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Determining the optimal duration of the COVID-19 suppression policy: A cost-benefit analysis

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Determining the optimal duration of the COVID-19 suppression policy: A cost-benefit analysis

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ABSTRACT

Without any intervention, the novel coronavirus would cost the U.S. economy over \$9 trillion. A suppression policy aims to reduce the number of new cases through strict social distancing measures by closing schools and non-essential businesses. Less restrictive, a mitigation policy aims to merely slow the growth in new cases by limiting close interactions and isolating contagious individuals. Assuming that the suppression phase will be replaced by the mitigation phase until a vaccine availability, we find that the optimal duration of the suppression phase is shorter the higher its economic cost and the more effectively both phases reduce virus transmission. Finally, the often proposed on-off suppression policy is less economically efficient than a continuous suppression regime imposed at the beginning of an outbreak.

JEL classification: I10, I18

Keywords: COVID-19, Pandemic Curve, Attack Rate, Cost-Benefit Analysis, Non-Pharmaceutical Interventions, Public Health Policy, Suppression, Mitigation, Lockdown

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Without any intervention, the novel coronavirus would cost the U.S. economy over \$9 trillion. A suppression policy aims to reduce the number of new cases through strict social distancing measures by closing schools and non-essential businesses. Less restrictive, a mitigation policy aims to merely slow the growth in new cases by limiting close interactions and isolating contagious individuals. Assuming that the suppression phase will be replaced by the mitigation phase until a vaccine availability, we find that the optimal duration of the suppression phase is shorter the higher its economic cost and the more effectively both phases reduce virus transmission. Finally, the often proposed on-off suppression policy is less economically efficient than a continuous suppression regime imposed at the beginning of an outbreak.

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I. Introduction

The pandemic spread of COVID-19 poses an unprecedented threat to the U.S. economy and the quality of life. Experts agree that a vaccine will most likely not become widely available until about 18 months from now.¹ In the absence of a vaccine or effective drug treatments, a non-pharmaceutical intervention is paramount. Such an intervention helps in two respects. First, by reducing the virus transmission rate, it lowers the total number of illnesses and fatalities. Second, it shifts the peak of the pandemic curve further out in time, and by then pharmaceutical treatments may become available.

We assume that a non-pharmaceutical intervention will start with a suppression policy followed by a mitigation policy until drug treatments or a vaccine become available. As discussed in Ferguson et al. (2020), a suppression policy “aims to reverse epidemic growth, reducing case numbers to low levels and maintaining that situation indefinitely.” Suppression can be achieved by restricting travel, closing schools and nonessential businesses, banning social gatherings, and asking citizens to shelter in place. These measures, often referred to as a “lockdown,” are highly restrictive on social freedoms and damaging to the economy.² In contrast, a mitigation policy “focuses on slowing but not necessarily stopping epidemic spread.” Mitigation measures may involve discouraging air travel while encouraging telecommuting, requiring companies to provide physical separation between workers, banning large gatherings, isolating the vulnerable, and identifying and quarantining contagious individuals and their recent contacts. This paper analyzes the optimal duration of the suppression phase before it is replaced by the mitigation phase; in turn, the mitigation phase is assumed to last until a vaccine becomes available 18 months later.

We model the COVID-19 pandemic curve using the SIR (susceptible, infected, recovered) model widely used in epidemiology. At the beginning of an epidemic, when no one in the population is immune, an infected person will, on average, infect R_0 other people over the period they are infectious. R_0 measures the degree of contagiousness of an infectious disease and is referred to

¹See, e.g., Anthony Fauci’s statement in the March 31, 2020, White House press conference.

²Throughout the paper, we use the terms “suppression phase” and “lockdown” interchangeably.

as the “basic reproduction number” because it quantifies how a virus reproduces in the population. As is common in SIR models, we assume that people who have recovered develop immunity and, therefore, would not be able to get infected nor infect others. When $R_0 < 1$, the number of new cases declines, and when $R_0 > 1$, the number of new cases initially grows until a sufficient fraction of the population becomes infected or already immune, and after reaching a peak starts to gradually decline. As discussed in Ferguson et al. (2020), the suppression phase can achieve $R_0 < 1$, while the mitigation measures are unlikely to bring R_0 below 1. Therefore, the number of new cases are expected to decline during the suppression phase and to start rising again during the mitigation phase, albeit at a slower rate than in a non-intervention scenario.

We find the optimal duration of the lockdown phase by evaluating each additional week of the lockdown in terms of its incremental benefit against the incremental cost it imposes on the economy. Obviously, the longer the lockdown lasts, the larger the reduction in the number of new cases it will achieve, and the further into the future it will shift the peak of the pandemic curve because the curve will start rising from a smaller seed (the initial number of cases) during the mitigation phase. If a policymaker’s only objective were to minimize the attack rate (the fraction of the population who will become symptomatically ill), the optimal solution would be to extend the suppression policy to 78 weeks, until the vaccine becomes available. However, after a certain point in time, the incremental benefit achieved from reducing the attack rate starts to decline quickly. Hence, the policy should be kept in place only until the incremental benefit of an additional week of suppression falls below the cost it imposes on the economy.

The benefit of a non-pharmaceutical intervention would come from the reduction in the attack rate, thereby reducing the cost of the outbreak. This cost has three components: (1) the loss of productivity due to missed work; (2) the cost of medical interventions; and (3) the value of statistical life (VSL) of the fatalities.

Once a person is infected, they may be symptomatic or not. A symptomatic person will have one of four outcomes. (1) They may have mild symptoms and recover without any medical help. (2) They may make an outpatient visit. (3) They may experience severe symptoms and be hos-

pitalized. (4) They may be hospitalized and then die. Each progressively worse outcome entails higher economic costs associated with the illness. Cost estimates are obtained from the literature on seasonal influenza and the probability of each outcome from the CDC analysis on the confirmed cases of COVID-19;³ these probabilities are adjusted for the likelihood that a fraction of infections was never diagnosed due to the lack of widespread testing.

The optimal stopping time heavily depends on the suppression policy's effectiveness: The less effective it is, the longer suppression should be kept in place. We use the assumption of Ferguson et al. (2020) that the natural R_0 of COVID-19 is 2.4, a value that is consistent with other estimates. If the lockdown drastically reduces the number of close interactions between individuals, it would also reduce the basic reproduction number. Using survey evidence, Jarvis et al. (2020) estimate that the U.K. lockdown reduced the average number of daily contacts by 73%, and R_0 to about 0.62.

In our estimations for the U.S., we use two different assumptions for R_0 of the suppression policy: 0.7 and 0.5. For the mitigation phase that comes after the suppression phase, we assume that its effectiveness can be improved through contact tracing but only if the number of new illnesses is relatively small. Otherwise, the system will become overwhelmed and contact tracing would not be possible. We assume that mitigation without contact tracing reduces R_0 to 1.3 (which is the average R_0 for seasonal influenza), and if contact tracing is possible, mitigation will reduce the R_0 to 1.1. (We run sensitivity analysis with alternative assumption for the mitigation-phase R_0 .) Once a vaccine becomes available, we assume that it will be highly effective and reduce R_0 to a very low value of 0.3. At this time, all non-pharmaceutical intervention can be stopped. The R_0 assumptions are summarized in Table I.

Policymakers should resist the pressure to lift the lockdown prematurely. Lifting the lockdown too soon may erase the gains made in reducing the number of new infections, and the pandemic curve will materialize in its entirety before a vaccine becomes available. Additionally, a policy of alternating on-off lockdowns has been frequently proposed. However, if the lockdown is lifted and then re-imposed some time later, it will need to be kept in place for a longer total duration to

³<https://www.cdc.gov/mmwr/volumes/69/wr/mm6912e2.htm>.

achieve the same reduction in the attack rate as a one-time lockdown instituted at the beginning of the outbreak. Hence, the on-off policy is less economically efficient.

Three reasons may explain persistent calls to lift the lockdown too quickly. First, a healthy young individual is likely to have a mild form of the illness, and, therefore, catching the virus poses a lower risk to them than to the more vulnerable in society, creating a negative externality that may not be adequately priced in by the individual. Second, since COVID-19 is virtually symptom-free in children, the risks of the pandemic may be widely perceived as more acceptable (Tumpey et al. (2018)). Finally, since the costs of a lockdown are felt in real time in the form of inconveniences and lost paychecks and the benefits from reducing then number of illnesses and deaths come in the future, some individuals may perceive these benefits as hypothetical and underestimate them; alternatively, they may be using extremely high discount rates.

We estimate the optimal duration of the suppression policy based on our assumptions for the initial conditions and for COVID-19-specific parameters, but we would like to caveat the findings by pointing out that these inputs are not yet precisely estimated. To the extent possible, we obtain the inputs from COVID-19 studies, and when those are not available, we use the estimates from the seasonal influenza literature; and some assumptions are made by the author. The large unknowns are how well the suppression policy is working at reducing R_0 in the U.S. and what R_0 will be achieved during the mitigation phase. Other crucial inputs are the infection fatality rate and the fraction of asymptomatic illnesses. We run sensitivity analysis to check how the optimal duration of the lockdown would change depending on the assumptions.

The rest of the paper is organized as follows: Section II models the pandemic curve under different assumptions and estimates the cost of the COVID-19 outbreak. Section III calculates the optimal stopping time for the suppression policy. Section IV concludes.

II. Estimating the cost of the outbreak

In this section we estimate the economic cost of the COVID-19 outbreak in the U.S.. We follow closely the methodology used in studies of the costs of seasonal and hypothetical pandemic influenza outbreaks (e.g., Molinari et al. (2007) and CEA (2019)).⁴

A. Costs of the COVID-19 infection

An individual infected with the COVID-19 virus can have two outcomes: they can be asymptomatic or exhibit symptoms. Asymptomatic individuals do not miss work and do not incur any medical costs, although they can still infect others at the same rate as symptomatic individuals. Conditional on being symptomatic, an individual can have one of the progressively worse outcomes: (1) have mild symptoms and require no medical intervention, (2) have more severe symptoms and require an outpatient visit, (3) be hospitalized and survive, and (4) die from the coronavirus complications. This probability tree is plotted in Figure 1.

What is the fraction of asymptomatic cases? Mizumoto et al. (2020) analyze the data from the quarantined Diamond Princess cruise ship and find that the asymptomatic fraction was 17.9%. However, experts believe that the asymptomatic fraction should be significantly higher in the general population since that sample consists predominately of older adults. For example, a *New York Times* article cites an expert estimating “... that about 40 percent in the general population might be able to be infected without showing signs of it”.⁵ We will, therefore, use the assumption that 40% of all infections are asymptomatic.

Symptomatic individuals may fall into two groups: high-risk and low-risk. Those in the high-risk group have pre-existing conditions that increase the likelihood of complications. In addition, we divide the population into age groups since older individuals tend to have worse immune systems and tend to develop more severe symptoms. Table II describes the probability that a symp-

⁴Throughout the paper we will use the terms “flu” and “influenza” interchangeably.

⁵“Infected but Feeling Fine: The Unwitting Coronavirus Spreaders,” *New York Times*, March 31, 2020.

omatic individual experiences each of the four possible outcomes of the disease as a function of their age and risk status. The probabilities used in this table are obtained from COVID-19 studies whenever available, and otherwise probabilities from the seasonal flu literature are used, as described in the table caption. The table also includes the costs associated with each outcome for a symptomatic individual in different age and risk groups. Since COVID-19 is also a viral illness, we assume that it is appropriate to use medical risks and costs associated with seasonal influenza; however, if COVID-19 manifests more severely or leaves survivors with long-term negative health effects, we would be underestimating the associated costs, and the benefit of the suppression policy would be larger than what we currently estimate. For the calculation of the costs of lost productivity due to illness, we use the assumption in CEA (2019) that one missed work day represents a productivity loss of \$151.88. For the individuals who die, society loses some productivity due to their inability to work during the illness period and, more importantly, the dollar value of life. The latter is estimated from the studies assessing how much money people are willing to pay increase the probability of staying alive—the so-called value of statistical life (VSL). For this reason, we do not add the medical costs for people who die because those are already factored into the VSL. Following CEA (2019), we use inflation-adjusted VSL values by age group from Aldy and Viscusi (2008), who estimate them from the wage premia paid by riskier jobs.⁶

For each pandemic scenario considered, we calculate the total number of symptomatic individuals in each risk and age group that would fall into each of the four possible disease outcome categories. We then multiply these numbers by the associated costs and sum them up to obtain the overall cost of an outbreak scenario.

B. Modeling the pandemic curve under different scenarios

We use the SIR model to project the number of new COVID-19 infections at a weekly frequency. The starting point of our analysis is 4/21/2020 (this is our week 0). We use the initial conditions

⁶While the authors are unable to estimate VSL for children, other studies obtain estimates from parents' willingness to pay for children's medical costs. The children's VSL estimate does not enter into the total cost calculation since COVID-19 studies assess a near-zero fatality risk for the younger age group.

as of this date to project the evolution of the outbreak.⁷ We calculate the forward-looking costs of the outbreak scenarios we consider from this time on and ignore the costs already incurred. Going off the requirement for sick people to self-isolate for 14 days, we assume that a newly infected person is contagious for two weeks, during which time they will infect R_0 other people at the start of the outbreak due to the lack of immunity in the population. The number of other people a contagious person infects is assumed to be spread evenly across the two weeks, with $R_0/2$ other people infected in both the first and the second week of the illness. Additionally, we assume that the recovered individuals develop immunity and will not get infected or infect others and those currently ill cannot be re-infected.

As the outbreak progresses, more and more people develop immunity, and a contagious person becomes increasingly more likely to come into contact with someone who is already immune (or sick, since sick people cannot be infected twice) and not pass on the virus. The increasing fraction of the immune is what explains the bell shape of the pandemic curve. At the start of an outbreak, the number of new cases increases at a close-to-exponential rate, assuming $R_0 > 1$: the first sick person, on average, infects R_0 other people, the R_0 newly sick people infect another R_0^2 people, and so on. However the rate of increase in the number of new infections starts to slow as more people become immune (or happen to be sick at the time). The number of new infections eventually peaks and then starts to decline to zero. Without any intervention, an infection will die out naturally after a sufficient fraction of the population develops immunity. The objective of a public health intervention, as we consider it in this paper, is to reduce the infection attack rate (AR)—the fraction of the population that becomes symptomatically ill over the course of an outbreak—while achieving the optimal cost-benefit tradeoff of such an intervention.

⁷As of 4/21/2020, CDC reports 776,093 confirmed cases in the U.S. (<https://www.cdc.gov/coronavirus/2019-ncov/cases-updates/cases-in-us.html>). Using our assumption that 50% of cases were never diagnosed, we estimate the actual number of cases to be roughly 1.5 million. Given that the lockdown was in place for the prior five weeks and the number of new cases has been declining, we estimate the number of new cases to be roughly 179,000 in week 0 and 229,621 one week prior. These are the starting assumptions for all projections.

B.1. The no-intervention scenario

As mentioned earlier, we use the assumption of Ferguson et al. (2020) that COVID-19 has a natural $R_0 = 2.40$, a number that is consistent with other COVID-19 studies.⁸ This R_0 value is higher than R_0 assumptions used for modeling pandemic influenza (e.g., CEA (2019)). In case of a pandemic flu, some older people may have experienced a similar flu strain in the distant past, making them immune and lowering the R_0 of the outbreak. In contrast, COVID-19 is an entirely novel virus to which no humans have immunity.

If all non-pharmaceutical interventions were to stop in week 0, letting the outbreak progress naturally, we estimate that the AR will be 55.46%, and the total number of deaths will top 1.3 million.⁹ The cost of the pandemic going forward is estimated to be \$9.08 trillion, which is 42% of the 2019 GDP. (The no-intervention COVID-19 pandemic curve is plotted in Figure 2.) Given the high cost of an uncontrolled pandemic, a non-intervention scenario is not an acceptable option.

B.2. Modeling the suppression policy at different durations

We make two assumptions for the R_0 that the suppression policy can achieve: the pessimistic assumption of $R_0 = 0.7$ and the optimistic assumption of $R_0 = 0.5$. These values fall on both sides of $R_0 = 0.62$ that Jarvis et al. (2020) estimate the lockdown has achieved in the U.K. If the suppression policy were to remain in place for 78 weeks, until a vaccine becomes available, we estimate that, going forward, for the $R_0 = 0.7$ assumption, the attack rate would be 0.16% and the total economic cost of the outbreak would be \$20.18 billion. For the $R_0 = 0.5$ assumption, these values would be 0.09% and \$8.72 billion, respectively. The pandemic curves for these scenarios are plotted in Figure 3. These costs are orders of magnitude below the cost of the no-intervention policy. However, the suppression policy undeniably puts a substantial burden on the economy, and it may be optimal to end it before a vaccine becomes available.

⁸For example, Zhang et al. (2020) estimate a similar value of 2.28.

⁹Our fatality estimate is lower than the 2.2 million estimated in Ferguson et al. (2020) (page 7). The reason is that our population-weighted infection fatality rate (IFR) is 0.74%, which is lower than the IFR of 0.9% in that paper.

We assume that once stopped, the suppression policy will be replaced by a less socially restrictive and economically costly mitigation policy, as described in Ferguson et al. (2020), and the mitigation policy will be kept in place until a vaccine becomes available. While it is unclear what R_0 a mitigation policy can achieve, Ferguson et al. (2020) argue that it will be above 1.00, implying that the number of new cases will start going up again. We will assume that if the number of new cases exceeds 50,000 per week, it would be difficult to implement contact tracing, and mitigation will achieve $R_0 = 1.3$, thereby assuming that it will be spreading at the rate of seasonal influenza (Biggerstaff et al. (2014) find that the median R_0 for seasonal influenza is 1.28). (In sensitivity checks, we also experiment with the mitigation R_0 values of 1.2, 1.5, and 1.9.) However, if the number of new infections falls below 50,000, we assume that it would be possible to do contact tracing, and R_0 will drop to 1.1.

Figures 4 and 5 plot pandemic curves that will materialize when the suppression phase is extended by a certain number of weeks into the future, as indicated above each picture, for the $R_0 = 0.7$ and $R_0 = 0.5$ assumptions, respectively. The plots show that after the suppression policy is replaced by the mitigation policy, the number of new cases starts to rise again because the R_0 of the mitigation policy is assumed to be greater than one.

The upper-left plots in both figures show that if the suppression is abandoned after another two weeks, the entire pandemic curve will have the time to materialize before a vaccine becomes available. Therefore, the gains that suppression made in reducing the number of new cases will be erased. However, if the suppression policy is kept in place long enough, the pandemic curve will be cut off because the number of cases drops sharply after a vaccine becomes available. Comparing Figures 4 and 5, it can be seen that when suppression is more effective ($R_0 = 0.5$ vs. $R_0 = 0.7$), it achieves a greater reduction in the number of new cases over the same length of time, and the pandemic curve builds up from a lower initial number of cases during the mitigation phase. Hence, the more effective the suppression policy, the less time it needs to achieve a desired reduction in the attack rate.

For the ease of the exposition, we will quantify the incremental benefits achieved from extending the suppression policy beyond two weeks from week 0 and then replacing it with the mitigation policy until a vaccine is available. Therefore, keeping the suppression policy for only another two weeks is our baseline scenario (the relevant baseline scenarios are presented in the upper-left plots of Figures 4 and 5). We estimate that the cost of the baseline scenario is roughly the same for the two suppression R_0 assumptions. The reason is that, as discussed above, under both assumptions, the pandemic curve will have a chance to fully materialize before a vaccine availability. The forward-looking cost of the baseline scenarios is estimated to be \$4.2 trillion, or almost 20% of the 2019 GDP. Table III summarizes the estimated AR, fatalities, and the total costs for the baseline scenarios.

Turning first to the more pessimistic assumption of suppression $R_0 = 0.7$, we estimate that extending the suppression policy by another six weeks produces only small savings derived from the incremental reduction in the AR relative to the baseline scenario; the AR is reduced by only 0.12 percentage points, and the savings amount to \$22 billion. When the suppression phase is instead extended by another 10 weeks, it can be seen that the right-hand tail of the pandemic curve gets cut off by the vaccine availability. As the result, the AR is reduced by 1.5 percentage points, and the savings relative to the baseline scenario total \$334 billion. Extending the suppression phase by another 12 weeks produces more clearly visible results, as more of the right-hand tail gets cut off. The AR is reduced by 7.1 percentage points relative to the baseline scenario, and the incremental savings equal \$1.48 trillion. When the suppression phase is extended by another 15 or 18 weeks, the reductions in the AR are much greater and equal to 21.6 and 25.1 percentage points, respectively, and the corresponding savings amount to \$3.70 trillion and \$4.12 trillion.

For the more optimistic $R_0 = 0.5$ assumption for the suppression policy effectiveness, we calculate the following incremental benefits from the extending suppression policy further in time. A 4-week extension produces a reduction in the AR equal to 0.2 percentage points relative to the baseline, and incremental savings of \$32 billion. A 6-week extension, lowers AR by 2.3 percentage points relative to the baseline, and the incremental savings total \$526 billion. Extending the suppression phase by another 8-, 9-, or 11-weeks, reduces the AR by 17.8, 23.1, and 25.3 percentage

points relative to the baseline, respectively, and produces the corresponding incremental savings of \$3.20 trillion, \$3.89 trillion, and \$4.15 trillion.

Figure 6 plots the incremental savings relative to the baseline achieved from extending the suppression policy beyond two additional weeks as the function of how many more weeks it will be kept in place and plots these savings for the two suppression R_0 assumptions. At two weeks, incremental savings equal to zero because this is our baseline. Initially, the savings increase very slowly with each additional week of extension—this is consistent with the discussion above that extending the suppression policy by only a few weeks does not achieve substantial savings because the pandemic curve has the time to realize almost fully. However, after a certain point, the incremental savings start rising at an increasing rate, then eventually at a decreasing rate, and finally start to plateau. (Consistent with the above discussion, it can be seen that a sharp increase in incremental savings occurs sooner when the suppression policy is more effective.) Given that the lockdown's benefits start to decrease after a certain duration and that it is very costly to the economy, it may be, therefore, optimal to lift the lockdown before a vaccine becomes available. The optimal stopping time is estimated in the next section.

III. Estimating the optimal duration for the suppression policy

A. Incremental cost the suppression policy

The suppression policy is significantly costlier to economy than the mitigation policy. Both policies will reduce the economic activity relative to normal times, but the suppression policy is more damaging. By banning social gatherings, restricting travel, and closing schools, the lockdown disproportionately affects certain sectors of the economy and reduces the productivity of working adults with underage children, since the children need to be supervised and home schooled during work hours. We will provide a very rough estimate of what these incremental costs may be. These estimates could be updated as more data on economic activity are released.

The first component of the cost is the reduced productivity of working adults with children under 18 years old. There are 158,130,000 working adults in the U.S., and 40.66% of U.S. households have children under the age of 18.¹⁰ We assume that each adult in the household with children under 18 loses 35% of their productivity. Using the assumption that we used in the cost-of-the-outbreak calculation, that a productive work day contributes \$151.88 to the GDP, we estimate the total weekly cost of reduced productivity to be \$17.09 billion.

The restrictions on social gatherings and travel would have a large negative effect on certain sectors of the economy. Using the sector definitions from the Census Value Added table, we assume that the affected sectors are: (1) Arts, Entertainment, Recreation, Accommodation, and Food Services (4.2% of value added in 2018), (2) Retail Trade (5.5% of value added), (3) Transportation and Warehousing (3.2% of value added), and (4) Other Services, Except Government (2.1% of value added). We further assume that relative to the mitigation policy baseline, these sectors will experience an incremental decline in output equal to 50% for Arts, Entertainment, Recreation, Accommodation, and Food Services, and Transportation and Warehousing; 20% for Retail Trade and 10% for Other Services, Except Government. Multiplying these projected percentage declines by sector output, we calculate that these sectors will reducing output by \$18.70 billion per week when the suppression policy is in place.

Adding together these two costs, we estimate the suppression phase imposes incremental cost of \$35.79 billion per week relative to the mitigation phase (if extended to a year, these incremental costs would amount to 8.7% of GDP).¹¹ In the sensitivity analysis in Section C, we assume that the incremental cost of suppression may be twice as high.

It must be noted that a number of other potential costs and benefits of suppression have not been considered in the calculation above. Certain aspects of the lockdown create both shorter- and longer-term economic and health benefits. One such benefit is the reduction in traffic and the

¹⁰Source: Statista.

¹¹This value is consistent with other estimates. For example, OECD (2020) assesses that the lockdown will decrease GDP of developed economies by 20-25%, which translates to \$83-\$103 billion per week for the United States. Given that the demand for certain services will be below normal during the mitigation phase as well, the *incremental* cost relative to mitigation is in line with our estimate.

ensuing reduction in the number of traffic fatalities and injuries, which was estimated to fall by half during the lockdown in California (Shilling and Waetjen (2020)). This drop would translate into a substantial dollar benefit if VSL and the medical costs of caring for the injured are taken into account. Another benefit of reduced traffic is lower pollution, which may result in positive health effects. With widespread telecommuting and less traffic, employees may gain productive hours. Additionally, with fewer people on the streets, crime was reported to drop by as much as 20%.¹² Finally, an increased reliance on technology will likely achieve more workplace flexibility in the future, allowing more people to enter the workforce and increasing future DGP growth; finally, the wider use of technology may also reduce operating costs by introducing more efficiency into certain tasks, such as meetings and collaborations.

The lockdown has additional costs that we have not quantified. With long periods of physical isolation, some may develop mental health problems, resulting in a lower productivity in the future. The reduced access to medical services during the lockdown may have negative health consequences in the longer term. As a result of the economic downturn, the number of business and personal bankruptcies will increase, resulting in dead-weight losses associated with a less efficient re-deployment of assets and a potential loss of intellectual property. Finally, the lower quality of education during the home schooling period may result in a marginally less productive future workforce.

B. Optimal duration for the suppression policy

Optimally, the lockdown should end before its incremental benefit falls below its incremental cost to the economy. Using our assumptions for the starting conditions, the COVID-19 parameters and the costs of illness, we estimate that under the pessimistic assumption of the suppression policy's effectiveness (ϵ , with the assumption that $(R_0 = 0.7)$, the lockdown should be extended by another 18 weeks, and under the optimistic assumption ($R_0 = 0.5$), the lockdown should be extended by another 11 weeks. After subtracting the incremental cost of the lockdown incurred over that length

¹²“Coronavirus crisis leads to steep drop in recorded crime,” *The Guardian*, March 26, 2020.

of time, we estimate the associated net benefit relative to the baseline scenario of lifting the lockdown after two more weeks to equal \$3.54 trillion, or 16.56% of the 2019 GDP, for the $R_0 = 0.7$ assumption, and \$3.83 trillion, or 17.86% of GDP, for the $R_0 = 0.5$ assumption.

C. Sensitivity to the assumptions and additional considerations

The calculations above rely on the set of assumptions that we used. Given a large number of unknowns, the findings should be caveated, and below, we discuss the sensitivity of the results to different assumptions.

Infection fatality ratio. Given the lack of widespread testing for COVID-19, the infection fatality rate may be below our assumed values. For example, Mizumoto et al. (2020) estimate that the IFR for COVID-19 is only between 0.04% and 0.12%, while the population-weighted IFR that we use in the paper is 0.74%. We re-run our calculations using the lower population-weighted IFR of 0.08% (the midpoint of the range above) by multiplying our initial IFR for each age group by the ratio 0.08%/0.74%. With this substantially lower IFR, we estimate that for the $R_0 = 0.7$ assumption for the suppression policy's effectiveness, the optimal lockdown duration is reduced from 18 to 16 weeks (with the total net benefit of \$221 billion), and for the $R_0 = 0.5$ assumption, from 11 to 10 weeks (with the total net benefit of \$462 billion). However, if the incremental cost of the lockdown were twice as high as our initial assumption and equal \$72 billion/week, it would not make economic sense to do a lockdown under the $R_0 = 0.7$ assumption.

It may be also argued that the actual IFR is higher than what we assumed in light of the mounting evidence that a substantial number of deaths caused by COVID-19 have been falsely attributed to other reasons. With a higher IFR, the optimal duration of the lockdown could be lengthened.

Effectiveness of the mitigation phase and the incremental cost of the lockdown. We make alternative assumptions on how effective the mitigation policy will turn out to be when contact tracing is not possible. We consider three alternative mitigation R_0 values. We assume that the R_0 could be lower than our assumption and equal 1.2, or higher and equal 1.5 or 1.9. We also

assume that the incremental cost of the lockdown to the economy may be twice as large as what we estimated and equal to \$72 billion per week instead. The optimal duration of the lockdown ranges between 10 and 19 weeks. Optimal lockdown durations corresponding to the different assumptions and the associated net benefits are summarized in Table IV.

A number of other inputs are also important for estimating the optimal lockdown duration. Like the IFR, the asymptomatic fraction is another key input. The higher the fraction of asymptomatic illnesses, the lower the total cost of the pandemic. Additionally, reports have emerged of long-term negative health consequences of the COVID-19 infection, and if true, the cost of the outbreak would be higher than our estimate. A higher estimated cost of the outbreak should generally lengthen the optimal lockdown duration. An element not considered is the potential nonlinearities in the IFR: If the demand for medical resources begins to exceed capacity, the IFR would increase, resulting in a higher total cost of the outbreak. Thus, another benefit of a longer lockdown is that it buys time to build up medical capacity to prepare for the future increase in cases, and this particular benefit may lengthen the optimal duration of the lockdown.

Finally, it has been frequently suggested by policy makers that an on-off lockdown policy may be preferred to an uninterrupted initial lockdown: under this policy, when the number of new cases increases beyond the handling capacity during the mitigation phase, another lockdown should be imposed to bring the number of cases down again. Economically, the on-off lockdown policy is less efficient than a one-time initial lockdown of the same duration because under the constant-cost assumption, both policies would have the same cost but the on-off policy will result in a higher attack rate. The on-off lockdown policy may make sense if: (1) the cost of the lockdown to the economy is not constant over time but increases with each successive week of the lockdown or (2) it is difficult to forecast how effective the mitigation phase will be and it may be optimal to learn by experimenting.

IV. Conclusion

To our knowledge, this paper presents the first attempt to estimate the optimal duration of the COVID-19 lockdown by analyzing its costs and benefits. Our results show that the lockdown is unlikely to achieve the desired benefit if lifted too soon. The optimal lockdown duration depends critically on its effectiveness at reducing the number of new infections. The more effective it is, the sooner it should be replaced with the less economically costly mitigation phase until a vaccine becomes available. The lockdown should be also lifted sooner, the lower the coronavirus's infection fatality rate, the more effectively the mitigation phase can slow the infectious spread, and the higher is the lockdown's cost to the economy. Under the assumptions used in the paper, we estimate that extending the lockdown to an optimal stopping point instead of lifting it after only two more weeks would produce a substantial net benefit equal to about 17% of GDP.

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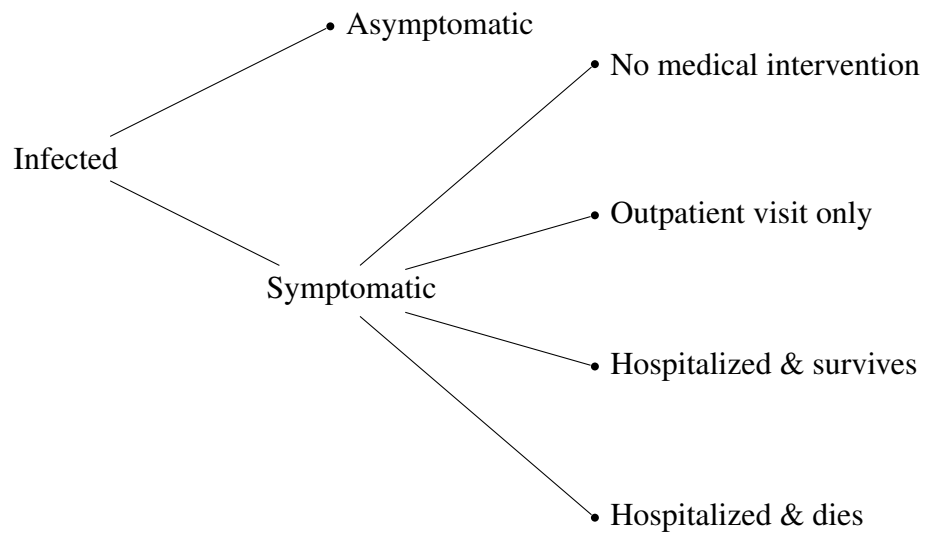


Figure 1. Outcomes for an infected person. The figure presents possible outcomes for a person infected with the COVID-19 virus.

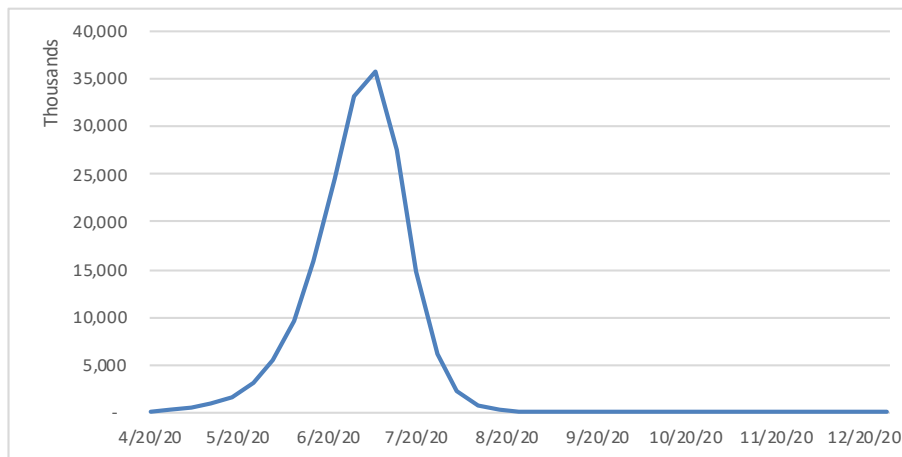
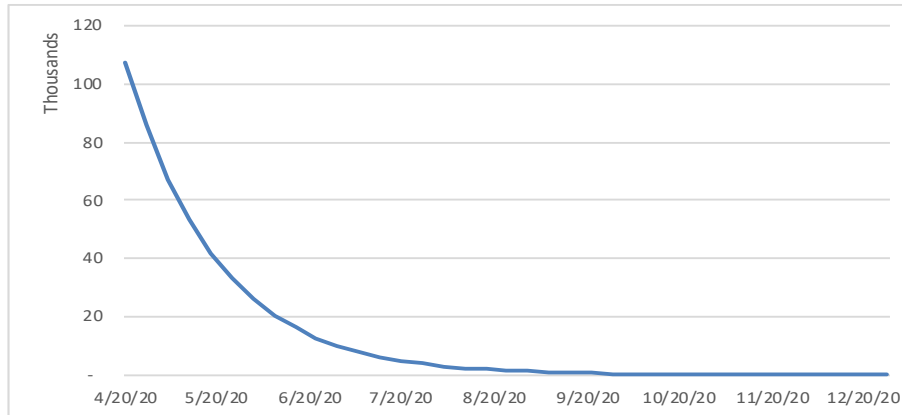


Figure 2. New symptomatic cases with no intervention. The figure plots the number of new symptomatic COVID-19 cases over time assuming that all non-pharmaceutical interventions stop. The contagious period is assumed to last 2 weeks and $R_0 = 2.4$. The fraction of symptomatic cases is 0.6, and asymptomatic individuals can infect others at the same rate as symptomatic individuals. Going forward, the attack rate is 55.46%, the total number of deaths is 1,342,513, and the cost of the outbreak is \$9.08 trillion, or 42% of GDP.

Suppression policy $R_0 = 0.7$



Suppression policy $R_0 = 0.5$

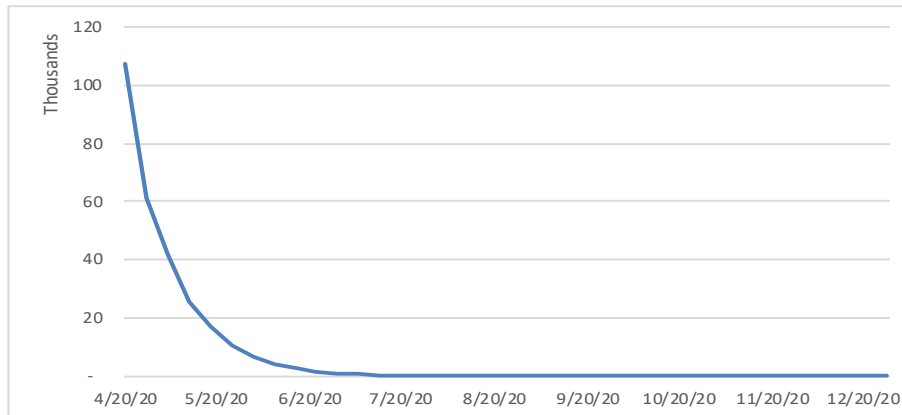


Figure 3. New symptomatic infections with suppression policy in place for 78 weeks. The figures plots the number of new symptomatic infections for COVID-19 with the suppression policy in place for 78 weeks, with R_0 as indicated above each chart. The infectious period is assumed to last 2 weeks, the fraction of symptomatic cases is 0.6, and asymptomatic individuals can infect others at the same rate as symptomatic individuals. When $R_0 = 0.7$, going forward, AR=0.16% and the total cost of the outbreak is \$20.18 billion, and when $R_0 = 0.5$, AR=0.09% and the total cost of the outbreak is \$8.72 billion.

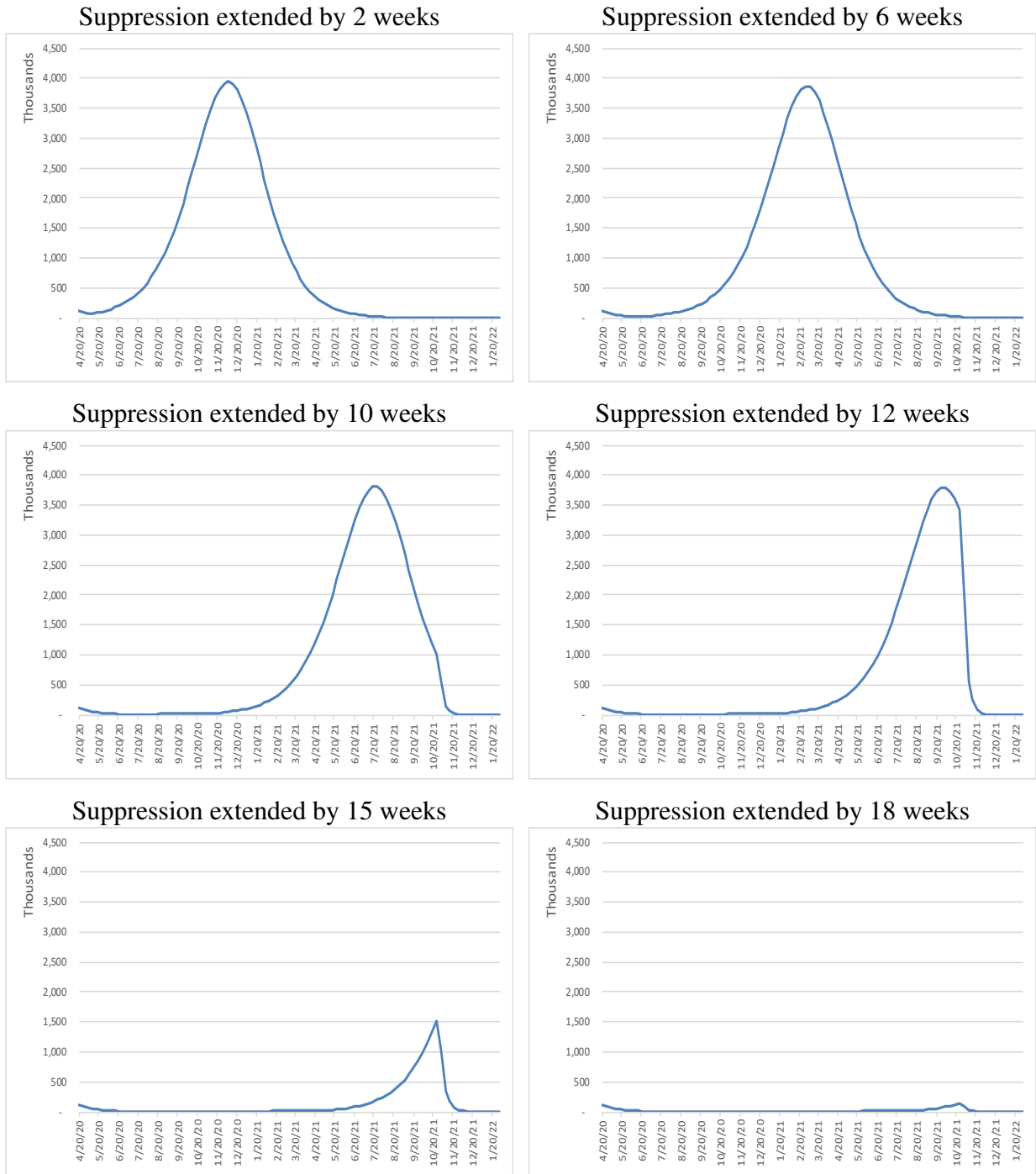


Figure 4. New symptomatic infections with suppression policy extended to the number of weeks indicated above each graph, assuming that suppression policy achieves $R_0 = 0.7$. The figures plot the COVID-19 pandemic curves when the suppression policy is extended by the number of weeks indicated above each graph, after which the mitigation policy is adopted. If the number of new cases is below 50,000, the mitigation policy $R_0 = 1.1$, otherwise it is 1.3. After a vaccine becomes available in 78 weeks, $R_0 = 0.3$.

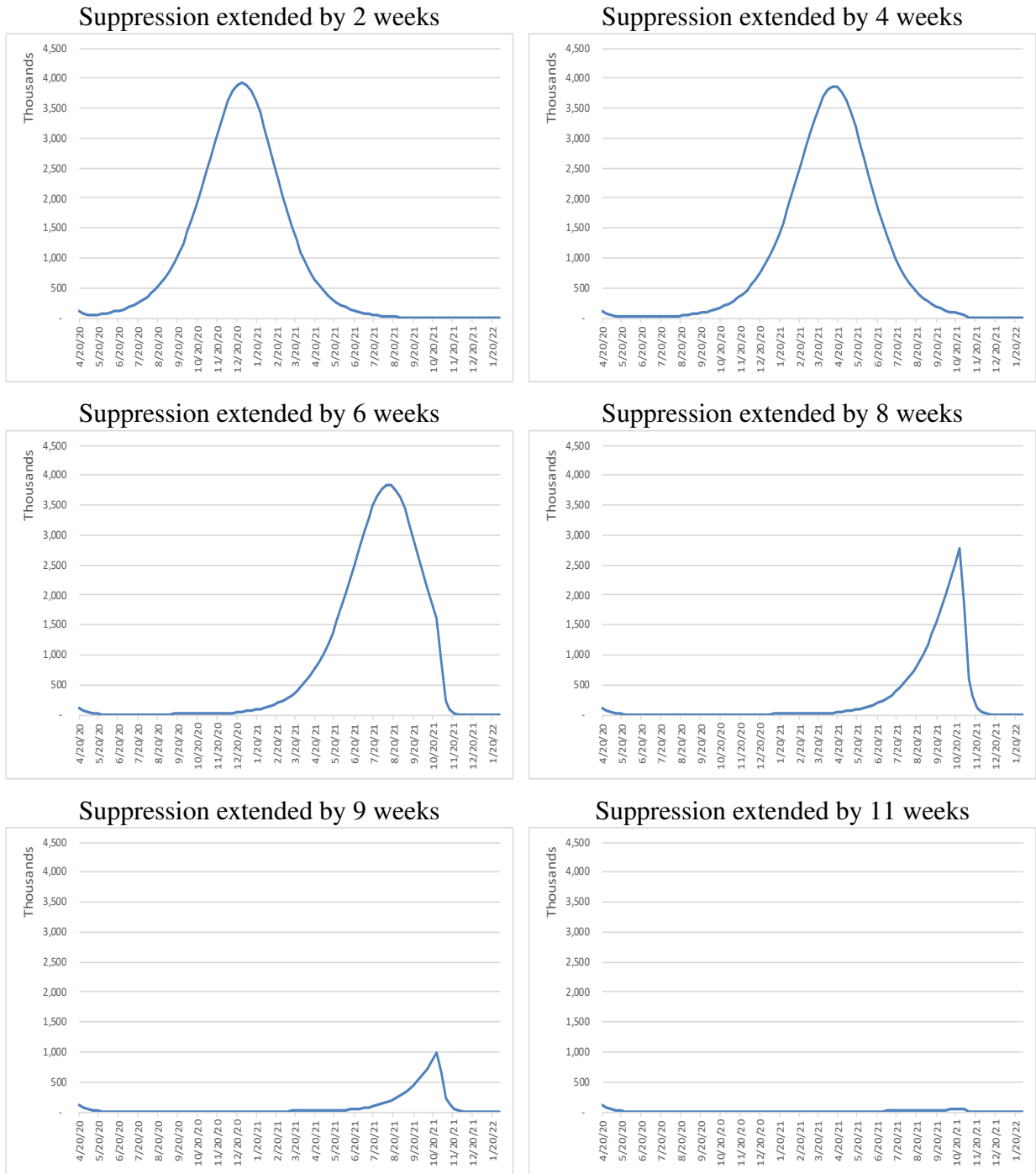
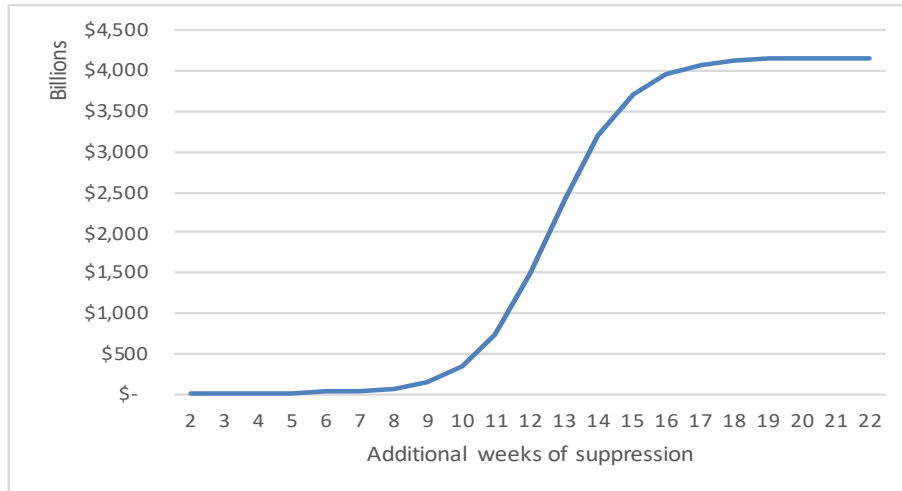


Figure 5. New symptomatic infections with suppression policy extended to the number of weeks indicated above each graph, assuming that suppression policy achieves $R_0 = 0.5$. The figures plot the COVID-19 pandemic curves when the suppression policy is extended by the number of weeks indicated above each graph, after which the mitigation policy is adopted. If the number of new cases is below 50,000, the mitigation policy $R_0 = 1.1$, otherwise it is 1.3. After a vaccine becomes available in 78 weeks, $R_0 = 0.3$.

$$R_0 = 0.7$$



$$R_0 = 0.5$$

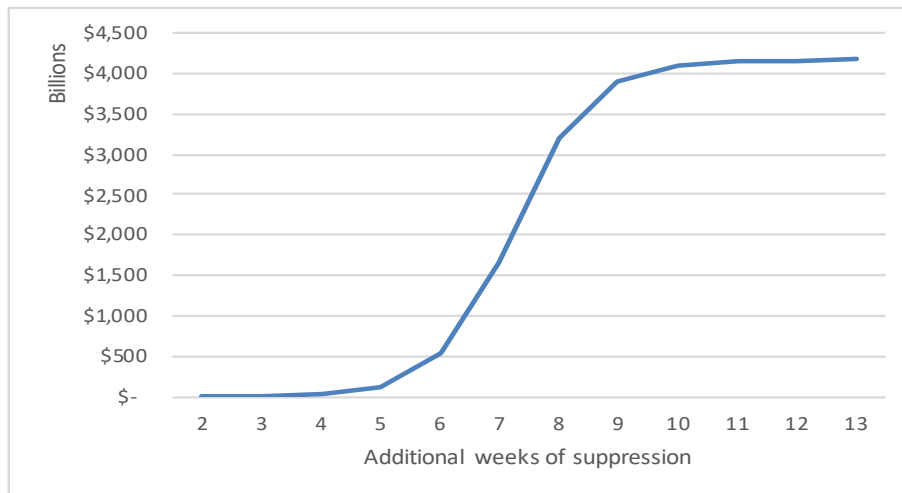


Figure 6. Incremental savings from extending suppression beyond two weeks. The figures plot incremental savings from extending the suppression policy beyond two weeks, after which the mitigation policy is adopted. If the number of new cases is below 50,000, the mitigation policy $R_0 = 1.1$, otherwise it is 1.3. After a vaccine becomes available in 78 weeks, $R_0 = 0.3$.

Table I
Assumptions about R_0

This table presents the assumptions about R_0 as a function of public health strategies and vaccine availability.

Public health strategy	R_0
No intervention	2.4
Suppression scenarios:	
- pessimistic	0.7
- optimistic	0.5
Mitigation	1.3 (if $> 50,000$ new cases/week)
	1.1 (if $\leq 50,000$ new cases/week)
After vaccine is available	0.3

Table II
Risks Associated with COVID-19 Infection by Age Group

This table presents the risks and per-person medical costs conditional on the outcome of the COVID-19 infection, by age group. The assumptions for the ratio of hospitalizations and fatalities are obtained from CDC (2020) and adjusted for the assumption that only 50% of COVID-19 cases are observed due to the lack of widespread testing. The assumptions on the percentages of high-risk cases and the associated medical costs are drawn from CEA (2019), Table 2, and for the age groups that did not appear in that table, the estimates are averaged between the adjacent age groups.

	Age Group						
	0-19	20-44	45-54	55-64	65-74	75-84	≥85
% of US population	25%	33%	13%	13%	9%	5%	2%
% high-risk	8%	15%	24%	33%	51%	51%	51%
Probability of outpatient visit							
- low-risk patients	32%	32%	32%	31%	62%	62%	62%
- high-risk patients	77%	63%	63%	63%	82%	82%	82%
Clinical outcomes							
Conditional on infection being diagnosed							
Prob. of hospitalization	2%	18%	25%	25%	36%	45%	51%
Probability of death	0%	0%	1%	2%	4%	7%	19%
Unconditional, assuming only 50% of infections are diagnosed							
Prob. of hospitalization	1.0%	8.8%	12.4%	12.7%	18.0%	22.3%	25.4%
Probability of death	0.0%	0.1%	0.3%	1.0%	1.9%	3.7%	9.4%
Case not medically attended							
Medical cost (all risk)	\$5	\$5	\$5	\$5	\$5	\$5	\$5
Lost productivity (all risk)	\$76	\$76	\$76	\$76	\$152	\$152	\$152
Outpatient visit							
Low-risk medical cost	\$161	\$212	\$233	\$254	\$410	\$410	\$410
Low-risk lost productivity	\$152	\$152	\$228	\$304	\$456	\$456	\$456
High-risk medical cost	\$1,098	\$1,227	\$1,234	\$1,240	\$806	\$806	\$806
High-risk lost productivity	\$608	\$304	\$456	\$608	\$1,063	\$1,063	\$1,063
Hospitalization							
Low-risk medical cost	\$25,408	\$32,174	\$34,960	\$37,745	\$19,379	\$19,379	\$19,379
Low-risk lost productivity	\$1,367	\$1,823	\$1,899	\$1,974	\$1,974	\$1,974	\$1,974
High-risk medical cost	\$70,938	\$80,760	\$75,334	\$69,908	\$28,346	\$28,346	\$28,346
High-risk lost productivity	\$3,493	\$3,189	\$3,417	\$3,645	\$2,734	\$2,734	\$2,734
Fatalities							
Low-risk lost productivity	\$1,367	\$1,823	\$1,899	\$1,974	\$1,974	\$1,974	\$1,974
High-risk lost productivity	\$3,493	\$3,189	\$3,417	\$3,645	\$2,734	\$2,734	\$2,734
VSL (\$, mil.)	5.76	12.34	10.05	7.75	5.29	5.29	5.29

Table III
Baseline scenarios

This table presents the estimates for the attack rate, number of deaths, and the total cost that will be incurred in the future for the baseline scenario, which assumes the suppression policy will be kept in place only for two more weeks before being replaced by the mitigation policy until a vaccine becomes available in week 78.

Assumption for the suppression policy R_0	Attack rate	Fatalities	Total cost (\$, trillions)
$R_0 = 0.7$	25.64%	620,353	\$4.19 (19.6% of GDP)
$R_0 = 0.5$	25.62%	619,753	\$4.19 (19.6% of GDP)

Table IV
Sensitivity of the optimal duration of the suppression phase to the assumptions

This table presents the optimal duration of the suppression phase as a function of the suppression-phase R_0 , the R_0 that mitigation can achieve if the number of new cases exceeds 50,000 per week, as well as the incremental cost of the suppression policy. If the number of new cases is 50,000 per week or below, the mitigation $R_0 = 1.1$, and after the vaccine becomes available in week 78, $R_0 = 0.3$. The right-hand column presents the incremental net benefit of continuing the suppression phase until the optimal stopping time calculated relative to the benchmark scenario of stopping it two weeks from now.

Suppression R_0	Assumptions		Optimal lockdown duration	Net benefit relative to 2-week benchmark (\$, trillion)
	Incremental cost of suppression	Mitigation R_0		
0.7	\$36 billion	1.2	17 weeks	\$2.42
		1.3	18 weeks	\$3.54
		1.5	19 weeks	\$5.21
		1.9	19 weeks	\$7.21
	\$72 billion	1.2	16 weeks	\$1.91
		1.3	17 weeks	\$3.00
		1.5	18 weeks	\$4.64
		1.9	19 weeks	\$6.60
0.5	\$36 billion	1.2	10 weeks	\$2.67
		1.3	11 weeks	\$3.83
		1.5	11 weeks	\$5.51
		1.9	11 weeks	\$7.51
	\$72 billion	1.2	10 weeks	\$2.38
		1.3	10 weeks	\$3.82
		1.5	11 weeks	\$5.19
		1.9	11 weeks	\$7.18