A DYNAMIC SIMULATION OF A TERRORIST SMALLPOX THREAT

Jaime E. Hays†, Michael J. Karapetian†, Christine A. Keenan†, Keith W. Buffinton‡, Christopher J. Zappe‡
Bucknell University
Lewisburg, Pennsylvania 17837 U.S.A.
email: buffintk@bucknell.edu

† Bucknell University undergraduate students; ‡ Bucknell University faculty

Abstract

This study analyzes the simulated effects of a terrorist smallpox attack in two major metropolitan cities. A brief background on the smallpox disease is given, as well as important reasons why a potential smallpox outbreak is such an enormous and dangerous threat. A simulation model, which was developed using the Vensim software package based on current theories concerning the disease, is illustrated and thoroughly tested in order to study the effects of a smallpox outbreak. Social, economic and political variables are altered within the model in order to complete a more comprehensive study. Finally, the best policies for controlling the disease (ring vaccination vs. mass vaccination) are determined so as to minimize deaths and infections.

Keywords

Smallpox, Mass Vaccination, Ring Vaccination, Bioterrorism, National Security, Epidemiology

1. Background

Smallpox is a serious, contagious disease caused by the Variola virus. There is no specific treatment for the disease, and it can only be prevented via vaccinations. The virus most noticeably results in raised bumps that appear all over the body and face. The primary form of the virus is Variola Major, which has a 30% death rate [1].

Smallpox is generally transmitted through direct face-to-face contact with an infected person. The virus can also be transmitted through bodily fluids or contaminated objects such as bedding or clothing.

The seven stages of the virus are as follows:

1. Incubation period (7-17 days) – not contagious and shows no symptoms;
2. Initial symptoms (2-4 days) – minimal infectivity, flu-like symptoms;
3. Early rash (approximately 4 days) – very contagious, red bumps and rash appear all over body and face;
4. Pustular rash (approx. 5 days) – contagious, bumps raise and become pus filled;
5. Pustules and scabs (approx. 5 days) – contagious, pustules begin to scab over;
6. Resolving scabs (approx. 6 days) – contagious, scabs begin to fall off leaving permanent scars;
7. Scabs resolved – not contagious, all scabs fall off body.

Total duration of disease: 3 to 4 weeks [2]

Currently, the only known sources of the smallpox virus are in laboratories within the United States and the former Soviet Union. However, with the fall of the Soviet Union, the exact location of many of the stockpiles is not certain and thus a cause for concern. While an effective vaccine has been developed, it can result in adverse and even fatal side effects in some cases. Mass vaccinations for the disease have not been administered to the general public since the virus was officially eradicated in 1980 by the World Health Organization [3]. For further research and information on the smallpox disease, see our bibliography for relevant sources [2], [4].

2. Problem Articulation

Smallpox is perceived by the World Health Organization, the Center for Disease Control, and a majority of the general public to be a very dangerous and deadly disease. Although smallpox technically is considered eradicated, stockpiles still exist in the United States, the former Soviet Union, and possibly other places around the world. Due to its great potential harm, smallpox is an ideal agent for a bio-terrorist attack on the United States, European Union or other countries. Major cities around the world, such as New York City, London and Tokyo, are concerned about the threat of a biological warfare attack using smallpox. Repercussions of such a smallpox attack would include societal, economical, and political issues. We analyze the potential threat and consequences of a bio-terrorist attack on two large cities, such as New York City and Los Angeles, largely based on various characteristics of the smallpox virus.

For the present study, the idea that such an event is possible is largely based on various aspects of the smallpox virus. These include the fact that most members of society would be highly susceptible to such a virus and the virus is highly contagious. During the incubation period there are no physical symptoms of the smallpox virus. Although the incubation period could lead to confusion as to where the virus was initially contracted, the source could be determined employing current technologies. Combining the contagiousness and the incubation period of the virus makes smallpox an ideal agent for a bio-terrorist attack.

The fact that smallpox is believed to be an ideal virus for a biological terrorist attack provides a basis for evaluation to predict the ensuing course of events. Many studies have been completed and models created to try to accurately predict the course of events [5]. The model created for this project is based on an initial infection occurring in a metropolis, such as New York City, in the subway system. The premise designed here is that the virus would be released into the air through a ventilation system.

There are many important social issues that play a role in a possible smallpox attack. For instance, the general nature and symptoms of the disease (e.g., incubation period, infectivity) factor into the outcome of an attack. An infected person will not become contagious until after the incubation period is over, at which time he starts to show flu-like symptoms. This will influence whether authorities can recognize an attack and vaccinate the infected population before symptoms arise and the virus is spread to other people. The initial number of people exposed to the disease needs to be considered, as well as the contact rate with other people for the disease to spread. The smallpox mortality rate (approximately 30%) [2] should be accounted for when figuring the susceptible and infected populations. Finally, social responses need to be taken into account, such as quarantines, hospitalization or lack thereof, and mass hysteria in the general public if an attack occurs. All of these social variables will affect the ability of the government and health officials to contain the disease.

The economy will also be affected if a smallpox attack is launched. First, the costs of containing and eradicating the disease are immense. Costs to create and distribute the vaccine are just one aspect of this economic impact. Additional staff will need to be hired, including security personnel to facilitate the vaccination process and to control other panic and hysteria issues within the general population, all of which cost money. The added costs from hospitalizations and deaths also need to be considered. Lost profits due to business and building closings dependent on the threat and the location of the smallpox release will hurt the economy. Lastly, lack of investor confidence will have an adverse affect on the global market.

Political variables need to be considered as well. Government response time to the attack is extremely important in fighting the disease and containing it before an epidemic arises. Vaccination policy is an important aspect of the system in the form of the following questions: Who receives the vaccination first? Is vaccination mandatory or voluntary? Ring versus mass vaccination (i.e, vaccinating only those most likely to be exposed to infected individuals versus vaccinating the entire susceptible population)?

Reference models of past historic outbreaks of smallpox are used to help determine the outcomes and consequences of a bio-terrorist attack in the future. We look at the infectivity of the disease and various ways to combat it in order to make the model more realistic.

3. Model Assumptions & Essentials

The simulation of a smallpox outbreak is performed using a modified SIR (Susceptible-Infectious-Recovered) model [6]. The SIR model, commonly used to represent the dynamics of the spread of an infectious disease, utilizes three key stocks to model the course of the disease. These three stocks are susceptible population, infectious population and deceased population. Other variables such as total population, infectivity, contact rate and average duration of the illness are included to create an accurate representation of a wide range of diseases.

The main modifications made to the SIR model were the introduction of a second city (e.g., Los Angeles), a stock variable entitled immune population, and a vaccination rate variable. Given the estimated value for the mortality rate, it is imperative that the portion of people who contract the disease yet who survive be included in the model output. Furthermore, with the addition of a vaccination loop, there is another segment of the population that feeds into the immune population stock. This stock is essential for accurately modeling potential system behavior. Both the model for the ring vaccination and that for mass vaccination can be found in the Appendix.

The smallpox outbreak was modeled in two different forms: first, using a mass vaccination technique; and secondly, using a ring vaccination technique. The mass vaccination will vaccinate all susceptible individuals. The ring vaccination will only vaccinate the infected people and those with whom they come in close contact (e.g. family members and co-workers). Because the loops vary between the two vaccination methods and not simply the numbers in the equations, it was more efficient to model each system separately for testing purposes. For those interested in a complete list of variables and the values used in simulations, please contact the authors.

The susceptible population represents the portion of people who have the ability to contract the smallpox virus when exposed to it. The variables which directly affect susceptible population are infection rate and vaccination rate. If people are already infected or vaccinated, they are no longer a part of the susceptible population. The initial value of the susceptible population is based on total population, infectious population and immune population.

The contact rate represents the number of people per day that one individual has the ability to infect. This value is based on the disease specifications that it can be transmitted through droplets in the air in a 6 foot radius. Based on research and reasonable estimates, the contact rate was set to a value of 3 with units of people/person-day [5].

The total population represents the total number of people who live in the particular city (New York City or Los Angeles). These numbers were based on values in the year 2000 from the census bureau. To simplify the model, it was assumed that this value was fixed and would only fluctuate due to deaths.

The infectivity is the variable that represents the 'potency' of the virus. In other words, it reflects how likely is it that a person who is exposed to the smallpox virus will become fully infected. This value was based upon historical data and chosen to be 10% [4].

The infection rate is a critical variable in the model that determines the number of susceptible people who become part of the infectious population. It is based on the infectivity, contact rate, susceptible population, infectious population and total population. The units for this variable are people per time. The variable represents the number of people per day that will become infected based on the previously listed variables.

The initial infectious population is the number of people who were originally exposed to and contracted the virus. The infection rate is in units of people and was set to a value of 200. This number was established from research on the subway usage in New York City as well as information that also affected the contact rate. This included a person's "infectious range" and the logistics of the spread of the virus initially upon release (http://www.ny.com/transportation/subways/).

The infectious population is the number of people who are infected with the smallpox virus. It is assumed that once a person moves into this stock, they have moved past the incubation period and are now contagious. The length of the incubation period varies from 7-17 days [2]. A value of 10 days was used as the incubation period in the model. The reason for selecting a duration on the lower end of the range is that the ability to infect more people is greater and a more intense outbreak will result. This will not necessarily create a 'worst case scenario' but will improve policy recommendations for a more intense problem. The incubation period was included in the infection rate equation with a delay on the contact rate. This delay is a 'one time' delay, in that it delays any new infectious individuals only for the first ten days. Based on the infection rate, the number of people who will contract the virus is the integral of the infection rate, deducting the mortality rate and recovery rate [6].

The travel rate represents the fraction of infectious people that move from one city to another. A value of 1/1000 was used as a reasonable fraction of travelers. The important simplifying assumption associated with this variable is that travel only occurs from the first city to the second and never in the reverse direction.

The average duration of the illness is the variable that represents the approximate number of days it takes for a person to completely recover from the disease. From contraction to a fully-recovered, non-contagious state, the mean duration is 30 days. The illness takes slightly longer than 2 weeks to run its course, and added to this value is the delay in infectivity [2].

The recovery rate represents the proportion of people who will become infectious, recover, and survive. This value is dimensionless and is widely found to be approximately 70% [2]. However, this percentage must take into account the infectious population and the length of time that they are sick.

The vaccination rate is a more complicated variable, as it must take into account the stock of the vaccine, maximum number of people able to be vaccinated in a single day as well as any delays that may occur due to the government response. The vaccination rate represents the number of people per day who can receive the smallpox vaccine. The number of doses of smallpox currently available in the United States is more than adequate to vaccinate both cities completely and therefore the supply of the vaccine was disregarded [7].

In the ring vaccination model, the vaccination rate was designated as the number of people that the infectious individual contacts (contact rate) as well as the infectious person. However, it is important to note that a maximum of 500,000 people can be vaccinated per day using either technique, thus limiting the vaccinated population [8].

The technique used in the mass vaccination model was largely based on the susceptible population. Like the ring vaccination model, an "if, then, else" statement was used to assess the number of people who could be vaccinated each day. For this model, 500,000 people of the susceptible population could be vaccinated daily, until the susceptible population fell below 500,000 people, at which the entire remaining population would be vaccinated.

Because ring vaccination is dependent on the infectious population and contact rate, both of these variables are linked to this rate. However, like the mass vaccination model, only the deceased population and immune population are linked to the vaccination rate as outputs. Because the vaccine is a live virus, there is a risk of death associated with each administered dose.

The immune population is the number of people who have either fully recovered from the virus or who have been successfully vaccinated against the smallpox virus. This population is a function of both the recovery rate and vaccination rate. It is expressed as the sum of these two values and is in units of people, with an initial value of zero.

The mortality rate is the number of people per day who die from contraction of the smallpox virus or through complications that arise from vaccination. Like the recovery rate, this percentage was found to be relatively consistent through the literature [3], [5]. The accepted mortality percentage is 30%. The mortality rate variable is also as a function of the total infectious population and the average duration of illness [2].

The deceased population represents the number of people who die each day as a result of the smallpox outbreak. It is directly affected by the mortality rate of the virus and the fraction of people vaccinated who may die from the vaccine.

The two-city model is based on several assumptions and essential simplifications. They are as follows:

- City 1 Population - 8,800,300
- City 2 Population - 9,637,490
- Initial Infected Pop. - 200*
- Avg. Duration of Illness - 30 days
- Contact Rate is same for both cities
- Contact Rate - 3*
- Infectivity - 10%*
- Recovery Rate - 70%
- Mortality Rate - 30%
- Government Response Time - 21 days*
- Travel Rate – (0.001) *x* Infectious Population

* parameter varied during testing

The other essential simplifications are that there is only travel from City 1 to City 2, the infectivity is zero for the first 10 days of the simulation, and the maximum per day vaccination rate is 500,000 people/day [4]. Refer to the appendix for the simulation model.

4. Findings & Results

The model is designed to compare the advantages (and disadvantages) of the ring vaccination and mass vaccination methods. Therefore, when testing the model, it is first checked for its reproducibility of trend behaviors for both methods. The first step in the analysis process is to look for the proper shape of the various stocks and variables. For the infectious population, the expected trend is a relatively sharp increase and decline as eventually all people that acquire the disease become immune or die. The susceptible population is expected to eventually go to zero assuming all people either contract the disease or are vaccinated. Lastly, the immune population and deceased population are expected to increase in some manner. A summary of some of these graphs can be seen below (Note the 2nd variable labeled with a '2' represents the second city):

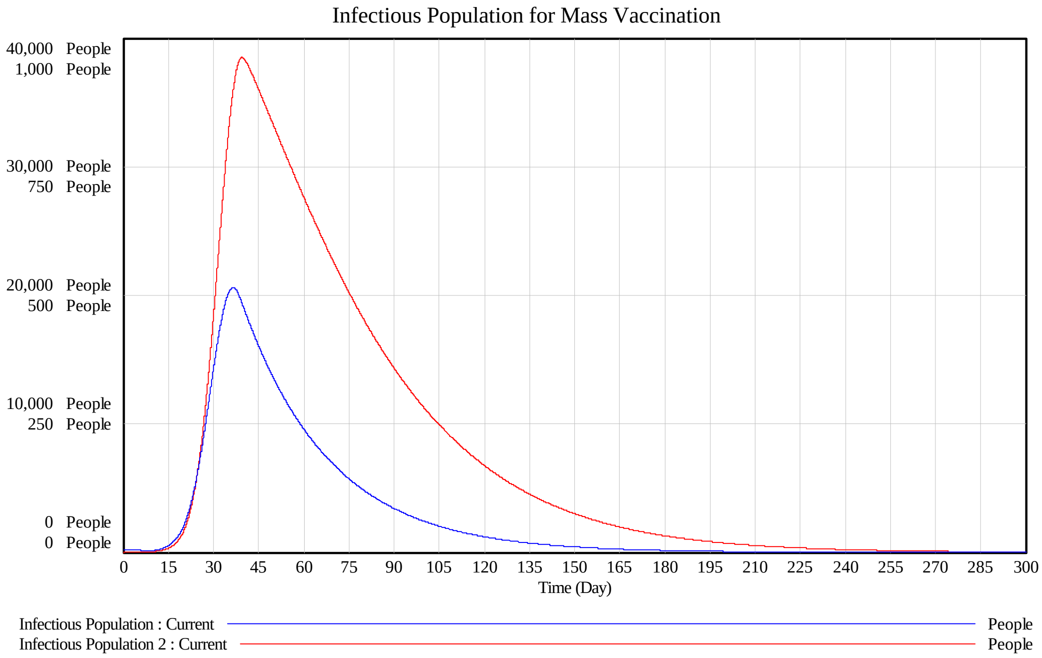

Figure 1: Infectious Population for Mass Vaccination.

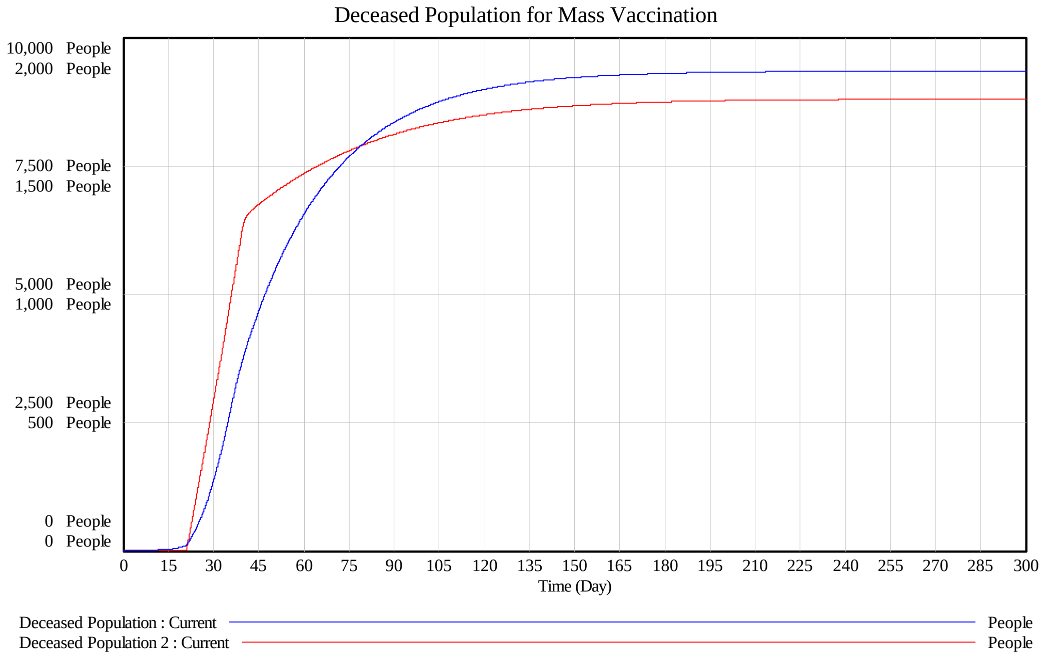

Figure 2: Deceased Population for Mass Vaccination.

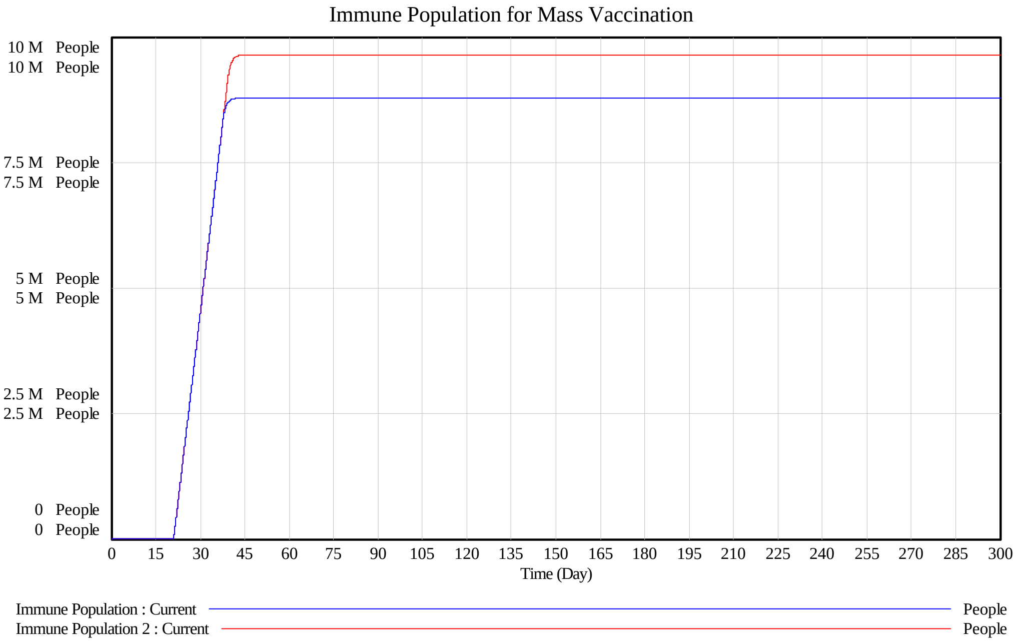

Figure 3: Immune Population for Mass Vaccination.

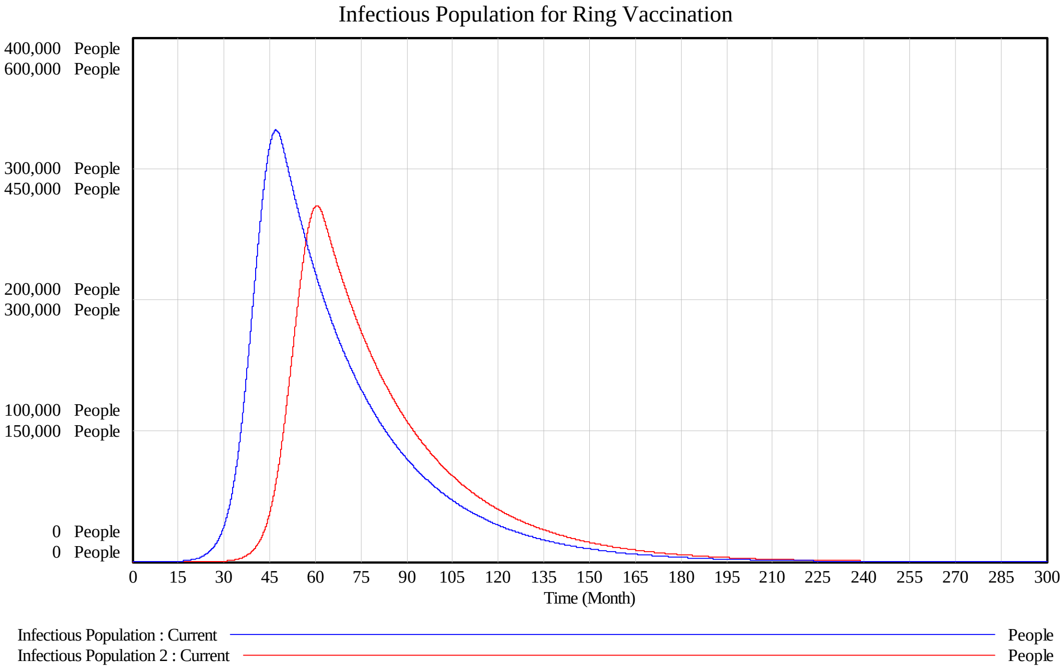

Figure 4: Infectious Population for Ring Vaccination.

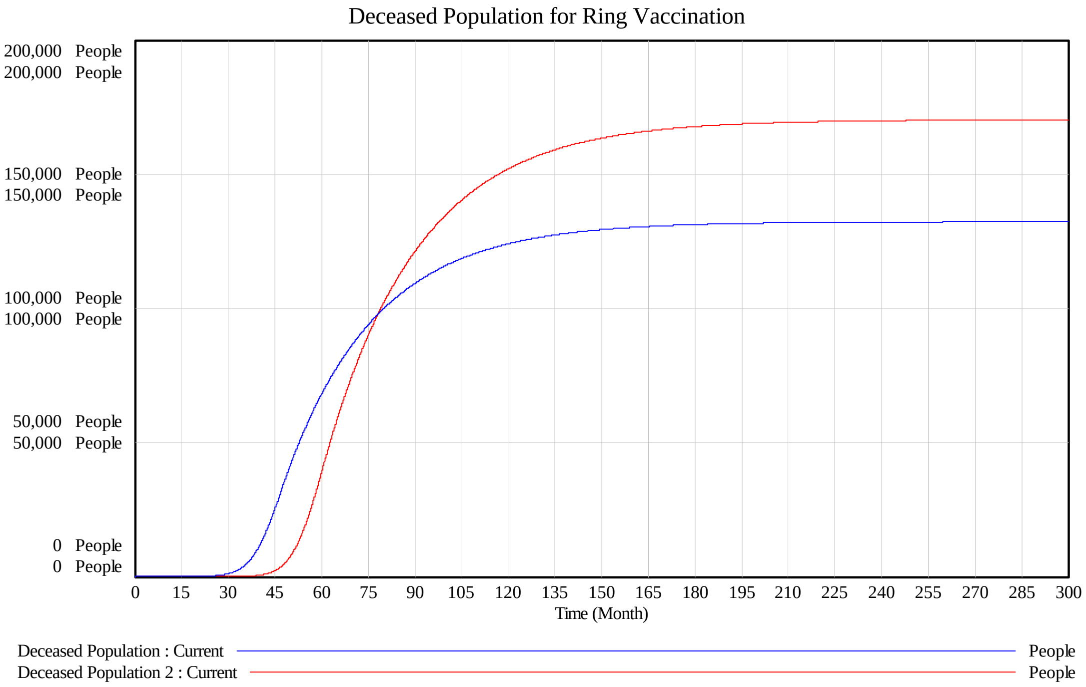

Figure 5: Deceased Population for Ring Vaccination.

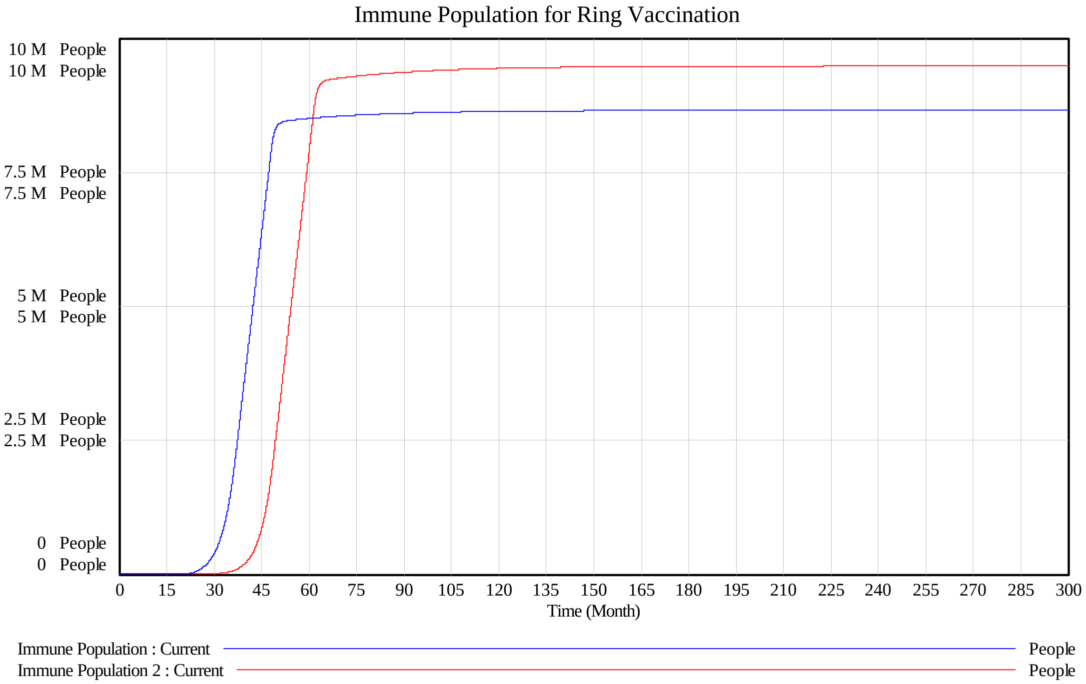

Figure 6: Immune Population for Ring Vaccination.

Notice the differences between the total infectious and deceased populations using the mass vaccination method versus the ring vaccination method. Both the infected and deceased populations are significantly higher when the ring vaccination method is employed. According to the models used here, nearly twenty-six times as many people die when the ring vaccination method is applied.

In terms of sensitivity and robustness under extreme conditions, the model fares relatively well with extreme conditions. At low values for contact rate (1 person per person-day), the model predicts that the mass vaccination technique is superior with respect to deaths and number of people who acquire the disease. At a more realistic contact rate of 3 people per person-day, the model also predicts that the mass vaccination technique is superior.

However, at higher contact rates (10 people per person-day), the model shows that the ring vaccination technique and mass vaccination techniques are about the same in all aspects. When other variables, such as infectivity, total population, initial infectious population, travel rate, mortality rate, recovery rate, and average duration of illness are changed, the specific numbers change (for example, how many people become immune); however, the relative trends in terms of when one technique is better than the other remain the same. This indicates that the model is sensitive to input parameters, but robust in terms of the model predictions. See the Appendix for complete testing results.

The contact rate strongly influences whether the ring vaccination method is effective, because it is the primary factor in how quickly the disease will spread. The higher the contact rate, the faster the number of infected people increases. At lower contact rates the mass vaccination is most effective, because the majority of the population becomes immune from the vaccine before the disease has a chance to infect a large number of people. At low-to-medium contact rates the number of infected people using the ring vaccination method is larger than the values using the mass vaccination method.

The final aspect of the testing process deals with the government response time variable. This variable feeds directly into the vaccination rate, where the vaccination rate is defined as zero until the set number of days (government response time) pass. A fixed delay is used for this calculation. These results also indicate mass vaccination is a superior technique. A complete list of equations can be obtained by contacting the authors' address.

5. Analysis of Results

While the model is a simplified representation of a two city-system, it provides information that would be effective in developing a policy for response in a smallpox attack. In order to truly analyze various policies concerning a bio-terrorist attack using the smallpox disease, we will take into account an open system of the entire United States of America (population of over 290 million people) when discussing various policy issues outlined below.

Several policy issues would arise in the event of a smallpox outbreak. One of these issues concerns the infected population. The disease is an airborne virus, which means that it can be spread through close contact (up to 6 feet) between two people. Due to the fear of contracting the disease, it is assumed that once the outbreak is publicized, people will avoid public settings. This will result in lost business productivity, affecting the global market. The enormous costs of controlling and halting the spread of the disease in an attack will lead to an upset economy. Even after the outbreak is quelled and the disease is officially declared eradicated once more, the impact of the terror from such an attack will be lasting.

One of the major concerns in the event of a smallpox attack is selecting a vaccination procedure. Both the mass and ring combative strategies have their own serious consequences. The effectiveness of the ring vaccination is debatable if the attack is not recognized at the onset of the first cases of smallpox. If government officials cannot identify an initial infected population, it will be hard to pinpoint exactly who needs to be vaccinated, making this procedure a hit or miss attempt of stopping the spread of smallpox.

On the other hand, if mass vaccination is chosen the vaccination hierarchy could be a major issue. Healthcare and elected officials will have to determine a proper distribution strategy. For instance, the hierarchy could be: first immunizing healthcare workers, then the infected and their families, but who next? Unfortunately, but realistically, social issues such as race, gender, and ethnicity could play a role in determining who receives the limited doses of the smallpox vaccine and in what priority.

Another vaccination policy that is very important is whether or not to make vaccination mandatory by law or voluntary by individuals. A percentage of people will die from receiving the vaccine. Mandating vaccination for every person in an infected area is counter to the idea of individual freedom. At the same time refusing the vaccination and then contracting the disease and infecting others is taking one's individual freedom to a point where others are hurt. Past judicial decisions concerning the *Federal Quarantine Law* "indicate that forcible inoculation and quarantine of infected patients may be constitutional" [5]. If a mandatory vaccination decision is made, a strong public response from such a policy could occur. In the Dark Winter exercise cited above, the American Civil Liberties Union sues the state of Pennsylvania, a state in which the initial bio-terrorist attack has occurred, for forcing mandatory vaccinations of patients and their close contacts, as well as implementing a newly imposed plan for travel restrictions. (The Dark Winter exercise was a study conducted by Johns Hopkins Center for Civilian Biodefense, Center for Strategic and International Studies, ANSER, & Memorial Institute for the Prevention of Terrorism in order to simulate a possible bio-terrorist attack on our country using the smallpox disease.) These policy decisions concerning mandatory vaccination or quarantines at the government or state level should not be taken lightly.

A third issue that would need to be addressed if there were a bio-terrorist attack using the smallpox disease would be the amount of time worldwide health officials take not only to recognize the attack, but to decide on and initiate a plan to combat the virus. Due to the 7-17 day incubation period of the smallpox virus, during which an infected individual is not contagious, governments have approximately 3 to 4 days in order to vaccinate the initial exposed population in order to halt the spread of the virus. If governments do not recognize the attack or initiate a plan of response before these days pass, the potential for the disease to spread and become an epidemic greatly increases. In our model, we assume that the worldwide health officials do not recognize the disease until day 21, when it is too late to stop the initial spread of smallpox throughout the population.

All of the above policies and decision points are interrelated with each other in combating a smallpox attack. The amount of time the government takes to identify the disease, to decide which vaccination strategy to employ, and to implement the policy is critical in countering a smallpox attack. Synergies exist between all policy variables, thus, creating a need to consider them all together and not each one separately.

6. Conclusions, Recommendations and Future Work

Through testing and analysis of our dynamic system model, and further detailed research on the history of the smallpox virus, we have reached a number of general conclusions and recommendations on certain government responses in the wake of a bio-terrorist attack using smallpox. First, we believe that a mass vaccination of all people living in close proximity of the initial outbreak, and all people in a close proximity of other smallpox cases, is the best strategy for vaccination. Compared to the ring vaccination strategy, our model shows that mass vaccination for an average contact rate (approximately 3 people/person-day) would result in a lower infected and deceased populations. Furthermore, unless the attack is caught in the first few days and the response is initiated immediately, the effectiveness of the ring vaccination drops drastically. Under realistic circumstances, we believe that mass vaccination is the better policy decision.

Along with the mass vaccination policy, we believe that a government should mandate the vaccinations to those people living in the infected areas and who have come in contact with an infected individual. Although this could cause social uprisings and protests against the violation of individual civil liberties, we believe it imperative that all people who have been in contact with the disease be vaccinated to help prevent its spread. Also, we believe that a vaccination hierarchy should exist in which health care workers and members of defense organizations receive the vaccination first. After that, the vaccination should be distributed on an as-needed basis to those who are infected and those living in close proximity and who come in contact with the infectious people. Health care workers are essential in helping to fight the disease and administer the vaccine as well as care to the already infected individuals. Therefore, we believe that reserving a specified amount of vaccine for these individuals is important. Finally, no matter what the policy decisions would be, we believe that it is essential to the safety and health of a country that a government acts at the first sign of a smallpox attack. If an extended period of time is taken to collect information and evaluate each possible decision and its consequences, important time will be wasted that is needed to stop the spread of smallpox.

As we have demonstrated throughout this study, the opportunity for smallpox to be used as a biological warfare weapon poses a serious threat to the world. We have chosen variables that have been deemed relevant to the situation and important in modeling the impacts of a smallpox attack in major metropolitan areas. Through sensitivity analysis and testing of our system model, we have determined the best policy decisions to make in the situation of an outbreak. In short, we believe that an immediate, mandatory, mass vaccination is the most effective way to combat the disease.

References

[1] World Health Organization. “WHO Fact Sheet on Smallpox.” [online] http://www.who.int/emc/diseases/smallpox/factsheet.html. Oct 2001.

[2] CDC. “Smallpox Overview.” [online] http://www.cdc.gov/smallpox. 2003.

[3] Flight, Colette. BBCi History. “Smallpox: Eradicating the scourge.” [online] http://www.bbc.co.uk/history/discovery/medicine/smallpox_01.shtml. 2002.

[4] Infectious Diseases Society of America “Bioterrorism Information & Resources.” [online] http://www.vaccinationnews.com/DailyNews/October2002/Smallpox13.htm. 1 Oct 2002.

[5] “Dark Winter.” Johns Hopkins Center for Civilian Biodefense, Center for Strategic and International Studies, ANSER, & Memorial Institute for the Prevention of Terrorism. 23 June 2001.

[6] J. D. Sterman, Business dynamics: systems thinking and modeling for a complex world (Boston: Irwin McGraw-Hill, 2000).

[7] CNN. “Breast-fed baby exposed to smallpox vaccine virus.” [online] http://www.cnn.com/2004/HEALTH/02/13/smallpox.reut/index.html. 13 Feb 2004.

[8] CNN. “NY faced last U.S. smallpox outbreak.” [online] http://www.cnn.com/2002/HEALTH/12/13/smallpox.ny/. 14 Dec 2002.

Appendix

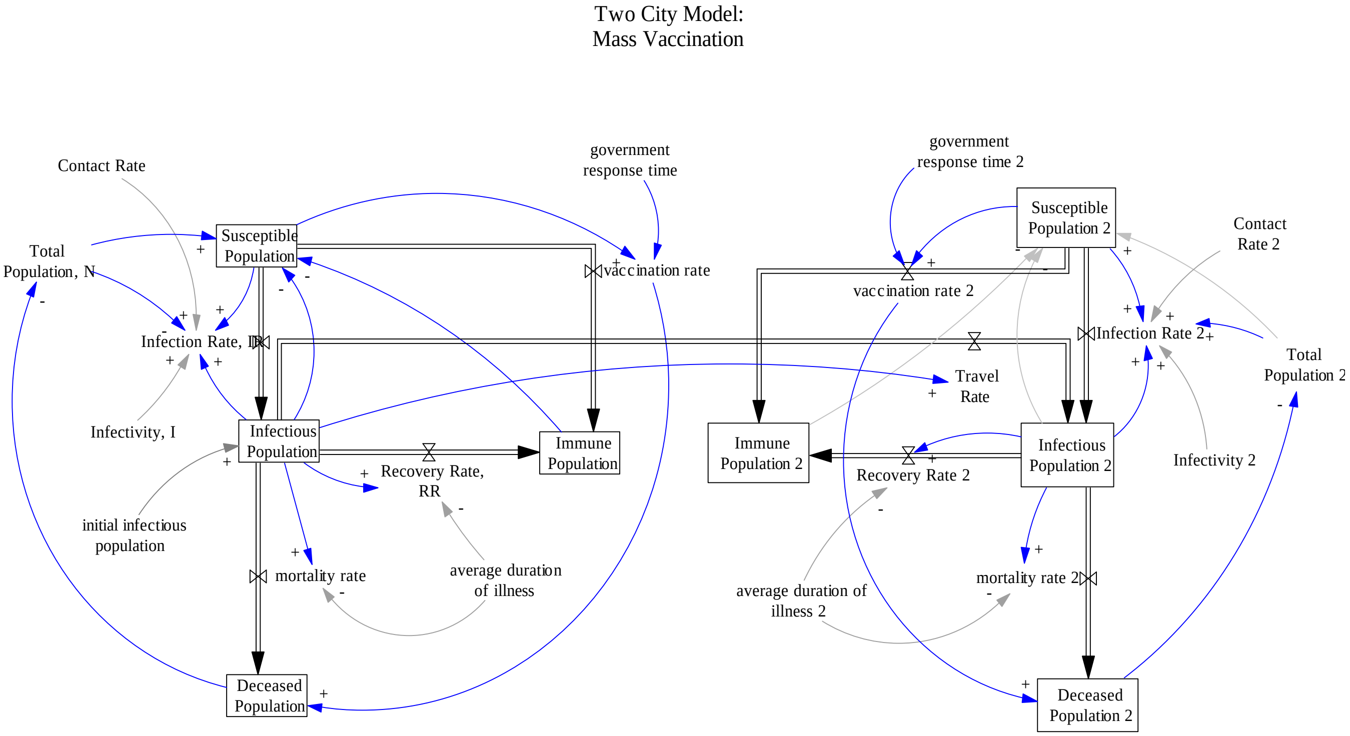

Figure 7: Mass Vaccination Model

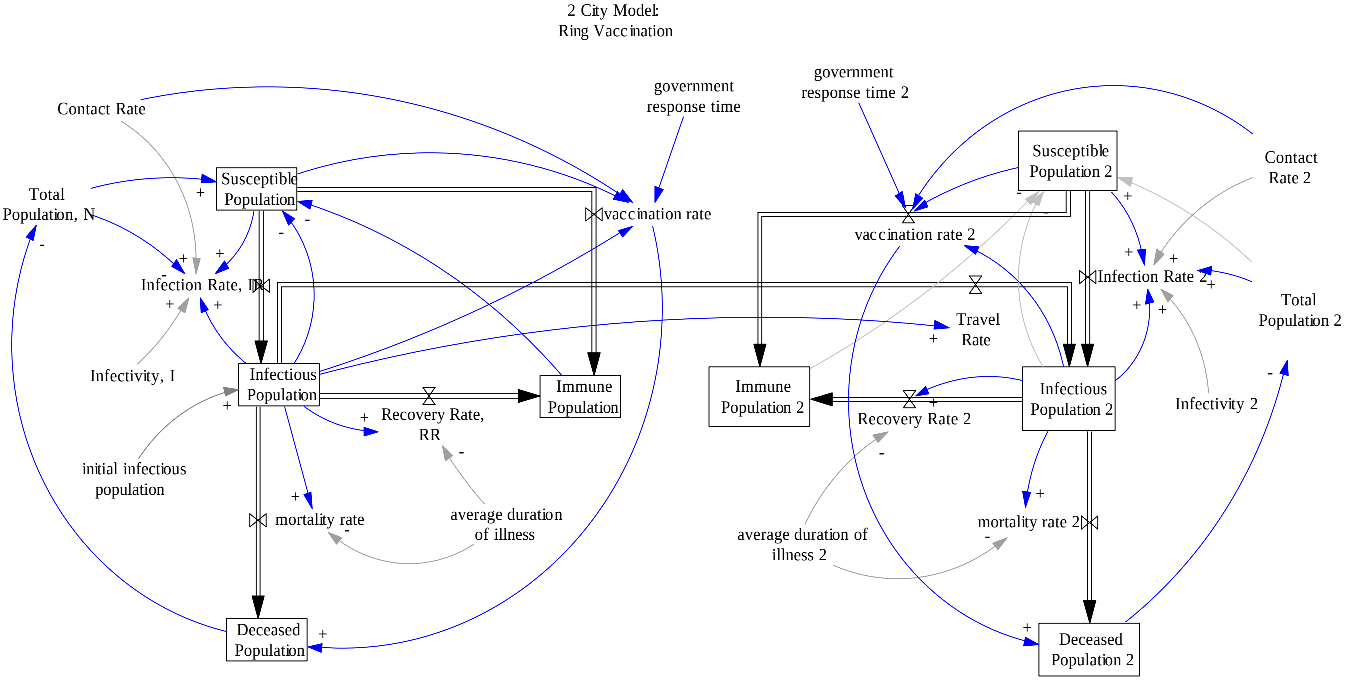

Figure 8: Ring Vaccination Model