INTERNATIONAL ECONOMIC REVIEW
Vol. 0, No. 0, September 2022 DOI: 10.1111/iere.12609

VACCINE HESITANCY, PASSPORTS, AND THE DEMAND FOR VACCINATION*

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Vaccine hesitancy is modeled as an endogenous decision within a behavioral epidemiological model with endogenous agent activity. It is shown that policy interventions that directly target costs associated with vaccine adoption may counter vaccine hesitancy whereas those that manipulate the utility of unvaccinated agents will either lead to the same or lower rates of vaccine adoption. This latter effect arises with vaccine passports whose effects are mitigated in equilibrium by reductions in viral/disease prevalence that themselves reduce the demand for vaccination.

1. INTRODUCTION

Vaccine hesitancy, whereby individuals elect not to be vaccinated, has been a long-standing issue in public health. During the COVID-19 pandemic, such factors have meant that the adoption of vaccines has been short of what might generate lasting herd immunity in many populations. This has led to the creation of incentives to stimulate adoption, education campaigns to provide information on vaccine safety, and calls for vaccine passports.

One factor that has been documented to counter vaccine hesitancy has been the prevalence of the relevant virus/disease itself. Oster (2018) found that an outbreak in a county in the year prior led to a 28% increase in childhood vaccinations. This raises an interesting question: *If vaccine adoption reduces prevalence, does that very adoption drive observed vaccine hesitancy?* And if there is an endogenous behavioral effect, does this change the impact of proposed policies to counter hesitancy?

This article examines this issue. In so doing, vaccine adoption is endogenously driven by prevalence and vice versa. In addition, the underlying model is a behavioral epidemiological model where individuals can take costly social distancing actions to manage their own infection risk if they remain unvaccinated. The simple model presented here demonstrates that this can have a significant impact on the efficacy of various interventions to counter hesitancy. Blanket incentives/education for vaccination involve inframarginal effects that are costly which limit their desirability as a means of encouraging vaccination. More critically, it is demonstrated that vaccine passports are ineffective (in this model, completely ineffective) at improving vaccination rates and may reduce them as the restrictions imposed by passports reduce prevalence. This implies that while vaccine passports (or credentials) may be useful in assuring others that someone has a lower risk of being infectious, they are unlikely to be useful as a punitive tool to counter vaccine hesitancy.[1]

The literature on the economics of vaccines has proven more subtle than the textbook treatments of vaccination would suggest. These often state that vaccine adoption is, liter-

*Manuscript received October 2021; revised August 2022.

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[1] It is shown below that this effect arises during a pandemic when vaccine hesitancy is sufficient that herd immunity is not reached. Vaccine passports (like those used for childhood diseases and entry into school) can increase the demand for vaccines when there is not a pandemic in effect.

ally, a textbook example of a positive externality and so requires government intervention to encourage adoption and reduce free-riding. But as Francis (1997) demonstrated, when embodied within an epidemiological model of viral spread, those externalities do not necessarily manifest themselves in terms of socially suboptimal vaccinations. Indeed, he shows that with homogeneous agents and a perfect vaccination but for their personal cost of vaccination, the decentralized and socially optimal vaccination outcomes coincide.[2]

This article builds on Francis (1997) and presents a model with his underlying structure of homogeneous agents but for vaccination costs and the introduction of a perfectly effective vaccine. But as policies such as vaccine passports involve costly restrictions on agent activity, a behavioral model is built where agents endogenously choose their activity/social distancing (using a similar structure to Toxvaerd, 2020, but with discrete time).[3] Auld and Toxvaerd (2021) present preliminary evidence that vaccinations did impact on people's social activity in the COVID-19 pandemic. The focus here is not on the social optimality of any policies per se but their impact on total vaccination take-up.

Of particular policy interest is the use of vaccine passports. These involve agents carrying a proof of vaccination to be permitted into various activities (e.g., travel, entertainment, and even work). Such requirements have been common place for school entry and the military even outside of pandemic conditions. This article's particular interest is in their use and their impact on vaccine hesitancy. The conventional wisdom is that by imposing restrictions on unvaccinated people, this will counter any drivers of their hesitancy. This conventional intuition does not take into account the impact of prevalence that is both the significant driver of vaccine demand and endogenous. It is shown that it is *precisely because vaccine passports reduce prevalence* (indeed, this is also a goal of a passport system), that they reduce incentives to be vaccinated thereby potentially increasing actual hesitancy.[4] That is, prevalence drives the demand for vaccination but a passport, by directly reducing this by restricting activity, reduces vaccination demand. This is not to say that vaccine passports do not perform their protective function nor that requirements will not work outside of a pandemic (indeed, the results reverse when there is no pandemic) but that expectations that they will drive increases in vaccination demand are unlikely to be met.

The article proceeds as follows: First, the standard susceptible-infected-recovered (or SIR) model is presented followed by its behavioral analog. Second, vaccines are introduced and the equilibrium with both endogenous activity and vaccine adoption is analyzed. Finally, various policies, specifically passports, are explored and their impact on vaccination rates is characterized. A final section concludes with a list of the article's obvious shortcomings in the hope of infecting someone to overcome them.

Economists studying the spread of AIDS first began to include behavioral elements in models of epidemics; for example, Philipson and Posner (1993), Geoffard and Philipson (1996), Kremer (1996), and empirically by Greenwood et al. (2019). Gersovitz and Hammer (2004) introduced forward-looking, rational economic agents into epidemiological models exploring the different effects that prevention versus treatment might have on the dynamics of epidemics (see Philipson, 2000; Gersovitz, 2011; McAdams, 2021; Gans, 2022, for reviews of subsequent developments). The models of Toxvaerd (2020) and Rachel (2020) examine microfounded models of endogenous social distancing comparing how decentralized outcomes compare with socially optimal outcomes.

[2] Chen and Toxvaerd (2014) demonstrate that when agents are heterogeneous and vaccination is imperfect, this equivalence not longer holds. See also Gersovitz (2003) and Toxvaerd, Flavio, and Robert Rowthorn. "On the management of population immunity." Journal of Economic Theory (2022): 105501.

[3] Talamàs and Vohra (2020) also show that behavioral effects can impact on vaccination by changing the network of interactions—similar in spirit to Kremer (1996). However, their focus is on whether imperfect vaccines may create increased prevalence instead of on vaccine adoption per se which is costless in their model.

[4] The U.S. President, in announcing a widespread COVID-19 vaccine mandate for employment in September 2021 explicitly stated that the goal was to "increase vaccinations among the unvaccinated with new vaccination requirements."

In relation to vaccination, Rowthorn and Toxvaerd (2020) examine the appropriate mix of prevention and treatment whereas Goodkin-Gold et al. (2020) looks at vaccine pricing where epidemiological effects are anticipated and influenced. Makris and Toxvaerd (2020) examine how behavior responds to the imminent arrival of a vaccine—showing that it tends to induce more caution. None of these behavioral models examine vaccine hesitancy, which is the focus here.

2. THE STANDARD SIR MODEL

Let $\{S(t), I(t), R(t)\}$ denote the shares (and levels) of the population (normalized to be of size 1 over a continuum of agents) who are either susceptible to the virus, infected with the virus or removed (i.e., recovered or dead) from the virus at time $t \geq 0$. It is assumed that time is discrete. In the SIR model, these variables are assumed to evolve according to the following dynamic equations:

$$S(t+1) - S(t) = -\beta S(t)I(t),$$

$$I(t+1) - I(t) = (\beta S(t) - \gamma)I(t),$$

$$R(t+1) - R(t) = \gamma I(t).$$

Here, γ is the probability that an infected person will be removed in any given period whereas β is the probability that a susceptible person will become infected by an infected person in a given period. Observe that the number of infections in the population will be falling (i.e., $I(t+1) < I(t)$) if $\frac{\beta}{\gamma}S(t) < 1$ and will be rising (i.e., $I(t+1) > I(t)$) if $\frac{\beta}{\gamma}S(t) > 1$. The LHS of these inequalities is the effective reproduction number, $\mathcal{R}_t$. Since $S(0) \approx 1$, then $\mathcal{R}_0 = \frac{\beta}{\gamma}$. $\mathcal{R}_0$ is the basic reproduction number which has the interpretation as the total expected number of infections one infectious person will create over the life of their infection.

We now consider what happens when a vaccine becomes available. We will assume that the vaccine is perfect in that it allows a susceptible agent to be moved to the recovered category. Suppose that if prevalence is $I(t)$, then suppose a susceptible individual's benefit to being vaccinated at t is $B(I(t))$; an increasing function.[5] Below we will microfound $B(.)$ with behavioral elements. For the moment, we want to consider the demand for vaccines when individuals may be hesitant. To model vaccine hesitancy, agents must face an individual cost associated with being vaccinated. While the sources of such costs are nuanced and a mixture of real costs and perceived costs (MacDonald et al., 2015), here we abstract from these sources by capturing them in a single parameter, θ. $\theta > 0$ is a once-off reduction in utility from being vaccinated. It is assumed that θ is distributed among the population according to the distribution function, $F(\theta)$. Thus, if a vaccine appears at time t, individuals for whom $B(I(t)) \geq \theta$ will be vaccinated whereas others will not.

Vaccination is a way of moving people from the susceptible to the recovered population segments. Of key interest in this model is the herd immunity threshold that is reached when $S(t)$ becomes low enough, through either acquired or vaccinated immunity, so that $\mathcal{R}_t < 1$. This threshold, for $1 - S(t)$ is $1 - \frac{1}{\mathcal{R}_0}$. A goal of many vaccination programs is to ensure that the total of the recovered and vaccinated shares exceeds this threshold allowing the pandemic to abate without any further interventions.[6]

In the context of the simple model of vaccine demand presented thus far, note that when a vaccine becomes available (say at t), then if the herd immunity threshold is expected to be reached, $I(t)$ will be expected to fall from t onward. In this case, all agents for whom

[5] This qualitative property will be microfounded below but is typically argued, informally, see Philipson (2000).

[6] This is not to say that further vaccination beyond this threshold may be worthwhile as infections and health costs can continue thereafter. See Gans (2020) for a discussion.

$B(I(t)) \geq \theta$ will be vaccinated at t and no other agents will be vaccinated thereafter (as $B(I(t')) \leq B(I(t))$ for all $t' > t$). As the share of susceptibles who would be vaccinated under these conditions is $F(B(I(t)))$, then so long as $(1 - F(B(I(t))))S(t) \leq \frac{1}{\mathcal{R}_0}$, herd immunity would be reached. If, however, $(1 - F(B(I(t))))S(t) > \frac{1}{\mathcal{R}_0}$, then $I(t)$ will continue to increase over time which makes pinning down vaccine demand difficult without more structure on $B(I(t))$. It is that task that we turn to next.

3. THE BEHAVIORAL SIR MODEL

The fact that the standard SIR model lacked behavioral elements has not been lost on epidemiologists. In particular, it has been recognized that people might observe current prevalence (that is, $I(t)$) and modify their own behavior so as to reduce infection risk. However, the mathematical epidemiologists have typically taken what economists would call a "reduced-form" approach to this. For instance, they might posit a variable, $x \in [0, 1]$, that is a filter reducing the impact of β on new infections. That variable is then assumed to be a decreasing function of $I(t)$; for example, $x(I(t))$.[7]

3.1. *Model Setup.* To provide a microfoundation of $B(.)$, we note that the benefits of being vaccinated come from being able to avoid infection and also in being able to alter behavior (such as social distancing) that would otherwise be used to manage individual infection risk. For simplicity, it is assumed that all agents are the same in terms of their preference for activity and in terms of their costs of becoming infected although, as already assumed, they will differ in terms of their preferences to being vaccinated.[8]

Agents choose their level of activity, $x_i(t) \in [0, 1]$. This activity gives them a per period utility value of $u(x_i(t))$ where, for simplicity, this has a functional form of $u(x_i(t)) = u - (1 - x_i(t))c$ (for a constant, $u \geq c$). Agents have a common discount factor of $\delta < 1$. If an agent becomes infected, they incur an additional loss, L, in utility unless they die in which case they can incur no utility thereafter. An infected agent has a probability, γ of becoming no longer infectious in each period they are infected. At that point, with probability ρ, they survive and become immune. Otherwise, they die. Either way they are part of R, the set of removed agents.

An agent's activity choices at t are determined by the condition, $\{S, I, R\}$, they are in at that time. If they are part of R and have not died, they are no longer infectious or at risk. Hence, they will set their activity, $x_i(t) = x_R = 1$ and will earn an expected present discounted payoff of $\frac{u}{1-\delta}$. In this, there is an implicit assumption that a recovery means a full recovery to the utility they would earn had the epidemic not emerged.

3.2. *Infected Agent Activity.* For an infected agent (a member of I), they are infectious and sick. Their instantaneous utility is $u - (1 - x_I(t))c - L$ and their expected discounted payoff is

$$V_I(t) = u - (1 - x_I(t))c - L + \delta(\gamma V_R + (1 - \gamma)V_I(t + 1)),$$

where here $V_R = \rho \frac{u}{1-\delta}$. Note that, being self-interested, infected agents set $\hat{x}_I(t) = 1$ for all t and, thus, their expected discounted payoff becomes:

$$V_I = \frac{u - L + \delta(1 - \gamma)\rho \frac{u}{1-\delta}}{1 - \delta\gamma}.$$

[7] See, for example, Eksin et al. (2019) who also explore assumptions where $x(I(t), R(t))$ is decreasing in both variables, that they argue is a model of "long-term awareness" in contrast to "short-term awareness" where x is a function of $I(t)$ alone.

[8] The model here is related to that provided by Gans (2022) but is presented here with a simplified set of options regarding activity and symmetry among agents.

3.3. *Susceptible Agent Activity.* For both the infected and recovered agents, their choice of economic activity is not impacted upon by the state variables, $\{I(t), S(t)\}$. Thus, the key to the behavioral approach to epidemiology are the choices of the susceptible. Their instantaneous utility is $u-(1-x_S(t))c$ and their expected discounted payoff is

$$V_S(t) = u-(1-x_S(t))c+\delta(p(x_S,\hat{x}_I I(t))V_I+(1-p(x_S(t),\hat{x}_I I(t)))V_S(t+1)),$$

where $p(x_S(t), x_I I(t))$ is probability that an agent becomes infected at time t (the consequences of which are felt at time $t+1$).

The structure of $p(x_S(t), x_I I(t))$ depends on how activity translates into an individual's risk of infection. The standard SIR model assumes that susceptible individuals face a probability, β, of becoming infected if they interact with an infected individual. Thus, it is natural to posit that $p(x_S(t), x_I I(t)) = \beta x_S(t)x_I I(t)$.

A susceptible individual will choose $x_S(t)$ to maximize $V_S(t)$ holding the state variables, $\{I(t), S(t)\}$, and their future path as given. Given this, note that:[9]

$$\text{(BEH)} \qquad \hat{x}_S(t) = \begin{cases} 0 & c < \beta x_I I(t)\delta(V_S(t+1)-V_I) \\ 1 & c > \beta x_I I(t)\delta(V_S(t+1)-V_I). \end{cases}$$

If $c = \beta x_I I(t)\delta(V_S(t+1)-V_I)$, agents will be indifferent between 0 and 1. We will show below that, in equilibrium, agents will mix between these two extremes under certain conditions that will generate an infection path that makes them indifferent over the level of activity. Thus, in each time period t, the net benefit to activity is zero and agents earn $u-c$ in those periods.

It is useful to note, however, that $I(t)$ may be such that $c > \beta x_I I(t)\delta(V_S(t+1)-V_I)$ always. In particular, note that if an agent were to choose $x=0$ in each period, then $V_S = \frac{u-c}{1-\delta}$. As, in equilibrium, $\hat{x}_I = 1$, then $x=0$ is never optimal if $c > \beta I(t)\delta(\frac{u-c}{1-\delta} - \frac{u-L+\delta(1-\gamma)\rho\frac{u}{1-\delta}}{1-\delta\gamma})$ or

$$I(t) < \underline{I} \equiv \frac{c(1-\delta)(1-\gamma\delta)}{\beta\delta((1-\gamma)u(\delta-\rho)+(1-\delta)L-c(1-\gamma\delta))}.$$

As will be shown below, this condition is met at the beginning and end of a pandemic and, thus, in equilibrium, susceptible agents will set $x_S = 1$ at those times.

It is instructive to briefly anticipate and explore the transition to prevalence below $\underline{I}$. Suppose that the equilibrium path of $\hat{I}(t)$ is declining in t so that there is a point where $\hat{I}(T-1) > \underline{I} > \hat{I}(T)$ and also where $\hat{I}(T) > \hat{I}(t)$ for all $t > T$. Then at T, all susceptible agents will choose $x_S(T) = 1$ and $V_S(T) \geq \frac{u+\delta\beta\hat{I}(T)V_I}{1-\delta(1-\beta\hat{I}(T))}$. Note that this implies that (i) $V_S(T) > V_S(T-1) = u-c+\delta V_S(T)$; and (ii) if $c = \beta\hat{I}(t)\delta(V_S(t+1)-V_I)$ for $t < T$, then

$$V_S(t) = (1-\delta^{T-t})\frac{u-c}{1-\delta} + \delta^{T-t}V_S(T).$$

This does not mean that agents socially distance until period T but that some share do such that the net benefit from positive activity in each period is 0 up until T. In what follows, a critical focus of analysis will be the impact of vaccine policies on this utility which itself, as we will show, drives the demand for vaccination.

3.4. *Equilibrium Analysis.* The behavior of individual agents in choosing their activity level aggregates into new infecteds. Recall that the expected number of new infecteds is equal

[9] All equilibrium variables will be donned a $\hat{\cdot}$.

to $\beta x_S(t)S(t)I(t)$ (where in an abuse of notation we now refer to $x_S(t)$ as the average level of activity chosen by susceptibles at t) while in each period $\gamma I(t)$ infecteds are removed. Thus,

$$\frac{I(t+1)-I(t)}{I(t)} = \beta x_S(t)S(t) - \gamma.$$

At $t=0$, when $S(0)=1$ and $I(0)=0$, if $\mathcal{R}_0 = \frac{\beta}{\gamma} > 1$, $I(1) > 0$ and growing if $x=1$ for all agents. Thus, initially, it is clear that agents will have no incentive to socially distance until $I(t) > \underline{I}$.

Given this, we can demonstrate the following:

PROPOSITION 1. *If $\mathcal{R}_0 > 1$, then there exists times $\{\underline{T}, \overline{T}\}$ with $\overline{T} > \underline{T}$ such that: (i) for $t < \underline{T}$ and $t \geq \overline{T}$ where $\hat{x}_S = 1$ and (ii) $t \in (\underline{T}, \overline{T})$ where a share, $x_S(t)$ of susceptible agents choose $x = 1$ and the remainder choose $x = 0$ with each earning an expected flow payoff of $u - c$.*

PROOF. The existence of $\underline{T}$ and $\overline{T}$ are given by our earlier observation that $\hat{x}_S = 1$ for all agents for $I(t) < \underline{I}$ at the beginning and end of a pandemic. For $t \in (\underline{T}, \overline{T})$, let a share, $x_S(t)$ of susceptibles choose $x = 1$. Note that this will arise if $c = \beta\hat{I}(t)\delta(V_S(t+1) - V_I)$ which implies that

$$\hat{I}(t) = \frac{c}{\beta(V_S(t+1) - V_I)}.$$

This, in turn, implies that

$$\frac{\hat{I}(t+1)-\hat{I}(t)}{\hat{I}(t)} = -\frac{V_S(t+2)-V_S(t+1)}{V_S(t+2)-V_I} < 0$$

by our earlier observation that $V_S(t+2) > V_S(t+1)$ for all $t > \underline{T}$. Thus, $\hat{I}(t)$ must be decreasing over $t \in (\underline{T}, \overline{T})$. This, in turn, implies that $\frac{1}{x_S(t)} > \frac{\beta}{\gamma} S(t)$. Note also that given agent symmetry, this implies that $x_S(t)$ is nondecreasing in t for $t \in (\underline{T}, \overline{T})$. □

The proposition is just a discrete time version of the result of Rachel (2020) (and a related result by Toxvaerd, 2020). For our purposes, the important feature is that when agents are actively socially distancing (i.e., between $\underline{T}$ and $\overline{T}$), their flow utility is $u - c$ because the equilibrium infection rate, $\hat{I}(t)$, is such that they are indifferent as to their level of activity. If not, they will adjust their activity accordingly and bring the infection rate back to that level. In equilibrium, therefore, $\hat{I}(t)$ peaks at $\hat{I}(\underline{T})$ and falls, thereafter with $\mathcal{R}_t$ just below 1 for $t > \underline{T}$.[10] This fact will be important as a key benefit from being vaccinated will be that agents will no longer have to choose to socially distance.

4. VACCINE AVAILABILITY AND ADOPTION

We now consider what happens when a vaccine becomes available and known to agents at some point, $t > \underline{T}$; that is, in the period where agents are choosing to socially distance.[11] We will assume that the vaccine is perfect in that it allows a susceptible agent to be moved to the recovered category. Thus, an agent choosing to be vaccinated at t, will receive a benefit

[10] Note that this also implies that at $\overline{T}$, herd immunity has been achieved and, thus, the prevalence will not rise again even as all agent activity involves no social distancing.

[11] If agents anticipate the vaccine's arrival, then this would alter their incentives prior to that date; specifically, they would become more cautious (Makris and Toxvaerd, 2020). If the vaccine arrives prior to $\underline{T}$ agents would not be socially distancing but may choose to do so.

of $B(.) = V_R - V_S(t)$. Note that $V_S(t)$ will change overtime and be impacted by the number of vaccinated people. In particular, the benefits from being vaccinated are typically higher when $I(t)$ is increased for t and beyond (Philipson, 2000).

We continue to model vaccine hesitancy as before using θ as the once-off of cost of vaccination where θ varies among individuals according to $F(\theta)$. Each period after a vaccine is available, an agent chooses whether to vaccinate or not and, if not, what level of activity to choose. The following proposition characterizes the equilibrium outcome:

PROPOSITION 2. *Suppose that a vaccine becomes available at $t' \in (\underline{T}, \overline{T})$. Let $\hat{\theta}$ be θ such that $\hat{\theta} = V_R - \hat{V}_S(t'; \hat{\theta})$. Then all agents for whom $\theta \leq \hat{\theta}$ will be vaccinated and no additional vaccinations will be chosen after t'. Equilibrium prevalence, $\hat{I}(t)$ will be (weakly) lower in every period $t > t'$ than it would be if no vaccine had become available at t'.*

PROOF. The first step is to demonstrate that if a share $F(\hat{\theta})$ of susceptibles at t' are vaccinated, then equilibrium prevalence will be lower. From the proof of Proposition 1, this equilibrium prevalence satisfies $\hat{I}(t) = \frac{c}{\beta(V_S(t+1)-V_I)}$ for $t < \overline{T}$. Beyond $\overline{T}$ prevalence continues to fall in t and $\overline{T}$ is, therefore, decreasing in the vaccination level. Thus, $S(t)$ now becomes $(1 - F(\hat{\theta}))S(t)$ and, consequently, $\hat{I}(t+1)$ is lower and hence $V_S(t+1)$ is higher for each $t > t'$. Hence, equilibrium prevalence in each period is lower.

The second step is to use this fact to note that this means that $V_R - V_S(t)$ will be falling in t for each $t > t'$. Thus, if $\theta > V_R - V_S(t')$ it will be greater than $V_R - V_S(t)$ for each $t > t'$. Thus, any agent willing to be vaccinated at time $t > t'$ is willing to be vaccinated at t'.

Finally, the share $F(\theta)$ who are vaccinated at t' determine $V_S(t)$ for $t > t'$. Thus, the equilibrium threshold of vaccination costs, $\hat{\theta}$ will be determined by $\hat{\theta} = V_R - \hat{V}_S(t'; \hat{\theta})$. As θ can be arbitrarily large or small and $F(.)$ is continuous, this equality exists. □

Vaccine demand is driven primarily by the risk and consequences of being infected. The vaccine eliminates that risk which is a direct benefit of being vaccinated. This also has the indirect benefit of relieving the need to mitigate that risk through social distancing (at least when $t' < \overline{T}$). Both of these benefits depend on prevalence and expected prevalence, $I(t)$ where higher prevalence reduces $V_S(t)$. This means that, other things being equal, an increase in $I(t)$ will induce some agents to vaccinate. However, the equilibrium effects that arise from lower prevalence and from agents' endogenous activity choices immiserize this effect to some degree. Thus, for all agents, their highest willingness to pay arises when a vaccine becomes available and, therefore, there is immediate vaccination demand with no demand thereafter.

5. POLICIES TO COUNTER HESITANCY

5.1. *Lowering Vaccine Cost.* The first set of policies targets the cost θ associated with being vaccinated. Although this may include persuasion and educational efforts, it is also the case that a direct monetary subsidy, τ, could also increase vaccination rates.[12]

Although a welfare analysis involves subtle trade-offs, if we take a view, common among public health officials, that vaccination rates should be the minimum amount to cause the effective reproduction rate, $\mathcal{R}_t$, to fall below 1 (see also Budish, 2020), then we would set τ so that:

$$(1 - F(\hat{\theta}(\tau)))S(t) < \frac{1}{\mathcal{R}_0},$$

[12] For instance, Chevalier et al. (2021) show that locating distribution centers closer to lower-income neighborhoods increases vaccination rates. Brehm et al. (2022) provide an analysis of lotteries in encouraging vaccinations. Iyer et al. (2022) show that monetary payments can encourage vaccinations.

where $\hat{\theta}(\tau)$ is defined by $\hat{\theta}(\tau) - \tau = V_R - \hat{V}_S(t'; \hat{\theta(\tau)})$. That is, τ is set to achieve herd immunity.

Note that, under our assumptions, in the absence of an intervention, agents who were previously infected and have recovered from the disease would not choose to vaccinated as they already face no risk and do not socially distance, and so face a strictly positive cost, θ, from being vaccinated. However, for those whom $\hat{\theta}(\tau) > \theta > \hat{\theta}(0)$, they will choose to be vaccinated under the intervention. Given this, the total cost of the subsidy program would be $\tau(F(\hat{\theta}(\tau))S(t) + F(\hat{\theta}(0))R(t))$ in order to achieve a marginal effect on vaccine hesitancy of $(F(\hat{\theta}(\tau)) - F(\hat{\theta}(0)))S(t)$.

5.2. *Vaccine Passports.* Another set of policies targets the utility of susceptible agents; namely, reducing that utility. The primary example of this is the vaccine passport. A passport policy restricts that activity, x, of *all* agents who do not show proof of vaccination. This is done by restricting activity of certain types or perhaps restricting other aspects of activity (such as mask-wearing requirements).

Here, a simple view of a passport policy is taken and it is assumed that the policy caps the activity of all unvaccinated agents at $\bar{x}$. The idea here could be that activity along the [0,1] dimension is ranked from those that are most essential (close to 0) to those that are most optional (close to 1). Unvaccinated agents are prohibited from the most optimal activities where $x > \bar{x}$.[13] A benefit of this is that infected agents are kept away from those activities as are those who are still susceptible. In this way, the policy has an intended effect of reducing disease prevalence.

This policy also has the effect of limiting the activities of recovered and infected agents. In the absence of a restriction, they would set $x = 1$. For the recovered agent, this is a pure welfare loss but it now means that those for whom $\frac{(1-\bar{x})c}{1-\delta} \geq \theta$ will be vaccinated.[14] Even though their status is temporary, infected agents for whom $\frac{(1-\bar{x})c}{1-\delta} \geq \theta$ will also be vaccinated. However, as a matter of practice, this is the same as a recovered agent being vaccinated as vaccine dose regimens likely last more than the infectious period for most diseases. For practical purposes, however, we can treat infected people as unvaccinated and, thus, by implication, their activity is restricted to $\bar{x}$.

The target of the passport policy are the susceptible agents—both to counter hesitancy and protect them. The protection element is subtle. Given the restrictions on activity (and assuming they bind on the susceptible agents), the probability that a susceptible agent becomes infected is now $\beta\bar{x}^2 I(t)$ as both infected agents and susceptible agents are potentially restricted in their activity. However, while this is possible in terms of exposure probabilities, the fact that infected agents and susceptible agents are restricted to the same activities means that the probability that a given agent that a susceptible agent encounters is infected is equal to the portion of infected people in the population unadjusted for activity level. Thus, following the spirit of analyses such as Kremer (1996) and Talamàs and Vohra (2020), it is reasonable to suppose that the probability of infection remains at most $\beta\bar{x}I(t)$.

It is possible that a susceptible agent, who becomes infected and then recovers, will prefer not to be vaccinated if they had chosen not to be vaccinated while susceptible. However, this is not certain. Thus, for unvaccinated agents when there is a vaccine passport policy, we have:

$$V_R(\bar{x}, \theta) = \max\{\frac{u - (1 - \bar{x})c}{1 - \delta}, \frac{u}{1 - \delta} - \theta\}$$

[13] There are other ways of modeling passports. For instance, distinct activities could be explicitly modeled. However, the approach here surfaces the first-order effects and, thus, keeps the analysis simple.

[14] If the passport covered proof of recovery from the virus then these agents would not be vaccinated. However, this depends on the measurement of recovery and whether recovery was equivalent to vaccination in terms of efficacy in preventing future infection or infectiousness.

$$V_I(\bar{x},\theta) = \max\{\frac{u - L - (1-\bar{x})c + \delta(1-\gamma)\rho\frac{u-(1-\bar{x})c}{1-\delta}}{1-\delta\gamma}, \frac{u - L + \delta(1-\gamma)\rho\frac{u}{1-\delta}}{1-\delta\gamma} - \theta\}.$$

Note that a sufficient condition for these agents to continue to be unvaccinated is that $\frac{(1-\bar{x})c}{1-\delta} < \theta$. The lower $\bar{x}$ is, the lower are the utilities from being infected and then recovered. This will impact on the incentives of a susceptible agent in their choice of activity as it removes one of the benefits from being infected—not having to manage the risk of infection.

It is important to note that a vaccine passport will not increase and can only decrease the infection rate in every period; that is $\hat{I}(t,1) > \hat{I}(t,\bar{x})$ for all $t > t'$ (assuming the passport is introduced with the vaccine). The question, however, is whether it will increase the total share of susceptibles being vaccinated? Recall that an individual susceptible agent with vaccine cost of θ will choose to be vaccinated if $V_R - V_S(t') \geq \theta$. Moving from a passport with no restrictions (1) to one where activity is restricted to $\bar{x}$, only $V_S(t')$ is potentially altered as V_R remains at $\frac{u}{1-\delta}$ if the agent is vaccinated prior to being infected and only is reduced if the agent is unvaccinated following being infected.

The above discussion indicates that a vaccine passport may reduce the demand for vaccination through two routes: by reducing V_R and also by causing a reduction in $\hat{I}(t)$ which, as we noted earlier, was otherwise a driver of the payoff to susceptible agents. The following proposition demonstrates that, in fact, a lower $\bar{x}$ will not increase and often decrease the demand for vaccination in equilibrium but for one special case that will be discussed below.

PROPOSITION 3. *Let $\overline{T}(1)$ be the equilibrium point in the absence of a vaccine passport (but with vaccines available) beyond which susceptible agents would choose $x_S = 1$. If a vaccine and passport is introduced at $t' < \overline{T}(1)$, this will result in either the same or fewer vaccinated susceptibles compared with the case where there is no vaccine passport.*

PROOF. We consider two cases where (i) $t' < \overline{T}(\bar{x})$ and (ii) $t' \in [\overline{T}(\bar{x}), \overline{T}(1)]$. We want to show that $V_S(t,1) \leq V_S(t,\bar{x})$ which would imply that $V_R - V_S(t,1) \geq V_R - V_S(t,\bar{x})$ and that the vaccine passport reduces the benefits from vaccination for susceptible agents.

First, if $t' < \overline{T}(\bar{x})$, unvaccinated but susceptible agents will choose to continue to socially distance following the introduction of a vaccine passport. Thus,

$$V_S(t,1) - V_S(t,\bar{x}) = (1 - \delta^{\overline{T}(1)-t'})\frac{u-c}{1-\delta} + \delta^{\overline{T}(1)-t'}V_S(\overline{T}(1),1) - (1 - \delta^{\overline{T}(\bar{x})-t'})$$
$$\frac{u-c}{1-\delta} - \delta^{\overline{T}(\bar{x})-t'}V_S(\overline{T}(\bar{x}),\bar{x})$$
$$= \delta^{\overline{T}(1)-t'}\left(V_S(\overline{T}(1),1) - \frac{u-c}{1-\delta}\right) - \delta^{\overline{T}(\bar{x})-t'}\left(V_S(\overline{T}(\bar{x}),\bar{x}) - \frac{u-c}{1-\delta}\right).$$

Note however that at $\hat{T}(1)$, $V_S(\overline{T}(1),1) \approx \frac{u-c}{1-\delta}$ while $V_S(\overline{T}(\bar{x}),\bar{x}) \geq \frac{u-c}{1-\delta}$ as it involves less social distancing and a lower rate of infection as a result of the vaccine passport. Thus, we have demonstrated that $V_S(t,1) \leq V_S(t,\bar{x})$ in this case.

Second, if $t' \in [\overline{T}(\bar{x}), \overline{T}(1)]$ unvaccinated but susceptible agents would not choose to socially distance in the absence of a vaccine passport where they would have otherwise. Thus,

$$V_S(t,1) - V_S(t,\bar{x}) = (1 - \delta^{\overline{T}(1)-t'})\frac{u-c}{1-\delta} + \delta^{\overline{T}(1)-t'}V_S(\overline{T}(1),1) - V_S(t',\bar{x})$$
$$= \delta^{\overline{T}(1)-t'}\left(V_S(\overline{T}(1),1) - \frac{u-c}{1-\delta}\right) - \left(V_S(t',\bar{x}) - \frac{u-c}{1-\delta}\right).$$

Recalling again that $V_S(\overline{T}(1), 1) \approx \frac{u-c}{1-\delta}$ while $V_S(t', \bar{x}) > \frac{u-c}{1-\delta}$, this demonstrates that $V_S(t, 1) < V_S(t, \bar{x})$ for this case as well, completing the proof. □

In summary, either the vaccine passport restrictions bind on susceptible agents or they do not. If they do not bind, those restrictions reduce the utility of infected/recovered agents which makes susceptible agents more cautious in equilibrium. The equilibrium prevalence adjusts to this making susceptible agents indifferent in terms of activity levels chosen. Thus, their utility remains as if they chose to mitigate all activity. This leaves the gain from being vaccinated the same as when there were no vaccine passports. If the restrictions do bind on vaccinated agents, prevalence is reduced and this increases the utility of susceptible agents as they receive more by meeting the constraint than choosing a zero level of activity. This means that the gain from vaccination is lower than when there were no vaccine passports. Hence, passports, at best, do not counter vaccine hesitancy and, at worse, increase it. Moreover, as discussed earlier, passports lead to unnecessary vaccinations from recovered agents or to unnecessary restrictions on their activity. If this were the case, it would be reasonable to conjecture that they would be strictly suboptimal for a social welfare perspective.

The strong prediction of Proposition 3—a result of the simplicity and abstraction of the model—may appear to stand at odds with anecdotal and some preliminary empirical evidence (e.g., Oliu-Barton et al., 2022) that vaccine passports accelerated vaccination rates immediately following their introduction. The model here is, of course, an equilibrium model, and it may be that the observed increases in vaccination were the result of the salience of the policy and also adjustments to equilibrium. Specifically, in contrast to the model, because of shortages, vaccine passports were only introduced after there was significant vaccination. But it may have been that some people who valued activity more than others had yet to be vaccinated and vaccine passports did push them to be vaccinated. Finally, it is worth emphasizing, of course, that these results may be a refutation of the model's prediction and/or may be an indicator that factors not modeled—for instance, social stigma, pressure, liquidity constraints from work, or complementarities among activity between agents (as in McAdams, 2020)—are playing a mitigating factor. In this regard, the model's simplicity and abstraction from these factors helps identify a potential limitation on vaccine passport impacts that needs to be explicitly considered in any empirical evaluation of such policies.

The proposition relies on the vaccine (and associated passport) being available at a date whereby unvaccinated susceptible agents would still be socially distancing in the absence of a vaccine passport. It is instructive to note that, beyond this time, in the absence of a vaccine passport, as agents set $\hat{x}_S = 1$, the effective reproduction rate, $\mathcal{R}_t$, would be less than 1 and the pandemic would be at a point where it would continue to decline of its own accord. At this point, a vaccine passport policy could accelerate that decline. However, it is also possible that a very restrictive policy (e.g., with a low $\bar{x}$) could result in an increase in vaccine demand if introduced beyond that point.

To see this, note that if $t' > \overline{T}(1)$, then the benefits of being vaccinated $V_R - V_S(t, 1)$ in the absence of a vaccine passport (i.e., with $\bar{x} = 1$) will exceed those benefits when there is a vaccine passport, $V_R - V_S(t, \bar{x})$. A critical question is whether $V_S(t)$ is decreasing in $\bar{x}$. This will occur if (holding V_I constant):

$$c - \delta\beta\left(I(t) + \bar{x}\frac{\partial I(t)}{\partial \bar{x}}\right)(V_S(t+1) - V_I) < 0,$$

where, noting that, $I(t) = I(t-1)(1 + \beta\bar{x}S(t-1) - \gamma)$,

$$\frac{\partial I(t)}{\partial \bar{x}} = I(t-1)\beta S(t-1)$$

which gives

$$c - \delta\beta I(t-1)(1-\gamma+2\beta\bar{x}S(t-1))(V_S(t+1)-V_I) < 0.$$

It is clear that a sufficient condition for this to hold is that $\bar{x} > \frac{1}{2}$. If this does not hold, then if social distancing is not being practiced, the left-hand side is positive and a weaker vaccine passport would increase the expected discounted payoff from remaining susceptible to the virus. Of course, as noted above, a lower $\bar{x}$ can also reduce V_I. Suppose that we start from no passport (i.e., $\bar{x} = 1$) and lower $\bar{x}$ incrementally. Note that the derivative of $V_S(t)$ with respect to $\bar{x}$ evaluated at $\bar{x}$, taking into account the impact on V_I will be

$$\tfrac{\beta c\delta I(t-1)((1-\gamma)\delta\rho+1-\delta)(1-\gamma+\beta\delta S(t-1))}{(1-\delta)(1-\gamma\delta)} + c - \beta\delta I(t-1)(1-\gamma+2\beta\delta S(t-1))(V_S(t+1)-V_I),$$

which is positive. Thus, taking into account the effect of $\bar{x}$ on V_I as well, a vaccine passport will *increase* the demand for vaccination if implemented at this point. Intuitively, agents prefer in this case not to be restricted in their activities and so are more likely to be vaccinated when a passport is implemented.

What this means is that vaccine passports will reduce the demand for vaccinations only if the herd immunity threshold has not been reached. If that threshold is reached, then all agents will choose $x = 1$ and, thus, susceptible agents will have strictly higher utility when not restricting their activity. In this case, decreasing $\bar{x}$ for unvaccinated agents will lower their utility and, thus, increase the demand for vaccination. This helps explain why vaccine passports (used by many schools for vaccination against childhood diseases) are effective in overcoming hesitancy. The qualifier this article adds is that it is not an effective tool during a pandemic where because of hesitancy, the herd immunity threshold, $1 - \frac{1}{\mathcal{R}_0}$, has not yet been reached.

This analysis focuses purely on the motivation to use vaccine passports as a means of overcoming hesitancy. When a vaccine is imperfect (as all vaccines are) and some people cannot be vaccinated because the medical costs will always be too high, then a passport can be useful in assessing the riskiness of interactions between people and protecting unvaccinated people from becoming infected. In that sense, like testing, it is a means of overcoming the pandemic information problem (Gans, 2020). Thus, a vaccine passport is not a set of rights per se but, instead, a means of efficiently communicating risk. For this reason, many countries in managing COVID-19 are adopting credentials that signal low risk for a person if they have been vaccinated or if they have received a recent negative test. In certain environments, such as higher risk health or aged care facilities, vaccines can become mandatory to protect some who are not vaccinated or who face higher risks with imperfect vaccines. However, this is not a tool of overcoming hesitancy per se but overall protection of the vulnerable.

6. CONCLUSIONS

The model here exposes some first-order interactions between vaccine hesitancy, social distancing, and various policy interventions. However, like the work of Francis (1997) that it is based on, it is simplified and the results may not be robust to the introduction of augmentations to the epidemic model, variable vaccine costs, imperfect vaccines, imperfect information, spatial heterogeneity, heterogeneity in susceptibility, behavioral variability, and stochastic effects. In addition, the vaccine passport is a blanket one and not targeted and could, therefore, be structured in ways that may mitigate some of the effects addressed in this article (e.g., along the lines of Gersovitz, 2011). These are all potentially fruitful directions for future research.[15]

[15] Of course, while researching this article, France announced plans for a vaccine passport like policy and promptly had almost a million people sign up to be vaccinated. I should note that it is likely that was driven by simple inertia in people deciding to be vaccinated instead of the more longer-term issues associated with hesitancy that is the focus of

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the article here. That said, this could be a reflection of some other factor. At this stage, who can really tell but I will admit the news was inconvenient.