Analysis of Ebola Virus Disease of Post-Death Transmission

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Abstract. The Ebola Virus Disease was first discovered in 1976 near the Ebola River now known as the Democratic Republic of Congo (MMWR 2017). After the first initial epidemic, the virus aggravated heavily again in 2014 lasting until 2016 in West Africa (Ebola 2018). The world has coined this the Ebola Outbreak of 2014-2016. Unlike the initial outbreak in the 1970's the Ebola virus has adapted and evolved into the Zaire Ebola Virus. The Zaire Virus is the largest widespread outbreak of Ebola ever (Eichner). Due to being the largest outbreak in history, the government and medical officials were able to record an abundance of data. Analyzing the data, scientist and mathematicians soon realized that the deceased are capable of transmitting the Zaire virus to the living; also known as "Post Death Transmission" (Weitz 2014). We used Differential Equation's SEIRD model to mathematically model the Ebola Outbreak of 2014-2016 in Sierra Leone emphasizing on post-death transmission. In the paper, we will discuss the mathematical model of Ebola and show potential impacts of Ebola under different possible circumstances. Conclusions drawn from the epidemic models were that the Ebola Outbreak took its course mainly from the varied number of burial days.

Keywords: Ebola Virus (EVD), Zaire Virus, rVSV-ZEBOV, SIR, SEIRD, Susceptible, Exposed, Infected, Recovered, Dead, Center of Disease Control and Prevention (CDC), β_I, β_D, f, T_E, T_I, T_D, Type-5 Ebola Vaccine.

1 Introduction

The Ebola Virus occurring in 2014-2016, according to Scientists and Researchers, originated from 4 to 5 different strains of the original Ebola Virus in 1976 (Eichner). Of the 4 or 5 strains, the Zaire Virus strain accounts for most of the disease outbreak in West Africa in 2014 (Eichner). Countries affected were: Sierra Leone, Guinea, Liberia, Nigeria, and Mali. Nigeria and Mali were considered as isolated cases or limited outbreak of Ebola due to the early containment and relatively low number of cases (Ebola CDC 2018). On the other hand, Sierra Leone, Guinea, and Liberia were considered widespread outbreaks. Sierra Leone had 14,122 cases and 3,955 deaths, Guinea had 3,804 cases and 2,356 deaths, and Liberia had 10,666 cases and 4,806 deaths (Ebola CDC 2018). For the first time, do to advanced technology, the world was able to record and collect reliable data of the outbreak.

Scientist and Mathematicians researching and working to help reduce the outbreak have realized that the information known about the virus did not match with the actual number of cases. Previous knowledge of the Ebola Virus did not take into account that the virus can still live in the host whether the host and be transmitted is alive or dead. From previous studies conducted years ago, researchers realized that the transmission rate of Ebola Virus would not have infected this many people (Chretien 2015). After the realization medical scientist have confirmed that the Ebola Virus is still alive and had been infecting people during the burial rituals (Chretien 2015).

Studies confirmed that the first case of the infection in Sierra Leone was from a tribal healer who had been treating Ebola patients from across the nearby border with Guinea and died on 26 May 2014 (Manguvo 2015). At first doctors thought that the tribal healer was infected when he was healing the sick. Eventually they were able to confirm that the tribal healer was infected during the time he was helping with the funeral services (Manguvo 2015).

This paper will focus on the Sierra Leone and the Zaire Virus outbreak in 2014-2016. Due to the peculiar nature of the Zaire Virus having the ability to infect people from deceased host the research focuses on an analysis of the virus from post-death transmission.

2 Zaire Virus and Symptoms

The Zaire Virus is the main Ebola strain responsible for the outbreak in West Africa (Eichner). What makes this disease unique is the lack of cure and vaccines (Ebola 2018). The only way to survive the virus is to outlive the virus time span by taking appropriate medications. It appears that whomever has been infected once and then recovers becoming susceptible again will not be infected a second time. This however has never been tested. Currently, there are no treatments available but there is a vaccine rVSV-ZEBOV that was tested in 2015 and expected a licensure in 2018 (Ebola CDC 2018). Aside from the vaccine, in 2015 there was a recombinant adenovirus type-5 Ebola vaccine that was primarily used to defend against the virus (Ebola CDC 2018).

The one characteristic that makes this disease special compared to other diseases is that even though the outbreak concluded in 2016 the virus still lingers today (Ebola 2018). Do to the preparation and prevention, few people are infected each year. Even if they are infected the local government and medical professionals know how to quarantine to prevent the virus from having another outbreak. The incubation period or latent period of a disease is defined as a period where someone is infected with the disease, but cannot transmit the virus to another individual until onset of symptoms. Ebola has a latent incubation period, lasting 2 to 21 days (4-10 days being most common), making it difficult to diagnose infected individuals before onset of symptoms (Ebola CDC 2018).

2.1 Symptoms

The virus has multiple symptoms and all unique to the infected. Not all symptoms will happen, but the common final stage is unexplained hemorrhage which leads to certain death (Ebola CDC 2018).

1. Fever
2. Severe Headache
3. Muscle Pain
4. Weakness
5. Fatigue
6. Diarrhea
7. Vomiting
8. Abdominal Pain
9. Unexplained Hemorrhage

3 SIR and SEIRD Model

Differential Equations has the base model SIR. We used the modified SEIRD model to model the Ebola outbreak.

3.1 SIR

The SIR model is comprised of three differential equations for: Susceptible, Infected, and Recovered all in which are independent of time, t. The addition of all three equations at initial conditions sum up the initial population N.

The SIR Differential Equations are:

$$\frac{dS}{dt} = -\beta \frac{SI}{N} \tag{1}$$

$$\frac{dI}{dt} = \beta \frac{SI}{N} - \gamma I \tag{2}$$

$$\frac{dR}{dt} = \gamma I \tag{3}$$

$$N = S + I + R \tag{4}$$

3.2 SEIRD

The Ebola Virus has a unique case where the recovered class are capable of infecting the susceptible; therefore, a change in the SIR model is necessary. Because, of the nature of the virus where there are two Recovered classes we need to separate the Recovered class into two separate classes. For easier naming of the classes we kept one class as a Recovered Class. The Recovered Class represents the individuals that outlive the disease and is no longer considered infected. While the other class is called the Dead Class, which represents the individuals that died from the disease but are still infectious. This leads to a SEIRD model. SEIRD stands for Susceptible, Exposed, Infected, Recovered, and Dead.

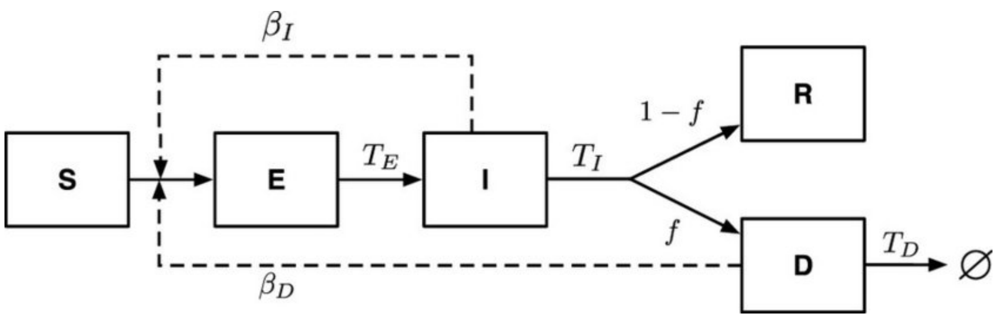


Fig. 1. Schematic model of SEIRD model. From left to right there are: Susceptible, Exposed. Infected, Recovered, and Dead. Aside from the classes there are: β_I which is the transmission rate for infected, β_D which is the transmission rate with dead individuals, T_E is the average exposed period, T_I is the average infectious period, T_D is the average infectious period after death, and f is the fraction of infected individuals that die.

The SEIRD Differential Equations are:

$$\frac{dS}{dt} = -\frac{\beta_I SI}{N} - \frac{\beta_D SD}{N} \tag{5}$$

$$\frac{dE}{dt} = \frac{\beta_I SI}{N} + \frac{\beta_D SD}{N} - \frac{E}{T_E} \tag{6}$$

$$\frac{dI}{dt} = \frac{E}{T_E} - \frac{I}{T_I} \tag{7}$$

$$\frac{dR}{dt} = \frac{(1-f)I}{T_I} \tag{8}$$

$$\frac{dD}{dt} = \frac{fI}{T_I} - \frac{D}{T_D} \tag{9}$$

$$N = S + E + I + R + D \tag{10}$$

The SEIRD model produces five Differential Equations where β_I is the transmission rate for contacts with infected individuals, β_D is the transmission rate associated with contacts with dead individuals, T_E is the average expose period, T_I is the average infectious period, T_D is the average period of infectiousness after death, and f is the frequency of infected individuals who die.

4 Result and Analysis

The central idea of this Ebola Research is to mathematically model the event of Ebola and various parameters to see the potential growth of the epidemic. The reason behind this is that each dynamic system behaves in similar patterns, but causes large changes as parameters differ. Here we will analyze the potential differences when other possible parameters are changed. The parameters that we will alter are: f which is frequency of infected individuals that dies and T_E which is the average exposed period of an individual.

According to the culture and economy of Sierra Leone many of the families will have different funeral services. Being a prominent factor in this epidemic model the length of the funeral services were taken into account. Citizens of Sierra Leone have funeral practices that last from one day to one week, therefore; we will use the more commonly used lengths of the funeral services. Aside from analyzing the T_D values, the fraction of people who die value; f, and the incubation period are analyzed. The base values are: $T_E = 11$, $T_I = 8.5$, $T_D = 2$, 4, and 6 days, f = 0.7, $B_D = 0.20$, $B_I = 0.25$, and N = 10^6 (Weitz 2014).

The parameters that were taken in comparisons for each of our parameters were burial days: T_D at 2, 4 and 6 days, the fraction of people who die; f respect to different burial days, the average exposed period or incubation period, T_E.

4.1 Base Models

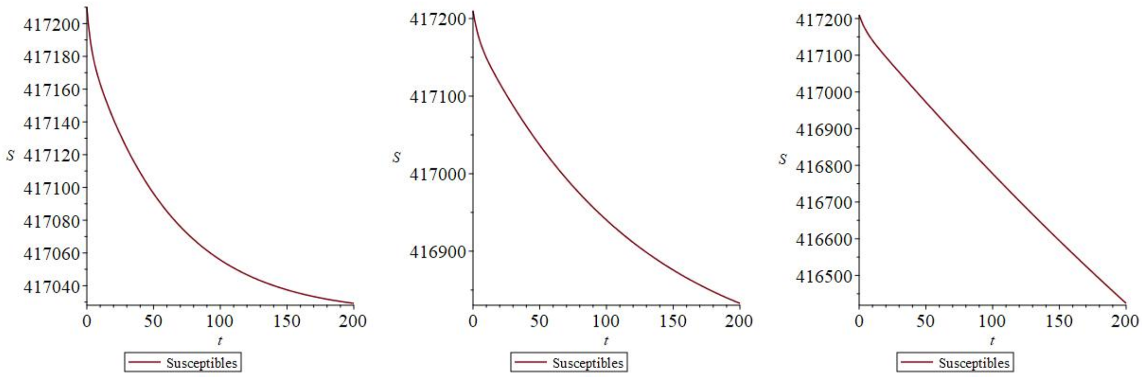


Fig. 2. Susceptible Model: $T_D = 2$ days, $T_D = 4$ days, and $T_D = 6$ days

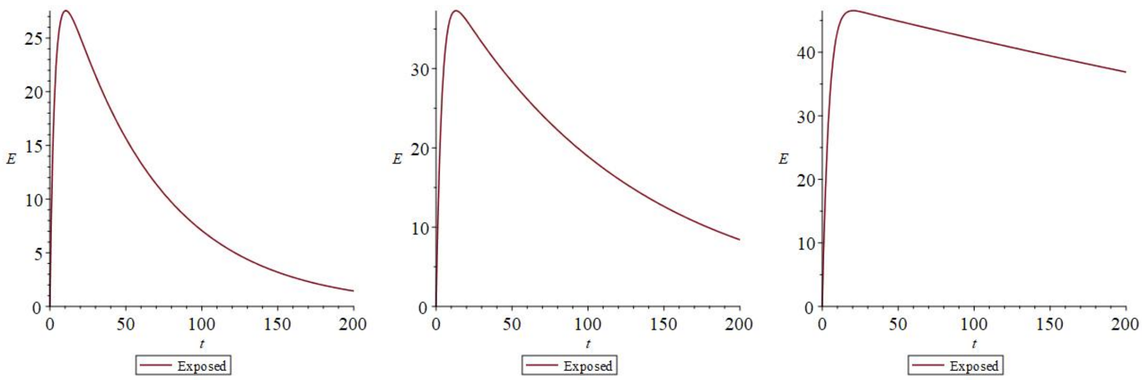


Fig. 3. Exposed Model: $T_D = 2$ days, $T_D = 4$ days, and $T_D = 6$ days

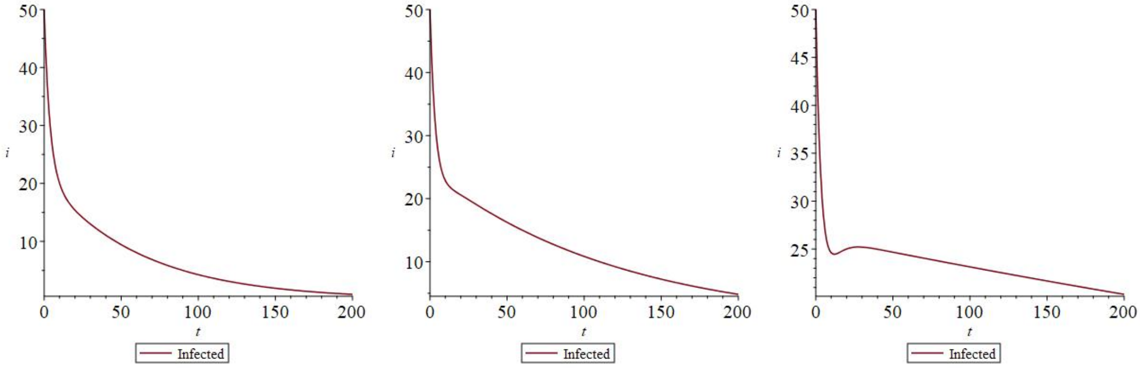


Fig. 4. Infected Model: $T_D = 2$ days, $T_D = 4$ days, and $T_D = 6$ days

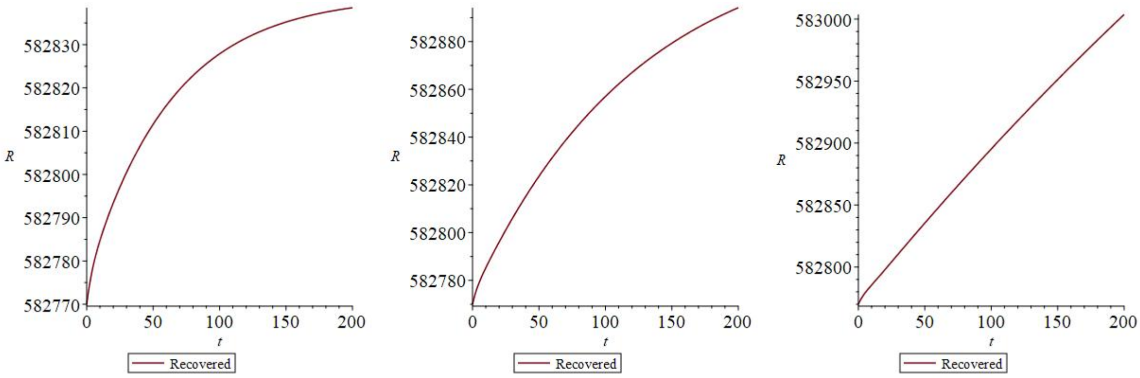


Fig. 5. Recovered Model: $T_D = 2$ days, $T_D = 4$ days, and $T_D = 6$ days

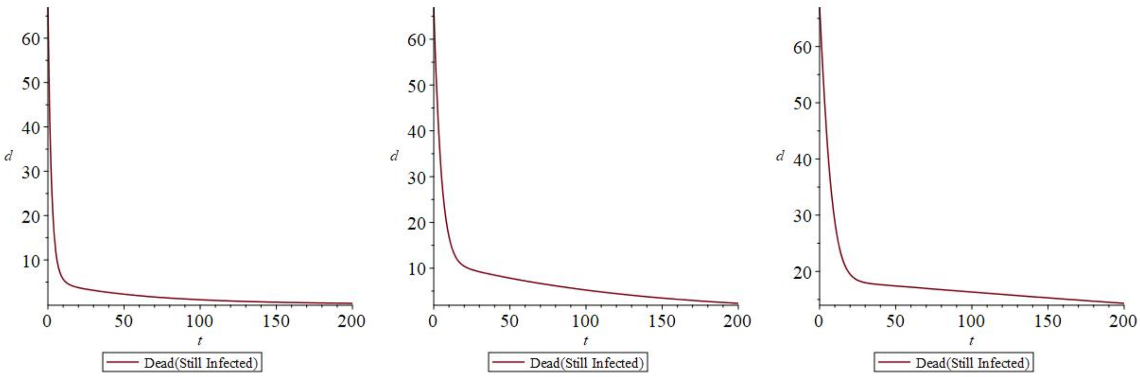


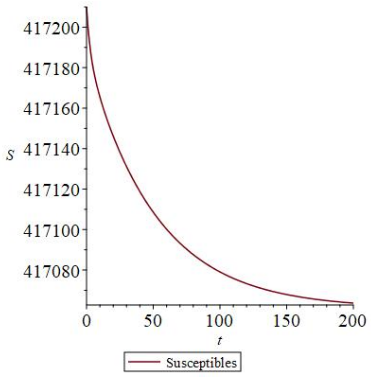
Fig. 6. Dead Model: $T_D = 2$ days, $T_D = 4$ days, and $T_D = 6$ days

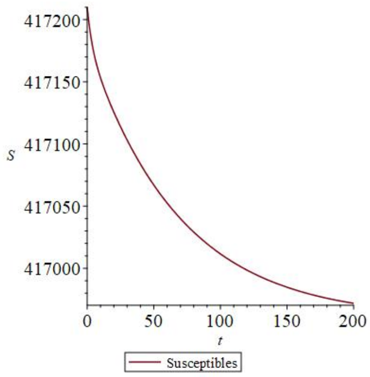
From producing the base models of the Ebola Outbreak we can see that comparing the three different funeral lengths; 2 days and 4 days services behaves similarly (Figure 2-6). The primary difference between 2 and 4 day services is the length that the outbreak will last. As expected having more time around the virus gives a higher percentage of transmitting the virus. Therefore, 4 day funeral services will have allowed for the outbreak to last longer than 2 day funeral services.

The most important thing to take from the base models is the different behavior from 6 day funeral services (Figure 2-6). Figure 4, represents a potential growth in the infected class unlike the other two base models. The potential growth occurs within fifteen days from the initial model representation, but eventually dies out just like the rest of the base models (Figure 4).

Comparing the three base models and real world data (Ebola CDC 2018), we can conclude the best model that represents what happened is when $T_D = 4$ days. From Figure 4, you can see that $T_D = 4$ holds the closes match up to real data that was collected. What we can tell is the what happened matches somewhere between 4 and 6 day funeral services. 2 day funeral services do occur but not as frequent as 4 days and slightly less than 6 days. Therefore, we can conclude that if funeral services were reduced to shorter amount of days it will allow the epidemic to die off relatively quick. The Ebola Outbreak lasted approximately 214 days and our model shows an approximation of the virus lasting about 225. This implies an absolute error of 0.0514%.

4.2 Modified f Models





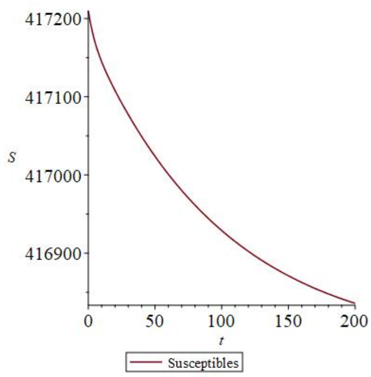


Fig. 7. Susceptible Model: $T_D = 2$ days - f = 0.4, $T_D = 4$ days - f = 0.4, and $T_D = 6$ days - f = 0.4

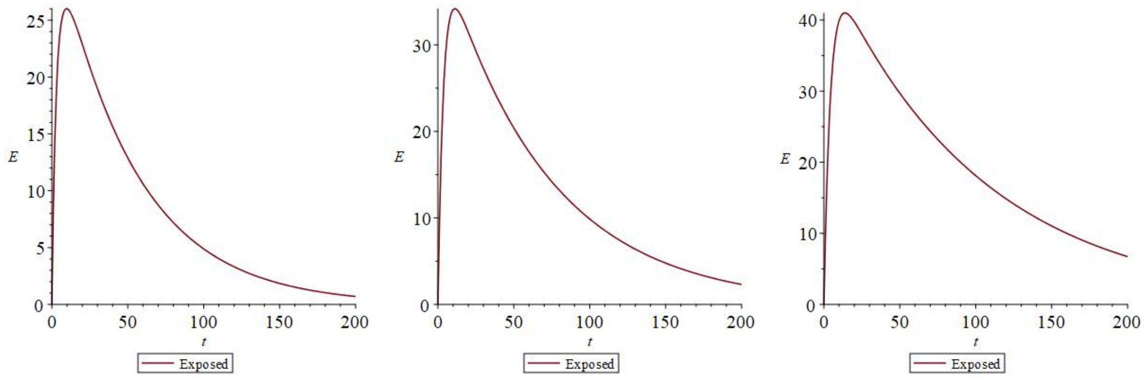


Fig. 8. Exposed Model: $T_D = 2$ days - f = 0.4, $T_D = 4$ days - f = 0.4, and $T_D = 6$ days - f = 0.4

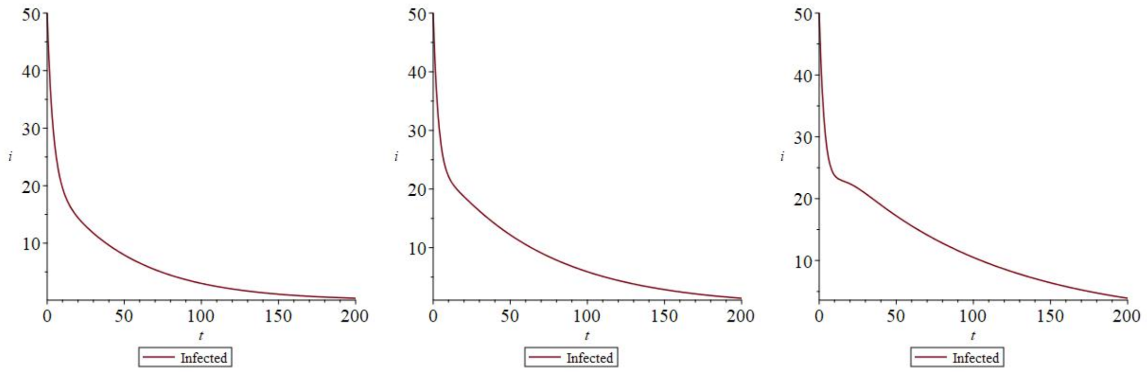


Fig. 9. Infected Model: $T_D = 2$ days - f = 0.4, $T_D = 4$ days - f = 0.4, and $T_D = 6$ days - f = 0.4

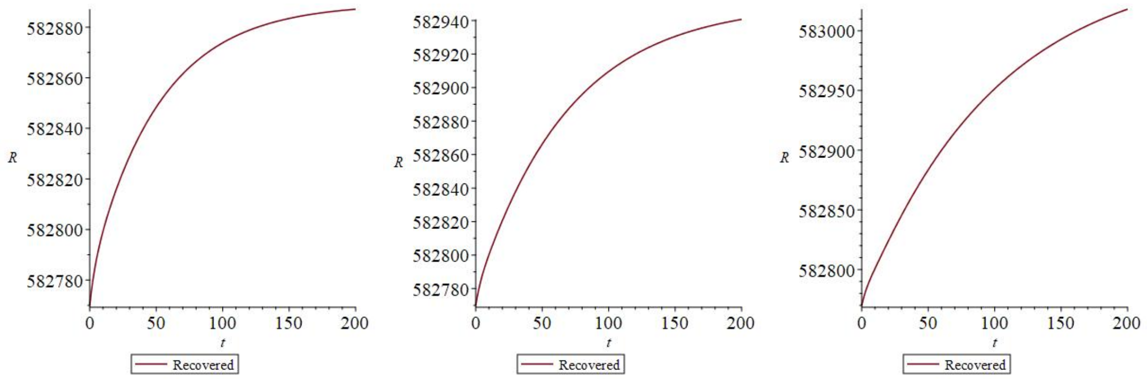


Fig. 10. Recovered Model: $T_D = 2$ days - f = 0.4, $T_D = 4$ days - f = 0.4, and $T_D = 6$ days - f = 0.4

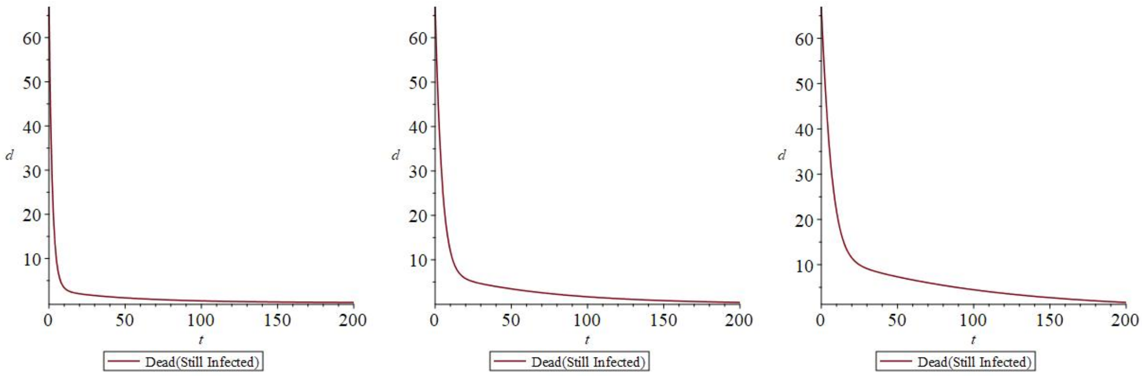


Fig. 11. Dead Model: $T_D = 2$ days - f = 0.4, $T_D = 4$ days - f = 0.4, and $T_D = 6$ days - f = 0.4

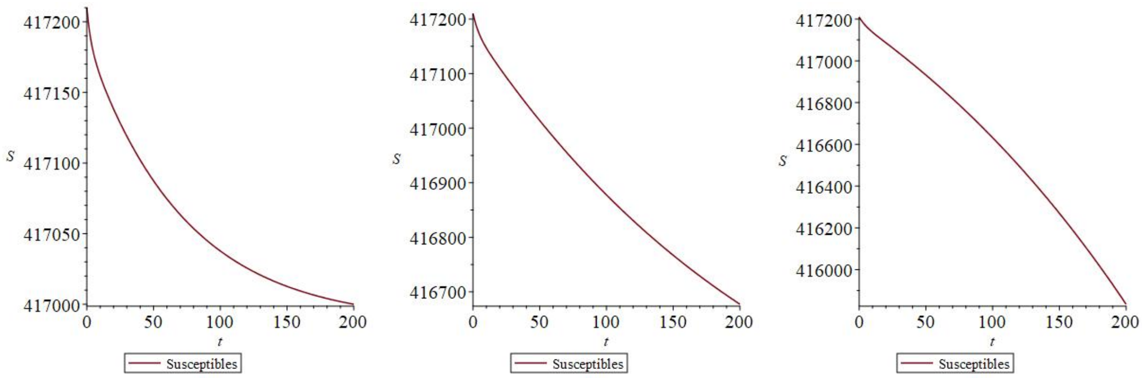


Fig. 12. Susceptible Model: $T_D = 2$ days - f = 0.9, $T_D = 4$ days - f = 0.9, and $T_D = 6$ days - f = 0.9

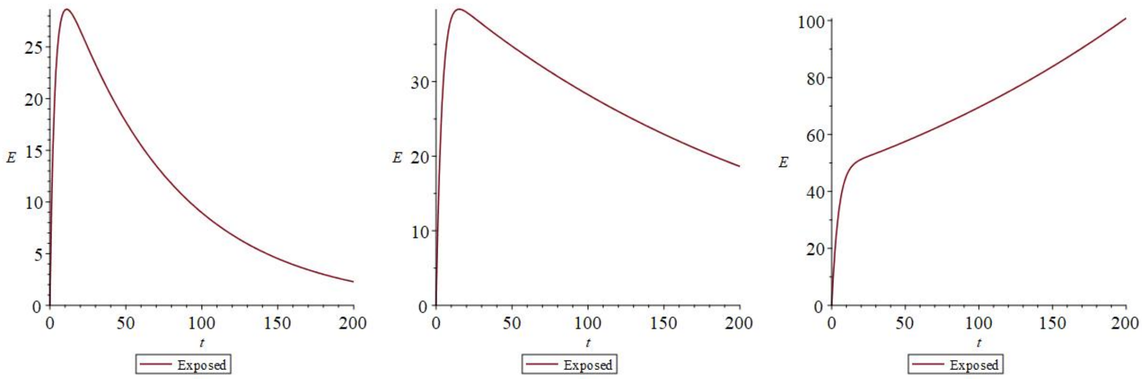


Fig. 13. Exposed Model: $T_D = 2$ days - f = 0.9, $T_D = 4$ days - f = 0.9, and $T_D = 6$ days - f = 0.9

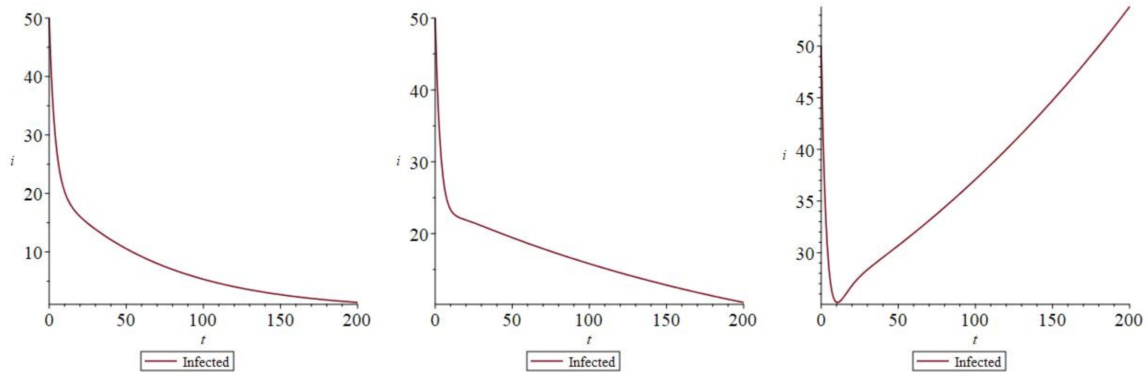


Fig. 14. Infected Model: $T_D = 2$ days - f = 0.9, $T_D = 4$ days - f = 0.9, and $T_D = 6$ days - f = 0.9

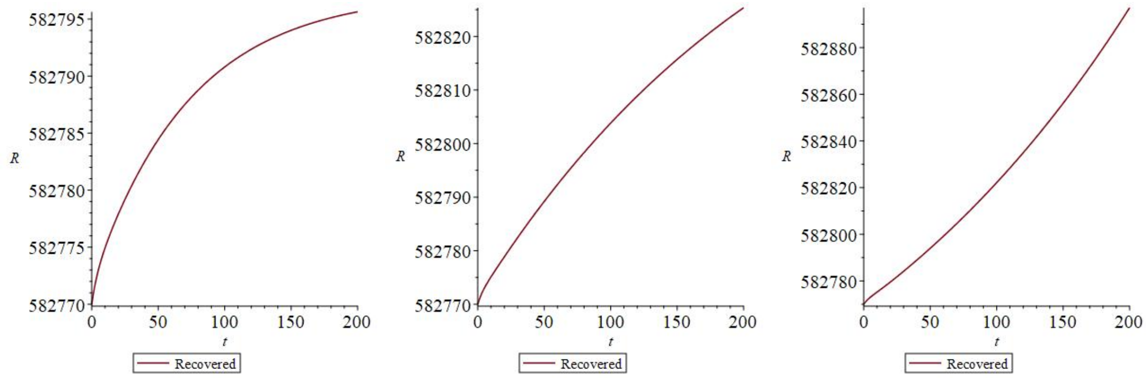


Fig. 15. Recovered Model: $T_D = 2$ days - f = 0.9, $T_D = 4$ days - f = 0.9, and $T_D = 6$ days - f = 0.9

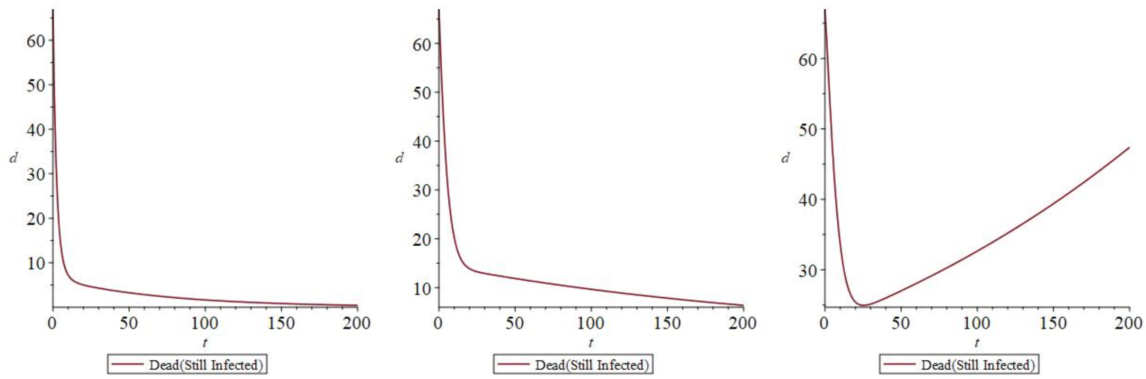


Fig. 16. Dead Model: $T_D = 2$ days - f = 0.9, $T_D = 4$ days - f = 0.9, and $T_D = 6$ days - f = 0.9

We next take a look at is what will happen when the fraction of infected individuals who die, f, is varied. The base model has f = 0.7. Since the base model is at 0.7 we took a look at f values less than 0.7 (Figures 7-11) and values greater than 0.7 (Figures 12-16). Values tested were $0 < f < 1$. After testing multiple values, the f values that represented possible events best are 0.4 and 0.9 (Figures 7-16).

For f = 0.4 the model shows that the behavior is similar to the base models for all three T_D = 2, 4, and 6 respectively. We concluded that the f = 0.4 models shows that the outbreak time line will be shorter to the base models.

For f = 0.9 the model shows a significant difference compared to base models (Figures 12-16). The epidemic models produced shows that for $T_D = 2$ or 4 days the epidemic will not die off nearly as fast. For $T_D = 2$ we see that the virus will die off in similar matter but approximately 30-50 days longer, while when $T_D = 4$ we see that the virus will not die off as quick as the base model (Figure 14). The base model shows the Ebola dying around 200 days (Figure 4), but here in the modified f value we see the virus dying off at approximately 500 days. The huge difference we see when f = 0.9 is that the virus will grow and not die off like real world data (Figure 14). Real world data shows that the outbreak's time line is approximately 2 years with most cases occurring within the first few hundred days; however, if most situations were $T_D = 6$ and if f = 0.9 the epidemic will grow fast and early (CDC Ebola 2018).

4.3 Modified T_E Models

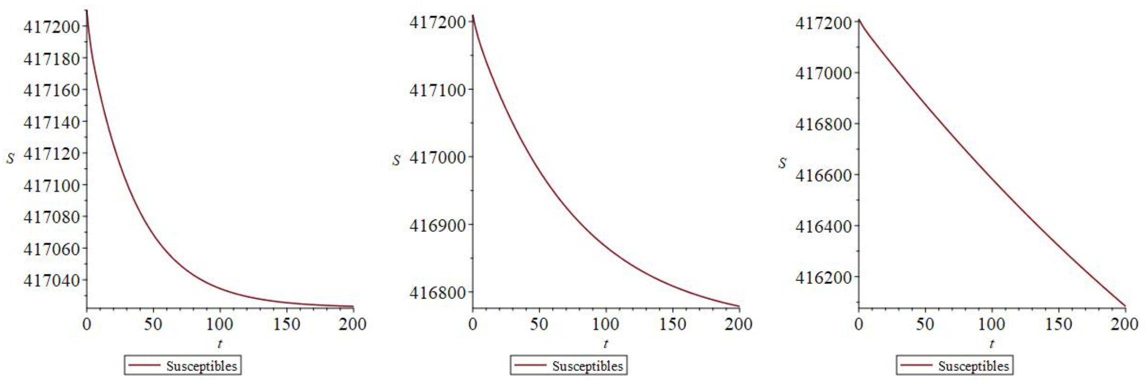


Fig. 17. Susceptible Model: $T_D = 2$ days - $T_E = 4$, $T_D = 4$ days - $T_E = 4$, and $T_D = 6$ days - $T_E = 4$

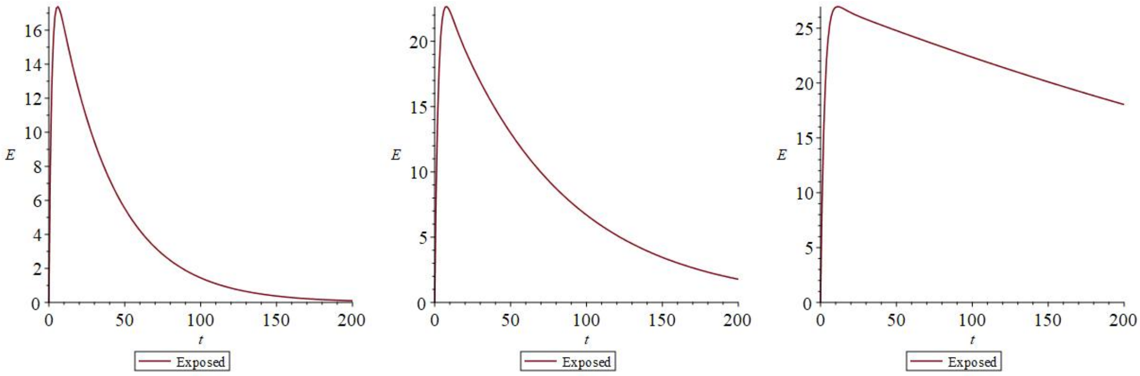


Fig. 18. Exposed Model: $T_D = 2$ days - $T_E = 4$, $T_D = 4$ days - $T_E = 4$, and $T_D = 6$ days - $T_E = 4$

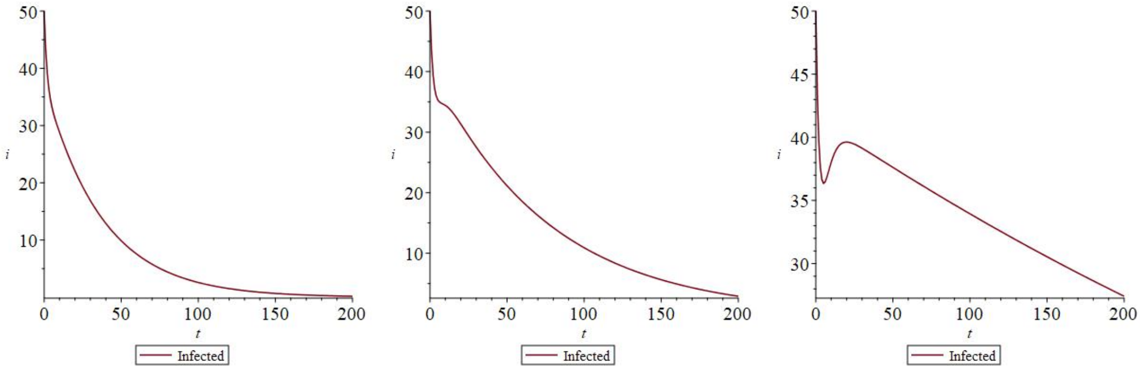


Fig. 19. Infected Model: $T_D = 2$ days - $T_E = 4$, $T_D = 4$ days - $T_E = 4$, and $T_D = 6$ days - $T_E = 4$

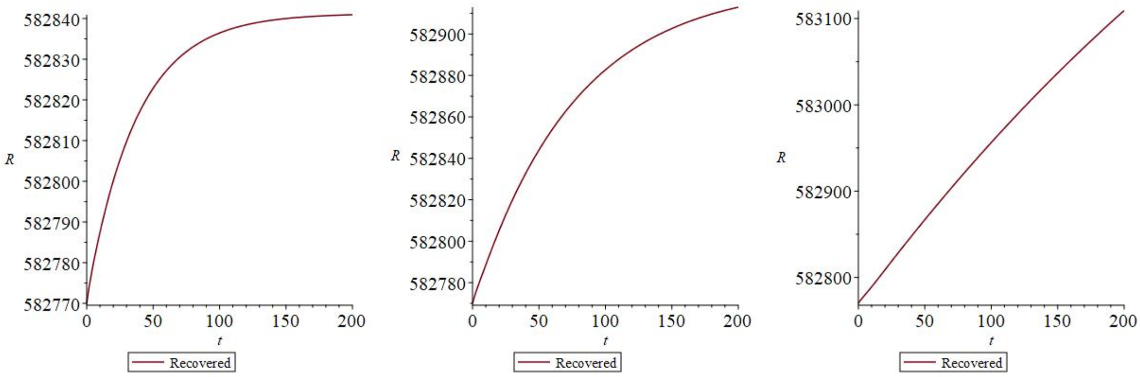


Fig. 20. Recovered Model: $T_D = 2$ days - $T_E = 4$, $T_D = 4$ days - $T_E = 4$, and $T_D = 6$ days - $T_E = 4$

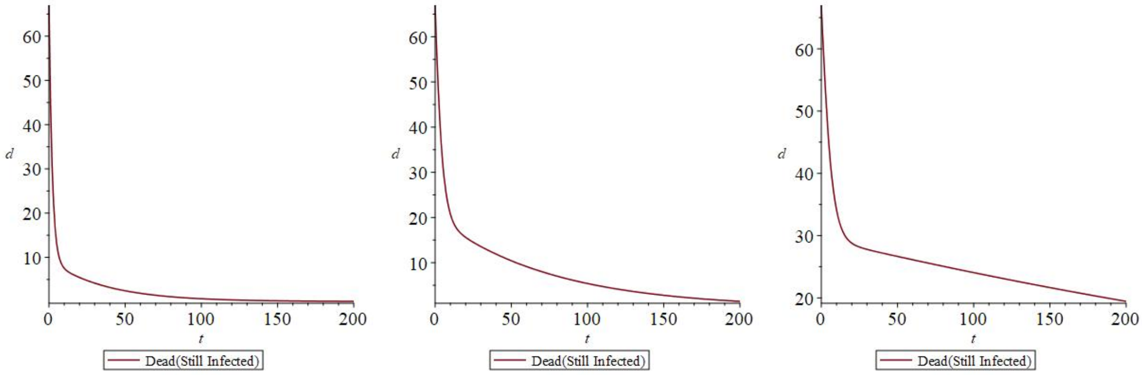


Fig. 21. Dead Model: $T_D = 2$ days - $T_E = 4$, $T_D = 4$ days - $T_E = 4$, and $T_D = 6$ days - $T_E = 4$

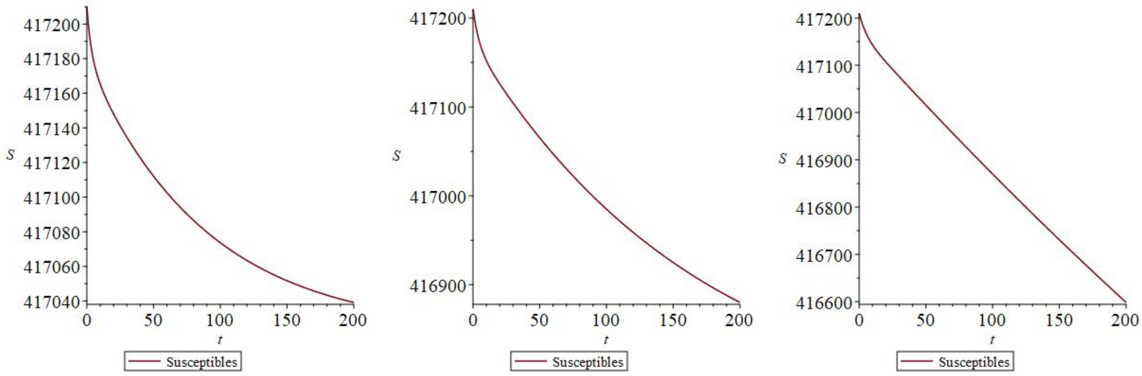


Fig. 22. Susceptible Model: $T_D = 2$ days - $T_E = 18$, $T_D = 4$ days - $T_E = 18$, and $T_D = 6$ days - $T_E = 18$

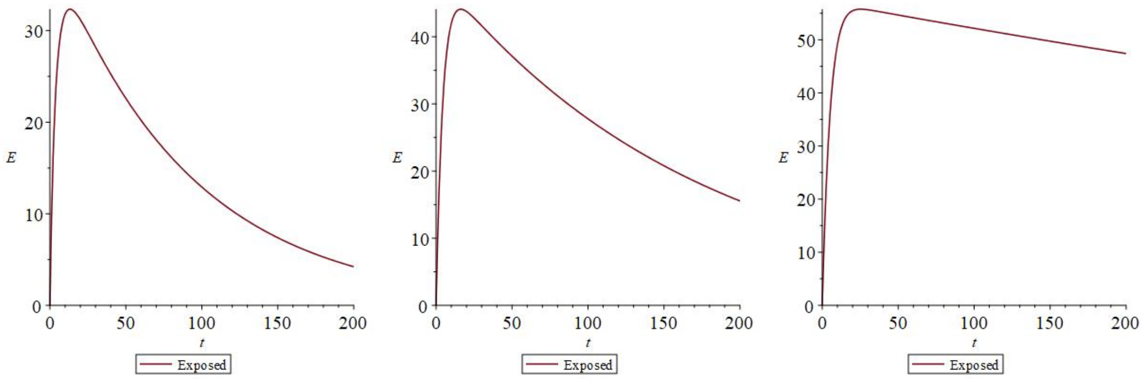


Fig. 23. Exposed Model: $T_D = 2$ days - $T_E = 18$, $T_D = 4$ days - $T_E = 18$, and $T_D = 6$ days - $T_E = 18$

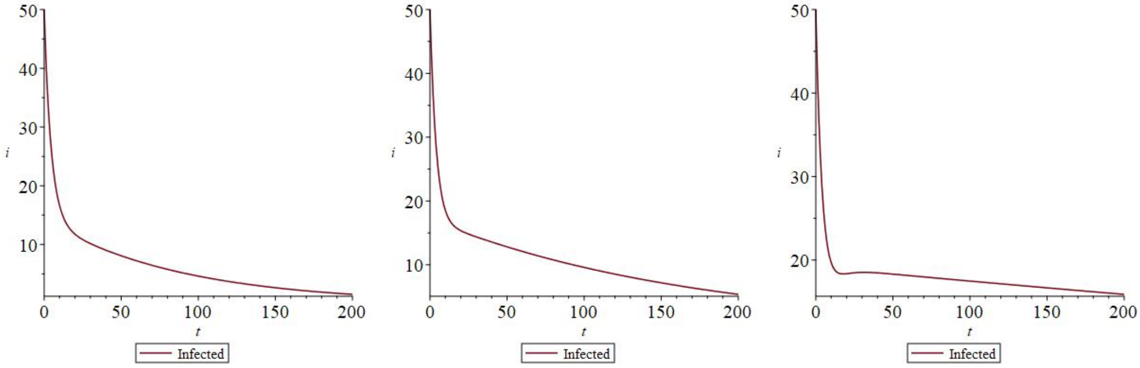


Fig. 24. Infected Model: $T_D = 2$ days - $T_E = 18$, $T_D = 4$ days - $T_E = 18$, and $T_D = 6$ days - $T_E = 18$

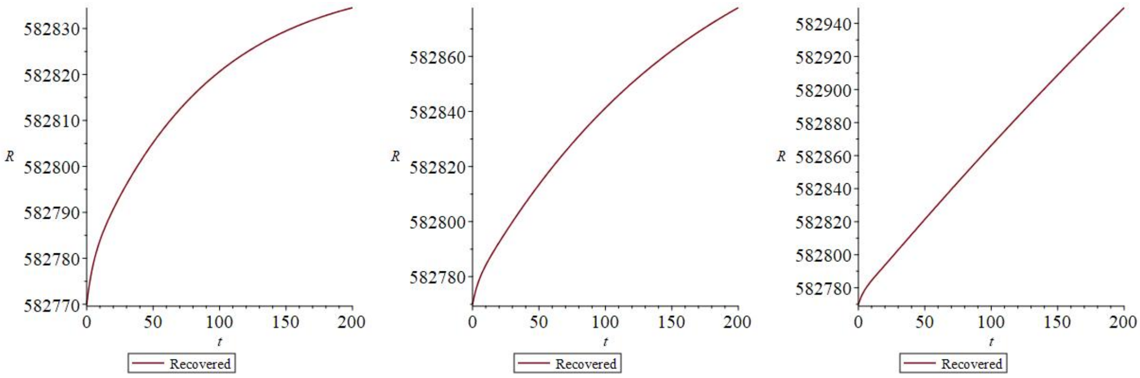


Fig. 25. Recovered Model: $T_D = 2$ days - $T_E = 18$, $T_D = 4$ days - $T_E = 18$, and $T_D = 6$ days - $T_E = 18$

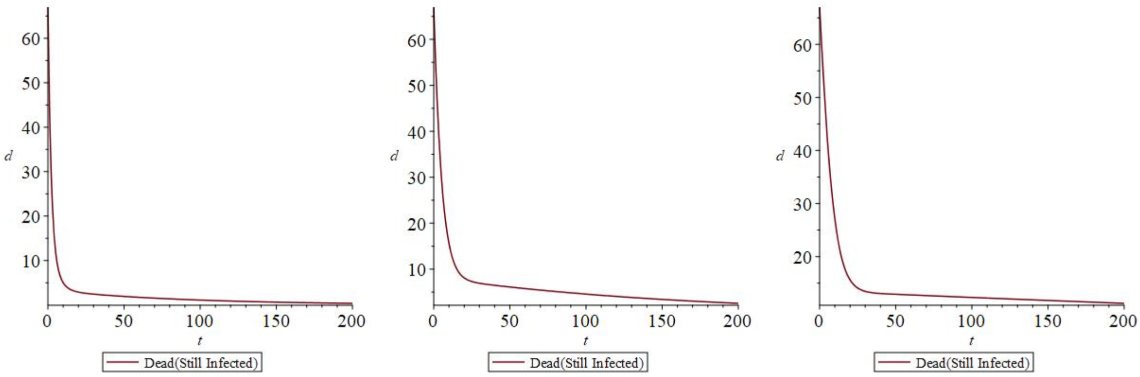


Fig. 26. Dead Model: $T_D = 2$ days - $T_E = 18$, $T_D = 4$ days - $T_E = 18$, and $T_D = 6$ days - $T_E = 18$

Lastly, we looked at is the possible events with the incubation periods or T_E values. From reliable data (Ebola 2017) we see that the T_E values are from 2 to 22 or $2 < T_E < 22$. From averages collected by the CDC (CDC Ebola 2018) we set $T_E = 11$ days. From testing possible T_E values we see that at different T_E values will change the outcome of the epidemic dramatically. Again we will chose two values that represent possible results that is smaller than 11 and larger than 11. The two values that best represented the values were $T_E = 4$ and $T_E = 18$ (Figure 17-26).

First we look at $T_E = 4$ (Figure 17-21). To begin, a smaller T_E value means that people will become infected much earlier than compared to larger T_E values. Since the infection will occur early is also correlates with faster infection rates. The main conclusion is that people will get infected much faster with smaller T_E values, but leads to the infection overall dying faster (Figure 19).

Next we take a look at, $T_E = 18$ (Figure 22-26). When $T_E = 18$ this means that the average of people becoming infected will be around 18 days instead of the base model at 11 days. From the models, it shows that the if the incubation period is larger than 11 days it will benefit the humans. The larger the T_E values the higher chance the epidemic will die. With larger T_E values it allows for less chance of people getting infected because of external factors and precautions taken into place (Figure 24).

4.4 Conclusions

The primary focus of this research was to use Differential Equations to create a model representation of 2014-2016 Ebola Outbreak in Sierra Leone in the form of a SEIRD Model. The base model uses parameters: $T_E = 11$, $T_I = 8.5$, $T_D = 2$, 4, and 6 days, f = 0.7, $B_D = 0.20$, $B_I = 0.25$, and N = 10^6. From the production of the base models we draw possibilities from it by altering parameters to model the dynamic system. Again, the parameters we changed were: the frequency, f and the length of the exposed period, T_E. Our results showed that when f < 0.7 showed that outbreak time line will be shorter compared to base models while f > 0.7 showed an epidemic time line longer than the what was implied from the base models. On the other hand, $T_E < 11$ showed that the infected will grow faster but leads to the overall epidemic ending faster. While when $T_E > 11$ it implies that with knowledge of the infection precautions can easily be placed which leads to a possibility of the epidemic not being as catastrophic as it was.

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