	1121	61

Table 8.2 Initial parameters

Variables			
μ_1	μ_2	β_j	T^k
0.5	0.5	10	3

Table 8.3 Cost and time

Affected area	Cost				Time			
	a	b	c	d	a	b	c	d
1	3	4	7	8	3	2	5	4
2	4	5	6	8	2	1	4	6
3	7	6	6	8	5	4	4	6
4	5	4	6	9	2	2	4	7
5	6	7	5	7	4	5	4	5
6	4	5	4	5	2	1	3	1
7	4	5	4	5	2	2	3	1
8	3	4	7	5	1	1	1	2
9	5	3	8	4	3	1	3	5

10	3	5	3	2	1	3	2	2
11	4	8	4	5	2	6	2	1
12	4	5	6	4	1	3	2	2
13	5	8	6	3	3	6	4	2
14	9	5	6	7	7	3	4	5
15	4	5	7	6	2	2	4	4
16	5	6	6	8	5	5	4	6
17	4	4	4	4	3	3	3	1
18	6	6	6	8	5	4	5	6
19	5	7	5	4	2	5	3	3
20	5	3	8	4	3	2	3	4
21	4	8	5	5	2	6	2	2
22	4	5	4	4	1	3	2	4
23	5	7	6	3	4	6	4	2
24	9	5	6	5	7	5	4	5
25	4	3	7	6	2	4	4	4
26	5	6	6	8	4	5	4	6
27	4	2	4	4	3	3	4	3
28	6	8	6	8	5	4	3	6
29	5	7	5	4	2	5	1	3
30	5	5	8	4	3	2	3	2

We use K-means clustering method to determine the distribution plan according to the quantity demand of emergency medical supplies of every regions.

The results are shown as following:

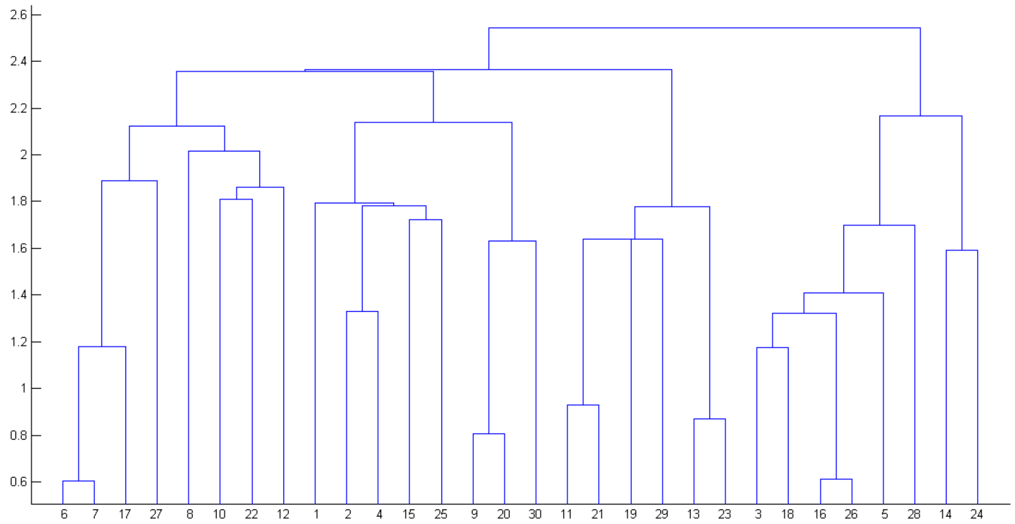


Figure 8.1 Clustering tree

Table 8.4 Results of clustering the affected areas

Group	Number of affected area
1	6,7,8,10,12,17,22,27
2	1,2,4,9,15,25,30
3	11,13,19,21,23,29
4	3,5,14,16,18,24,26,28

Thirty affected areas are divided into four groups according to different emergency degree. The first group is the most urgent, and other groups take following place in order. When delivering emergency medical supplies, the areas with high priority are basically satisfied, and the unsatisfied area are mostly included in the low priority group. As a consequence, we can draw the conclusion that the proposed approach meets the objective to effectively control the affected areas with a relatively high degree of urgency when the amount of medicine is deficient.

IV. Conclusions

4.1 Conclusions of the problem

- By analyzing the S-I model and S-I-D model, we find that the spreading speed of Ebola virus disease increased when the daily contact rate increase. What's more, most people will be infected in a short time;
- When the daily contact rate increase, the maximum of percentage of people infected will become larger and the time approaching the peak will become shorter;
- In view of results by analyzing the two different models, we should make sure the daily contact rate is small enough to reduce the percentage of infected people. That is to say, the infected people should be isolated so that they will be unable to effectively contact with susceptible people;
- The S-I-D model is more suitable for simulating the reality when compared with S-I model;
- By applying of K-means clustering method, thirty affected areas are divided into four groups according to different emergency degree. When delivering emergency medical supplies, the area with high priority are basically satisfied. As a consequence, we will approach meets the objective to effectively control the affected areas.

4.2 Methods used in our models

- Ode45 in Matlab: an efficient way to solve differential equations;
- K-means clustering method: writing our own program in Matlab.

4.3 Applications of our models

- Establish a mathematical model to describing the spread law of Ebola virus disease, forecast the climactic moments and give corresponding preventive and control measures;
- Provide the government an efficient delivery system to minimize the transportation cost and time cost by applying K-means clustering method.

V. Future Work

- Firstly, models in this paper do not take the undetermined incubation period into account. If possible, try to establish a new mathematical model to simulate the actual situation;
- Secondly, population migration should be considered, we can try to add a random quantity in all areas of the model to simulate the truly situation;
- Finally, time of the Ebola virus simulation is so long that the influence of natural birth and death rate should not be ignored. Therefore, we should take that two parameters into account in the future work.

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VII. Appendix

A Letter for Announcement

Every distinguished, dear media:

Good afternoon, ladies and gentlemen. First of all, I want to appreciate for your attention to the world medical association.

Today is a milestone for the whole world people fighting against Ebola virus disease! What I want to announce today is an important news that we have developed a kind of medicine, which can control the Ebola virus disease. Meanwhile, it can also cure patients who is not advanced.

We have established an efficient mathematic model to predict the spread of Ebola virus disease after a lot of calculations. The calculation results indicate that Ebola virus disease can be stopped as long as the patients are isolated effectively and immediately.

Fortunately, we have studied the distribution plan of emergency medical supplies among thirty affected areas, and finally find an optimal delivery system to minimize the transportation cost and time cost. This model have been tested and verified by the top medical researchers of the world.

What we have to do next is establishing the worldwide emergency team composed of all the countries in the world. We will contact with every countries' Ebola medical association to guarantee our medicine deliver efficiently and effectively. Now, every countries, especially the countries which have high risk to erupt Ebola have been arranged enough medical staffs and guards to maintain the medical influence and social stability.

There is another good news, UN have joined the campaign to develop the efficiency and protect the medicine used rationally. The generous organization also provides a large amount of capital to the poor African countries which suffered a lot from Ebola virus disease. Another organization, Red Cross has cooperated with some local medical researches and hospitals to provide safe team and place to guarantee the measure that isolating the infected people immediately and improving productivity to ensure the supply of drugs.

One last words, the spread of Ebola virus disease will be stopped in limited time with the worldwide people effort.

Thanks for your attention and support!

Thank you all!