ANDREW ATKESON
University of California, Los Angeles

Behavior and the Dynamics of Epidemics

ABSTRACT A model of private and public behavior to mitigate disease transmission during the COVID-19 pandemic over the past year in the United States addresses two questions: What dynamics of infections and deaths should we expect to see from a pandemic? What are our options for mitigating the impact of a pandemic on public health? I find that behavior turns what would be a short and extremely sharp epidemic into a long, drawn-out one, with, at best, a modest impact on the long-run death toll from the disease. Absent the development of a technological solution, such as vaccines or life-saving therapeutics, additional public health interventions suffer from rapidly diminishing returns in improving long-run outcomes. In contrast, rapidly implemented non-pharmaceutical interventions, in combination with the rapid development of technological solutions, could have saved nearly 300,000 lives relative to what is now projected as of mid-June 2021 to occur over the long run.

During the first half of the twentieth century, Americans enjoyed tremendous gains in health and life expectancy as infectious diseases were drastically curtailed thanks to major medical advances and significant investments in sanitation and public health. Annual mortality rates from infectious disease in the United States fell by an order of magnitude from nearly 800 per 100,000 in 1900 to under 50 per 100,000 by 1960, in a steady downward trend interrupted, dramatically, by the 1918–1919 influenza epidemic (Armstrong, Conn, and Pinner 1999).[1] But as the HIV/AIDS pandemic made evident, and the COVID-19 pandemic reinforced,

Conflict of Interest Disclosure: The author did not receive financial support from any firm or person for this article or from any firm or person with a financial or political interest in this paper. He is currently not an officer, director, or board member of any organization with an interest in this paper.

1. To place the mortality from COVID-19 in historical perspective, note that in the United States it was roughly 100 per 100,000 in 2020 and may very well reach this level again in 2021. So while mortality from COVID-19 will not reach the levels experienced during the Spanish flu, it will clearly be the most significant short-term increase in mortality from infectious disease in the United States in at least sixty years.

infectious diseases are far from vanquished (Morens and Fauci 2020). In fact, the risk of experiencing another pandemic in the not too distant future is considerable. For example, according to a September 2019 estimate by the president's Council of Economic Advisers, there is a 4 percent probability of an influenza pandemic annually. If such a pandemic were to occur it would, at the high end, cause nearly $4 trillion in economic damage and over half a million deaths (Council of Economic Advisers 2019).

Given that we are likely to see significant outbreaks of infectious disease in the future, this moment, after a year of COVID-19, seems an opportune time to reexamine our models of disease dynamics and the policy options for disease control implied by these models. What dynamics of infections and deaths should we expect to see from a pandemic? What are our options for mitigating the impact of a pandemic on public health? How might this mitigation be done in a manner to reduce the negative impact of a pandemic on the economy? These are questions that will provoke new research in light of worldwide data from this COVID-19 pandemic for years to come.

But, with one year of data on COVID-19 now available, one conclusion seems clear: the endogenous response of both public and private behavior to the prevalence of COVID-19 has transformed this epidemic from what standard epidemiological models predicted to be a short, but exceedingly intense, episode into a drawn-out pandemic that will have an impact on public health and the economy over several years, until, with luck, the technological solutions of vaccination and life-saving therapeutics bring this disease under much greater control worldwide.[2]

In this paper, I use a simple model of our experience with COVID-19 in the United States over the past year to explore how the interaction of disease and behavior changes the dynamics of an epidemic and constrains our options for mitigating the impact of a pandemic on public health absent a technological solution such as vaccines and life-saving therapeutics. Based on this model, I present four conclusions.

First, the behavioral responses that we have seen to COVID-19 over the past year, both private and public, have had a powerful impact in "flattening the curve," reducing peak levels of daily infections and deaths by an order of magnitude relative to predictions of standard epidemiological models. These behavioral responses, however, are forecast to have only a

2. It is clear that the development of vaccines for COVID-19 has been a technological marvel. There also appears to be considerable promise for the development of therapeutics that could substantially reduce the severity of the disease and thus complement vaccines in bringing the pandemic to an end worldwide. See Saelens and Schepens (2021) for a description of such therapeutics.

modest impact in reducing the long-term death toll from COVID-19 relative to predictions of standard epidemiological models in the absence of the development of technological solutions such as vaccines or life-saving therapeutics. Absent such technological solutions, the long-run death toll in the United States would approach 1.25 million over a five-year period, even with the private and public efforts at mitigation that have been undertaken. Thus, without the success of vaccines that we have now experienced here in the United States as of mid-March 2021, we would have been halfway through this pandemic in terms of cumulative deaths. Moreover, absent the development of technological solutions, my model implies sharply diminishing returns to further non-pharmaceutical interventions in reducing the long-run death toll from COVID-19 even if such measures had been implemented early in 2020 and maintained for a long, but finite, length of time. Thus, absent a technological solution, we would be faced with few options for further mitigating the long-run impact of COVID-19 on public health.

Second, here in the United States, we have been very fortunate with our success in developing and now implementing effective vaccines against COVID-19. With vaccines, the long-run death toll from COVID-19 is forecast to be roughly 600,000, or about half the level without such a technological solution. This forecast takes into account both the relaxation of private and public efforts at disease control that we have seen in spring 2021 and the arrival of new, more contagious variants of the virus. Clearly, Operation Warp Speed and the associated research effort has been a scientific and public health achievement of historic importance.

Third, in contrast to the case of no technological solutions being developed, strong non-pharmaceutical interventions implemented early on are highly complementary with speedy development of vaccines and life-saving therapeutics in that they save lives by delaying illness and death until such technological solutions are available. This model forecast that plausible additional non-pharmaceutical interventions, applied early on and consistently over time on top of the policies that were implemented at state and local levels, could have reduced the long-term death toll from COVID-19 in the United States to roughly 300,000 over a five-year period. This forecast takes into account the likely countervailing relaxation of private and state and local mitigation efforts had such interventions been implemented at a federal level. Based on this forecast, I conclude that here in the United States, over the course of the past 14 months, we failed to take actions that would have saved hundreds of thousands of lives. Given the success of a number of countries in containing COVID-19 over the past year while preserving economic activity, it is entirely plausible that such non-pharmaceutical interventions would not have led to high economic costs and, in fact, might have led to better economic outcomes.

Fourth, and finally, looking ahead, we face a future in which COVID-19 will remain a threat as long as it is prevalent elsewhere in the world and in which new pandemic threats will likely arise. We should use the worldwide experience with COVID-19 to guide investments in public health infrastructure that will allow us to rapidly identify and react to pandemic threats with more effective and less costly non-pharmaceutical interventions. Such investments have a strong "public good" rationale and would be highly complementary with increased investments in the scientific and clinical research infrastructure to rapidly develop technological solutions such as vaccines and life-saving therapeutics for future threats from infectious disease.

I. Epidemic Dynamics with and without Behavior

The public health policies enacted around the world to combat COVID-19 have been guided by standard epidemiological models built on the susceptible-infected-removed (SIR) framework developed by Kermack and McKendrick (1927). These models simulate disease transmission as arising when infectious individuals (corresponding to the I in SIR) interact with others. Through this interaction, a virus or other pathogen succeeds in infecting those who have no immunity and are thus susceptible (corresponding to the S in SIR), turning such agents into newly infectious individuals. Individuals who gain immunity from prior infections or vaccinations are said to be removed (corresponding to the R in SIR) as they no longer contribute to the transmission of the disease. The progress of the epidemic through the population is mechanical as the rate at which infectious people interact with others is assumed to be invariant to the current prevalence of the disease.

When applied to COVID-19, three quantitative implications of this standard model stand out.[3] First, the model gives dire forecasts for the peak of the disease's first wave—10 to 20 percent of Americans were predicted to be sick with COVID-19 simultaneously at the first peak of infections absent drastic efforts such as lockdowns to slow transmission. At current estimates of the infection fatality rate for COVID-19, this rate of infection would have corresponded to peak death rates on the order of 30,000 to

3. See Atkeson (2020) and Stock (2020) for expositions of these predictions of standard SIR models from one year ago.

60,000 deaths per day.[4] Second, this standard model forecast that if efforts to slow transmission through lockdowns were applied early on but were only temporary, this dramatic first peak would be delayed but not prevented: cases and deaths would explode again once efforts to slow transmission were relaxed. Third, this standard model offered dramatic long-run predictions of the kind made famous by Angela Merkel in March 2020—that more than two-thirds of Germany's population were forecast to experience infections (if not vaccinated) before the pandemic would end through herd immunity.[5] Again, applying current estimates of the average infection fatality rate for COVID-19 in the United States, this implies a long-run death toll on the order of 1.49 million or more.[6]

These implications of a standard epidemiological model for the magnitude of the first peak and the long-run impact of COVID-19 in terms of infections are driven by a single parameter known as the basic reproduction number of the virus (the R_0).[7] The implications of these infections for deaths from COVID-19 are determined by the average infection fatality rate across the infected population. While we now know that the infection fatality rate from COVID-19 varies widely with age and other factors, estimates of the disease burden from COVID-19 from the Centers for Disease Control and Prevention (CDC) are consistent with an average infection fatality rate of 0.5 percent across the entire infected population in the United States for 2020.[8] The emergence of new, more transmissible virus variants with higher basic reproduction numbers makes the predictions of standard epidemiological models for peak infections and long-run impact even more dire.

4. This estimate for peak deaths is likely understated given that such a wave of infections would clearly have overwhelmed the health care system.

5. See Die Bundesregierung [Cabinet of Germany], "An Address to the Nation by Federal Chancellor Merkel," n.d., https://www.bundesregierung.de/breg-de/themen/coronavirus/statement-chancellor-1732296; and CNN, "Merkel Believes 60–70% of Germany's Population Will Be Infected," March 11, 2020, https://edition.cnn.com/world/live-news/coronavirus-outbreak-03-11-20-intl-hnk/h_ab9bb8236fa91a9bf63cdbc7a69e0f10.

6. This forecast for the cumulative death toll in this model scenario does not take into account that the infection fatality rate would likely have risen substantially due to congestion in the health care system if the first wave of infections had approached anything close to the levels forecast by this standard model.

7. See Randolph and Barreiro (2020) for a description of the calculations and considerations involved.

8. The CDC estimates that 83 million Americans had been infected by the end of December 2020. Total COVID-19 deaths reached 445,000 thirty days later, giving an average estimated infection fatality rate, including the delay from infection to death, of slightly over 0.005. See CDC, "Estimated Disease Burden of COVID-19," https://www.cdc.gov/coronavirus/2019-ncov/cases-updates/burden.html.

It is now clear that the first prediction of standard epidemiological models for the first peak of infections and deaths was off by at least an order of magnitude—it is unlikely that more than 2 percent of Americans have ever been infected simultaneously, and the peak of daily deaths in America from COVID-19 has fortunately stayed under 4,000. Looking at data worldwide, it appears that the second prediction of standard epidemiological models is also off, perhaps by an order of magnitude. While many locations within the United States and abroad have suffered severe second or third waves of COVID-19 deaths after relaxing costly public measures to control disease transmission, these waves have been much smaller than predicted by a standard SIR model.

In contrast, the standard SIR model's third prediction, regarding long-run impact, looks to be closer to the mark. While the precise threshold of herd immunity—the fraction of the population that has to gain immunity through infection or vaccination before the pandemic can end—is not yet empirically resolved, available data from locations such as Manaus, Brazil, which has experienced high rates of infection, and from Israel, the United Kingdom, and the United States, each of which have high vaccination rates with effective vaccines as of mid-March 2021, indicate that the predictions of a standard epidemiological model for the long-run impact of COVID-19 are likely correct: this pandemic will not resolve until high proportions of the population have acquired immunity either through infection or vaccination.[9]

I.A. Behavior Regulates Disease Dynamics

How does consideration of the impact of behavior on the progression of a pandemic help us understand this relationship between the predictions of a standard SIR model and observed outcomes?

Within economics, Tomas Philipson pioneered the study of the interaction of behavior and the spread of disease in his work on the HIV/AIDS pandemic. In a chapter in *Handbook of Health Economics*, summarizing work on that pandemic, Philipson (2000) argued that epidemiological models should incorporate prevalence-elastic private demand for costly measures to prevent the spread of infectious disease. Such models, he maintained, offered two fundamental economic insights.

9. See Sabino and others (2021) and Mallapaty (2021) regarding data from Manaus and Israel on the empirical herd immunity threshold. The CDC COVID-19 data tracker site reports on vaccination rates in the United States. Data on vaccination rates in the United Kingdom are available at Gov.UK, "Coronavirus (COVID-19) in the UK," https://coronavirus.data.gov.uk/details/vaccinations.

The first insight is that costly private efforts to prevent disease transmission are self-limiting—as disease incidence falls, these costly efforts to control disease spread are relaxed and the disease reemerges.

Within the United States, it appears that this observation holds for public policies aimed at COVID-19 as well—state and local disease control measures are often conditioned on measures of disease prevalence such as infections or hospitalizations, and these public measures aimed at the control of COVID-19 are relaxed as disease prevalence falls. In the model I present below, I interpret this correlation between public policies and disease prevalence as arising from a public behavioral response to shifting political calculations as disease prevalence rises and falls, that is, as a social-choice behavioral response that is conceptually similar to private behavioral responses. I thus interpret the reduced form behavioral response of transmission rates to disease prevalence in my model as resulting from a combination of private and public reactions to disease prevalence.

The second insight is that the private and public behavioral response to changing disease prevalence partially offsets the impact of additional non-pharmaceutical interventions aimed at disease control. In short, the effect of a specific non-pharmaceutical intervention is limited by its success as private and public efforts aimed at disease control are relaxed in response.

That both public and private prevalence-elastic demand for costly measures to control disease are self-limiting is a particularly powerful insight for understanding where the standard epidemiological model fails as a description of disease dynamics and where it succeeds. In joint work with Karen Kopecky and Tao Zha (Atkeson, Kopecky, and Zha 2021), we find that the data on the progression of the COVID-19 pandemic across many countries and US states throughout 2020 conform strikingly well to a core prediction of the standard epidemiological model modified to include prevalence-elastic demand for disease prevention—that after the first phase of the pandemic in which disease grows rapidly, the growth rates of infections and deaths should remain in a relatively narrow band around zero until the pandemic is over.[10]

The intuition for this prediction regarding disease dynamics in the context of a model with prevalence-elastic demand for disease prevention is simple. If new infections and daily deaths from the disease grow too high, people and governments make costly efforts to avoid interaction and thus slow

10. Joshua Gans (2020) reviews the implications of epidemiological models with a prevalence-elastic demand for costly measures to prevent disease transmission and much of the work by others on this topic.

disease spread. Likewise, if the prevalence of the disease falls, people and governments relax those costly measures to prevent disease transmission and the prevalence of the disease rises again. The reaction of behavior, both public and private, to the prevalence of the disease regulates the equilibrium prevalence of the disease in the same way that cruise control regulates the velocity of a car on a highway that winds up and down hills. The equilibrium level of daily deaths, corresponding in this analogy to the velocity of the car, remains within a relatively narrow band (relative to that predicted by a standard SIR model) in response to shocks having an impact on disease transmission because of the stabilizing role of endogenous prevalence-elastic public and private disease avoidance behavior. The impact of this behavior then is to transform what would otherwise be a short and sharp disease episode into a much more slowly evolving and drawn-out phenomenon.

What are the implications of a model with prevalence-elastic demand for disease prevention for the long-run impact of an epidemic? Here the insight that the demand for disease prevention is self-limiting is particularly relevant. For an epidemic to end, the prevalence of the disease must fall toward zero. As disease prevalence falls toward zero, the demand for costly disease prevention efforts also falls toward zero, and hence the disease will come back unless the population has already achieved herd immunity measured at prepandemic levels of behavior. That is, the predictions for the long-run impact of COVID-19 using a standard epidemiological model should continue to hold.[11] Given estimates of the basic reproduction number around 3, or now higher with new variants, this herd immunity threshold should kick in when significantly less than one-third of the population remains susceptible.[12]

This logic implies that, absent a vaccine or the development of life-saving therapeutics, the implications of a model that includes a prevalence-elastic demand for disease prevention for the long-run impact of a pandemic in terms of cumulative infections and deaths should be similar

11. More complex models that emphasize heterogeneity and the network structure of human interaction potentially offer more optimistic implications for the long-run impact of COVID-19. See, for example, Ellison (2020), Akbarpour and others (2020), Azzimonti and others (2020), and Boppart and others (2020).

12. On the transmissibility of the UK variant, see Davies and others (2021); for the even higher transmissibility of the Indian variant, see "Delta Coronavirus Variant Believed to Have 60% Transmission Advantage—UK Epidemiologist," Reuters, June 9, 2021, https://www.reuters.com/business/healthcare-pharmaceuticals/delta-coronavirus-variant-believed-have-60-transmission-advantage-uk-2021-06-09/.

to that of a standard epidemiological model. The slowing of the epidemic that results from a behavioral response to disease prevalence can reduce the cumulative death toll by reducing the extent to which cumulative infections in the long run overshoot the herd immunity threshold, but this behavioral response does not reduce the cumulative impact of the epidemic to a point below this threshold. In the case of COVID-19 in the United States, in the model I present below, this would be a cumulative death toll on the order of 1.24 million.

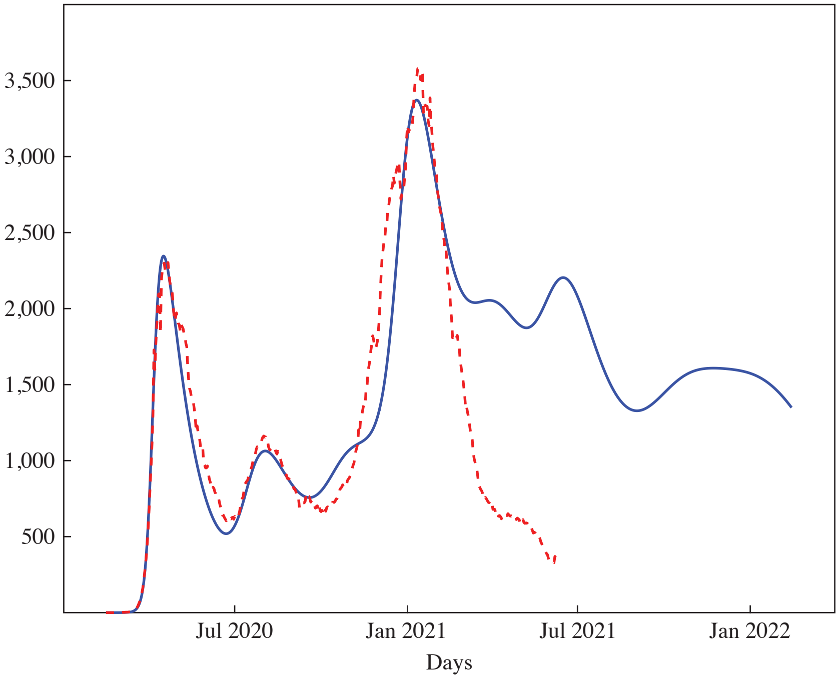
I.B. A Quantitative Illustration

To illustrate these points regarding the predictions of a standard epidemiological model and one with a prevalence-elastic demand for disease prevention for the dynamics of an epidemic, I turn to a model of the dynamics of deaths from the COVID-19 epidemic in the United States that I presented in a recent working paper (Atkeson 2021) and which is included as an online appendix to this paper. This model accounts for the dynamics of deaths from COVID-19 in the United States over the past year with shocks to transmission rates due to seasonality, due to the emergence of a new, more transmissible variant of the novel coronavirus, and due to potential changes in the prevalence-elasticity of demand for costly measures to mitigate disease transmission. (I refer to this third shock as "pandemic fatigue" as a shorthand description of a decline in the responsiveness of private and public demand for costly disease prevention measures to changes in disease prevalence. This shock is perhaps a reduced form for a more dynamic response of behavior as a pandemic wears on.)

This model accounts remarkably well for the pandemic's evolution in the United States over the past year. In the online appendix, I document that, in the model, a seasonal decline in transmission rates explains why the prevalence of COVID-19 dropped to relatively low levels in the summer of 2020. In the model, a decline in the strength of the behavioral response to disease prevalence in late fall—pandemic fatigue—explains the large waves of infections and deaths seen in the late fall and winter. The introduction of a more transmissible variant in early December together with the start of an aggressive vaccination program explain the progress of the epidemic in the spring of 2021.[13]

13. In the online appendix, I document the specific features of this model that allow it to fit the pattern of daily deaths observed over the past 14 months with relatively few shocks and discuss the procedure used to choose the model parameters. The fit of the model to the data is serendipitous. Further research is needed to develop behavioral models that can fit the wide range of experiences with COVID-19 seen across regions and countries of the world.

Figure 1. Daily Deaths with a Behavioral Response but No Vaccines



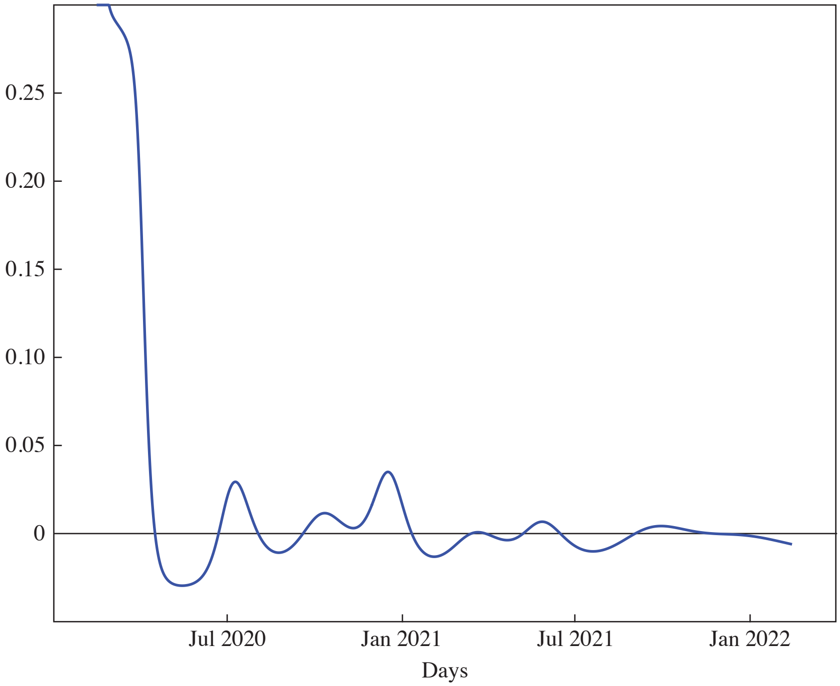
Sources: CDC and author's calculations.

Notes: Behavioral model implications for daily deaths in the United States from mid-February 2020 through mid-February 2022 are shown in the solid line. Seasonal variation, the introduction of a more contagious variant in December 2020, and prevalence-elastic demand for costly measures to slow disease transmission have an impact on transmission rates. The onset of pandemic fatigue in late 2020 accounts in large part for the peak in deaths in January 2021. Data on the seven-day moving average of daily deaths are shown in the dashed line. The forecast for cumulative deaths over a five-year period implied by this model is 1.24 million.

In figure 1, I show the model's prediction for daily deaths from COVID-19 in the United States from mid-February 2020 to mid-February 2022 (the solid line), and data on the seven-day moving average of daily deaths in the United States over the past year (the dashed line) downloaded from the CDC's COVID-19 data tracker website.[14] The behavioral model matches the data on deaths over the past year quite well, and it forecasts,

14. CDC, "COVID Data Tracker," https://covid.cdc.gov/covid-data-tracker/#datatracker-home. Note that these data on daily deaths omit roughly 14,000 deaths included in the CDC estimate of the cumulative death toll from COVID-19 available on the same site as these additional deaths were included retroactively due to reclassification of state and local death counts.

Figure 2. Growth Rate of Daily Deaths



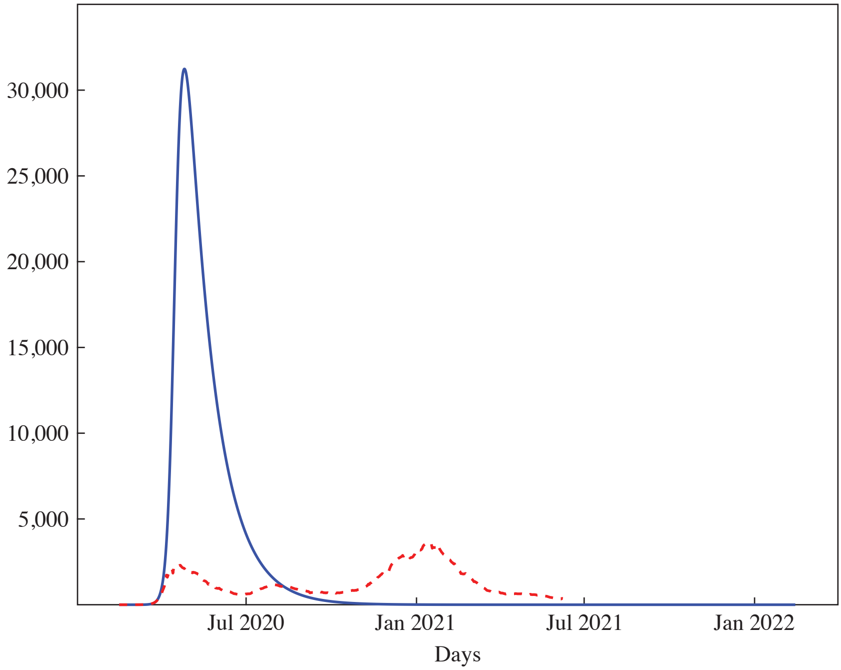
Source: Author's calculations.

Notes: The growth rate of daily deaths implied by the solution of the model shown in figure 1 shows that behavior closely regulates the growth rate of the epidemic after its initial phase of rapid growth.

absent vaccines, a continuation of the pandemic well into 2022. The predicted path of daily deaths through 2021 shown in this figure is driven by the spread of the new, more contagious virus variant in the model. The long-run cumulative death toll over a five-year period in this forecast run of the model in figure 1 is 1.24 million. The forecast shown in this figure does not include any consideration of the impact of vaccines, both to permit comparison with projections from a standard epidemiological model and to serve as a benchmark for the impact of vaccination efforts.

To illustrate the impact of the behavioral response to disease prevalence in shaping the growth rate of the epidemic, in figure 2 I show the model-implied growth rate of daily deaths from the simulation of the model shown in figure 1. We see in this figure that the growth rate of daily deaths starts out at a very high level—above 30 percent per day—and then falls rapidly toward zero and hovers around zero even with shocks due to seasonality

Figure 3. Daily Deaths with No Behavioral Response or Vaccines



Sources: CDC and author's calculations.

Notes: Standard model implications for daily deaths in the United States from mid-February 2020 through mid-February 2022 are shown in the solid line. Seasonal variation and the introduction of a more contagious variant in December 2020 have an impact on transmission rates, but this specification of the model has no prevalence-elastic demand for costly measures to slow disease transmission. Data on the seven-day moving average of daily deaths in the United States over the past year are shown in the dashed line. The forecast for cumulative deaths over this five-year period is 1.49 million.

in transmission, pandemic fatigue, and the introduction of new variants. In the model, the response of private and public behavior to the level of daily deaths acts to slam the brakes on the growth of the epidemic in its initial phase and then maintain that growth rate of daily deaths in a narrow band around zero in the face of shocks to transmission much as cruise control regulates the acceleration of a car on the highway.

To contrast the implications of this model incorporating a behavioral response to disease prevalence with the implications of a standard model without such a response, in figure 3, I show the prediction for daily deaths of the same model with the behavioral response to disease prevalence turned off (the solid line), relative to data on the seven-day moving average of daily deaths (the dashed line). As we see in this figure, the standard epidemiological model without a behavioral response overstates the first peak of daily deaths by at least an order of magnitude (these peak at over 30,000 per day), but then the pandemic comes quickly to an end in the fall of 2020. The cumulative death toll in this model forecast is 1.49 million. This prediction for the cumulative death toll is certainly larger than in the model with a behavioral response, but the gap between the two models in this dimension is much smaller than in their predictions for the initial peak and the time scale of the pandemic.[15]

What is evident from these figures is that incorporating a response of public and private behavior to disease prevalence gives a dramatically different forecast for the severity of disease peaks as well as for the speed with which this epidemic passes through the population. In this behavioral model, absent the introduction of vaccines, the pandemic takes two and a half years to play out rather than six to nine months as forecast by the standard model without consideration of behavior. The model's implications, however, for the long-run impact of the disease are not much altered by the consideration of behavior. In both basic and behavior variations, the model forecasts that a substantial majority of the population must become immune through infection or vaccination for the pandemic to end.

II. Private Behavior and Constraints on Policy

Given these insights on the impact of prevalence-elastic demand for disease prevention on the dynamics of an epidemic, what are our options for using public policy to mitigate the impact of a pandemic on public health? One insight that I have already mentioned is that there is likely to be an offsetting private behavioral response to public measures that limit the spread of disease—that is, that additional non-pharmaceutical interventions to control an epidemic may well be partially undone by private responses and the responses of other government actors to declining disease prevalence. The other insight is that public measures of disease prevention must be essentially permanent to result in a meaningful reduction of the long-run impact of an epidemic absent a technological solution such as a vaccine or the development of life-saving therapeutics.

We can use our simple behavioral model to illustrate the quantitative implications of these two insights. Imagine that through public policies

15. This difference between the cumulative death toll forecast in the model run in figure 3 and that in figure 1 is due to what is known as "overshooting" of herd immunity in the model without behavior in figure 3. See Bergstrom and Dean (2020) for an explanation of this concept.

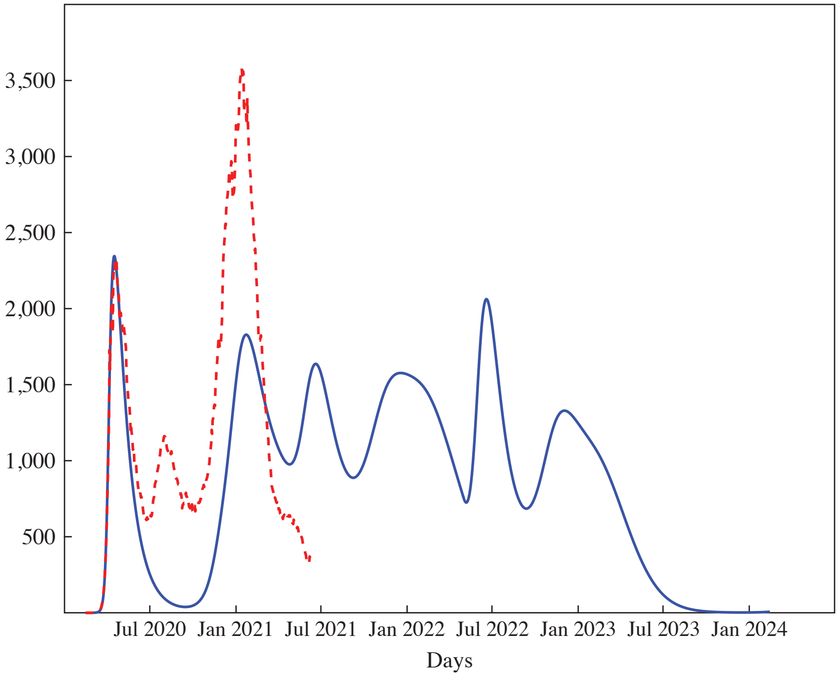
facilitating a wide range of disease control measures such as mask wearing and social distancing protocols, testing and contact tracing with isolation of infectious persons, and other measures, it was possible to significantly reduce the transmission rate of COVID-19, holding fixed seasonality and the level of costly disease control measures undertaken by both private agents and state and local authorities. Imagine that these policy interventions are undertaken for a fixed period of time independent of disease prevalence. In this sense, I imagine that these interventions are undertaken independently of the political process that leads currently observed public interventions to rise and fall with disease prevalence. Here, for purposes of illustration, I imagine these interventions as being carried out by the federal government.

In figure 4, I show a simulation of the model with such measures put in place for a two-year period from May 1, 2020, through May 1, 2022. Here I assume that these additional mitigation measures are put in place independent of the level of daily deaths and that they act to reduce disease transmission by 40 percent—a factor of $exp(-0.5)$—on top of whatever reductions in transmission are brought about by private and public changes in behavior undertaken in response to disease prevalence. I show the model implications for daily deaths over a four-year period as a solid line and the data on the seven-day moving average of daily deaths in a dashed line. As we see in this figure, these disease control measures, when imposed on top of those arising in equilibrium from the prevalence-elastic demand of both private agents and public authorities for costly measures to control disease, have a significant impact in reducing deaths from the disease in the first year. Then, in this simulation, in early 2021, the arrival of the new variant and, in mid 2022, the abandonment of these disease control measures leads to significant spikes in forecast deaths. Over the long run, the cumulative death toll is 1.22 million—almost exactly what we found in the simulation in figure 1 that had no such additional disease control measures imposed. This simulation indicates sharply diminishing returns to additional non-pharmaceutical interventions absent a technological solution such as a vaccine or life-saving therapeutics.

II.A. Waiting for a Technological Solution

We saw in figure 4 that additional but temporary disease control measures do not significantly reduce the long-run public health impact of the epidemic in the absence of a technological solution such as vaccines or life-saving therapeutics. How does the analysis of the impact of such measures change when there is a good prospect that a vaccine or therapeutics

Figure 4. Daily Deaths with Extra Mitigation but No Vaccines



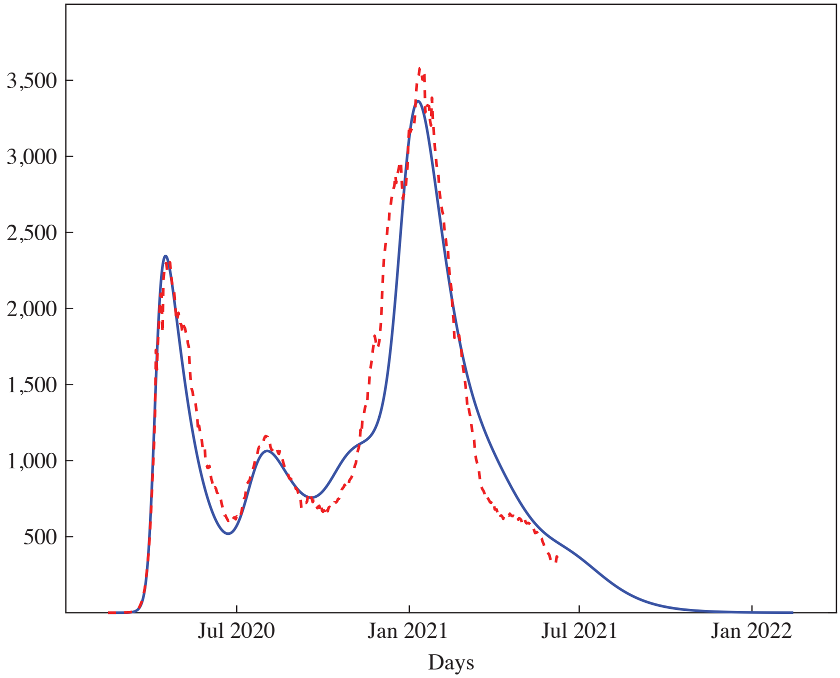
Sources: CDC and author's calculations.

Notes: Predictions of the model for the evolution of daily deaths from COVID-19 in a version in which disease control measures—such as masks, social distancing, testing with contact tracing, and isolation of the infected—cut the transmission rate of the disease by 40 percent, a factor of *exp(−0.5)*, holding fixed the level of private and state and local disease control efforts undertaken in response to the prevalence of the disease. These measures are assumed to be in place for two years from May 1, 2020, to May 1, 2022. While these disease control measures are effective in reducing deaths in the first year, they do not succeed in later years. The data on the seven-day moving average of daily deaths are shown in the dashed line. The cumulative death toll implied by this model is 1.22 million—nearly the same as shown in the simulation in figure 1.

might arrive? Here I use the model to show that such measures can have a significant long-run public health benefit in reducing deaths from disease while waiting for the arrival of that technological solution.

In figure 5, I show the implications of the model for the evolution of daily deaths (the solid line) when a program of vaccination starts on January 1, 2021, at a pace sufficient to succeed in protecting half of the US population by July 1, 2021. This vaccine is assumed to prevent both illness and disease transmission by the vaccinated. The data on the seven-day moving average of daily deaths are again shown in a dashed line. To

Figure 5. Daily Deaths with a Behavioral Response and Vaccines



Sources: CDC and author's calculations.

Notes: Predictions of the model for daily deaths from COVID-19 (in the solid line) in a simulation with a vaccination program starting on January 1, 2021, that proceeds at a rate fast enough to protect half of the population by July 1, 2021. In this simulation, the vaccine is assumed to protect against illness and to prevent disease transmission by the vaccinated. The data on the seven-day moving average of daily deaths are shown in the dashed line. To see the predicted impact of the vaccine on the dynamics of the epidemic, compare the solid line for model-implied daily deaths in 2021 in figure 1 to the solid line here. The cumulative death toll over a five-year period in this simulation is 595,000.

see the model-implied impact of this vaccination program on the epidemic, one can compare the solid lines in figures 1 and 5. Here we see that, in the model, this vaccination program significantly reduces the forecast impact of the new variant in late spring 2021 and brings the epidemic to an end late by summer or fall 2021. Note that here the vaccination program succeeds despite the model-implied relaxation of public and private efforts at disease prevention in response to falling daily deaths.

The long-run death toll predicted by the model with this vaccination program is 595,000, less than half of what is forecast in the absence of a vaccine (in the simulations in figures 1 and 4). In this sense, the vaccination program succeeds in substantially reducing cumulative deaths in a manner that a two-year program of disease mitigation absent a vaccine does not.

But now consider the model-implied scenario for cumulative deaths if the temporary disease mitigation measures used in the simulation in figure 4 had been imposed starting May 1, 2020, and the same vaccination program applied in the simulation in figure 5 had started on January 1, 2021. With this combination of temporary disease mitigation measures and a successful vaccination program, the cumulative death toll implied by the model would have been only 302,000. Clearly, the combination of temporary disease control measures applied while waiting for a technological solution can save many lives. The lesson here is that there are tremendous complementarities between early and aggressive mitigation and the development of a technological solution such as vaccines or life-saving therapeutics in terms of reducing the public health impact of a pandemic.

III. Conclusion

The global COVID-19 pandemic has clearly demonstrated that the risks from the emergence of new infectious diseases, which epidemiologists have been speaking about for years, are terribly real. This pandemic has also posed a severe test of public health strategies and capabilities worldwide. In many countries, the associated economic impact has been as severe as any downturn seen since the Great Depression. How might we do better next time?

Based on the lessons about the interaction of behavior and disease dynamics discussed here, I suggest the following three-part strategy to improve our public health and economic response to emerging infectious disease.

First, we need to invest in our disease surveillance capabilities worldwide, perhaps using the infrastructure developed for worldwide influenza surveillance as a model.[16] It is certainly worth a lot of money to have the capacity to identify the threat from a new infectious disease anywhere in the world before it gets going so as to buy time to mount a public health and scientific response.

Second, we must consolidate all that has been learned about the implementation of non-pharmaceutical public health measures for disease control

16. World Health Organization, "Preventing the Next Human Influenza Pandemic: Celebrating 10 Years of the Pandemic Influenza Preparedness Framework," https://www.who.int/news/item/21-05-2021-preventing-the-next-human-influenza-pandemic-celebrating-10-years-of-the-pandemic-influenza-preparedness-framework.

over the past year so that we might be able to quickly implement those measures that have been proven to effectively slow the spread of an infectious disease with the least cost to the economy. Given the widespread discussion of pandemic fatigue in the population, we should also look at policies for infectious disease control that have low personal costs and thus have a greater chance of enjoying widespread voluntary adherence. A number of countries, many of them in Asia, have been able to keep COVID-19 infections and deaths to low levels over the course of the past year with effective public health interventions based on travel restrictions, testing, contact tracing, and isolation of infected individuals while preserving considerable economic activity and personal autonomy. Several universities in the United States have also succeeded at control of COVID-19 infections with extensive testing and isolation regimes.[17] As we have seen from the model simulations in this paper and these real-world experiences, public health measures that allow us to wait for the development of a technological solution to a global pandemic with minimal loss of life and economic damage can be extremely valuable. Given the public-good nature of infectious disease surveillance and public health system preparedness to implement rapidly scalable countermeasures, it seems a high priority to fund these capabilities at the federal level.

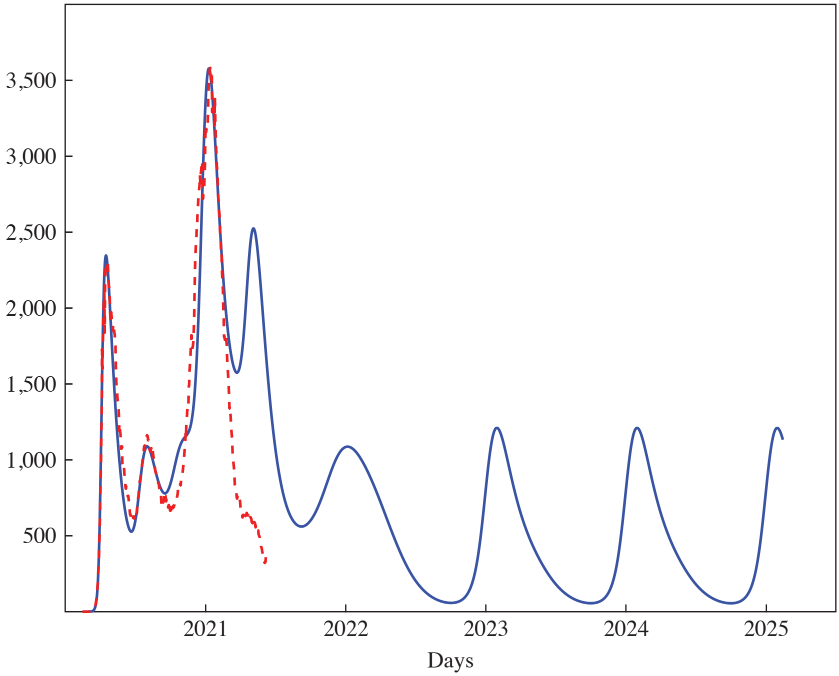
Third, we need to invest in new models for accelerating the development, financing, and distribution of vaccines and life-saving therapeutics for emergent disease. In the end, it is these technological solutions that will allow us to contain the long-run impact of new pandemics once they become global.[18]

To illustrate the urgency of addressing these public health priorities now, consider one final model scenario. As long as COVID-19 remains prevalent worldwide, new mutations of the virus are likely to emerge and there is increasing evidence that such mutations might allow COVID-19 to evade the immunity conferred by prior infection and vaccines. In such a scenario, COVID-19 could be an endemic seasonal disease that might

17. See, for example, the experience of the University of Illinois at Urbana-Champaign and that of Georgia Tech: University of Illinois, "On-Campus COVID-19 Testing Data Dashboard," https://covid19.illinois.edu/on-campus-covid-19-testing-data-dashboard/; Georgia Tech, "Covid-19 Exposure and Health Alerts," https://health.gatech.edu/coronavirus/health-alerts.

18. See Council of Economic Advisers (2019) for a careful analysis of the economic and public health rationale for a large federal investment in such technologies. See Angus, Gordon, and Bauchner (2021) for a discussion of current difficulties in conducting rapid clinical trials of new treatments in the United States.

Figure 6. Daily Deaths with Waning Immunity



Source: Author’s calculations.

Notes: Predictions of the model for daily deaths from COVID-19 (solid line) in a simulation with a vaccination program starting on January 1, 2021, that proceeds at a rate fast enough to protect half of the population by July 1, 2021. The data on the seven-day moving average of daily deaths are shown in the dashed line. In this simulation, immunity acquired from prior infection or vaccination is assumed to last 18 months on average. The vaccination program is assumed to continue at a constant rate throughout the entire period with new booster shots conferring immunity against new variants as they occur. Even with a program of booster vaccines and continued prevalence-elastic behavior, in this simulation roughly 100,000 Americans die each year from COVID-19 on a persistent basis.

require essentially permanent efforts at disease control.[19] To illustrate how such a scenario might play out, I simulate the model with vaccines shown in figure 5 with a version of the virus circulating that is two-thirds more transmissible than the original virus, but in which immunity from infection or vaccination lasts on average for only 18 months. I show the resulting forecast path of daily deaths in the United States from COVID-19 over a five-year period in figure 6. In this simulation, I assume that the vaccination

19. See, for example, Murray and Piot (2021); see also Lavine, Bjornstad, and Antia (2021).

program continues at a constant rate of roughly 1.3 million vaccinations per day throughout the forecast period. As one can see in this figure, the epidemic is forecast in this scenario to settle into a regular seasonal pattern killing over 100,000 Americans per year even with new vaccines and a response of public and private behavior to the changing prevalence of the disease. Clearly, in such a scenario, we would benefit greatly from finding ways to mitigate this disease on an ongoing basis at a lower economic cost.

ACKNOWLEDGMENTS I would like to thank Michael Droste, Karen Kopecky, Ben Moll, Steven Shafer, James Stock, and Tao Zha for many useful conversations.

References

Akbarpour, Mohammad, Cody Cook, Aude Marzuoli, Simon Mongey, Abhishek Nagaraj, Matteo Saccarola, Pietro Tebaldi, Shoshana Vasserman, and Hanbin Yang. 2020. "Socioeconomic Network Heterogeneity and Pandemic Policy Response." Working Paper 27374. Cambridge, Mass.: National Bureau of Economic Research. https://www.nber.org/papers/w27374.

Angus, Derek C., Anthony C. Gordon, and Howard Bauchner. 2021. "Emerging Lessons from COVID-19 for the US Clinical Research Enterprise." *JAMA* 325, no. 12: 1159–61.

Armstrong, Gregory L., Laura A. Conn, and Robert W. Pinner. 1999. "Trends in Infectious Disease Mortality in the United States during the 20th Century." *JAMA* 281, no. 1: 61–66. https://doi.org/doi:10.1001/jama.281.1.61.

Atkeson, Andrew. 2020. "What Will Be the Economic Impact of COVID-19 in the US? Rough Estimates of Disease Scenarios." Working Paper 26867. Cambridge, Mass.: National Bureau of Economic Research. https://www.nber.org/papers/w26867.

Atkeson, Andrew. 2021. "A Parsimonious Behavioral SEIR Model of the 2020 COVID Epidemic in the United States and the United Kingdom." Working Paper 28434. Cambridge, Mass.: National Bureau of Economic Research. https://www.nber.org/papers/w28434.

Atkeson, Andrew, Karen A. Kopecky, and Tao Zha. 2021. *Behavior and the Transmission of COVID-19*. Staff Report 618. Minneapolis: Federal Reserve Bank of Minneapolis. https://www.minneapolisfed.org/research/staff-reports/behavior-and-the-transmission-of-covid19.

Azzimonti, Marina, Alessandra Fogli, Fabrizio Perri, and Mark Ponder. 2020. "Pandemic Control in ECON-EPI Networks." Working Paper 27741. Cambridge, Mass.: National Bureau of Economic Research. https://www.nber.org/papers/w27741.

Bergstrom, Carl T., and Natalie Dean. 2020. "What the Proponents of 'Natural' Herd Immunity Don't Say." *New York Times*, May 1. https://www.nytimes.com/2020/05/01/opinion/sunday/coronavirus-herd-immunity.html.

Boppart, Timo, Karl Harmenberg, John Hassler, Per Krusell, and Jonna Olsson. 2020. "Integrated Epi-Econ Assessment." Working Paper 28282. Cambridge, Mass.: National Bureau of Economic Research. https://www.nber.org/papers/w28282.

Council of Economic Advisers. 2019. *Mitigating the Impact of Pandemic Influenza through Vaccine Innovation*. Washington: Author. https://trumpwhitehouse.archives.gov/wp-content/uploads/2019/09/Mitigating-the-Impact-of-Pandemic-Influenza-through-Vaccine-Innovation.pdf.

Davies, Nicholas G., Sam Abbott, Rosanna C. Barnard, Christopher I. Jarvis, Adam J. Kucharski, James D. Munday, and others. 2021. "Estimated Transmissibility and Impact of SARS-CoV-2 Lineage B.1.1.7 in England." *Science* 372, no. 6538. https://science.sciencemag.org/content/372/6538/eabg3055.

Ellison, Glenn. 2020. "Implications of Heterogeneous SIR Models for Analyses of COVID-19." Working Paper 27373. Cambridge, Mass.: National Bureau of Economic Research. https://www.nber.org/papers/w27373.

Gans, Joshua S. 2020. "The Economic Consequences of $\hat{R} = 1$: Towards a Workable Behavioral Epidemiological Model of Pandemics." Working Paper 27632. Cambridge, Mass.: National Bureau of Economic Research. https://www.nber.org/papers/w27632.

Kermack, William Ogilvy, and A. G. McKendrick. 1927. "A Contribution to the Mathematical Theory of Epidemics." *Proceedings of the Royal Society of London A* 115: 700–721.

Lavine, Jennie S., Ottar N. Bjornstad, and Rustom Antia. 2021. "Immunological Characteristics Govern the Transition of COVID-19 to Endemicity." *Science* 371, no. 6530 (February): 741–45. https://science.sciencemag.org/content/371/6530/741.

Mallapaty, Smriti. 2021. "Vaccines Are Curbing COVID: Data from Israel Show Drop in Infections." *Nature*, February 5. https://www.nature.com/articles/d41586-021-00316-4.

Morens, David M., and Anthony S. Fauci. 2020. "Emerging Pandemic Diseases: How We Got to COVID-19." *Cell* 182, no. 5: 1077–92. https://doi.org/10.1016/j.cell.2020.08.021.

Murray, Christopher J. L., and Peter Piot. 2021. "The Potential Future of the COVID-19 Pandemic: Will SARS-CoV-2 Become a Recurrent Seasonal Infection?" *JAMA* 325, no. 13: 1249–50.

Philipson, Tomas. 2000. "Economic Epidemiology and Infectious Diseases." In *Handbook of Health Economics, Volume 1B*, edited by Anthony J. Culyer and Joseph P. Newhouse. Amsterdam: North-Holland.

Randolph, Haley E., and Luis B. Barreiro. 2020. "Herd Immunity: Understanding COVID-19." *Primer* 52, no. 5: 737–41.

Sabino, Ester C., Lewis F. Buss, Maria P. S. Carvalho, Carlos A. Prete Jr., Myuki A. E. Crispim, Nelson A. Fraiji, and others. 2021. "Resurgence of COVID-19 in Manaus, Brazil, Despite High Seroprevalence." *Lancet* 397, no. 10273: 452–55.

Saelens, Xavier, and Bert Schepens. 2021. "Single-Domain Antibodies Make a Difference." *Science* 371, no. 6530: 681–82.

Stock, James H. 2020. "Data Gaps and the Policy Response to the Novel Coronavirus." Working Paper 26902. Cambridge, Mass.: National Bureau of Economic Research. https://www.nber.org/system/files/working_papers/w26902.