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Great Expectations: Social Distancing in Anticipation of Pharmaceutical Innovations

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"Our strategy is to suppress the virus, protecting the economy, education and the NHS, until a vaccine can make us safe".

- Matt Hancock, UK Health Secretary, October 1, 2020.[1]

"Vaccines and therapeutic drugs might be available in a year or so's time. But it is a foolish strategy to rely on them, and to keep us in lockdown – or other severe social-distancing measures – until such a time".

- Ross Clark, The Spectator, April 2020.[2]

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[1] https://www.gov.uk/government/speeches/extended-measures-to-protect-more-areas-of-england-from-coronavirus

[2] Britain Can't Rely on a Vaccine to Ease Lockdown Restrictions, The Spectator, https://www.spectator.co.uk/article/britain-can-t-rely-on-a-vaccine-to-ease-lockdown-restrictions

1. Introduction

In the absence of effective vaccines and antiviral treatments, individuals and public health authorities have been entirely reliant on non-pharmaceutical interventions such as social distancing and lockdowns. These interventions, while often justified, have proven extremely costly from both a social and an economic perspective and there is a general recognition that such restrictive measures as shelter-in-place orders are not sustainable in the long run. Equally, it is widely recognized that until effective pharmaceutical interventions become available, a return to normality is unlikely to be possible. In short, containing the epidemic will involve social distancing to some extent till vaccines and treatments become available. But an important question remains. Once the pharmaceutical innovations appear on the horizon, how will and should people behave leading up to that moment? In other words, how exactly is social distancing phased out? This is the question we consider in the present analysis.

In this paper, we study positive and normative questions of infection control via non-pharmaceutical interventions (NPIs), when pharmaceutical innovations are anticipated. In particular, we are interested in better understanding how the anticipation of effective vaccines and treatments changes ex-ante incentives to engage in social distancing and how such effects differ across innovations. To this end, we study a stylized susceptible-infected-recovered (SIR) model of infection control in which decision makers can reduce infection risk at a cost. At some known future time T, a perfectly functioning pharmaceutical innovation such as a vaccine or a treatment becomes available, obviating any further social distancing. A perfect treatment means that any infected individual who is treated immediately recovers, while a perfect vaccine means that anyone who is vaccinated obtains perfect and lasting immunity. In this setting, we characterize the equilibrium and socially optimal paths of social distancing. We show that these paths depend on whether the innovation is a treatment or a vaccine. The reason for this is that while treatment can be given to any infected individual regardless of when the individual was infected (in particular, irrespective of whether the individual was infected before or after the arrival of the treatment), only susceptible individuals can benefit from the arrival of the vaccine. The effect of this is that for treatment, the value of social distancing decreases as the arrival date approaches. In fact, on the date of arrival, no social distancing takes place at all. In contrast, before the arrival of the vaccine, social distancing by individuals is ramped up just before arrival, to increase the chances that they can benefit from the vaccine.

To illustrate these points, we consider three scenarios. In the benchmark, no pharmaceutical innovation ever arrives and so the decision makers must resort to social distancing throughout the epidemic. In addition, we consider the case where the innovation arrives before peak prevalence is reached in the benchmark scenario and the case where it arrives after. These three cases allow us to not only determine how the arrival of the innovation influences pre-innovation social distancing efforts, but also how this dependence changes across the stages of the epidemic.

It should be noted that strictly speaking, the key date for the purpose of decision making is the date of availability, rather than the date of innovation. Thus our analysis equally applies to situations where the pharmaceutical innovations have already been made but where decision makers are awaiting delivery of the vaccine or treatment, as the case may be.

The paper contributes to the larger literature on economic epidemiology, in particular to the literatures on social distancing and on the interaction of several instruments of disease control. Rowthorn and Toxvaerd (2020) analyze the interaction of equilibrium and socially optimal social distancing and treatment in a model of recurrent infection (SIS) when both are present, while Toxvaerd and Rowthorn (2020) consider equilibrium and socially optimal use of treatment and vaccination in isolation in an SIR environment. Toxvaerd (2019) considers the welfare effects of policies such as pre-exposure prophylaxis in an SIS model of social distancing. Giannitsarou, Kissler and Toxvaerd (2020) study a model of socially optimal social distancing in an SEIRS model with vital dynamics. In their model, the social planner values lives beyond the active planning horizon, after which the disease is no longer a concern. They show that the social planner may have an incentive to increase the number of survivors at the end of the planning horizon, thus prompting an increase in social distancing as the end date approaches. Some of our results have a similar character, although they differ in the details and in their interpretation. Toxvaerd (2020) and Makris (2020) consider equilibrium social distancing in settings where no pharmaceutical interventions are forthcoming and are therefore comparable to our benchmark scenario.

In a macroeconomic model of disease propagation, Eichenbaum, Rebelo and Trabandt (2020) consider the possibility of a vaccine or a treatment that arrives with a constant probability in each period. As in our paper, they characterize how the possible arrival of these pharmaceutical innovations interact with other decisions, in their case over consumption and labour supply. In contrast to our results, they show that in the competitive equilibrium, the possibility of such innovations makes very little difference in their framework. A central difference between our setup and theirs is that the arrival process has a constant hazard rate (i.e. the arrival probability is constant over time), whereas in our model, individuals know that arrival is approaching as time passes. This introduces an additional source of non-stationarity to our model over and above that in the underlying epidemiological dynamics. Last, Bognanni et al. (2020) consider a spatial macroeconomic-epidemiological model of social distancing in which a vaccine may arrive. In contrast to our analysis, theirs do no feature forward-looking behavior and thus their results are not directly comparable to ours.

2. DECENTRALIZED DECISION MAKING

Consider a susceptible-infected-recovered compartmental model of an infectious disease. Time is continuos and at some instant t, an individual is either susceptible and belongs to the compartment $\mathcal{S}(t)$, infected and infectious and belongs to the compartment $\mathcal{I}(t)$ or recovered and immune, thus belonging to the compartment $\mathcal{R}(t)$. We will denote the measures of these compartments by $S(t)$, $I(t)$ and $R(t)$ respectively. In this model, infection spreads though meetings between susceptible and infected individuals at a rate that depends on underlying biology and social distancing behavior. In particular, we assume that behaviour reduces the infectiousness parameter β to some level $\beta(1-d(t)) < \beta$, where $d(t) \in [0,1]$ is a measure for social distancing. Once infected, individuals recover spontaneously at some exogenous rate $\gamma > 0$[3]. The dynamics are given by

$$\dot{S}(t) = -\beta(1-d(t))I(t)S(t) \quad (1)$$

$$\dot{I}(t) = I(t)\left[\beta(1-d(t))S(t)-\gamma\right] \quad (2)$$

$$\dot{R}(t) = \gamma I(t) \quad (3)$$

$$1 = S(t)+I(t)+R(t) \quad (4)$$

$$S(0) \approx 1, S(0)+I(0)=1, S(0) > \gamma/\beta \quad (5)$$

Assume that the individuals earn some flow payoff $\overline{\pi} > 0$ while susceptible but experience a decrease in flow payoffs to some level $\underline{\pi} < \overline{\pi}$ while infected. Once they recover, they return to earning flow payoff $\overline{\pi}$. Individuals discount the future at rate $\rho > 0$.

Let $p_i(t) \in [0,1]$ denote the probability at instant $t \geq 0$ of residence in health state $i = \mathcal{S}, \mathcal{I}, \mathcal{R}$ for the individual. At time $T > 0$, a pharmaceutical intervention becomes available (either treatment or vaccine). For all times $t < T$, the individual can only mitigate infection risk by choosing social distancing $d(t) \in [0,1]$ at cost $c(d(t))$ with $c' > 0$ and $c'' \geq 0$. For simplicity, we can take $c(d) = d^2/2$ where $c'(d) = d$ and $c''(d) = 1$.

The problem to be solved by a susceptible individual is given by

[3]The model is readily extended to include the possibility of disease-induced mortality. One simple way to include this possibility is to replace γ with $\gamma/(1-\sigma)$, where $\sigma \in [0,1]$ is the probability that the individual will die of the disease before recovering. This formalisation of mortality is discussed further in Keeling and Rohani (2008).

$$\max_{d(t)\in[0,1]} \int_0^T e^{-\rho t} \left\{p_{\mathcal{S}}(t)[\overline{\pi} - c(d(t))] + p_{\mathcal{I}}(t)\underline{\pi} + p_{\mathcal{R}}(t)\overline{\pi}\right\} dt + e^{-\rho T}[p_{\mathcal{S}}(T)V_{\mathcal{S}} + p_{\mathcal{I}}(T)V_{\mathcal{I}} + p_{\mathcal{R}}(T)V_{\mathcal{R}}] \tag{6}$$

In this objective function, V_i is the expected net present value of entering the post-innovation phase inhabiting health state $i = \mathcal{S}, \mathcal{I}, \mathcal{R}$. These values depend on the nature of the pharmaceutical innovation and will be further characterized below.

The individual's problem is solved subject to the following system of differential equations:

$$\dot{p}_{\mathcal{S}}(t) = -(1 - d(t))\beta I(t)p_{\mathcal{S}}(t), \quad p_{\mathcal{S}}(0) = 1 \tag{7}$$
$$\dot{p}_{\mathcal{I}}(t) = (1 - d(t))\beta I(t)p_{\mathcal{S}}(t) - \gamma p_{\mathcal{I}}(t) \tag{8}$$
$$\dot{p}_{\mathcal{R}}(t) = \gamma p_{\mathcal{I}}(t) \tag{9}$$

It is worth emphasizing that under decentralized decision making, each individual takes the aggregate dynamics as given and chooses a path of social distancing in order to maximize his or her individual expected discounted utility. The outcome is thus one of perfect foresight equilibrium, in which the aggregate dynamics that the individuals anticipate when choosing their social distancing policies actually materializes.

Let $\lambda_i^D(t)$ denote the costate variables for the state variables $p_i(t)$, $i = \mathcal{S}, \mathcal{I}, \mathcal{R}$. Then the individual's current-value Hamiltonian is given by

$$H^D = p_{\mathcal{S}}(t)[\overline{\pi} - c(d(t))] + p_{\mathcal{I}}(t)\underline{\pi} + p_{\mathcal{R}}(t)\overline{\pi} \tag{10}$$
$$-\lambda_{\mathcal{S}}^D(t)(1 - d(t))\beta I(t)p_{\mathcal{S}}(t) \tag{11}$$
$$+\lambda_{\mathcal{I}}^D(t)[(1 - d(t))\beta I(t)p_{\mathcal{S}}(t) - \gamma p_{\mathcal{I}}(t)] \tag{12}$$
$$+\lambda_{\mathcal{R}}^D(t)\gamma p_{\mathcal{I}}(t) \tag{13}$$

A necessary condition for individual maximization is that

$$\frac{\partial H^D}{\partial d(t)} = -p_{\mathcal{S}}(t)c'(d(t)) + \beta I(t)p_{\mathcal{S}}(t)[\lambda_{\mathcal{S}}^D(t) - \lambda_{\mathcal{I}}^D(t)] = 0 \tag{14}$$

which can be re-written as

$$c'(d(t)) = \beta I(t)[\lambda_{\mathcal{S}}^D(t) - \lambda_{\mathcal{I}}^D(t)] \tag{15}$$

This equation just means that for the individual to be best responding, the marginal cost of social distancing must equal the marginal benefit, measured by the avoided expected utility cost from becoming infected. With quadratic costs, we get that

$$d(t) = \beta I(t)[\lambda_{\mathcal{S}}^D(t) - \lambda_{\mathcal{I}}^D(t)] \tag{16}$$

To complete the characterization of the equilibrium path of social distancing, we need to determine the evolution of the three costate variables and impose the appropriate transversality conditions. The laws of motion for the costate variables are:

$$\begin{aligned} \dot{\lambda}_{\mathcal{S}}^D(t) &= \rho\lambda_{\mathcal{S}}^D(t) - \frac{\partial H^D}{\partial p_{\mathcal{S}}(t)} \\ &= \lambda_{\mathcal{S}}^D(t)\left[\rho + (1-d(t))\beta I(t)\right] - \lambda_{\mathcal{I}}^D(t)(1-d(t))\beta I(t) - [\overline{\pi} - c(d(t))] \end{aligned} \tag{17}$$

$$\begin{aligned} \dot{\lambda}_{\mathcal{I}}(t) &= \rho\lambda_{\mathcal{I}}^D(t) - \frac{\partial H^D}{\partial p_{\mathcal{I}}(t)} \\ &= \lambda_{\mathcal{I}}^D(t)\left[\rho + \gamma\right] - \lambda_{\mathcal{R}}^D(t)\gamma - \underline{\pi} \end{aligned} \tag{18}$$

$$\dot{\lambda}_{\mathcal{R}}^D(t) = \rho\lambda_{\mathcal{R}}^D(t) - \frac{\partial H^D}{\partial p_{\mathcal{R}}(t)} = \rho\lambda_{\mathcal{R}}^D(t) - \overline{\pi} \tag{19}$$

Last, the transversality conditions are

$$\lambda_{\mathcal{S}}^D(T)e^{-\rho T} = V_{\mathcal{S}} \tag{20}$$

$$\lambda_{\mathcal{I}}^D(T)e^{-\rho T} = V_{\mathcal{I}} \tag{21}$$

$$\lambda_{\mathcal{R}}^D(T)e^{-\rho T} = V_{\mathcal{R}} \tag{22}$$

The transversality conditions will play a prominent role in this analysis and so it is useful to recall their interpretation.[4] In general, the costate variable $\lambda_i^D(t)$ captures the value of being in state $i = \mathcal{S}, \mathcal{I}, \mathcal{R}$. The transversality conditions simply express the present value of residence in the different health states on the date of innovation as being equal to the post-innovation continuation value, which depends on the health state in which the individual enters this phase (and is further analyzed in what follows) and on the nature of the pharmaceutical intervention.

The salvage values on the right-hand sides of the transversality conditions (20), (21) and (22), are value functions that depend on the post-innovation regime, and on whether the innovation is a treatment or a vaccine. With costly or imperfect innovations, e.g. with a partially protective vaccine or a treatment that only induces recovery with a delay, there will generally be a role for social distancing even after the arrival of the pharmaceutical innovation. While this is conceptually a straightforward extension of our analysis, we focus on the simpler case in which the innovations are costless and perfect. This means

[4] This is a fixed-end-time problem with a salvage value. The transversality conditions for this case are given in Caputo (2005, Theorem 10.3, p. 277).

that post-innovation, there is no role for social distancing. This simplification allows us to focus on the characterization of social distancing and how it is affected by the anticipation of the innovation. In a later section, we outline how our main conclusions are modified when imperfections in vaccines and treatment are taken into account.

After substituting the explicit policy (16) into (1)-(3) and (17)-(19), we have reduced the problem to analyzing the behavior of the system of differential equations for $(S(t), I(t), R(t), \lambda^D_{\mathcal{S}}(t), \lambda^D_{\mathcal{I}}(t), \lambda^D_{\mathcal{R}}(t))$ with appropriate terminal conditions for the costate variables and appropriate initial conditions for the epidemic variables.

Before embarking on the detailed analysis of equilibrium social distancing when pharmaceutical innovations are anticipated, we will briefly discuss the benchmark in which individuals only rely on non-pharmaceutical interventions throughout. In this setting, each individual's behavior is dictated by two considerations, namely current prevalence and the future path of the epidemic. First, because an individual's present probability of becoming infected is proportional to disease prevalence, as this changes so does the incentive to self-protect, all else equal. Second, the value of remaining healthy, which justifies engaging in costly social distancing, changes across the stages of the epidemic. From the perspective of an individual, who treats the path of the epidemic as exogenously given, infection risk is hump-shaped. This means that there will typically be two dates at which a given prevalence level is reached; at the first, prevalence is increasing while at the second, it is decreasing. But the individuals will value protection more on the second date than on the first. This is because on the first date, future infection hazards are much greater than on the second date and thus the value of getting safely through the next small time interval is higher later in the epidemic.

The upshot of this is that while the incentive of individuals to self-protect qualitatively follows disease prevalence, they also intensify over time, ceteris paribus.

2.1. The Case of a Perfect Treatment. Assume that the treatment is costless and works instantaneously. This means that once the treatment becomes available, there is no need for costly social distancing. This is because any individual that becomes infected can immediately recover at no cost and thereby essentially neglect the risk of infection. Consequently, the value functions in the post-treatment phase are

$$V_{\mathcal{S}} = V_{\mathcal{I}} = V_{\mathcal{R}} = \frac{\overline{\pi}}{\rho} \tag{23}$$

In other words, the health state of an individual going into the post-treatment phase is completely immaterial for the individual's wellbeing. A susceptible or recovered individual will earn flow payoff $\overline{\pi}$ (recalling that the former will expend no effort on social distancing), while an infected individual can ensure this same flow payoff instantaneously

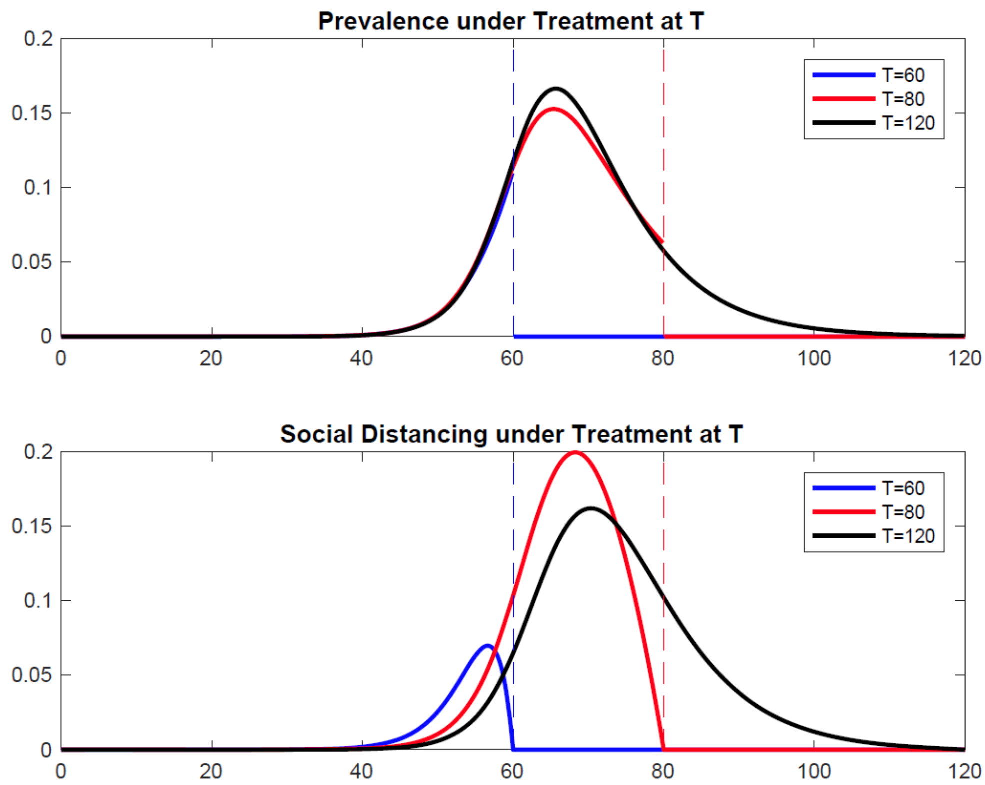

Figure 1: Equilibrium Prevalence and Social Distancing When Anticipating Treatment.

through treatment at no cost.

The equilibrium dynamics in this scenario are illustrated in Figure 1, where the upper panel shows disease prevalence while the lower panel shows social distancing. We consider three cases, namely arrival of a treatment in period 60, 80 and 120, respectively. The black line shows the benchmark case in which the innovation arrives when the disease has practically died out, namely $T = 120$. In this case, treatment plays essentially no role for aggregate dynamics. In contrast, the blue line shows a case in which the treatment arrives before peak prevalence is reached in the benchmark. Several features of this case are worth noting. First, at early stages of the epidemic, social distancing is significantly higher than in the benchmark. This has the effect of suppressing disease prevalence. Second, we see that social distancing is gradually phased out entirely, reaching zero on the date that treatment arrives. The reason for this is that as the arrival of treatment approaches, the welfare loss from falling ill becomes lower, because there is a higher chance of making use of the treatment. An individual who becomes infected at time $T - \varepsilon$ is not much worse off than someone who gets infected at time T, because he or she will only be in the infected state momentarily till the treatment arrives. Third, we note that there is a discontinuity in disease prevalence when the treatment arrives. The reason is that under our assumptions of costless and perfect treatment, once the innovation arrives at date T, infected individuals all get treated immediately, causing both disease prevalence and incidence (i.e. cases of new infections) to drop to zero. With imperfect treatment, these curves would have kinks at date T but not necessarily discontinuities.

Last, the red line shows a case in which the treatment only arrives after peak prevalence is reached in the benchmark. In this case, social distancing is also higher than the benchmark at the early stages (which in turn suppresses disease prevalence), and is eventually phased out entirely to reach zero on the date of arrival. It should be noted that the effects of anticipated innovations in treatment depend on the rate of recovery from infection. The faster people recover from infection, the lower is pre-innovation social distancing.

Overall, the paths of equilibrium social distancing start at a negligible level. Social distancing starts intensifying as prevalence picks up. It then peaks, before being phased out completely by the arrival date of the treatment. It is notable that the earlier the treatment arrives, the earlier is social distancing exerted and the faster does it peak. As a natural consequence of this path of social distancing, equilibrium disease prevalence is on the whole lower than in the no-innovation benchmark.

2.2. The Case of a Perfect Vaccine. Assume that the vaccine is costless, has no side effects and provides instantaneous and perfect protection against infection in perpetuity. In this case, a susceptible individual will immediately vaccinate as soon as the vaccine becomes available and therefore earn flow payoff $\overline{\pi}$ from then onward. This means that the value functions for susceptible and recovered individuals in the post-vaccine phase are

$$V_{\mathcal{S}} = V_{\mathcal{R}} = \frac{\overline{\pi}}{\rho} \tag{24}$$

In contrast, infected individuals cannot benefit from the vaccine and earn $\underline{\pi}$ while infected. Once recovered, their flow payoff increases to $\overline{\pi}$. Thus the value function for an infected individual is

$$V_{\mathcal{I}} = \frac{1}{\rho}\left[\frac{\rho\underline{\pi}}{\rho+\gamma} + \frac{\gamma\overline{\pi}}{\rho+\gamma}\right] \tag{25}$$

This is simply the expected net present value for an individual who is infected and who will recover at rate $\gamma > 0$.

Direct inspection shows that for the case of a vaccine, $V_{\mathcal{I}} < V_{\mathcal{S}} = V_{\mathcal{R}}$. This is the reason that decision-makers, whether individuals or the social planner (discussed shortly), attach an added value to entering the post-vaccine regime while still susceptible.

The equilibrium dynamics for this scenario are illustrated in Figure 2. Again, the black line shows the benchmark case where vaccine only arrives when the disease has

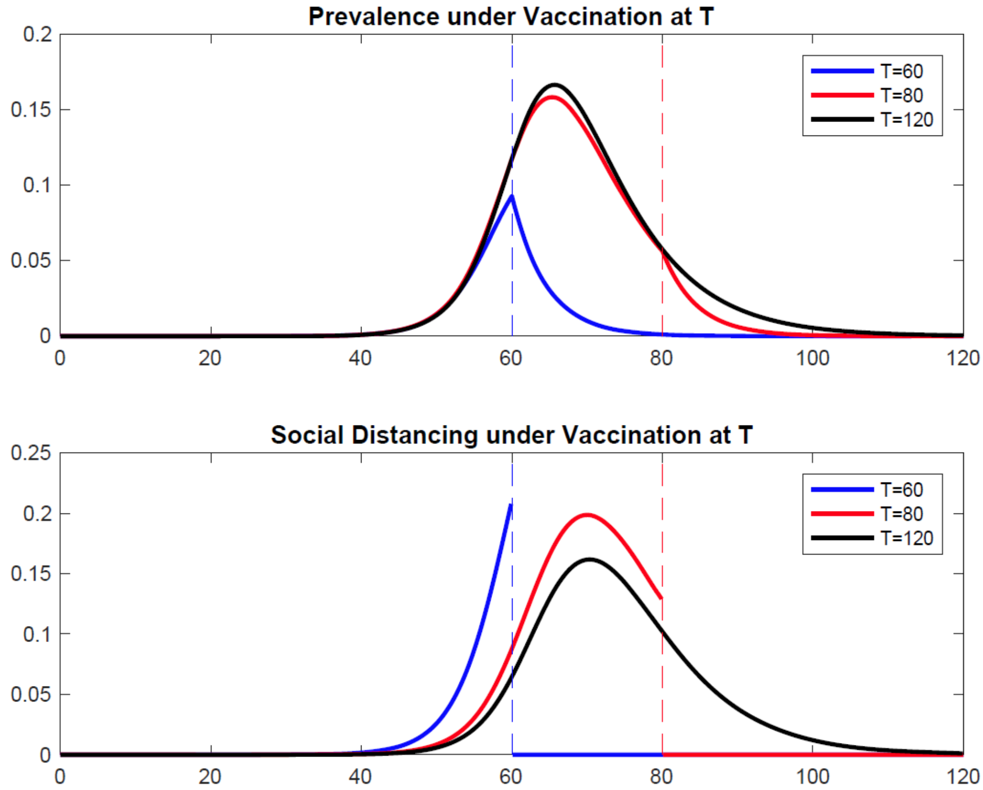

Figure 2: Equilibrium Prevalence and Social Distancing When Anticipating Vaccination.

practically died out, at $T = 120$. The blue line shows the case where the vaccine arrives before peak prevalence has been reached in the benchmark. We see that in this case, social distancing is uniformly higher than in the benchmark case till the innovation arrives. In turn, this causes a suppression of disease prevalence. The same pattern is evident from the red line, showing a case where the vaccine arrives after the peak. In both cases, we note that disease prevalence is continuous. Once the vaccine arrives, all remaining susceptible individuals get costlessly immunized such that there are no new infections. Any individuals who entered the post-innovation phase as infected slowly recover, causing disease incidence to become negative. This accounts for the tapering off of prevalence after the innovation date.

In contrast to the case of treatment, when the vaccine arrives there is a discontinuity in social distancing. The reason is that as soon as the vaccine arrives, all remaining susceptible individuals immediately become immunized. As the vaccine and social distancing are perfect substitutes in avoiding infection but the vaccine is costless, it is optimal to cease social distancing and instead get immunized. In contrast, an individual who is still susceptible at time $T - \varepsilon$ has a very strong incentive to engage in costly social distancing, because remaining susceptible for just a moment longer ensures that the individual can benefit from perfect and costless protection in the post-vaccine regime.

Last, we note that the earlier the vaccine arrives, the higher is the equilibrium path of social distancing. This in turn causes a lower path of disease prevalence.

3. CENTRALIZED DECISION MAKING

We next consider the first-best path of pre-innovation social distancing. The problem to be solved by the social planner is given by

$$\max_{d(t)\in[0,1]} \int_0^T e^{-\rho t} \left\{S(t)[\overline{\pi} - c(d(t))] + I(t)\underline{\pi} + R(t)\overline{\pi}\right\} dt + e^{-\rho T}[S(T)V_{\mathcal{S}} + I(T)V_{\mathcal{I}} + R(T)V_{\mathcal{R}}] \tag{26}$$

subject to

$$\dot{S}(t) = -\beta(1-d(t))I(t)S(t) \tag{27}$$

$$\dot{I}(t) = I(t)\left[\beta(1-d(t))S(t) - \gamma\right] \tag{28}$$

$$\dot{R}(t) = \gamma I(t) \tag{29}$$

$$1 = S(t) + I(t) + R(t) \tag{30}$$

$$I(0) \approx 0, I(0) + S(0) = 1, S(0) > \gamma/\beta \tag{31}$$

Note that in contrast to the problem solved by the individuals under decentralized decision making, the social planner explicitly takes into account that its choice of aggregate social distancing influences the aggregate dynamics of the disease.

Letting $\lambda_i^C(t)$ denote the costate variables for the state variables $i = S(t), I(t), R(t)$, the planner's current-value Hamiltonian is given by

$$H^C = S(t)[\overline{\pi} - c(d(t))] + I(t)\underline{\pi} + R(t)\overline{\pi} \tag{32}$$

$$-\lambda_{\mathcal{S}}^C(t)(1-d(t))\beta I(t)S(t) \tag{33}$$

$$+\lambda_{\mathcal{I}}^C(t)[(1-d(t))\beta I(t)S(t) - \gamma I(t)] \tag{34}$$

$$+\lambda_{\mathcal{R}}^C(t)\gamma I(t) \tag{35}$$

A necessary condition for the optimal policy is that

$$\frac{\partial H^C}{\partial d(t)} = S(t)\left[-c'(d(t)) + \beta I(t)\left(\lambda_{\mathcal{S}}^C(t) - \lambda_{\mathcal{I}}^C(t)\right)\right] = 0 \tag{36}$$

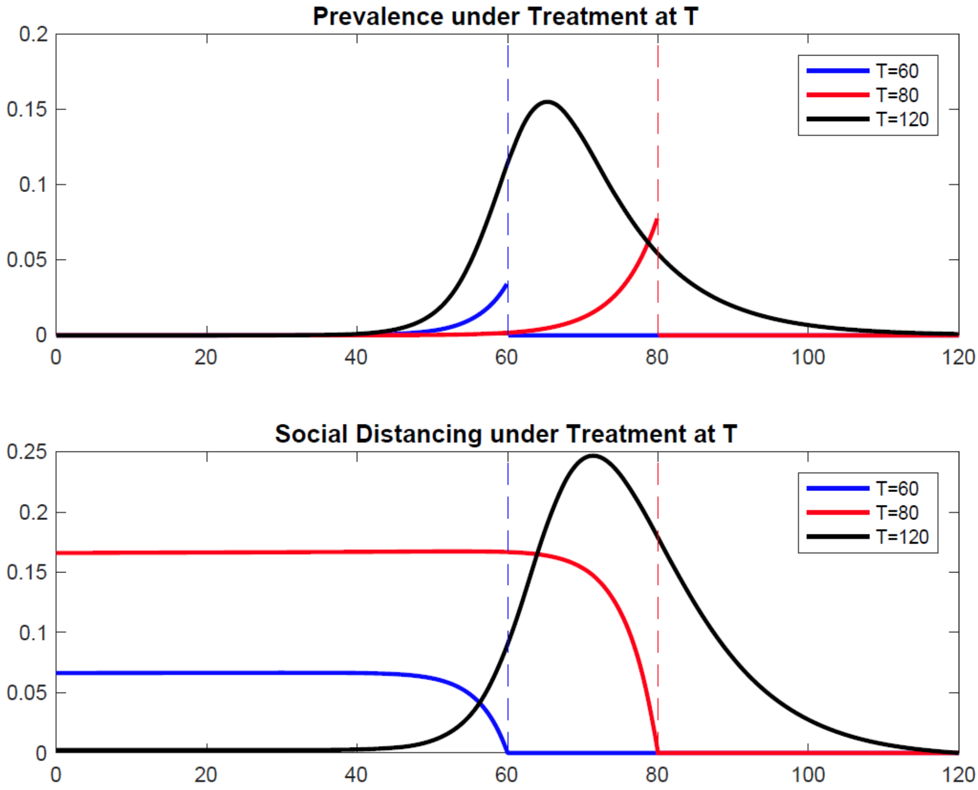

Figure 3: Optimal Prevalence and Social Distancing When Anticipating Treatment.

For quadratic costs, the socially optimal policy is given by

$$d^*(t) = \beta I(t) \left[\lambda_{\mathcal{S}}^C(t) - \lambda_{\mathcal{I}}^C(t)\right] \tag{37}$$

The laws of motion for the costate variables are then

$$\begin{aligned}
\dot{\lambda}_{\mathcal{S}}^C(t) &= \rho\lambda_{\mathcal{S}}^C(t) - \frac{\partial H^C}{\partial S(t)} && (38)\\
&= \lambda_{\mathcal{S}}^C(t)\left[\rho + (1-d(t))\beta I(t)\right] - \lambda_{\mathcal{I}}^C(t)(1-d(t))\beta I(t) - \left[\overline{\pi} - c(d(t))\right] && (39)\\
\dot{\lambda}_{\mathcal{I}}^C(t) &= \rho\lambda_{\mathcal{I}}^C(t) - \frac{\partial H^C}{\partial I(t)} && (40)\\
&= \lambda_{\mathcal{I}}^C(t)\left[\rho + \gamma - (1-d(t))\beta S(t)\right] + \lambda_{\mathcal{S}}^C(t)(1-d(t))\beta S(t) - \lambda_{\mathcal{R}}^C(t)\gamma - \underline{\pi} && (41)\\
\dot{\lambda}_{\mathcal{R}}^C(t) &= \rho\lambda_{\mathcal{R}}^C(t) - \frac{\partial H^C}{\partial R(t)} = \rho\lambda_{\mathcal{R}}^C(t) - \overline{\pi} && (42)
\end{aligned}$$

The transversality conditions are given by the counterparts of (20)-(22) under decentralized decision making, namely

$$\lambda_{\mathcal{S}}^{C}(T)e^{-\rho T} = V_{\mathcal{S}} \tag{43}$$

$$\lambda_{\mathcal{I}}^{C}(T)e^{-\rho T} = V_{\mathcal{I}} \tag{44}$$

$$\lambda_{\mathcal{R}}^{C}(T)e^{-\rho T} = V_{\mathcal{R}} \tag{45}$$

Before considering the effects of anticipated pharmaceutical interventions, we again consider the no-innovation benchmark. In contrast to individuals' equilibrium behaviour, the social planner cares about the welfare of the entire population, rather than that of a single individual. In practice, this means that the planner will want to keep track of both the evolution of susceptible and infected individuals. Under social planning, it is also the case that disease prevalence is hump-shaped, as was the case under equilibrium social distancing. But in addition, the planner is now sensitive to the wellbeing of the susceptibles, who decrease in measure over time. As in all SIR type models, herd immunity builds up over time, as infected individuals gradually recover and become immune to further infection.

3.1. The Case of a Perfect Treatment. Figure 3 shows the dynamics of prevalence and social distancing chosen by the central planner in anticipation of a treatment. Relative to the paths under equilibrium behavior, we note a number of differences, some qualitative and some quantitative. First, under first-best policies, social distancing is overall more extensive than in equilibrium except at the last stage before the innovation. This stems from the fact that the social planner factors in the positive externalities of disease prevention in choosing its optimal policy. This causes disease prevalence to be lower under the social optimum. Second, while the social planner also phases out social distancing completely by the innovation date, it implements a significant and relatively constant level from the outset until the late stages before the treatment arrives. This causes disease prevalence to be monotone increasing throughout the pre-innovation phase. On the innovation date, there is a discontinuous jump down to zero. In contrast, in equilibrium, prevalence can be non-monotone if the innovation date is after the date at which peak prevalence is reached in the no-innovation benchmark.

3.2. The Case of a Perfect Vaccine. Figure 4 shows disease prevalence and social distancing chosen by the central planner when anticipating a vaccine. Relative to the equilibrium paths of social distancing, the socially optimal ones have a few notable differences, qualitatively as well and quantitatively. First, optimal social distancing is generally more intensive than the equilibrium level (save for the final stretch before the innovation date). This is because the planner takes into account all external effects that

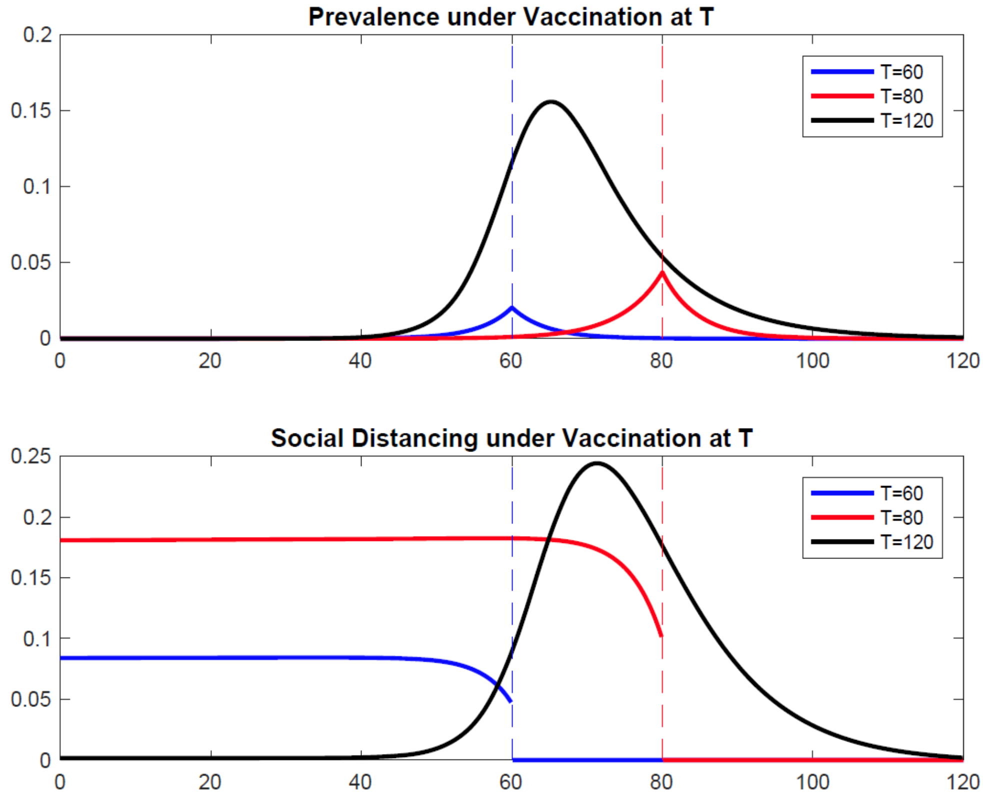

Figure 4: Optimal Prevalence and Social Distancing When Anticipating Vaccination.

flow from the imposed social distancing. In turn, this causes the socially optimal path of disease prevalence to be significantly lower than its equilibrium counterpart. Second, while equilibrium social distancing roughly follows the path of disease prevalence, with very low initial levels and a subsequent gradual increase, the socially optimal path features significant social distancing from the outset until the late stages before the arrival of the vaccine. Note that when a vaccine is anticipated, neither optimal nor equilibrium social distancing is phased out before the innovation date, as is the case when a treatment is anticipated. Although the final pre-innovation equilibrium level of social distancing is higher than that chosen by the social planner at the same date, we cannot conclude that individuals engage in too much social distancing. The reason is that because individuals have engaged in less social distancing till that point, disease prevalence is much higher in equilibrium than it would have been under social planning and therefore the two levels of social distancing are not directly comparable.

Recall that when anticipating a treatment, both individuals and the planner decrease social distancing at the end of the pre-innovation phase. In contrast, under the anticipation of a vaccine, the individuals ramp up social distancing while the planner decreases it. This can be explained as follows. Individuals attach a high value to reaching the post-vaccine phase as susceptibles and therefore ramp up protection till the very last moment. The planner also attaches a high value to this happening, but has managed aggregate prevalence throughout the pre-innovation phase. This means that just before the vaccine arrives, prevalence is relatively modest, allowing it to somewhat decrease social distancing. The optimal paths of social distancing are not phased out, but end at a strictly positive level. This is a testament to the value attached by the planner to increasing the measure of susceptibles that can benefit from the vaccine.

3.3. Aligning Private and Social Incentives. As is often the case in economic models of infection control, there is a wedge between private and social costs and benefits of social distancing. The reason is that individuals do not internalize the positive external effects that flow from their efforts to avoid infection. As shown in Rowthorn and Toxvaerd (2020), there are incentive schemes that correct for such external effects and implement the socially optimal outcomes. These can be subsidy/penalty schemes that are attached either to the protective behavior itself (like furlough schemes, which encourage people to stay at home rather than to go to work) or to the health status of individuals (like a reward for remaining uninfected). Often, such schemes are very complicated and must be modified as the epidemic progresses, which severely limits their practical use. In contrast, in the present setup there is a scheme that is very simple to implement and which may provide individuals some incentives to self-protect. Under this scheme, once the vaccine becomes available, individuals who get vaccinated also receive a reward. As the health state of an individual is known in our model, only those who have never been infected by date T will get vaccinated. This means that only at-risk individuals are eligible. This scheme achieves two separate goals. First, it incentivizes vaccine uptake, itself an activity that has strong positive externalities (see Chen and Toxvaerd, 2014). Second, it incentivizes social distancing in the pre-vaccination phase by rewarding those who make it through to the vaccination phase having never been infected. This scheme is both easy to communicate and to implement. It should be noted that this is a decidedly second-best policy and that it is unlikely to be possible to implement the first best through this scheme. The incentive scheme that implements the first-best outcome modifies the entire path of the costate variables. In contrast, the proposed second-best scheme only fixes the value of the costate variables at date T.

4. Discussion

In this paper, we have considered a stylized model of social distancing to analyze the effects of forthcoming pharmaceutical innovations on pre-innovation social distancing. We show that decision makers react differently to anticipated treatments and vaccines.

When anticipating a vaccine, it is important for the decision maker to reach the post-innovation phase while still susceptible, for otherwise the vaccine has no value. This means that as the arrival date of the vaccine approaches, the risk-reducing efforts are increased over time till the individual is effectively immunized. In contrast, when anticipating a treatment, reaching the post-innovation phase while susceptible is less critical. This is because someone who is (still) infected by the time that treatment becomes available can still benefit from treatment, therefore reducing the value of social distancing just before it becomes available. Thus social distancing is in this case entirely phased out, ceasing completely by the time the treatment arrives.

Although antiviral treatment will have an important role to play in managing the epidemic, effective mass vaccination is likely to make the most difference on aggregate. Our analysis makes an important point and offers a clear policy recommendation. The anticipated arrival of an effective vaccine should not be taken as a license to loosen restrictions and reduce social distancing. In contrast, individuals and public health authorities should redouble their efforts to reduce the number of new cases to ensure that people may actually benefit from the protection afforded by an effective vaccine once it arrives.

In the main analysis, we have for simplicity assumed that treatments and vaccinations were both costless and perfect. This allowed us to express the post-innovation value functions and thus the transversality conditions entirely in terms of model parameters. We will briefly discuss how our main insights change when the treatment or vaccine is imperfect.

In the case of imperfect treatment, there are several effects to consider. Assume that treatment, rather than inducing instant recovery, only does so with a delay. This is the formalization used in Toxvaerd and Rowthorn (2020). Since the treatment is costless, it will be taken up by any infected individual as soon as it becomes available. Thus the post-innovation value function will be a composite expression that takes into account both the flow payoff $\underline{\pi}$ earned while infected and the flow payoff $\overline{\pi}$ earned when recovered, suitably weighed by the rate at which the individual recovers under treatment. Thus relative to the case of a perfect treatment, the value function $V_{\mathcal{I}}$ is unambiguously lower. Turning to individuals who reach the post-innovation phase as susceptibles, it's clear that becoming infected now involves switching to a health state where the individual earns flow payoff $\rho V_{\mathcal{I}}$ rather than $\overline{\pi}$, as is the case when treatment induces instant recovery. This means that even though an imperfect treatment now becomes available, the individual must still engage in costly social distancing. For that reason, we have that $\rho V_{\mathcal{S}} < \overline{\pi}$. In other words, the value of reaching T as susceptible has now decreased. The value $V_{\mathcal{R}}$ remains unchained. Since two of the transversality conditions change in response to the imperfections in treatment, it is not possible in general to say what the net effect on pre-innovation social distancing is.

In the case of an imperfect vaccine, the effects are simpler to describe. Assume that once a vaccine is taken, it reduces the infectivity parameter β to $\sigma\beta$ where $\sigma \in [0, 1]$ is the failure probability of the vaccine. This formalization nests two extreme cases. When $\sigma = 0$, we are back in the perfect vaccine case at which no further social distancing is chosen after date T. When $\sigma = 1$, then the vaccine is completely useless and the innovation date T has no impact on social distancing; the paths of social distancing and prevalence mirror those of the $T \to \infty$ benchmark. For any intermediate value of the failure probability σ, the nature of the individual's problem is the same before and after the innovation date, but the post-innovation infectivity rate is now reduced because of the partial protection afforded by the vaccine. But relative to the perfect vaccine case, the post-innovation value function $V_{\mathcal{S}}$ is unambiguously lower as the individual will have to still engage in costly social distancing after vaccination, while the value functions $V_{\mathcal{I}}$ and $V_{\mathcal{R}}$ remain unchanged. This means that the transversality conditions are altered to make it less valuable to enter the post-innovation phase as a susceptible. This is reflected in a lower incentive to engage in social distancing ex-ante-innovation.

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