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Infectious Disease Simulation

Introduction

In this experiment, several programs were written in C++ that simulated the spread of disease through a population; different variables were altered and their effects on the spread of a disease within a population were entertained. Key variables that were studied were transmission rate or chance of infection on encounter and the percentage of inoculated individuals in the population. The simulation showed that, expectedly, lower transmission rates resulted in fewer people becoming sick, but also that higher inoculation rates lowered the percentage of those susceptible to disease that got infected.

Procedure

Several different main functions were created, but two fundamental different classes were created for the simulation. First, a class called "Person" was written that simulated an individual person in a population. It contained methods that returned the person's health status, returned whether or not a person had recovered from infection, infected the person, and updated the person's health status. The major data member in the class was the integer status of the individual, which represented one of several possibilities: infected, susceptible, recovered or inoculated.

The Person class was then used as an object in a larger "Population" class that contained a larger number of Person objects stored in a vector. The class evolved over the course of the experiment and not all members and methods in the class were used for every main function. The main data members specified in the class were:

- The number of days a person would be infected for
- The number of people a sick individual of the population would encounter
- The population size
- The probability of transmission
- The number of simulated days elapsed
- The number of inoculated individuals
- The number of individuals infected

The population class contained most of the methods that carried out the simulation. The class contained methods that were not used in every main and some that were only used under certain circumstances. They were:

- A constructor which took an input of the population size and created a variable that was the number of individuals in the population and created a vector of Person objects
- get_mem which, given an integer input of the location of an individual printed the individual's status to the screen
- set_transfer_prob which set the probability of transferring a disease upon contact with another person
- set_innoculate took an input of the probability that an individual would be inoculated and randomly inoculated members of the population
- get_data printed to the screen the number of days elapsed and the percentage of non-inoculated individuals who had been infected at some point in the simulation.
- random_infection infected a random individual in the population
- count_infected counted the number of individuals sick on any given day
- pop_status printed to the screen a visual representation of the status of the population on each day, where
    - + sick - the individual could infect others
    - - recovered - the individual has recovered from sickness and can no longer become infected
    - O susceptible - the individual can become infected
    - I inoculated - the individual has been vaccinated
- transmission simulated the disease spreading throughout a population where all sick people encountered a set number of people per day and each encounter had a chance to spread the disease to the encountered individual
- neigh_transmission was used to simulate spreading the disease only to the individual next to a sick individual. On a given day, the disease had a chance to spread to each sick person's neighbor
- update set the next day, counted the infected on a given day, updated the objects, would run the transmission method, and given a true boolean, would run pop_status
- update_neigh did the same as update, but ran neigh_transmission and always ran pop_status
- run_sim took an integer input from 0 to 4 and ran a set of different simulations corresponding to the integer
    - 0 - no transmission
    - 1 - transmission only to neighbor
    - 2 - transmission only to neighbors with inoculation

- 3 - spreading throughout the population where the infected encounter a random number of people per day
- 4 - spreading throughout the population with a very large population size

The semi-redundant methods within the population class were written so that only the two class files had to be edited and so that they could be used with any different main function. Each class was saved in its own file and compiled into object files and linked to the main programs that required them. The compiler g++ was used for most of the troubleshooting and testing using the IDE, sublime, though any C++ compiler should work.

Results and Analysis

For the case where only an individual becoming sick was simulated, the results were rather trivial. After a random number of days, the individual became sick and then recovered. Below is a sample output of the simulation, where Joe is the name of a random individual.

On day 1, Joe is susceptible
On day 2, Joe is susceptible
On day 3, Joe is susceptible
On day 4, Joe is susceptible
On day 5, Joe is susceptible
On day 6, Joe is susceptible
On day 7, Joe is susceptible
On day 8, Joe is susceptible
On day 9, Joe is susceptible
On day 10, Joe is susceptible
On day 11, Joe is susceptible
On day 12, Joe is susceptible
On day 13, Joe is susceptible
On day 14, Joe is susceptible
On day 15, Joe is sick
On day 16, Joe is sick
On day 17, Joe is sick
On day 18, Joe is sick
On day 19, Joe is sick
On day 20, Joe is recovered

As is seen from the sample output, the person is sick for the specified number of days and then recovers

A similarly trivial outcome resulted from simulated more than one individual where no transmission was used to spread the disease to the rest of the population. After an individual was infected, the simulation began and then ended once the sick person recovered. Below is a sample output of the simulation

```
On day   1 # sick:   1 :  + O O O O O O O O O
On day   2 # sick:   1 :  + O O O O O O O O O
On day   3 # sick:   1 :  + O O O O O O O O O
On day   4 # sick:   1 :  + O O O O O O O O O
On day   5 # sick:   1 :  + O O O O O O O O O
On day   6 # sick:   0 :  - O O O O O O O O O
```

Simulation (1)

As is seen, a person in the first position became infected, and recovered. Since no spreading was simulated, the simulation ended after that individual recovered.

The simulation became more interesting when spreading of the disease was introduced. At first only spreading to neighbors was introduced and depending on the transmission probability, the disease could spread rapidly or end abruptly. Below are two sample outputs for a 20% transmission probability.

```
On day   1 # sick:   1 :  O O O O O O O O O O O O O O +
On day   2 # sick:   1 :  O O O O O O O O O O O O O O +
On day   3 # sick:   1 :  O O O O O O O O O O O O O O +
On day   4 # sick:   1 :  O O O O O O O O O O O O O O +
On day   5 # sick:   1 :  O O O O O O O O O O O O O O +
On day   6 # sick:   0 :  O O O O O O O O O O O O O O -
```

Simulation (2)

```
On day   1 # sick:   1 :  O O O O O O O O O O O O O O +
On day   2 # sick:   2 :  O O O O O O O O O O O O O + +
On day   3 # sick:   3 :  O O O O O O O O O O O O + + +
On day   4 # sick:   3 :  O O O O O O O O O O O O + + +
On day   5 # sick:   3 :  O O O O O O O O O O O O + + +
On day   6 # sick:   3 :  O O O O O O O O O O O + + + -
On day   7 # sick:   2 :  O O O O O O O O O O O + + - -
On day   8 # sick:   1 :  O O O O O O O O O O O + - - -
On day   9 # sick:   1 :  O O O O O O O O O O O + - - -
On day  10 # sick:   1 :  O O O O O O O O O O O + - - -
On day  11 # sick:   0 :  O O O O O O O O O O O - - - -
```

Sample (3)

When transmission probability is low, the simulation stops with few people having become infected and simulation time is generally low. If transmission probability is increased, more people become infected and the simulation time increases as a result. Below, this is explained by the results of a simulation with 40% transmission probability.

```
On day   1 # sick:   1 :  O O O O O O O O + O O O O O O
On day   2 # sick:   3 :  O O O O O O O + + + O O O O O
On day   3 # sick:   4 :  O O O O O O O + + + + O O O O
On day   4 # sick:   4 :  O O O O O O O + + + + O O O O
On day   5 # sick:   6 :  O O O O O O + + + + + + O O O
On day   6 # sick:   6 :  O O O O O + + + - + + + O O O
On day   7 # sick:   4 :  O O O O O + + - - - + + O O O
On day   8 # sick:   4 :  O O O O O + + - - - - + + O O
On day   9 # sick:   5 :  O O O O + + + - - - - + + O O
On day  10 # sick:   4 :  O O O O + + - - - - - - + + O
On day  11 # sick:   4 :  O O O + + - - - - - - - + + O
On day  12 # sick:   4 :  O O O + + - - - - - - - + + O
On day  13 # sick:   3 :  O O O + + - - - - - - - - + O
On day  14 # sick:   2 :  O O O + - - - - - - - - - + O
On day  15 # sick:   2 :  O O + + - - - - - - - - - - O
On day  16 # sick:   1 :  O O + - - - - - - - - - - - O
On day  17 # sick:   1 :  O O + - - - - - - - - - - - O
On day  18 # sick:   1 :  O O + - - - - - - - - - - - O
On day  19 # sick:   1 :  O O + - - - - - - - - - - - O
On day  20 # sick:   0 :  O O - - - - - - - - - - - - O
```

Simulation (4)

As can be seen in this simulation, the duration is longer and fewer people remain susceptible. The bounds of this simulation become apparent when the transmission percentage is increased. If the transmission probability is increased to a large number, say 90%, then intuitively, the simulation should run very quickly with most or everyone having been infected; this is not the case for this simulation, however since the spread of disease is limited to only one or two people per day. The next two simulation results explain further:

On day 1 # sick: 1 : O O O O O O O O O O O O O + O
On day 2 # sick: 3 : O O O O O O O O O O O O + + +
On day 3 # sick: 4 : O O O O O O O O O O O + + + +
On day 4 # sick: 5 : O O O O O O O O O O + + + + +
On day 5 # sick: 6 : O O O O O O O O O + + + + + +
On day 6 # sick: 6 : O O O O O O O O + + + + + - +
On day 7 # sick: 5 : O O O O O O O + + + + + - - -
On day 8 # sick: 5 : O O O O O O + + + + + - - - -
On day 9 # sick: 5 : O O O O O + + + + + - - - - -
On day 10 # sick: 5 : O O O O + + + + + - - - - - -
On day 11 # sick: 5 : O O O + + + + + - - - - - - -
On day 12 # sick: 5 : O O + + + + + - - - - - - - -
On day 13 # sick: 5 : O + + + + + - - - - - - - - -
On day 14 # sick: 5 : + + + + + - - - - - - - - - -
On day 15 # sick: 4 : + + + + - - - - - - - - - - -
On day 16 # sick: 3 : + + + - - - - - - - - - - - -
On day 17 # sick: 2 : + + - - - - - - - - - - - - -
On day 18 # sick: 1 : + - - - - - - - - - - - - - -
On day 19 # sick: 0 : - - - - - - - - - - - - - - -

Simulation (5)

Simulation 1 lasts only 1 day less than the previous 40% transmission probability simulation. The transmission should have spread much faster with such an infectious disease; this simulation does show, however, that location can be a factor in the spread of disease. If one lives far away from an infectious outbreak, they may have ample time to evacuate if such a, infection is threatening enough. Contrast Simulation (6), which shows that when an infection begins in the center of a population, it can potentially spread much faster. The infection had infected everyone 4 days before than in Simulation (5)

```
On day  1 # sick:  1 :  O O O O O O + O O O O O O O O
On day  2 # sick:  3 :  O O O O O + + + O O O O O O O
On day  3 # sick:  5 :  O O O O + + + + + O O O O O O
On day  4 # sick:  7 :  O O O + + + + + + + O O O O O
On day  5 # sick:  9 :  O O + + + + + + + + + O O O O
On day  6 # sick:  9 :  O + + + + + - + + + + O O O O
On day  7 # sick:  9 :  + + + + + - - - + + + + O O O
On day  8 # sick:  8 :  + + + + - - - - - + + + + O O
On day  9 # sick:  7 :  + + + - - - - - - - + + + + O
On day 10 # sick:  6 :  + + - - - - - - - - - + + + +
On day 11 # sick:  5 :  + - - - - - - - - - - + + + +
On day 12 # sick:  3 :  - - - - - - - - - - - - + + +
On day 13 # sick:  2 :  - - - - - - - - - - - - - + +
On day 14 # sick:  1 :  - - - - - - - - - - - - - - +
On day 15 # sick:  0 :  - - - - - - - - - - - - - - -
```

Simulation (6)

The spread of disease is also affected by the number of people immune or inoculated from the disease. The next step in the simulation was to account for people in the infection becoming inoculated from the disease. Below in Simulation (7), the results of a simulation where transmission probability is 40% and inoculation percentage is 20% illustrate the effects.

On day 1 # sick: 1 : O O O O O O O + O O O I O I O O O O O O

On day 2 # sick: 1 : O O O O O O O + O O O I O I O O O O O O

On day 3 # sick: 3 : O O O O O O + + + O O I O I O O O O O O

On day 4 # sick: 4 : O O O O O O + + + + O I O I O O O O O O

On day 5 # sick: 6 : O O O O O + + + + + + I O I O O O O O O

On day 6 # sick: 5 : O O O O O + + - + + + I O I O O O O O O

On day 7 # sick: 6 : O O O O + + + - + + + I O I O O O O O O

On day 8 # sick: 5 : O O O + + + - - - + + I O I O O O O O O

On day 9 # sick: 4 : O O O + + + - - - - + I O I O O O O O O

On day 10 # sick: 2 : O O O + + - - - - - - I O I O O O O O O

On day 11 # sick: 3 : O O + + + - - - - - - I O I O O O O O O

On day 12 # sick: 2 : O O + + - - - - - - - I O I O O O O O O

On day 13 # sick: 2 : O + + - - - - - - - - I O I O O O O O O

On day 14 # sick: 3 : + + + - - - - - - - - I O I O O O O O O

On day 15 # sick: 3 : + + + - - - - - - - - I O I O O O O O O

On day 16 # sick: 2 : + + - - - - - - - - - I O I O O O O O O

On day 17 # sick: 2 : + + - - - - - - - - - I O I O O O O O O

On day 18 # sick: 1 : + - - - - - - - - - - I O I O O O O O O

On day 19 # sick: 0 : - - - - - - - - - - - I O I O O O O O O

Simulation 7

The simulation illustrates that inoculating the public can have an effect on the spread of disease, but the results are unrealistic. While this may be applied to large areas where a disease may not be able to get through an immune populace to get to a more susceptible group, in a small population, diseases don't stop because one infected person stands in the way, especially if such a disease is airborne or waterborne where it infects groups at a time; for the purpose of this simulation it is unrealistic because infected individuals interact with more than one or two people per day.

The next simulation addresses the concern that people encounter more than one person per day. The number of encounters per day was set to 5. This allowed for highly infectious diseases to spread much faster than only moderately infectious diseases, as is seen in Simulation (8) below.

On day 1 # sick: 1 : O O O O O O O + O O O O O O O O O O O O
On day 2 # sick: 12 : + + O + + + + + O O + + + + O O O O + O
On day 3 # sick: 18 : + + + + + + + + + + + + + + + + + O + + O
On day 4 # sick: 19 : + + + + + + + + + + + + + + + + + O + + +
On day 5 # sick: 20 : +
On day 6 # sick: 19 : + + + + + + + - + + + + + + + + + + + + +
On day 7 # sick: 8 : - - + - - - - - + + - - - - + + + + + - +
On day 8 # sick: 2 : - - - - - - - - - - - - - - - - - + - - +
On day 9 # sick: 1 : - - - - - - - - - - - - - - - - - + - - -
On day 10 # sick: 0 : -

Simulation 8

With just a 50% transmission probability, the disease was able to infect all people within just 5 days, before anyone had even recovered. It also showed that, with a low enough percentage of people inoculated, the disease can still spread to everyone. Simulation (9) shows the results of a simulation where the transmission probability is 30% and the percentage of inoculated people are also only 30%

On day 1 # sick: 1 : I O O I O I I O I O + O O O O O O O O I
On day 2 # sick: 1 : I O O I O I I O I O + O O O O O O O O I
On day 3 # sick: 1 : I O O I O I I O I O + O O O O O O O O I
On day 4 # sick: 4 : I O O I O I I O I O + + O O + + O O O I
On day 5 # sick: 7 : I + O I + I I O I + + + O O + + O O O I
On day 6 # sick: 8 : I + O I + I I O I + - + O + + + O + O I
On day 7 # sick: 10 : I + O I + I I O I + - + + + + + + + O I
On day 8 # sick: 12 : I + + I + I I + I + - + + + + + + + O I
On day 9 # sick: 10 : I + + I + I I + I + - - + + - - + + + I
On day 10 # sick: 7 : I - + I - I I + I - - - + + - - + + + I
On day 11 # sick: 5 : I - + I - I I + I - - - + - - - + - + I
On day 12 # sick: 3 : I - + I - I I + I - - - - - - - - - + I
On day 13 # sick: 1 : I - - I - I I - I - - - - - - - - - + I
On day 14 # sick: 0 : I - - I - I I - I - - - - - - - - - - I

Simulation (9)

Even with a sizable number of people inoculated, everyone not inoculated ended up having gotten the sickness. However, when the inoculation percentage increases, herd immunity starts to become evident. With the same infection probability rate, but 70% inoculation rate, the disease is halted at only one person as shown in Simulation (10)

On day	1 # sick:	1 : I O I I I I I I I O I I + I I I I I I I
On day	2 # sick:	1 : I O I I I I I I I O I I + I I I I I I I
On day	3 # sick:	1 : I O I I I I I I I O I I + I I I I I I I
On day	4 # sick:	1 : I O I I I I I I I O I I + I I I I I I I
On day	5 # sick:	1 : I O I I I I I I I O I I + I I I I I I I
On day	6 # sick:	0 : I O I I I I I I I O I I - I I I I I I I

Simulation (10)

The two people not inoculated in the population are protected from the infectious individual by the large number of inoculated members. They cannot become carriers themselves of the disease and so drastically decrease the possibility that other susceptible people become infected. This hypothesis becomes more evident as a simulation is run with more people. The following data are results from simulations with 30000 people.

Figure (1) shows the results of the simulation being run with the transmission percentage held at 20%, found by averaging the percent of non-inoculated infected for 5 runs each for 0, 25, 50, 60, 70, 80 and 90% inoculation percentage.

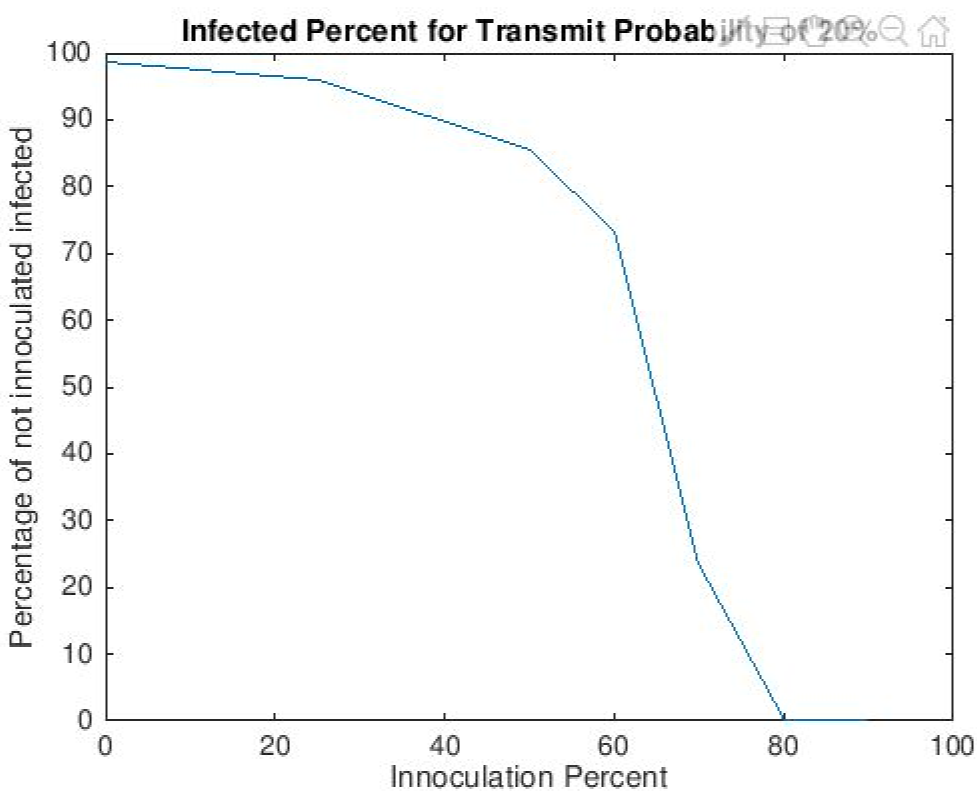

Figure 1

As can be seen in the figure, the infection rate drops sharply at around 50% inoculation rate and approaches zero as the inoculation percent approaches 80 percent. A higher order plot with more data points would yield a smoother plot, but given the population size in the simulation, the results should be fairly accurate. The simulated number of days also is shown in Figure (2).

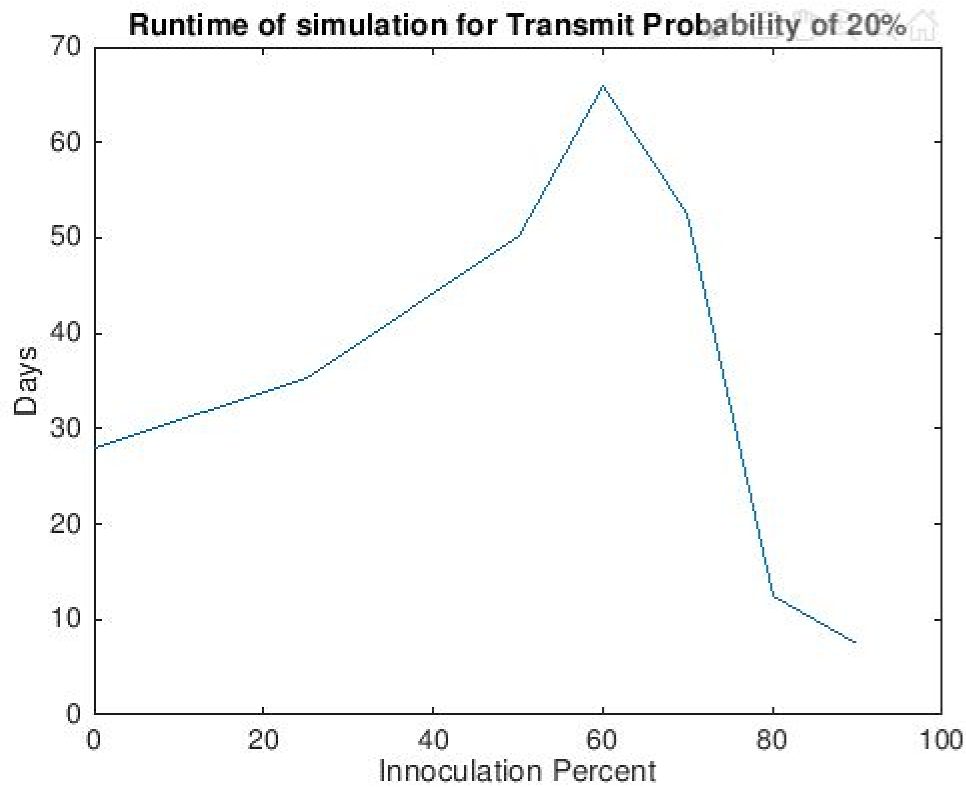

Figure 2

As can be seen, the duration that an infection lasts through a population peaks as the inoculation percentage approaches 60%, signaling that the more people are inoculated, the longer the infection takes to spread until enough people are vaccinated that the infection can barely spread at all.

Next, inoculation rate was held constant at 60% while transmissibility of the infection was varied. Transmissibility was varied to 10, 15, 20, 25, 30 and 40% upon encounter with an infected person. The results are shown in Figures 3 and 4.

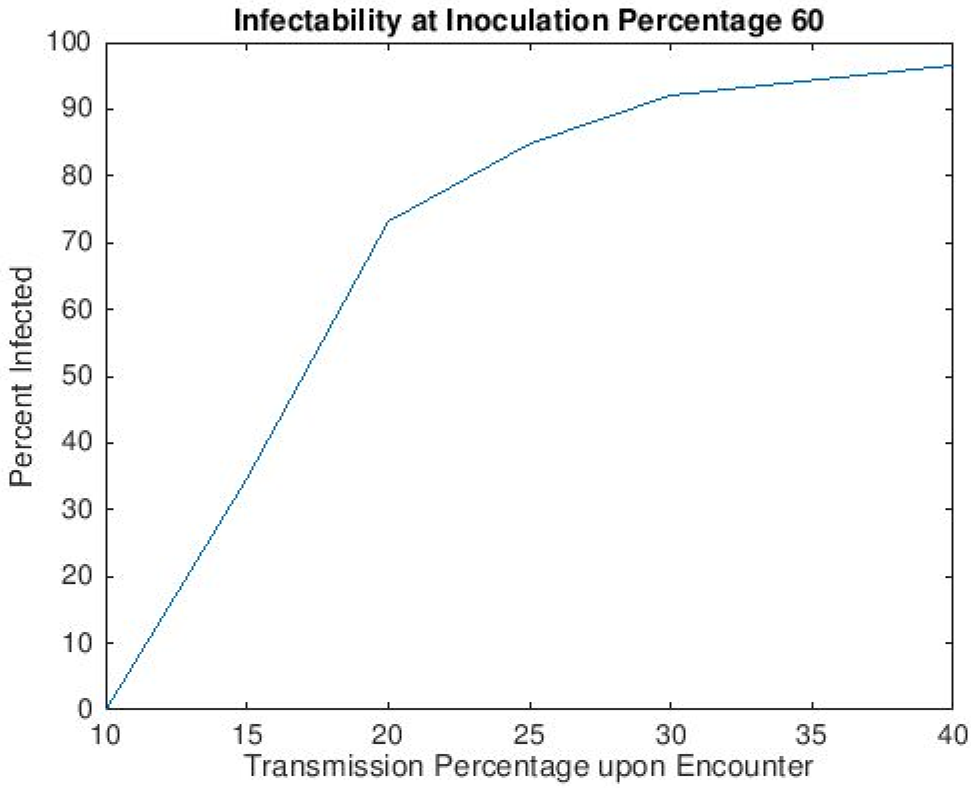

Figure 3

Figure (3) shows that the percent of people not vaccinated who become infected increases on a logarithmic scale, plateauing at around 35% transmissibility. When varying inoculated percentage of a population, duration of time that the infection spends in a population peaks somewhere in the middle as shown in Figure (4).

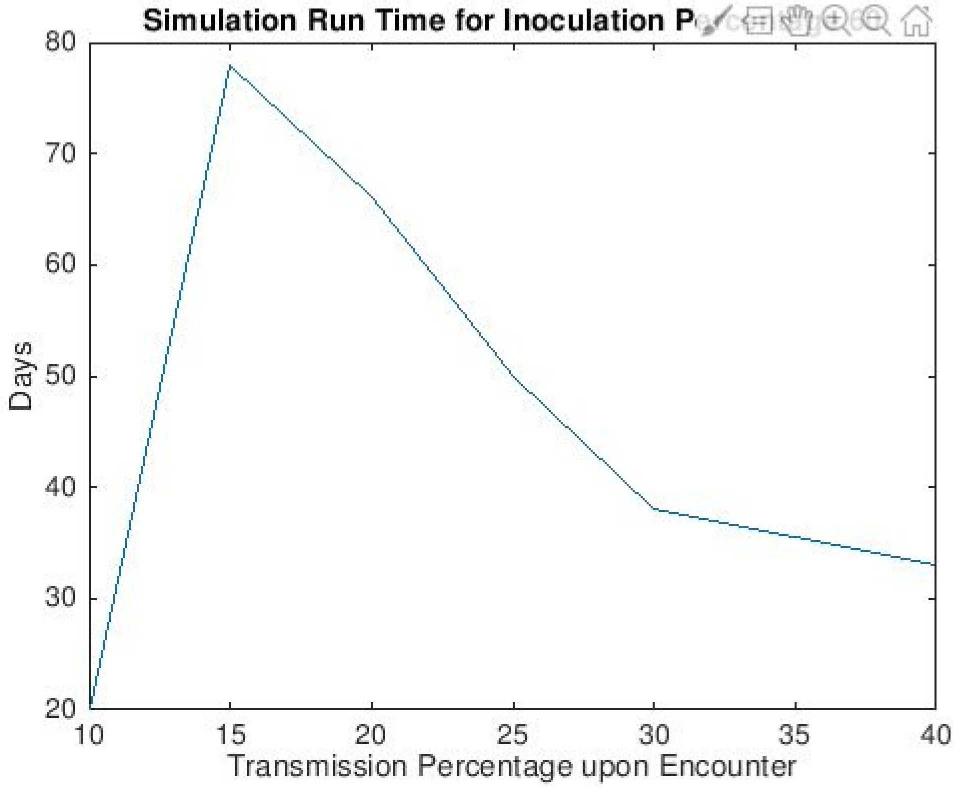

Figure 4

The length of time that an infection spends in a population is also a function of infectivity, but if the infection is too fast, it will vaccinate itself from the population when people build antibodies. If the infectivity is too low, the infection will similarly die out from lack of carriers.

Conclusion

The results of this study show the effects of two important features of an infection on its spread. If a disease spreads too fast or too slow, it will die out from lack of carriers or simply because the population will become resistant too quickly. If evolution of the disease were factored into this simulation, the results would have likely differed depending on the rate of mutation in the disease.

Inoculation can also have a dramatic effect on the spread of a disease. The results seem to agree with the findings of many world disease study centers in that herd immunity from a disease can function to protect those from the disease who are susceptible. If too few people are vaccinated, the susceptible people will become infected at a rate too high for the inoculated to affect.