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(出版者 / Publisher)
法政大学比較経済研究所 / The Institute of Comparative Economic Studies, Hosei University

(雑誌名 / Journal or Publication Title)
Journal of International Economic Studies

(巻 / Volume)
36

(開始ページ / Start Page)
139

(終了ページ / End Page)
156

(発行年 / Year)
2022-03

(URL)
https://doi.org/10.15002/00025452

Journal of International Economic Studies (2022), No.36, 139–156


# A Comparison of Behavior-Restriction and Test-and-Isolate Policies Using an Epidemiological Model

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**Abstract**

In this study, we analyze the effects of behavior-restriction and test-and-isolate policies on disease spread and the macro economy using a model that combines an epidemiological model (the Susceptible-Infected-Recovered [SIR] model) and an economic growth model (the Solow model). First, we compare the change in the spread of disease using three types of behavior-restriction policy and policy durations: 80% contact reduction over 30 days, 70% contact reduction over 60 days, and 60% contact reduction over 360 days. In each of these cases, policy adoption quickly suppresses the spread of the disease, but the disease spread resumes sometime after the policy lapses. To significantly reduce the total number of deaths in the 1,000 days following the beginning of the outbreak, behavioral restrictions would have to remain in place for considerable periods, such as a full year, and the economic losses from such a duration would be very high. Second, we show that shortening behavioral restrictions and introducing a test-and-isolate policy can reduce the spread of disease while reducing economic losses. We specifically derive an optimal policy for minimizing economic losses, excluding the cost of testing, with an upper limit on the total number of deaths associated with the disease: In the baseline analysis, we find the optimal scenario to be behavioral restrictions producing an 80% reduction in contact (equivalent to an approximate 55% reduction in excursions) implemented over about 60 days in combination with test-and-isolate at maximum test intensity over one year.

**Keywords:** COVID-19; SIR model; Behavioral-restriction policy; Test-and-isolate policy

**JEL codes:** E00; E69

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# 1 Introduction

The novel coronavirus infection (COVID-19), which first appeared at the end of 2019, has spread worldwide with the global movement of people. To prevent the spread of the disease, many countries have placed cities on lockdown, and Japan has adopted a policy aiming to reduce contact by 80%. Behavioral-restriction policies such as lockdowns and 80% reduction in contact have been shown to be effective in preventing the spread of COVID-19; however, the economic cost is extremely high. For this reason, many economists are now studying COVID-19.[1]

While economists have adopted various approaches to their analysis of COVID-19, the analysis using a mathematical epidemiological model known as the Susceptible-Infected-Recovered (SIR) model that has drawn attention from macroeconomists. The simplest SIR model presents a model comprising a system of difference equations (or differential equations)-considering the change in three types of state over time: (1) Susceptible: those who can be infected, (2) Infectious, and (3) Recovered (including deaths). Since the SIR model is compatible with dynamic macroeconomic models, many macroeconomists have used the SIR model in their analyses since the pioneering work of Atkeson (2020).

In this study, we use the SIR model to analyze how behavioral-restriction policy and test-and-isolate policy affect disease spread and economic activity. As in Holtemoeller (2020), the model used in this study is a SIR model connected to the Solow model, a standard model in economic growth theory, making it possible to simultaneously describe not only the spread of infection but also the economic activity. The simple SIR model is further extended to consider incubation periods and patients with asymptomatic infections. Additionally, the testing costs and the possibility of case fatality rates increasing with the number of hospitalized patients (treatment limits) are considered by the model.

The main features of this study are as follows: First, we compare how the spread of the infection changed under three types of behavioral-restriction policy and policy duration: 80% contact reduction (an approximate 55% reduction in excursions) for 30 days; a 70% contact reduction (an approximate 45% reduction in excursions) for 60 days, and a 60% contact reduction (an approximate 37% reduction in excursions) for 360 days. In each case, the introduction of a policy can quickly suppress the spread of infection; however, its spread resumes after a period following the policy's end. To significantly reduce the total number of deaths

[1] For example, the National Bureau of Economic Research's (NBER) working papers concerning COVID-19 can be found at: `https://www.nber.org/nber-studies-related-covid-19-pandemic-topic-area`.

in the 1,000 days following the beginning of the outbreak, behavioral restrictions would have to remain in place for considerable periods, such as a full year, and the economic losses from such a duration would be very high.

Second, we show that rather than long-term behavioral restrictions, the introduction of a test-and-isolate policy can suppress the spread of disease while also reducing economic losses. Specifically, we derive an optimal policy for minimizing economic losses, excluding the cost of testing, with an upper limit on the total number of deaths associated with the disease: In the baseline analysis, we find the optimal scenario to be behavioral restrictions producing an 80% reduction in contact (equivalent to an approximate 55% reduction in excursions) implemented over about 60 days in combination with test-and-isolate at maximum test intensity over one year.

The main characteristic of the analysis offered in this study is that we set an upper limit on the total number of deaths and searched for the optimal policy minimizing economic loss under the condition that the upper limit on deaths is not exceeded. Holtemoeller (2020) finds that the optimal policy in the sense of maximizing economic welfare will be a mix of behavioral restrictions and test-and-isolate, but that the total number of deaths under the optimal policy will increase.

Additionally, we assume a consumer utility function to consider economic welfare, which is not necessarily consistent with the model. Moreover, the optimal policy in the sense of minimizing economic losses shows that it is not desirable to rely entirely on behavioral restrictions. Instead, this study finds that by considering an upper limit on total deaths as a constraint, even in the absence of consideration for economic welfare, the optimal policy in the sense of minimizing economic loss is a mix of behavioral restrictions and test-and-isolate. We also show that the results are robust (1) where there are restrictions to the upper limit on testing intensity, (2) where the testing costs are high, (3) where the reinfections can occur, and (4) where the exposed persons affect new infections.

Atkeson (2020) carried out pioneering research bringing SIR model analysis to the field of economics. With the subsequent spread of COVID-19, many economists have conducted analyses using the SIR model. In Holtemoeller (2020), on which the model used in this study is based, economic activity can be analyzed by connecting the SIR model with the Solow model. Moreover, Holtemoeller (2020) introduced not only the behavioral-restriction policies analyzed by Atkeson (2020), but also test-and-isolate policies, and found that a mix of behavioral-restriction and test-and-isolate policy to be desirable in maximizing economic welfare.

There is no explicit consideration given to the optimization behaviors of economic agents in the models used by Holtemoeller (2020) and in this study, since they are based on the Solow model. Then again, Eichenbaum, Rebelo and Trabandt (2020a, 2020b, 2020c) connect the SIR model to a dynamic general equilibrium model, a standard model in contemporary macroeconomics, and there are therefore analyses that simultaneously consider the optimization behaviors of economic agents.[2] In particular, Eichenbaum, Rebelo and Trabandt (2020b) analyze the role of test-and-isolate policies, relating closely to this study. However, Eichenbaum Rebelo and Trabandt (2020b) do not consider testing costs, and this is a major point of difference from this study.

The remainder of this paper is organized as follows. First, we introduce the model in Section 2. In Section 3, we compare the effects of behavioral-restriction policy through numerical experiments using the model. We also derive the optimal policy that minimizes economic losses, setting an upper limit on the total number of deaths, and confirm the robustness of the results by changing the upper limit on testing intensity and testing costs. Lastly, we conclude in Section 4.

# 2 Models

## 2.1 Baseline SIR Model

The classic epidemiological model (SIR model) considers three types of state: (1) Susceptible: those who can be infected, (2) Infectious, and (3) Recovered (including deaths). In this study, based on the model used by Holtemoeller (2020), we consider the following expanded SIR model. First, the initial population is set to 100, and this population is separated into seven categories: (1) Susceptible: those who can be infected $S_t$, (2) Exposed, $E_t$, (3) Symptomatic Infectious, $I_t$, (4) Asymptomatic Infectious, $X_t$, (5) Hospitalized, $H_t$, (6) Recovered: those who have recovered and acquired immunity, $R_t$, and (7) Dead, $D_t$. The first period of the model is assumed to be 1 day. Assuming that the number of newly infected individuals is proportional to the product of Susceptible persons, $S_{t-1}$, and Infectious persons (The sum of $I_{t-1}$ and $X_{t-1}$) in the previous

[2]When using a dynamic general equilibrium model, it is necessary to consider aspects of imperfect information, such as whether economic agents know whether they are infected, whether they can understand the spread of infection within in the macro economy, and the negative externalities of their own behavior on the infection rate in the economy as a whole, which are difficult to analyze. The topic of externalities has been addressed by Eichenbaum, Rebelo and Trabandt (2020a), and information imperfections by Eichenbaum, Rebelo and Trabandt (2020b) and Hamano, Katayama and Kubota (2020), among others.

period, the transition equation for Susceptible persons $S_t$ is given by:

$$\text{Susceptible:} \qquad S_t = S_{t-1} - \bar{\beta}\,\frac{S_{t-1}(I_{t-1} + \phi_t X_{t-1})}{Pop_0}. \tag{1}$$

Here, $\bar{\beta}$ is a parameter for new infections; for the purposes of standardization, we divide the total by the initial population. $\phi_t$ is a parameter expressing the relative infectivity of Asymptomatic Infectious persons, $X_t$, against $I_t$.

Assuming that a certain fraction, $\sigma_I$, of Exposed persons, $E_t$, transition to Symptomatic Infectious $I_t$ and Asymptomatic Infectious $X_t$, the transition equation is given by:

$$\text{Exposed:} \qquad E_t = E_{t-1} + \bar{\beta}\,\frac{S_{t-1}(I_{t-1} + \phi_t X_{t-1})}{Pop_0} - \sigma_I E_{t-1}. \tag{2}$$

Let the proportion of infected individuals $\xi$ become Symptomatic, $I_t$, and the remainder,$1-\xi$, become Asymptomatic, $X_t$. Moreover, both in Symptomatic and Asymptomatic cases, it is assumed that proportion $\gamma_I$ will recover, while a proportion of Symptomatic persons, $\gamma_H$, will become seriously ill, becoming Hospitalized persons, $H_t$. The transition equation of infected persons is given as follows:

$$\text{Symptomatic infected:} \qquad I_t = I_{t-1} + \xi\sigma_I E_{t-1} - \gamma_I I_{t-1} - \gamma_H I_{t-1}, \tag{3}$$

$$\text{Asymptomatic infected:} \qquad X_t = X_{t-1} + (1-\xi)\sigma_I E_{t-1} - \gamma_I X_{t-1}. \tag{4}$$

While proportion $\delta_H$ of Hospitalized persons recover, proportion $\mu_t$ will unfortunately die. The transition equation for Hospitalized persons $H_t$, Recovered persons $R_t$, and Deaths, $D_t$, is given as follows:

$$\text{Hospitalized persons:} \qquad H_t = H_{t-1} + \gamma_H I_{t-1} - \delta_H H_{t-1} - \mu_t H_{t-1}, \tag{5}$$

$$\text{Recovered persons:} \qquad R_t = R_{t-1} + \gamma_I (I_{t-1} + X_{t-1}) + \delta_H H_{t-1}, \tag{6}$$

$$\text{Deaths:} \qquad D_t = D_{t-1} + \mu_t H_{t-1}. \tag{7}$$

To take medical limitations into account, in this study we assume that the case fatality rate, $\mu_t$, is a function of the increase in the number of hospitalized persons relative to the population, given by the following equation:

$$\mu_t = \bar{\mu} + b_\mu \left(\frac{H_{t-1}}{Pop_{t-1}}\right)^2. \tag{8}$$

Last, the total population, $Pop_t$, is defined as follows:

$$Pop_t = Pop_0 - D_t = S_t + E_t + I_t + X_t + H_t + R_t. \tag{9}$$

## 2.2 SIR-Solow model

The baseline model described above is a system of difference equations that capture the dynamics of infection numbers, to which the Solow model is docked so that economic activity can be considered.[3] The aggregate production function is a Cobb-Douglas function, given by the following equation:

$$Y_t = A_t K_t^{\alpha} N_t^{1-\alpha}. \tag{10}$$

Note that $A_t$ is total factor productivity, $K_t$ is capital input, $N_t$ is labor input, and $\alpha$ is the cost share of capital. If total factor productivity grows uniformly at an annual growth rate of $\gamma_A$, the transition equation is given by[4]

$$A_t = A_{t-1}(1 + \gamma_A)^{1/360} \tag{11}$$

Let labor input $N_t$ be the population $Pop_t$ that is not hospitalized, and let $\lambda$ be the fraction of the labor force such that:

$$N_t = \lambda(Pop_t - H_t). \tag{12}$$

Assuming a constant savings rate, $\gamma_K$, consumption $C_t$ is given by:

$$C_t = (1 - \gamma_K)Y_t. \tag{13}$$

Moreover, taking the annual capital consumption rate to be $\delta$, the transition equation for capital stock, $K_t$ becomes:

$$K_t = (1 - \delta)^{1/360} K_{t-1} + \gamma_K Y_{t-1}. \tag{14}$$

## 2.3 Introducing behavioral-restriction and test-and-isolate policies

Here we introduce behavioral-restriction policy (contact reduction policy) and test-and-isolate policy into the model introduced above. First, we define behavioral-restriction policy to be "policy that uniformly

[3]Although it is possible to model changes in labor supply and other factors based on the optimization behavior of economic agents, as shown in Eichenbaum, Rebelo, and Trabandt (2020a, 2020b, 2020c), we use a Solow model to keep the analysis as simple as possible.

[4]Here we follow Holtemoeller (2020) in setting 1 year = 360 days.

restricts the behaviors of susceptible, exposed, symptomatic, and asymptomatic persons at rate $\nu_t$." Since at this point the behaviors of both susceptible persons, $S_t$, and infected persons ($I_t$ and $X_t$) are reduced by share $\nu_t$, contact between the two groups is reduced, and new infections are halted at $(1-\nu_t)^2$ where there are no behavioral-restriction policies. This means, for example, for an 80% contact restriction, $(1-\nu_t)^2 = 0.2$, and so $\nu_t = 0.5528$, which corresponds to a reduction in excursions of about 55%. Based on the above, the transition equation for Susceptible persons, $S_t$, and exposed persons, $E_t$, is given as follows

$$\text{Susceptible persons:} \qquad S_t = S_{t-1} - \bar{\beta}(1-\nu_t)^2 \frac{S_{t-1}(I_{t-1} + \phi_t X_{t-1})}{Pop_0}, \tag{15}$$

$$\text{Exposed persons:} \qquad E_t = E_{t-1} + \bar{\beta}(1-\nu_t)^2 \frac{S_{t-1}(I_{t-1} + \phi_t X_{t-1})}{Pop_0} - \sigma_I E_{t-1}. \tag{16}$$

The test-and-isolate policy is defined as the "policy of testing a $\theta_t$ proportion of the population, excluding hospitalized and recovered patients and isolating detected positive individuals from socioeconomic activities by having them isolate in ordinary and appropriate places." We therefore divide infected persons not by the symptomatic and asymptomatic statuses used in the model, but by whether or not they test positive. $I_t$ is untested symptomatic infected persons, $\tilde{I}_t$ is tested, symptomatic infected persons, $X_t$ is untested asymptomatic infected persons, and $\tilde{X}_t$ is tested asymptomatic infected persons. Tested infected persons $\tilde{I}_t + \tilde{X}_t$ are isolated, and the number of such persons is taken to be $U_t$. Proportion $\delta_U$ of tested infected persons $U_t$ will recover. The transition equation of infected persons is given thus:

$$\text{Untested symptomatic infected persons:} \qquad I_t = I_{t-1} + \xi\sigma_I E_{t-1} - \gamma_I I_{t-1} - \gamma_H I_{t-1} - \theta_t I_{t-1}, \tag{17}$$

$$\text{Tested symptomatic infected persons:} \qquad \tilde{I}_t = \tilde{I}_{t-1} + \theta_t I_{t-1} - \gamma_H \tilde{I}_{t-1} - \delta_U \tilde{I}_{t-1}, \tag{18}$$

$$\text{Untested asymptomatic infected persons:} \qquad X_t = X_{t-1} + (1-\xi)\sigma_I E_{t-1} - \gamma_I X_{t-1} - \theta_t X_{t-1}, \tag{19}$$

$$\text{Tested symptomatic infected persons:} \qquad \tilde{X}_t = \tilde{X}_{t-1} + \theta_t X_{t-1} - \delta_U \tilde{X}_{t-1}. \tag{20}$$

The following equations express Hospitalized persons, Recovered persons, and the total population:

$$\text{Hospitalized persons:} \qquad H_t = H_{t-1} + \gamma_H(I_{t-1} + \tilde{I}_{t-1}) - \delta_H H_{t-1} - \mu_t H_{t-1}, \tag{21}$$

$$\text{Recovered persons:} \qquad R_t = R_{t-1} + \gamma_I(I_{t-1} + X_{t-1}) + \delta_U(\tilde{I}_{t-1} + \tilde{X}_{t-1}) + \delta_H H_{t-1}, \tag{22}$$

$$\text{Total population:} \qquad Pop_t = Pop_0 - D_t = S_t + E_t + I_t + X_t + \tilde{I}_t + \tilde{X}_t + H_t + R_t. \tag{23}$$

Since persons subject to behavior restrictions and isolated infected persons are unable to participate in economic activity, labor input, $N_t$ under those policies is given by the following:

$$N_t = (1 - \nu_t)\lambda(Pop_t - H_t - U_t). \tag{24}$$

Lastly, let the cost of testing be $\Phi$ per test, such that the total cost of testing, $T_t$ is given by:

$$T_t = \theta_t(S_t + E_t + I_t + X_t)\Phi. \tag{25}$$

# 3 Main Results

## 3.1 Parameter values

Many of the parameter values in the model are similar to those in Holtemoeller (2020). According to Wang et al. (2020), the duration of COVID-19 infection is 2.3 days and the incubation period is 5.2 days; therefore, $\gamma_I = 1/2.3$ and $\sigma_I = 1/5.2$. According to the World Health Organization (2020), 80% of infections in China were mild cases with a hospital stay of about 14 days, while severe cases were hospitalized for between three to six weeks.

We therefore take the weighted average of $0.8 \times 14 + 0.2 \times 31.5 = 17.5$ as the duration of hospitalization. We thus set $\delta_H = 1/17.5$. Since Li et al. (2020) estimated that 86% of the total infected population in China would not have been tested, we set $\xi = 1/8$. $\bar{\beta}$ is set such that the basic reproduction number is $R^o = \bar{\beta}/\gamma_I = 2.3$. The relative infectivity of an asymptomatic infected person is $\phi_t = 1$.

Following Holtemoeller (2020), we set $\gamma_H = 1/7$, with initial values of exposed persons, symptomatic and asymptomatic infected persons as $E_1 = 0.1393$, $I_1 = 0.0087$ and $X_1 = 0.0610$, respectively.

The form of the case fatality rate function differs from that in Holtemoeller (2020), but it is a quadratic function of hospitalized patients to account for medical treatment limitations. Here, taking $\bar{\mu} = 0.02$, $b_\mu$ is set such that $\mu_t = 0.1$ when $H_t/Pop_t = 0.001$.

Following Holtemoeller (2020), we set the parameters of the Solow model as follows: cost share of capital $\alpha = 0.36$, saving rate (ratio of investment to GDP) $\gamma_K = 0.21$, annual growth rate of total factor productivity $\gamma_A = 0.005$, capital depletion rate $\delta = 0.035$, and labor force participation rate $\lambda = 0.545$. The initial value of total factor productivity, $A_1$, is set such that initial production, $Y_1 = 100$ and that the Solow model steady-state is achieved before the initial period.

The cost of testing is assumed to take a baseline of $\Phi = 0.1$. Holtemoeller (2020) selects an extremely small value, $\Phi = 3.3 \cdot 10^5$; however, in our analysis, we assume that the cost of testing the entire population is 10% of GDP, and set $\Phi = 0.1$.[5] We also consider a case where $\Phi = 0.3$ in the robustness check presented in Section 3.5.

### 3.2 Comparison of the effects of behavioral-restriction policies and policy durations

First, we compare behavioral-restriction policies and their effects over their duration. Specifically, we compare the effects of (1) the 80% contact reduction policy for 30 days, (2) the 70% contact reduction policy for 60 days, and (3) the 60% contact reduction policy for 360 days. In each case, the policy begins on the 30th day. Here, an 80% contact reduction means that $(1 - \nu_t)^2 = 1 - 0.8)$, as we have seen in Equation (15), and, for example, in Policy (1), we set $\nu_t = 0.5528$ for the 30 days from the 30th day, and $\nu_t = 0$ otherwise. Note that we do not consider testing in this experiment and so set $\theta_t = 0$.

Figures 1 and 2 plot the number of infections, total deaths, and GDP by the 60th and 720th day, respectively. The number of infections, so-called Active Cases, is defined as $I_t + X_t + H_t$. Total deaths are given by $D_t$, while GDP is expressed using $Y_t$. As shown in Figure 1, while contact reduction policies are in place, their efficacy in preventing infection depends on their intensity. However, as the change in infections in Figure 2 shows, once the policy ends, the spread of infection will resume, albeit with a certain time lag. In the case with an 80% reduction in contact over 30 days, the spread of infection resumes promptly after the policy lapses, with the peak of the case explosion occurring on the 112th day (52 days after the policy). In the case with a 70% reduction in contact over 60 days too, the spread of infection reappears soon after the policy, with the peak of the case explosion occurring on day 159 (69 days after the policy lapses). In the case with a 60% contact reduction over 360 days, although no re-emergence of the infection's spread is observed for a fairly long period, the spread of infection increases around day 600, with the peak of the case explosion on the 683rd day (293 days after the policy lapses). Concerning total deaths as of the 1,000th day,

[5] By transforming equation (25),

$$\frac{T_t}{Y_t} = \theta_t \frac{S_t + E_t + I_t + X_t}{Y_t} \Phi$$

we now assume that initially $Y_1 = 100$ and that the total population is $Pop_1 = S_1 + E_1 + I_1 + X_1 = 100$. Since $\theta_1 = 1$ implies that the entire population is tested, $\Phi$ can be interpreted as the ratio of the cost of testing the entire population to GDP in the initial period.

2.1% of the population would die without policy intervention, compared with 1.7% in the case with 80% contact reduction for 30 days, 1.6% in the case with 70% contact reduction for 60 days, and 0.6% in the case with 60% contact reduction for 360 days.

These results show that one month or two months of behavioral-restriction does not make a significant difference in the number of deaths and that the spread of infection returns following a time lag after the policy lapse. This means that behavioral-restriction policies are merely a way to stall until a vaccine or effective treatment can be developed. Conversely, a year of contact reduction would (at least up to the 1,000th day), significantly reduce the number of deaths, but a year of sustained behavioral restrictions would risk significant damage to the macroeconomy.

Figure 1: The effects of behavioral-restriction policies (1): Up to day 60

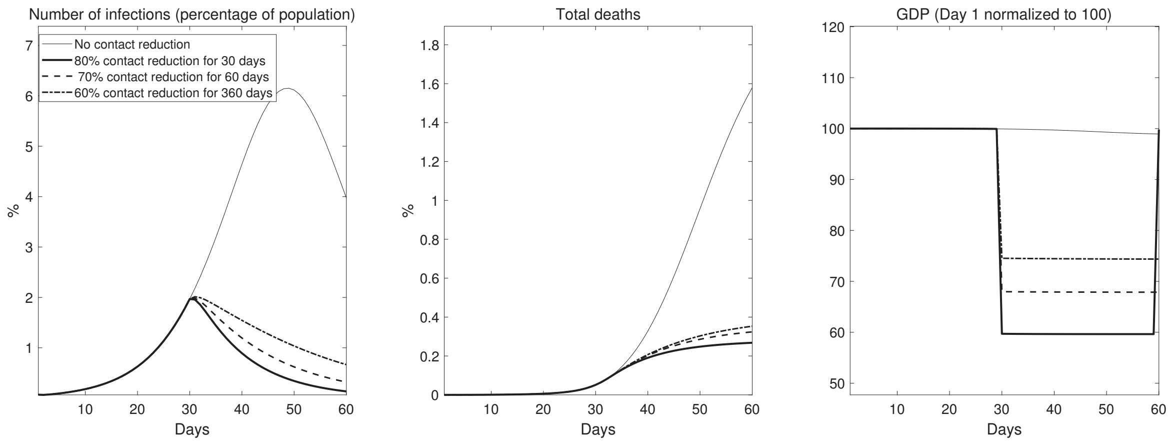
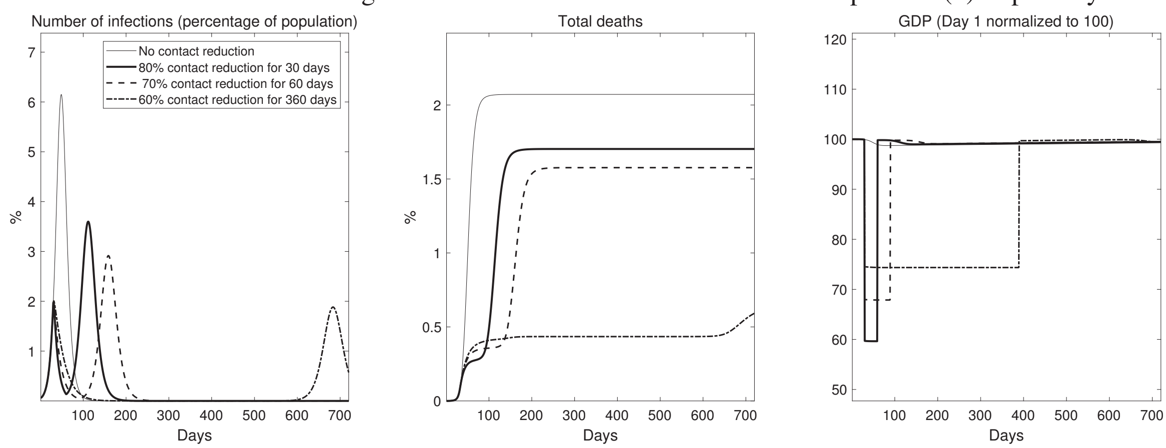



Figure 2: The effects of behavioral-restriction policies (2): Up to day 720



### 3.3 Test-and-isolate policies as alternatives to behavioral-restriction policies

We have seen the effects of behavioral-restriction policies, but prevention of the spread of infection using behavioral-restriction policy alone requires such policies to be implemented for long periods, and are highly damaging to the economy. A test-and-isolate policy could therefore be implemented in lieu of behavioral restrictions.

As shown in Equation (28), the number of new cases is determined by:

$$\bar{\beta}(1-\nu_t)^2 \frac{S_{t-1}(I_{t-1}+\phi_t X_{t-1})}{Pop_0}$$

However, if testing intensity in the previous period, $\theta_{t-1}$, is set appropriately, the number of new cases can be kept as $\nu_t$ because $I_{t-1}$ and $X_{t-1}$ are reduced through Equations (17) and(19). Here, since $\nu_t$ can finish at a lower value, labor supply, as defined by Equation (24), increases, which may also reduce the loss of economic activity.

### 3.4 An optimal policy package combining behavioral-restriction and test-and-isolate

The total number of fatalities is 0.2829% where 80% contact reduction ($(1-\nu)^2 = 1-0.8$) starts on the 30th day and continues for 360 days. Here we consider a policy package with the lowest economic loss (a behavioral-restriction and test-and-isolate combination), under the condition that the total number of deaths does not exceed this number. The economic loss when continuing 80% contact reduction for 360 days is 20.69% compared to when no infection occurs at all; and by combining test-and-isolate, we examine to what extent economic damage can be suppressed.

In this experiment, the contact reduction parameter $\nu_t$ is varied in increments of 0.05 from 0 to 0.55; the contact reduction period is varied in increments of 30 days from 0 to 360 days; the testing intensity $\theta$ is varied in increments of 0.1 from 0 to 1; the testing intensification period is varied in 30-day increments, from 0 to 360 days: We simulate and analyze the economic losses and a total number of fatalities during these periods. As before, we begin the policies at 30 days, and simulate for 720 days before calculating economic loss. To account for the cost of testing, economic loss is calculated as the percentage deviation from GDP (less the cost of testing) had there been no infection at all.

Table 1 shows the results for the optimal policy package. According to this table, to minimize economic loss, contact reduction should be limited to $\nu_t = 0.3$ (since $(1-0.3)^2 = 0.49$, this is an approximate 50%

reduction in contact) for 90 days, while testing should be increased to a maximum $\theta = 1$ and continued for one year. Economic loss, here, is 7.25%–much lower than the 20.69% economic loss incurred when 80% contact reduction is continued for 360 days.

Table 1: Optimal policy package (1)

| Contact reduction | | Increased testing | | Policy effect | |
|---|---|---|---|---|---|
| Period | $\nu$ | Period | $\theta$ | Economic loss | Total deaths |
| 90 | 0.3 | 360 | 1 | 7.25% | 0.2732% |

## 3.5 Robustness

It was shown in the previous subsection that a combination of behavioral restrictions and test-and-isolate can reduce the total number of fatalities to less than when 80% contact reduction is maintained for 360 days, while reducing economic losses. Here we confirm the robustness of this result by modifying the previous settings.

**(1) A scenario where the upper limit of testing intensity, $\theta$, is low** The upper limit for $\theta$ was set to 1 in the experiment in the previous section. $\theta_t = 1$ implies testing the entire population that is not known to be infected, but this is not always easy to do in practice. Thus, here we confirm the results when the upper limit of $\theta$ is set to lower values (0.25 and 0.1). In numerical experiments, the grid of $\theta$ is set to 0.01 increments, while all other settings remain the same as in the previous subsection.

Table 2 shows the results of experiments to find the optimal policy package when constraints are imposed on the upper limit of $\theta$. Where the upper limit on $\theta$ is 0.25, and bounded by the condition that total deaths cannot exceed the scenario with 80% contact reduction continued for 360 days, the policy minimizing economic losses should be $\nu = 0.45$ continued for 330 days, together with testing intensity $\theta = 0.25$ continued for 330 days. In this scenario, economic losses amount to 16.07%. Moreover, where the upper limit is set to 0.1, and bounded by the condition that total deaths cannot exceed the scenario with 80% contact reduction continued for 360 days, the policy minimizing economic losses should be $\nu = 0.55$ continued for 330 days, together with testing intensity $\theta = 0.08$ continued for 120 days. In this scenario, economic losses amount to 19.00%.

Although factors for minimizing economic losses such as the number of days' duration of a policy varies depending on the upper limit of $\theta$, in all cases we find that both behavioral restrictions and test-and-isolate are effective in reducing economic loss.

Table 2: Optimal policy package (2): Where there is an upper limit on $\theta$

| where $\theta \leq 0.25$ | | | | | |
|---|---|---|---|---|---|
| Contact reduction | | Increased testing | | Policy effect | |
| Period | $\nu$ | Period | $\theta$ | Economic loss | Total deaths |
| 330 | 0.45 | 330 | 0.25 | 16.07% | 0.2823% |

| where $\theta \leq 0.1$ | | | | | |
|---|---|---|---|---|---|
| Contact reduction | | Increased testing | | Policy effect | |
| Period | $\nu$ | Period | $\theta$ | Economic loss | Total deaths |
| 330 | 0.55 | 120 | 0.08 | 19.00% | 0.2820% |

**(2) A scenario where the cost of testing, $\Phi$, is high** The cost of testing was assumed to be $\Phi = 0.1$ in the experiment in the previous subsection. We set $\Phi = 0.3$, which is three times the baseline cost of testing, to confirm the robustness of the results. The parameter values and experiment methods are the same as before.

Table 3 shows the results of experiments to find the optimal policy package where testing costs are $\Phi = 0.3$. For an upper bound on $\theta$ of 1 (where there is no constraint on the upper bound), and bounded by the condition that total deaths cannot exceed the scenario with 80% contact reduction continued for 360 days, the policy minimizing economic losses should be $\nu = 0.3$ continued for 180 days, together with testing intensity $\theta = 0.8$ continued for 360 days. In this scenario, economic losses amount to 15.87%. Moreover, where the upper limit on $\theta$ is 0.25, and bounded by the condition that total deaths cannot exceed the scenario with 80% contact reduction continued for 360 days, the policy minimizing economic losses should be $\nu = 0.5$ continued for 300 days, together with testing intensity $\theta = 0.18$ continued for 360 days. In this scenario, economic losses amount to 17.76%. Finally, for an upper bound on $\theta$ of 0.1, and bounded by the condition that total deaths cannot exceed the scenario with 80% contact reduction continued for 360 days, the policy minimizing economic losses should be $\nu = 0.55$ continued for 330 days, together with testing intensity $\theta = 0.04$ continued for 240 days. In this scenario, economic losses amount to 19.23%.

Table 3: Optimal policy package (3): Where the cost of testing is high

| Baseline (no constraint on $\theta$) | | | | | |
|---|---|---|---|---|---|
| Contact reduction | | Increased testing | | Policy effect | |
| Period | $\nu$ | Period | $\theta$ | Economic loss | Total deaths |
| 180 | 0.3 | 360 | 0.8 | 15.87% | 0.2732% |
| Where $\theta \leq 0.25$ | | | | | |
| Contact reduction | | Increased testing | | Policy effect | |
| Period | $\nu$ | Period | $\theta$ | Economic loss | Total deaths |
| 300 | 0.5 | 360 | 0.18 | 17.76% | 0.2801% |
| Where $\theta \leq 0.1$ | | | | | |
| Contact reduction | | Increased testing | | Policy effect | |
| Period | $\nu$ | Period | $\theta$ | Economic loss | Total deaths |
| 330 | 0.55 | 240 | 0.04 | 19.23% | 0.2822% |

The above results are not significantly different from those for $\Phi = 0.1$, suggesting that besides behavior-restriction policies, test-and-isolate is also effective in reducing economic losses.

**(3) Case with reinfections** According to BNO News (2020)[6], reinfections of COVID-19 are confirmed. Then, we modify our model as follows. Recovered persons lose their antibodies to COVID-19 at a probability $\gamma_{RS}$ and become Susceptible.

$$\text{Susceptible persons:} \qquad S_t = S_{t-1} - \bar{\beta}(1-\nu_t)^2 \frac{S_{t-1}(I_{t-1} + \phi_t X_{t-1})}{Pop_0} + \gamma_{RS} R_{t-1}, \tag{26}$$

$$\text{Recovered persons:} \qquad R_t = R_{t-1} + \gamma_I (I_{t-1} + X_{t-1}) + \delta_H H_{t-1} - \gamma_{RS} R_{t-1}. \tag{27}$$

We set $\gamma_{RS} = 1/180$, that is consitent with the finding of UK Biobank (2021):the COVID-19 antibodies remain for at least 6 months.

In this setting, the total number of fatalities is 2.3927% where 80% contact reduction starts on the 30th day and continues for 360 days. Table 4 shows the results of experiments to find the optimal policy package with reinfections. It tells us that besides behavior-restriction policies, the test-and-isolate policy is still effective in reducing economic losses.

Table 4: Optimal policy package (4): Case with reinfections

| Baseline (no constraint on $\theta$) | | | | | |
|---|---|---|---|---|---|
| Contact reduction | | Increased testing | | Policy effect | |
| Period | $\nu$ | Period | $\theta$ | Economic loss | Total deaths |
| 240 | 0.2 | 360 | 1.0 | 9.62% | 2.3577% |
| Where $\theta \leq 0.25$ | | | | | |
| Contact reduction | | Increased testing | | Policy effect | |
| Period | $\nu$ | Period | $\theta$ | Economic loss | Total deaths |
| 360 | 0.45 | 300 | 0.25 | 17.45% | 2.3103% |
| Where $\theta \leq 0.1$ | | | | | |
| Contact reduction | | Increased testing | | Policy effect | |
| Period | $\nu$ | Period | $\theta$ | Economic loss | Total deaths |
| 360 | 0.5 | 330 | 0.1 | 18.95% | 2.3811% |

**(4) Case where Exposed persons affect new infections** In the case of COVID-19, there is possibility where Exposed persons affect the number of new infections. Then we modify the model as follows.

$$\text{Susceptible persons:} \quad S_t = S_{t-1} - \bar{\beta}(1-\nu_t)^2 \frac{S_{t-1}(E_{t-1} + I_{t-1} + \phi_t X_{t-1})}{Pop_0}, \tag{28}$$

$$\text{Exposed persons:} \quad E_t = E_{t-1} + \bar{\beta}(1-\nu_t)^2 \frac{S_{t-1}(E_{t-1} + I_{t-1} + \phi_t X_{t-1})}{Pop_0} - \sigma_I E_{t-1}. \tag{29}$$

We assume that the test cannot idenfity Exposed persons.

In this setting, the number of infections rapidly increases, and the peak of the case explosion occurrs on the 14th day. There is no difference between behavioral-restriction policies if the policies begin on the 30th day. Then, we consider the situation where the policies begin on the 10th day.

The total number of fatalities is 2.0090% where 80% contact reduction starts on the 10th day and continues for 360 days. Table 5 shows the results of experiments to find the optimal policy package.

[6] https://bnonews.com/index.php/2020/08/covid-19-reinfection-tracker/.

Table 5: Optimal policy package (5): Case where Exposed affects new infections

| Baseline (no constraint on $\theta$) | | | | | |
|---|---|---|---|---|---|
| Contact reduction | | Increased testing | | Policy effect | |
| Period | $\nu$ | Period | $\theta$ | Economic loss | Total deaths |
| 330 | 0.5 | 240 | 1.0 | 18.79% | 2.0047% |
| Where $\theta \leq 0.25$ | | | | | |
| Contact reduction | | Increased testing | | Policy effect | |
| Period | $\nu$ | Period | $\theta$ | Economic loss | Total deaths |
| 330 | 0.55 | 30 | 0.03 | 19.80% | 2.0038% |
| Where $\theta \leq 0.1$ | | | | | |
| Contact reduction | | Increased testing | | Policy effect | |
| Period | $\nu$ | Period | $\theta$ | Economic loss | Total deaths |
| 330 | 0.55 | 30 | 0.03 | 19.80% | 2.0038% |

The table suggests that besides behavior-restriction policies, the test-and-isolate policy is still effective in reducing economic losses.

# 4 Conclusion

In this study, we analyzed the effects of behavior-restriction and test-and-isolate policies on disease spread and the macro economy using a model that combines an epidemiological model (the SIR model) and an economic growth model (the Solow model). First, we compared the effects of three types of behavioral-restriction policies, and the duration of those policies, on the spread of infection: 80% contact reduction for 30 days, 70% contact reduction for 60 days, and 60% contact reduction for 360 days. In each case, introducing policy can quickly suppress the spread of infection; however, its spread resumes sometime after the policy lapses. To significantly reduce the total number of deaths in the 1,000 days following the beginning of the outbreak, behavioral restrictions would have to remain in place for considerable periods, such as a full year, and the economic losses from such a duration would be very high. Second, we showed that rather than long-term behavioral restrictions, introducing a test-and-isolate policy can suppress the spread of disease while also reducing economic losses. We particularly derived optimal policy for minimizing economic loss, excluding the cost of testing, with an upper limit on the total number of deaths associated with the disease. The baseline analysis showed that behavioral restrictions yielding an 80% contact reduction should be continued for 60 days, and that test-and-isolate should be continued for one year at maximum testing intensity.

This study analysis also raises several issues. One of these is parameter values: Although many parameters in the model are chosen in line with previous studies, they have not been calibrated to the Japanese data; herefore we may need to be cautious about directly adapting their quantitative implications to the Japanese economy. Another is an issue that concerns the model itself. To simplify the analysis, in this study we combined a very simple Solow model with the SIR model. At the same time, there are some studies, such as Eichenbaum, Rebelo and Trabandt (2020a, 2020b, 2020c), that join a dynamic general equilibrium model, in which economic agents perform optimizing behaviors, with the SIR model. As shown in the Lucas critique, it is desirable to use a dynamic general equilibrium model to forecast policy effects that capture changes in the optimization behavior of economic agents accompanying policy changes. It is therefore a topic for the future to analyze whether the conclusions of this study remain robust when using a dynamic general equilibrium model.

## References

[1] Atkeson Andrew, G. 2020. What will be the economic impact of COVID-19 in the US? Rough estimates of disease scenarios. NBER Working Paper No. 26867.

[2] Eichenbaum, Martin S., Sergio Rebelo, Mathias Trabandt. 2020a. The Macroeconomics of Epidemics. NBER Working Paper No. 26882.

[3] Eichenbaum, Martin S., Sergio Rebelo, Mathias Trabandt. 2020b. The Macroeconomics of Testing and Quarantining. NBER Working Paper No. 27104.

[4] Eichenbaum, Martin S., Sergio Rebelo, Mathias Trabandt. 2020c. Epidemics in the Neoclassical and New Keynesian Models. NBER Working Paper No. 27430.

[5] Hamano, Masashige, Munechika Katayama, and So Kubota. 2020. A Macroeconomic Analysis of COVID-19: Imperfect Information and Testing. mimeo.

[6] Holtemoeller, Oliver. 2020. Integrated Assessment of Epidemic and Economic Dynamics. IWH Discussion Papers No. 4/2020.

[7] Li, R., Pei, S., Chen, B., Song, Y., Zhang, T., Yang, W., Shaman, J., 2020. Substantial undocumented infection facilitates the rapid dissemination of novel coronavirus (SARS-CoV2). Science.

[8] Wang, C., Liu, L., Hao, X., Guo, H., Wang, Q., Huang, J., He, N., Yu, H., Lin, X., Pan, A., Wei, S., Wu, T., 2020. Evolving epidemiology and impact of non-pharmaceutical interventions on the outbreak of coronavirus disease 2019 in Wuhan, China. medRxiv .

[9] World Health Organization, 2020. Report of the WHO-China joint mission on coronavirus disease 2019 (COVID-19).

[10] UK Biobank. 2021. UK Biobank SARS-CoV-2 Serology Study. https://www.ukbiobank.ac.uk/media/x0nd5sul/ukb_serologystudy_report_revised_6months_jan21.pdf