Analyzing the Economic Impact on COVID-19 with Vaccination Based on the Epidemiological and Economic Models

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Abstract. In December 2019, COVID-19, a novel coronavirus disease, started in China and spread worldwide. The development of COVID-19 vaccines helped many countries in this world to diminish the disturbance caused by COVID-19. In order to explore the economic influence of COVID-19 with vaccination, this paper sets up 12 different scenarios with various daily vaccination rates and vaccination efficiencies to predict the cumulative fraction of the infective population based on a modified version of the SEVIR model, which is a basic quantitative model of infectious diseases. Inspired by previous research, we utilized the G-cube (G20) Model from the Computable General Equilibrium (CGE) model to estimate the GDP growth rate in the field of microeconomics based on prediction from previous data results of the SEVIR model. According to the results from this paper, we conclude that as the increase of daily vaccination rates and vaccine efficacy, the infection growth rate will decrease inversely.

Keywords: COVID-19 · SEVIR · GDP · computable general equilibrium · economic

1 Introduction

The COVID-19 pandemic, caused by severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), is a global pandemic of coronavirus disease 2019. This virus first began in Wuhan, China, in December 2019 and spread worldwide, leading to an ongoing pandemic. The World Health Organization (WHO) has already declared a Public Health Emergency of International Concern and a pandemic in 2020. In addition, due to the emergence of several variants of COVID-19, this virus has become one of the deadliest pandemics in history science 2021. This pandemic caused serious global social and economic disturbance. It has led to a large global recession and global political tensions. Fortunately, different kinds of COVID-19 vaccines, which is a vaccine that provides immunity against SARS-CoV-2, have been developed and produced in many countries by the end of 2020 [7]. The distribution of the vaccines is crucial for countries to diminish the spread, severity, and death of COVID-19.

This paper attempts to quantify vaccines' influence on global economics under different possible scenarios by setting the United States' data as the benchmark. The goal

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of the research is to predict the impact of economics based on current data and provide useful advice for economists and policymakers to accelerate economic rehabilitation. We first summarize now available research on the macroeconomic impact on diseases based on the previous experience from the evaluation of the global economics of SARS (Lee & McKibbin 2003) and Pandemic Influenza (McKibbin & Sidorenko 2006) Then, it explains the several crucial models: SEIRV model, Computable General Equilibrium (CGE) model, and G-cube models. The paper also collects all updated epidemiological data and data on vaccination efforts from Johns Hopkins Coronavirus Resource Center to adjust the model. The last part is to discuss the consequences of different scenarios from the model and make a conclusion of suggestion to policymakers.

2 Related Research

Infectious diseases affect the economy essentially through increased mortality and morbidity. There is a negative correlation between the GDP growth rate and the reproductive rate of epidemics (Pritchett and Summers, 1996; Bloom and Sachs, 1998 [5]; Bhargava and et al., 2001; Cuddington et al., 1994; Cuddington and Hancock, 1994; Robalino et al., 2002a; Robalino et al., 2002b; WHO Commission on Macroeconomics and Health, 2001; Haacker, 2004) [6].

Utilizing the data of mortality and morbidity to estimate the loss of labor source, we can roughly conclude the economic costs of the epidemic. Take the Acquired Immune Deficiency Syndrome as an example, this kind of virus affects labor source supply and household incomes, which increases business costs. On the other hand, the spread of HIV/AIDS also increases the investment in public health. Based on the past cross-country data, it was convenient to estimate whether the HIV/AIDS prevalence rates influence the growth of the economy (Robalino et al., 2002a; Robalino et al., 2002b; Haacker, 2004). The development of the Computable General Equilibrium (CGE) Model and the Susceptible-Infected-Recovered (SIR) [1] epidemic model also can help to evaluate the economic impact of epidemics (Kambou et al., 1992; Arndt and Lewis, 2001; Bell et al., 2004; Tiberiu Harko, 2014) [2].

However, the COVID-19 is more contagious than HIV, especially during the early period of the pandemic when there is no vaccine that can be used to treat it. Many studies of the SARS epidemic in 2003 prove that there is a significant shock to many countries' economies (Liu et al., 2005; Lee and McKibbin, 2003; Hai et al., 2004) [3]. As the research and development of the vaccine of infectious diseases, the morbidity and mortality from infections will be prevented. In the United States, the incidence of infectious diseases has fallen dramatically compared to the incidence before the vaccination (Roush and Murphy, 2007). This paper extends the earlier papers by McKibbin and Fernando (2020) [4], using updated data and considering the situation of vaccination.

3 Models

This paper uses two major models, SEIRV and CGE models. Firstly, we will utilize the SEIRV model to predict the situation of pandemics and estimate the accumulative fraction of the infective and accumulative fraction of the immunity population. Then, by using the data we predicted before, we can use the CGE model to calculate the GDP growth rate and economic shock.

3.1 SEIRV Model

Inspired by the earlier SEIR model from Rajapaksha (2021) [11], We designed the new version of the Susceptible-Exposed-Infected-Recovered-Vaccinated (SEIRV) Model with vaccination. The SEIRV model, named for its 5 compartments (Susceptible, Exposed, Infected, Recovered, Vaccinated), is a basic quantitative model of infectious diseases. We can use this model to express the influence of COVID-19 on a population.

$$\frac{dS(t)}{dt} = -\alpha(S/N)^{\beta}(t)I(t) - \delta\varepsilon S(t)$$

$$\frac{dE(t)}{dt} = \alpha(S/N)^{\beta}(t)I(t) + \alpha(V/N)^{\beta}(t)I(t) - \sigma E(t)$$

$$\frac{dI(t)}{dt} = \sigma E(t) - \gamma I(t)$$

$$\frac{dR(t)}{dt} = \gamma I(t) + \mu V(t)$$

$$\frac{dV(t)}{dt} = \delta\varepsilon S(t) - \alpha(V/N)^{\beta}(t)I(t) - \mu V(t)$$

In these equations, S(t) is the number of susceptible people, E(t) is the number of exposed people (infected, but not infectious), I(t) is the number of infected people, R(t) is the number of recovered people, V(t) is the number of vaccinated people. For more detail of the parameters in this model see attached Table 1. The following section will use the SEIRV model to estimate the accumulative fraction of infective and accumulative fraction of immunity in different scenarios.

3.2 Computable General Equilibrium (CGE) Model

By using actual economic data, the CGE model is a structural economic model, involving goods markets and factor or input markets, to estimate the simulation of the effect of external factors change (e.g. Policies) on the entire economy. We selected 2020–2021 as the base year with the current economic data. Based on the method used by McKibbinand (2006) and McKibbinand Fernando (2020), we utilized the CGE model to calibrate the model to fit the data. Through the CGE model, we can find out a static change in the level of GDP growth rate.

3.2.1 G-Cube (G20) Model

The G-cube is a multi-country, multi-sector, general equilibrium model. This model is the heterogeneous model combining the Dynamic Stochastic General Equilibrium (DSGE) Models and Computable General Equilibrium (CGE) Models. This version of the G-Cube model was developed by McKibbin and Wilcoxen (1999, 2013).

Table 1. Model parameters

Parameter	Definition	Value	Reference
R0	Basic Reproduction Number	3.32	(Alimohamadi, 2020) [10]
N	Total population	3.29×10^8 (American population as a base)	Assumed
α (alpha)	Transmission coefficient	$(R_0 * \gamma)$	Derived
β (beta)	Abrogation of infectivity	1.2	(McBryde, 2020) [12]
δ (delta)	Vaccination daily rate	0.0%, 0.1%, 0.3%, 0.5%	Assumed (WHO)
ε (epsilon)	Vaccination efficacy	65%, 80%, 95%	Assumed (Olliaro, 2021)[8]
σ^{-1} (sigma)	Incubation period	5 days	(Lauer, 2020) [9]
γ (gamma)	The rate of recovery from infections	8.5 days	(Lauer, 2020)
μ^{-1} (mu)	Time to develop protective immunity after vaccination	14 days (2 weeks)	(WHO)

4 Modeling Epidemiological Scenarios

4.1 SEIRV Model

Following the SEIRV model mentioned before, we set up four assumptions of different daily rates of vaccination and three assumptions of vaccination efficacy to twelves scenarios. We explore these scenarios based on the model and the latest available data on the COVID-19 from the World Health Organization. The purpose is to demonstrate the performance of vaccination at different daily rates and vaccination efficacy.

Based on the efficacy of current vaccines, which are already commercially available. We set up tree representative assumptions (65%, 80%, 95%). In addition, according to the daily rate of vaccination in different time periods (data from WHO), we conclude four scenarios (0.0%, 0.1%, 0.3%, 0.5%). See Table 2.

4.2 G-Cube Model

According to the results of the SEIRV model, we continue to predict the economic impact of COVID-19 with vaccination, through G-CUBE, by using the same twelve assumptions we assumed before. We set the data of the United States as the benchmark and use data derived from the SEIRV model to predict mortality rates and morbidity rates. Considering the reduction of labor supply through the calculation of mortality rates and morbidity rates, we could estimate the economic shocks of the COVID-19. See Table 3.

Table 2. TResults of SEIRV

Scenario	Country	vaccination daily rate	vaccination efficiency	accumulative fraction of infective	accumulative fraction of immunity
1	America	0.0%	65%	90.5%	90.5%
2	America	0.0%	80%	90.5%	90.5%
3	America	0.0%	95%	90.5%	90.5%
4	America	0.1%	65%	87.1%	90.9%
5	America	0.1%	80%	86.4%	91.0%
6	America	0.1%	95%	85.6%	91.1%
7	America	0.3%	65%	80.6%	91.7%
8	America	0.3%	80%	78.3%	92.0%
9	America	0.3%	95%	76.0%	92.2%
10	America	0.5%	65%	74.0%	92.4%
11	America	0.5%	80%	70.1%	92.8%
12	America	0.5%	95%	66.2%	93.1%

Table 3. Results of G-CUBE

Scenario	Country	vaccination daily rate	vaccination efficiency	accumulative fraction of infective	GDP loss
1	America	0.0%	65%	90.5%	4.25%
2	America	0.0%	80%	90.5%	4.25%
3	America	0.0%	95%	90.5%	4.25%
4	America	0.1%	65%	87.1%	2.79%
5	America	0.1%	80%	86.4%	2.73%
6	America	0.1%	95%	85.6%	2.63%
7	America	0.3%	65%	80.6%	2.14%
8	America	0.3%	80%	78.3%	1.95%
9	America	0.3%	95%	76.0%	1.74%
10	America	0.5%	65%	74.0%	1.45%
11	America	0.5%	80%	70.1%	1.26%
12	America	0.5%	95%	66.2%	0.95%

5 Results of SEIRV Model Prediction

5.1 Without Vaccination

Based on the data and diagram from Table 2 scenario 1–3, there is an exponential growth in infection and exposition, then reaches the peak around 104 days and 102 days respectively, (0.12, 104) and (0.18, 102). After that, there is a decline to 0. The fraction of recovered population and susceptible population crosses at (0.37, 102). Moreover, the susceptible curve and recovered curve stabilize around 140 days at (0.1, 140) and (0.9, 140). According to the state trajectory graph, the infectious population started to decrease when the infection rate was 1.2 at (0.3, 1.2). In addition, the cumulative curve exponentially grows and reaches the peak around 95 days, (0.905, 95).

5.2 Different Vaccine Efficiencies (65%, 80%, 95%) with Daily Vaccination Rates at 0.5%

Compare and contrast the data and diagram of Table 2 scenarios 10–12, if the vaccine efficiencies are 65%, 80%, 95% when the daily vaccination rate is 0.5%, the time reaching peak around 58 days,58.5 days, 59 days respectively. Moreover, when reaching a peak for vaccine efficiencies at 65%, 80%, 95%, there are 0.04, 0.045, 0.055 fractions of the population vaccinated respectively shown in the vaccination curve. When reaching a peak for vaccine efficiencies at 65%, 80%, 95%, there are 0.13, 0.12, 0.11 fractions of the population exposed respectively shown in the explosion curve. When reaching a peak for vaccine efficiencies at 65%, 80%, 95%, there are 0.085, 0.07, 0.075 fractions of the population infected respectively shown in the infection curve. In-state trajectory graphs, when the vaccine efficiencies were at 65%, 80%, 95%, the infectious population started to decrease when the infectious population was 0.8, 0.7, 0.6 respectively. When the vaccine efficiencies were at 65%, 80%, 95%, there are 0.740, 0.701, 0.662 accumulative fractions of the infective population and 0.924, 0.928, 0.931 accumulative fractions of the immunity population respectively shown in the cumulative curve.

5.3 Different Daily Vaccination Rates (0.0%, 0.1%, 0.3%, 0.5%) with Vaccine Efficacy at 95%

Compare and contrast the data and diagram of Table 2 scenario 3, 6, 9, 12, if the daily vaccination rate are 0.0%, 0.1%, 0.3%, 0.5%, when the vaccination efficacy is 95%, the time reaching peak around 102 days, 108 days, 59 days, 61 days respectively. Moreover, when reaching peak for daily rate at 0.0%, 0.1%, 0.3%, 0.5%, there are 0.0, 0.015, 0.04, 0.055 fraction of population vaccinated respectively showed in the vaccination curve. When reaching peak for daily rate at 0.0%, 0.1%, 0.3%, 0.5%, there are 0.18, 0.15, 0.14, 0.11 fractions of population exposed respectively showed in the explosion curve. When reaching peak for daily rate at 0.0%, 0.1%, 0.3%, 0.5%, there are 0.12, 0.095, 0.14, 0.11 fractions of population infected respectively showed in the infection curve. In state trajectory graphs, when the daily rate of the vaccination is 0.0%, 0.1%, 0.3%, 0.5%, the infectious population started to decrease when the infectious is 1.2, 1.0, 0.9, 0.7 respectively. When the daily rate of the vaccination is 0.0%, 0.1%, 0.3%, 0.5%, there are 0.905, 0.865, 0.760, 0.662 accumulative fraction of infective population and 0.905, 0.911, 0.922, 931 accumulative fraction of immunity population respectively showed in the accumulative curve.

6 Results of G-Cube Model Prediction

Based on the data from Table 3 Scenario 1–3, we predict that COVID-19 causes a GDP loss of about 4.25% without the intervention of the vaccination. Compare and contrast the data and diagram of Table 3 scenarios 10–12, if the vaccine efficiencies are 65%, 80%, 95% when the daily vaccination rate is 0.5%, the GDP loss is about 1.45%, 1.26%, 0.95% respectively. Compare and contrast the data and diagram of Table 2 scenario 3, 6, 9, 12, if the daily vaccination rate are 0.0%, 0.1%, 0.3%, 0.5%, when the vaccination efficacy is 95%, the GDP loss is about 4.25%, 2.63%, 1.74%, 0.95%.

7 Discussion

Generally, the results display that with the increase of daily vaccination rates and vaccine efficacy, the infection growth rate will decrease inversely.

1. When the daily vaccination rate keeps the same, as the vaccine efficacy increases, the vaccinated population increases, and the infectious population decreases.
2. When the vaccine efficacy keeps the same, as the daily vaccination rate increases, the vaccinated population increases, and the infectious population decreases.
3. When the daily vaccination rate reaches 0.3%, the time of infectious population reaching peak significantly shorten.
4. The marginal utility of both factors is diminishing because of the increase in the vaccinated population.
5. The increase of daily vaccination rate is more efficient to decrease the infectious population than increasing the vaccine efficacy.
6. There is about a total GDP loss of 4.25% without vaccination. However, if we implement the most efficient vaccine with the highest daily vaccination rate, the total GPD loss decrease to 0.95%, which is about four times less than the 4.25%.

8 Conclusion

This paper attempts to evaluate and predict the epidemiological and economic influence of COVID-19 with various vaccination scenarios. The modified SEIRV model and G-cube from the CGE model are essential to analyze the pandemic impacts. Based on the SEVIR model, we simulated and draw diagrams to illustrates the changing process of susceptible and recovered populations under different vaccination situations. According to the figures and data gained from models, we concluded the relationship between economics and COVID-19 with vaccination. From the epidemiological aspect, as the vaccine efficacy and the daily vaccination rate increase, the infectious population decrease but the immunity population increase. The daily vaccination rate has a more

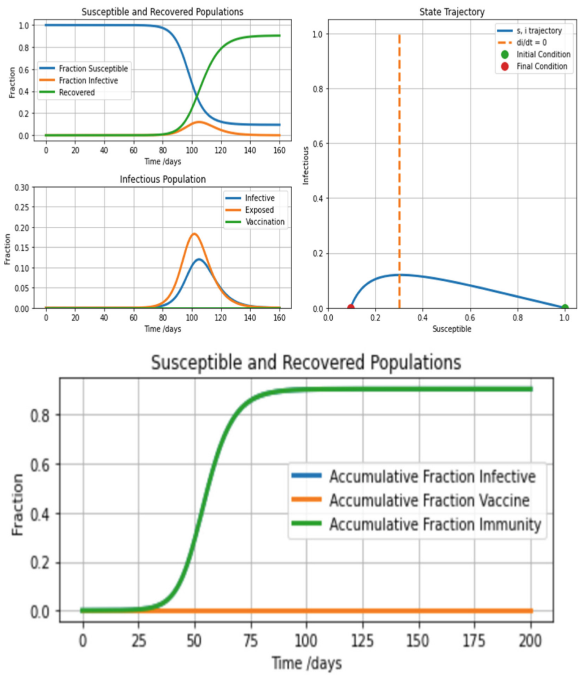

Fig. 1. Vaccine efficacy 65% and daily vaccination rates 0.0%

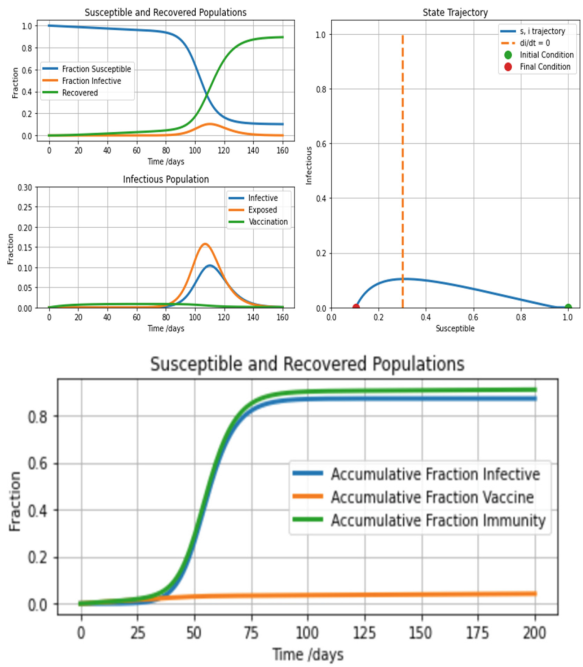

Fig. 2. Vaccine efficacy 65% and daily vaccination rates 0.1%

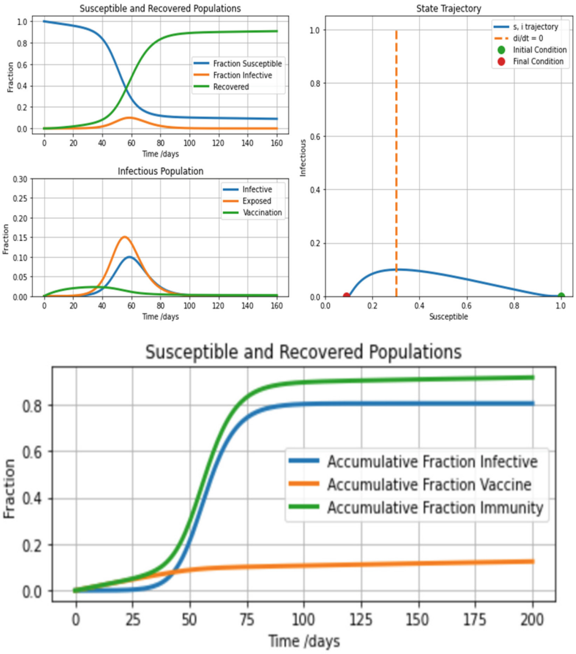

Fig. 3. Vaccine efficacy 65% and daily vaccination rates 0.3%

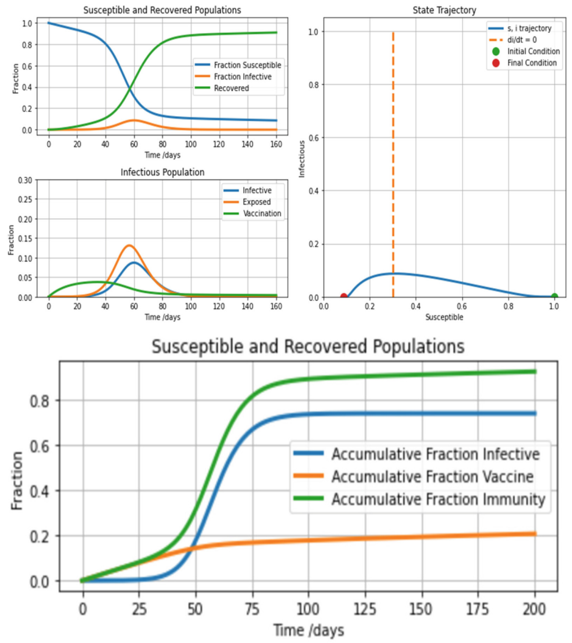

Fig. 4. Vaccine efficacy 65% and daily vaccination rates 0.5%

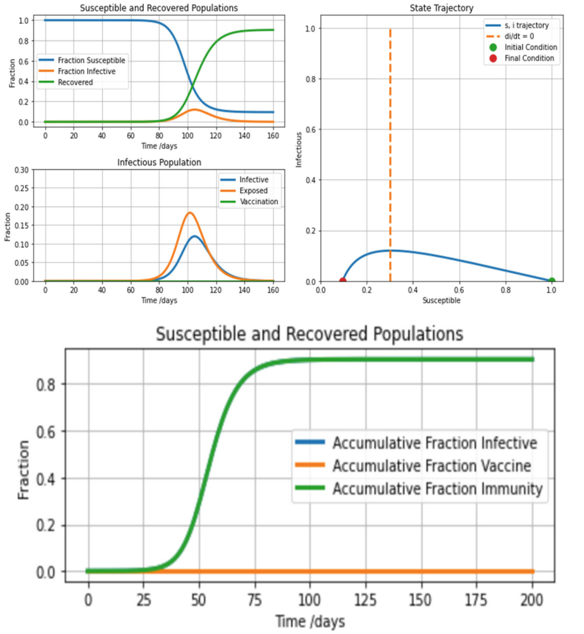

Fig. 5. Vaccine efficacy 80% and daily vaccination rates 0.0%

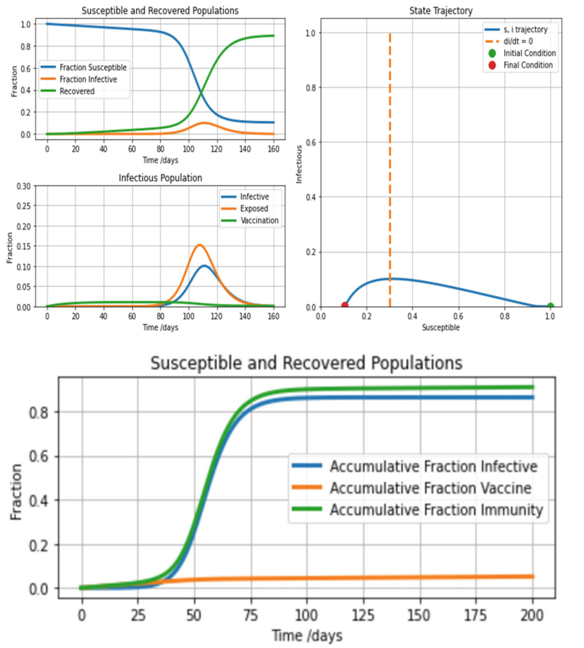

Fig. 6. Vaccine efficacy 80% and daily vaccination rates 0.1%

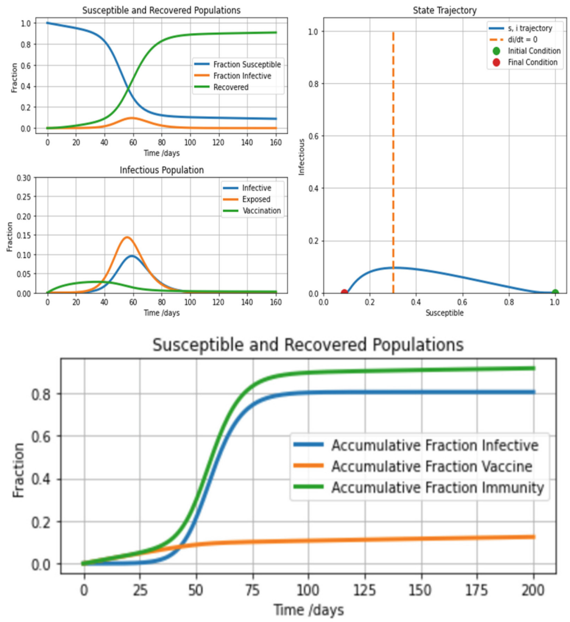

Fig. 7. Vaccine efficacy 80% and daily vaccination rates 0.3%

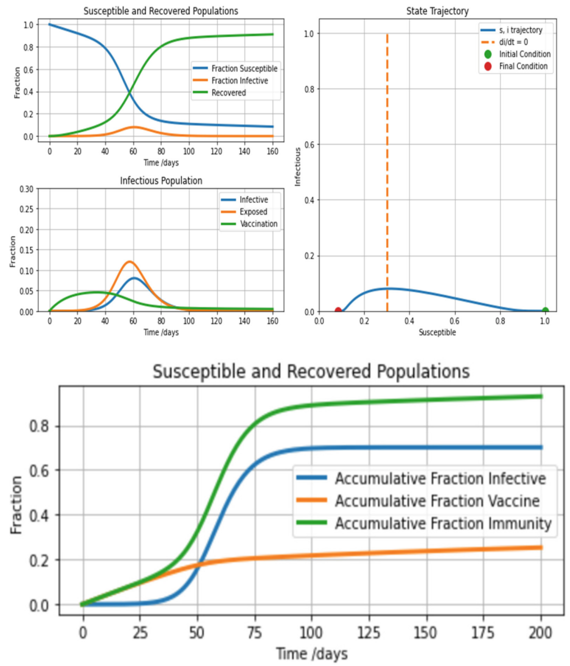

Fig. 8. Vaccine efficacy 80% and daily vaccination rates 0.5%

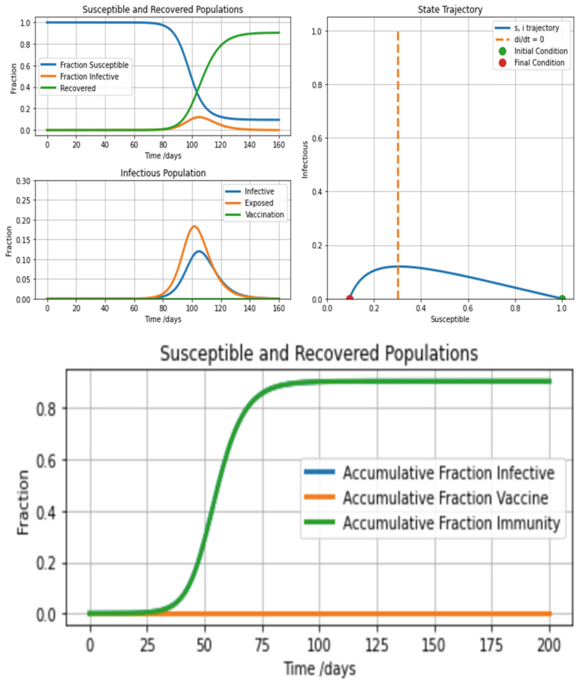

Fig. 9. Vaccine efficacy 95% and daily vaccination rates 0.0%

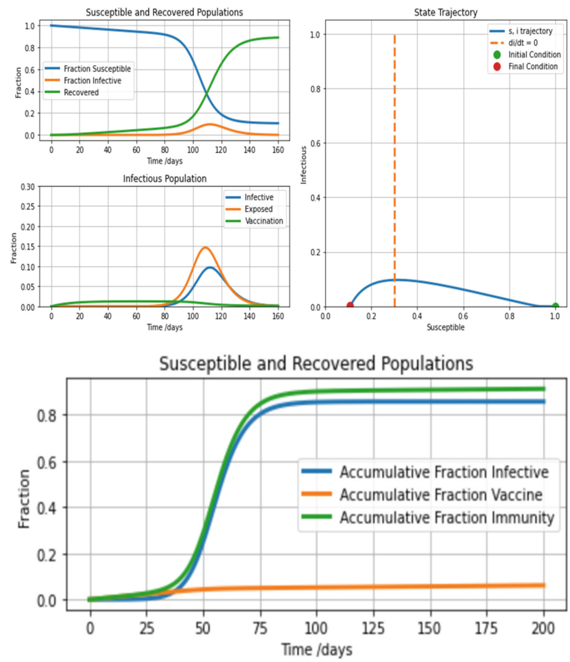

Fig. 10. Vaccine efficacy 95% and daily vaccination rates 0.1%

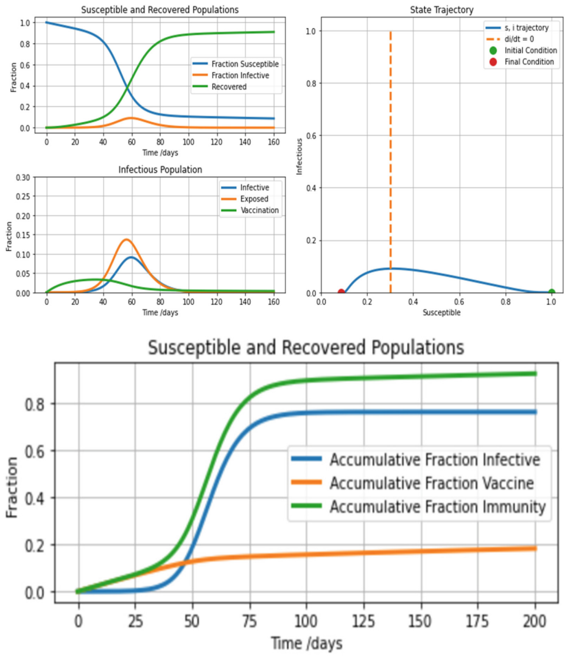

Fig. 11. Vaccine efficacy 95% and daily vaccination rates 0.3%

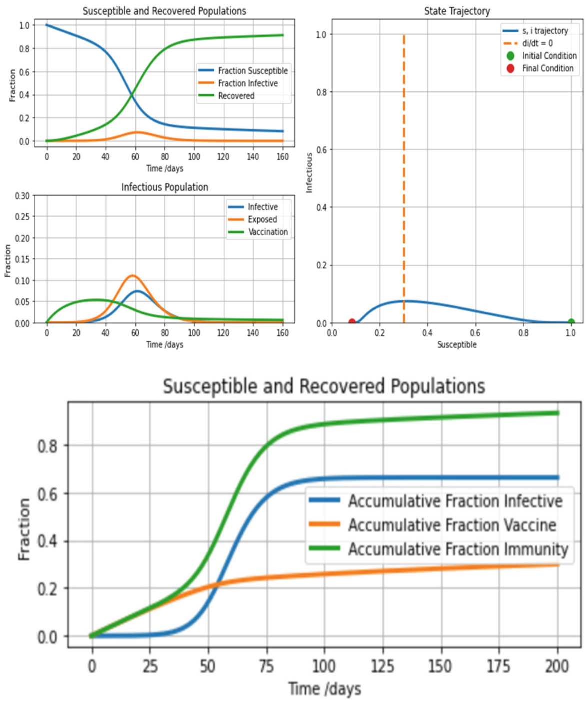

Fig. 12. Vaccine efficacy 95% and daily vaccination rates 0.5%

efficient effect on decreasing the infective population than the vaccine efficacy. From the economic aspect, as the vaccine efficacy and the daily vaccination rate increase, the GDP loss will increase. The efficient intervention with vaccination can at most decline the GDP loss about four times (Figs. 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11 and 12).

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