# ISYE 6644 Mini Project 2: Covid-19 Simulation in Florida

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## Abstract

For the past 1.5 years, many simulation models have been established to predict the spread of covid 19 to facilitate efficient control and management. While developing a complex and precise predictive model is beyond the scope of this project, we do attempt to improve the SIR model, which was used in project 1 to simulate the spread of flu in a classroom setting. We will incorporate a few factors to the basic SIR model, including exposed period, social distancing, birth/natural death/full vaccination rate, and then utilize it to simulate the Covid-19 spread in Florida.

The results show that 1) social distancing can slow down the spread and postpone the infectious peak dramatically. 2) when birth/natural death rates and the current full vaccination rate (46%) are considered, the infectious peak drops from 25% to 12%. When full vaccination rate reaches 80%, the infectious peak drops to 8% and becomes 0% after around Day 100. Therefore, both social distancing and vaccination are effective measures to prevent the pandemic spread.

A few limitations, such as lack of consideration for population mobility and the effectiveness of partial vaccination, constant transmission rate, are also discussed in the conclusion. Future research potentials are also proposed.

## Introduction

In mini project 1, we used the SIR (Susceptibles-Infected-Removed) model to simulate the spread of flu in a classroom setting with 21 students. Transmission rate and recovery rate are calculated to simulate how quickly susceptible students are infected and later recovered. Yet this scenario is trivial and some of its assumptions, such as lack of isolation rule (please refer to the report of our mini project 1), are somewhat unrealistic.

In this project, we attempt to improve the SIR model by considering other significant factors. Specifically, we will add social distancing, birth, natural death, and full vaccination rate, and utilize the modified models to simulate the Covid-19 spread in the state of Florida.

# Background and Description of Problem

## Background

First reported in December 2019 in Wuhan China, Covid-19 has already caused severe societal, economic, and political disruption across the world. Since the first case in the United States recorded on Jan 20, 2020, this pandemic has resulted in more than 33.7M cases and 605K deaths(https://news.google.com/Covid-19/map?hl=en-US&mid=%2Fm%2F09c7w0&gl=US&ceid=US%3Aen). To facilitate efficient control and management, many simulation models have been established in the first few months of the outbreak to predict how long it will last and how widely it will spread. Most of them, however, appeared to be far away from the number of real cases, due to the extremely sophisticated transmission pattern of Covid-19. With that being said, developing a complex and relevantly precise simulation model is definitely beyond the scope of this project, yet we still attempt to add a few more parameters to extend the basic SIR model that we used in our first mini project. We will use Florida as an example and assess the effectiveness of social distancing and vaccination.

In our first project, we have already explained the three components of the SIR model. Here we would like to briefly review the formula and variables as follows.

$$\text{Susceptible} \xrightarrow{\frac{\beta S I}{N}} \text{Infectious} \xrightarrow{\gamma I} \text{Recovered}$$

Figure 1: The Classic SIR model

S(t) stands for Susceptible, counting how many individuals, at time t, that have the possibility to get infected. t can be hours or days.

I(t) stands for Infected, representing how many there are in category I at time t.

R(t) is Removed, which is the number of individuals in the R category at time t (both recovered or passed away) (http://hplgit.github.io/prog4comp/doc/pub/._p4c-solarized-Python021.html).

The corresponding differential equations are:

$$\frac{dS}{dt} = -\frac{\beta SI}{N}$$
$$\frac{dI}{dt} = \frac{\beta SI}{N} - \gamma I$$
$$\frac{dR}{dt} = \gamma I$$

- γ is the recovery rate, which can be calculated as γ = 1/length of infectious period.
- γI is the rate at which infected people recover and become resistant to further infection.
- $R_0$, the Basic Reproduction Number, is the expected number of cases directly generated by one case in a population where all individuals are susceptible to infection (Davahli, Karwowoski, Sonmez, and Apostolopoulos, 2020).
- β is the transmission rate, It can be calculated by multiplying the transmission risk with the average number of contacts per day: $\beta = R_0 * \gamma$.
- N is the total population which equals to S+I+R.
- βSI/N is the rate at which the susceptible group interacts with the infectious group and gets infected.

## Estimated Parameter Values

Previous studies have estimated that the incubation and infectious periods of Covid-19 range from 3.3 to 7.9 days and 1.7 to 5.6 days, respectively (Boldog, Tekeli, Vizi, Denes, Bartha and Rost, 2020). We chose the medium values for both periods (an incubation period = 5.6 days and an infectious period = 3.6 days). The two models (SIR and SEIR) we used in this project calculate recovery rate differently. The former combines both incubation and infectious periods to calculate the recovery rate, $\gamma=1/(5.6+3.6) = 0.11$. The second model only uses the infectious period that $\gamma=1/3.6 = 0.28$. The majority of the estimates for $R_0$ in previous studies of Covid-19 range between 2 and 3. Again, we chose the medium 2.5 as our $R_0$. For the SIR model, $\beta = 2.5*0.11 = 0.275$, whereas for the SEIR model, $\beta = 2.5*0.28 = 0.7$.
https://jckantor.github.io/CBE30338/03.09-COVID-19.html

As we mentioned in Project 1, Collins and Abdela(2008) argue that it makes more sense to consider the proportions of each type of individual rather than their actual number. Then the new formulas are:

$$\frac{ds}{dt} = -\beta si$$
$$\frac{di}{dt} = \beta si - \gamma i$$
$$\frac{dr}{dt} = \gamma i$$

Where s = S/N, i = I/N, r = R/N

While the basic SIR model provides valuable information in the early stage of a pandemic, it does not take the characteristics of the epidemic and people’s reactions into account. It can be improved by adding more compartments and parameters. The following sections discuss a few modified models, including the SEIR model (with and without social distancing), and the SIR model plus a few additional parameters, such as birth, natural death, and full vaccination rates.

## The SEIR model

### Without social distancing

For Covid-19 infections, there is a significant latency period during which individuals have been exposed to the virus yet show no symptoms and are not infectious. This period has been modeled as compartment E (exposed) in the SEIR model.

$$\text{Susceptible} \xrightarrow{\frac{\beta SI}{N}} \text{Exposed} \xrightarrow{\alpha E} \text{Infectious} \xrightarrow{\gamma I} \text{Recovered}$$

Figure 2: The SEIR model

- $\beta SI/N$ is the rate at which a susceptible group interacts with an infected group, getting infected yet not infectious.
- $\alpha^{-1}$ is the mean latent period for the disease. Since the incubation period is 5.6 days, $\alpha=1/5.6 = 0.18$.
- $\alpha E$ is the rate at which the exposed population becomes infectious.
- $\gamma I$ is the rate at which infected people recover and become resistant to further infection.

The corresponding differential equations are:

$$\frac{ds}{dt} = -\beta si$$
$$\frac{de}{dt} = \beta si - \alpha e$$
$$\frac{di}{dt} = \alpha e - \gamma i$$
$$\frac{dr}{dt} = \gamma i$$

## With social distancing

For the first year of Covid-19 spread, no vaccine was available and social distancing, face mask, and quarantine were considered effective measures to mitigate the pandemic spread. We will incorporate social distancing to our SEIR model using the parameter u, which indicates the effectiveness of isolation control. $u \in [0,1]$. $u = 0$ means no social distancing at all. $u = 1$ meaning perfect isolation (Pan, Yao, Liu, Li, Wang, Dong, Kan, and Wang 2020). We would like to explore how social distancing strategy can affect the spread of an epidemic.

$$\text{Susceptible} \xrightarrow{(1-u)\frac{\beta SI}{N}} \text{Exposed} \xrightarrow{\alpha E} \text{Infectious} \xrightarrow{\gamma I} \text{Recovered}$$

Figure 3: The SEIR model with social distancing

The new formulas are:

$$\begin{aligned}\frac{ds}{dt} &= -(1-u)\beta si \\ \frac{de}{dt} &= (1-u)\beta si - \alpha e \\ \frac{di}{dt} &= \alpha e - \gamma i \\ \frac{dr}{dt} &= \gamma i\end{aligned}$$

## The SIR model with birth, natural death, and the full vaccination rate

In our mini project 1, we discussed that the original SIR model assumes a constant population over time. This makes sense as flu only lasts for a short period of time (around 25 days) in a classroom setting. Covid-19, however, may last for even a few more years and thus births and natural deaths need to be considered for a larger population. Thus, we would like to integrate the birth and natural death rates into the SIR model and make it more realistic.

In 2019, the state of Florida has 220,002 live newborns and 205,426 age-adjusted deaths. Since its population is 21.48 million, the birth rate and natural death rate are roughly equal to 1%. (https://www.cdc.gov/nchs/fastats/state-and-territorial-data.htm) We use mu to represent the equal birth and death rates in the formulas.

A few potent vaccines are officially coming in the beginning of 2021. We would like to explore the effectiveness of vaccines in controlling the spread of Covid-19. We add another parameter θ to represent the full vaccination rate. As of today (July 1, 2021), around 46% of the population in Florida have been fully vaccinated (https://usafacts.org/visualizations/covid-vaccine-tracker-states/state/florida). While we understand that one dose could provide partial immunization, we only consider the full immunization cases as it is hard for us to evaluate the partial effectiveness based on our current knowledge. The following is the corresponding differential equations (Fudolig and Howard, 2021):

$$\frac{d}{d_t}S = mu * (1-\theta)N - \beta\frac{I}{N}S - mu \cdot S$$

$$\frac{d}{d_t}I = \beta\frac{I}{N}S - \gamma I - \ mu \cdot I$$

$$\frac{d}{d_t}R = mu * \theta * N + \gamma I - \ mu \cdot R$$

# Main Findings

## The SIR model

We solve the differential equations above by using the scipy.integrate.odeint package. When we use the original SIR model without considering any additional parameters (such as birth and death rate) or taking any effective non-pharmaceutical interventions (such as social distancing), the result shows that the infectious peak arrives on around Day 120 after the first positive case and almost 25% of the population in Florida can get infected. Fortunately, social distancing and face cover have been required in Florida since April, 2020, one month after the detection of the first case on March 1, 2020 in Hillsborough County (https://www.wptv.com/coronavirus/first-coronavirus-cases-in-florida-announced-1-year-ago ) . Interestingly, the susceptible and removed population will become stable at the rates of 10% and 90% after the peak, which may suggest the effect of herd immunity.

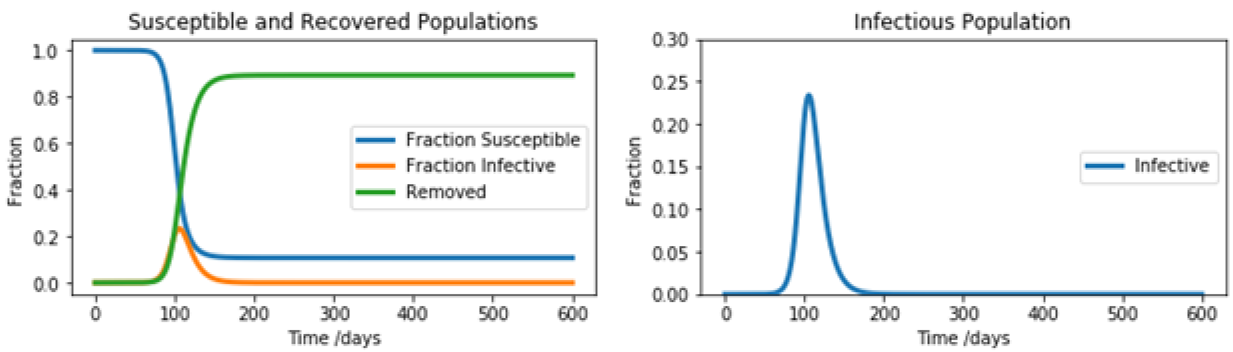


Figure 1. Result of the basic SIR model

## The SEIR model

Without social distancing, the infectious peak arrives around Day 140-150, with a lower infection rate (around 10%) as some people are just exposed to viruses and still in the latent period (around 15%). The result indicates that the addition of the Exposed compartment slows the outbreak slightly, yet it does not reduce the number of people who are eventually infected.

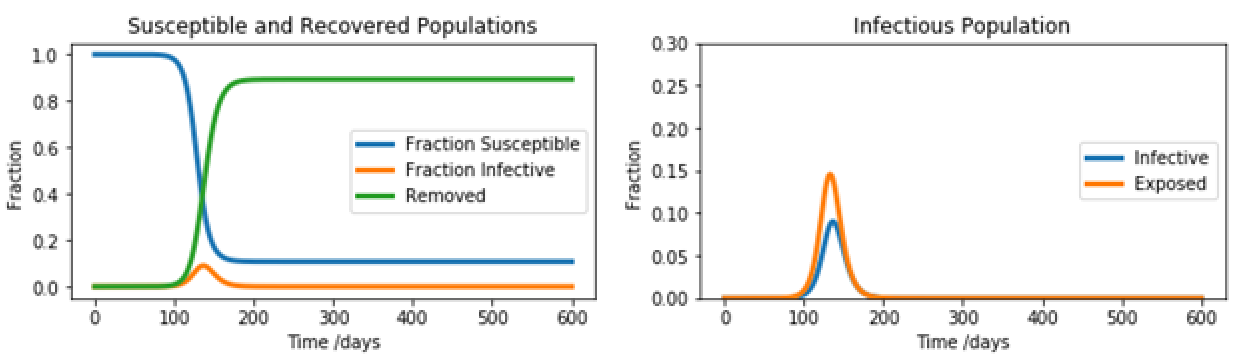


Figure 2. Result of the SEIR model

When the parameter of social distancing (u=0.2) is added to the SEIR model (Figure 3), the progress of the epidemic has been significantly slowed, reaching its peak on around Day 180-190. As well, the proportions of the infected and exposed population have been reduced to 5% and 10%, respectively.

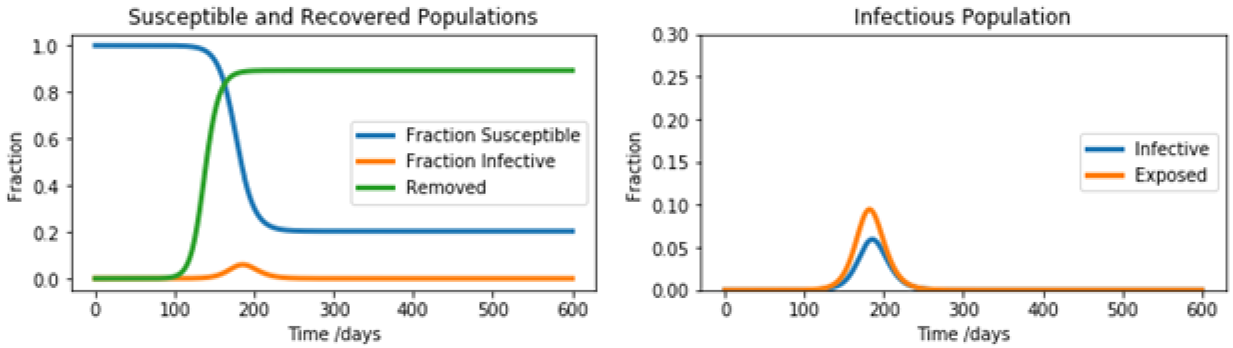


Figure 3. Result of the SEIR model plus social distancing (u=0.2)

When a stricter social distancing policy is implemented (u=0.5), the spread of COVID-19 has been slowed down dramatically with the peak appearing on around Day 320 (Figure 4). In fact, Florida has hit the peak on Jan 10, 2021, 280+ days after the social distancing mandate issued on March 27, 2020, not too far away from our result. The findings indicate that social distancing is an effective measure before the availability of vaccines and can release strain on health care resources and to gain precious time for making vaccines.

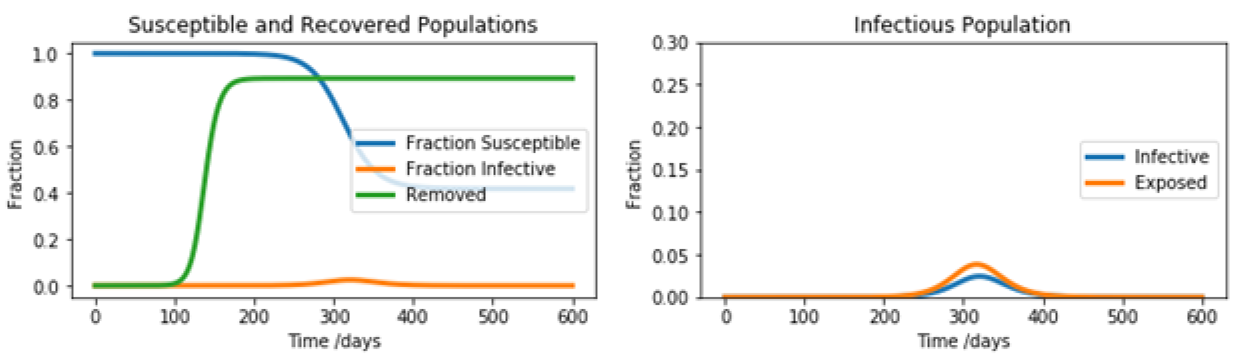


Figure 4. Result of the SEIR model plus social distancing (u=0.5)

## The SIR model with birth, natural death, and full vaccination rates

As aforementioned, with long-term pandemic, birth and natural death rates must be factored into the model for a large population. Also, a few potent vaccines have been available since 6 months ago, therefore, we will use the current status quo of the Covid-19 cases in Florida and estimate the effectiveness of the vaccine to control the pandemic. As of today, July 1, 2021, there are 133576 active cases (I), 2238956 removed cases(R), and the Susceptible Population = Total Population – I – R = 19107468. We will use them as the initial values for the formulas (https://www.worldometers.info/coronavirus/usa/florida/).

The plots show that when considering the equal birth and death rates (which is 1% in Florida) and the 46% full vaccination rate, Covid-19 reaches its peak around Day 50 with much lower infection rate, around 12% when compared to the previous rate of 25% of the SIR model (Figure 5). When the full vaccination rate reaches 80%, then the infectious peak drops to around 8% and will approach 0% after around Day 100 (Figure 6). The findings suggest that we should be able to wipe out Covid-19 if we vaccinate aggressively enough to 80%.

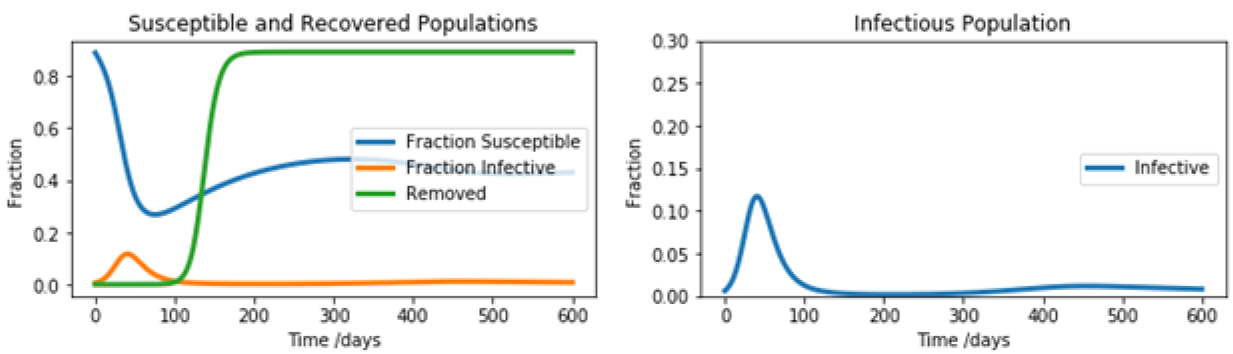


Figure 5. Result of the SIR model plus birth, natural death, and full vaccination rate (θ=0.46)

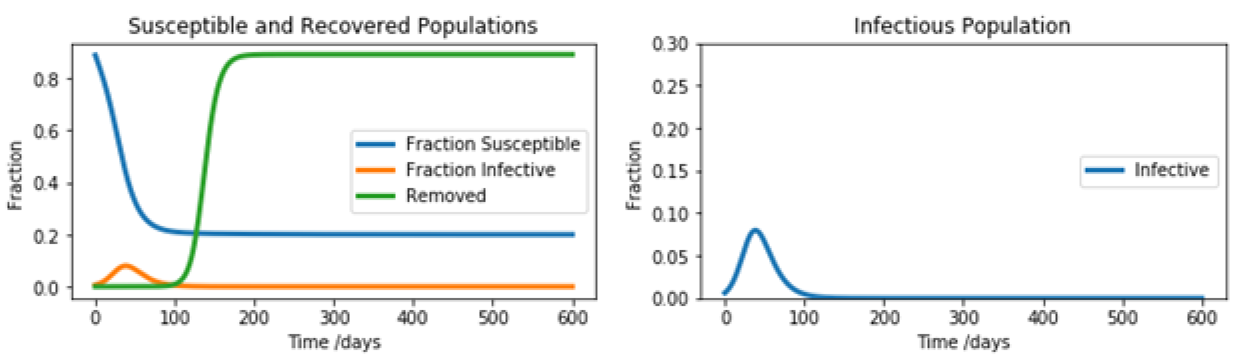


Figure 6. Result of the SIR model plus birth, natural death, and full vaccination rate (θ=0.80)

# Conclusion

This project aims to use the modified SIR models to simulate the Covid-19 spread in Florida.  Quite a few significant variables are integrated into the basic SIR model, such as the exposed period, social distancing, birth/natural death rate, and full vaccination rate.

The SEIR model shows that social distance can slow down the spread and postpone the infectious peak from around Day 140-150 to Day 180 (if the social distancing rate is 0.2) or Day 320 (if the social distancing rate is 0.5). This can gain precious time for making vaccines and release stress on medical resources.

When considering the equal birth and death rates, and full vaccination rate, the findings suggest that if vaccination rate can aggressively increase to 80%, then we will be able to reach the state of herd immunity very soon.

There is still considerable uncertainty to estimate the epidemiological characteristics due to the viral mutation. Our methods present some inherent limitations as a result of insufficient data and lack of knowledge about the more advanced simulation methods:

1. Static rather than dynamic models. In the models we developed, we assume there is no population mobility, which is unrealistic. For future research, population distribution and geographic connectivity need to be considered as they are key factors in accelerating the spreading process of epidemics.
2. Regarding the vaccination, in our proposed SIR model, we only consider how many people are fully vaccinated (two doses), yet research has suggested partial effectiveness of one dose.  We, however, lack relevant medical knowledge to measure the partial effectiveness quantitatively.
3. In this project, we added the social distance parameter to the SEIR model and considered infection latency as an E component. In the last SIR model, we added birth/death/vaccination rate. It would be better if we find relevant differential equations and integrate these parameters in one model.

4. In our proposed models, we only used the constant parameters throughout the whole simulation. In reality, however, the parameters, such as transmission rate, may change in before/after the outbreak, with/without quarantine control. Future research should use dynamic parameters during different periods.

# References


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