COVID-19 Vaccination and Financial Frictions in Emerging Markets*

Cristina Arellano
Federal Reserve Bank of Minneapolis
and University of Minnesota

Yan Bai
University of Rochester
and NBER

Gabriel Mihalache
Stony Brook University

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Abstract

We study the COVID-19 epidemic in emerging markets that face financial frictions and its mitigation through social distancing and vaccination. We find that restricted vaccine availability in emerging markets, as captured by limited quantities and high prices, renders the pandemic exceptionally costly compared to economies without financial frictions. Improved access to financial markets enables a better response to the delay in vaccine supplies, as it supports more stringent social distancing measures prior to wider vaccine availability. We show that financial assistance programs to such financially constrained countries can increase vaccinations and lower fatalities, at no present-value cost to the international community.

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1 Introduction

Vaccination campaigns against COVID-19 in many emerging markets have lagged behind those of developed economies, with mounting human and economic costs from the pandemic. Countries relied initially on mitigation measures that limit social interactions but more recently focus has shifted towards the acquisition of scarce vaccines. Governments have implemented fiscal transfers, to support consumption and the unemployed, but in emerging markets such fiscal programs and vaccine imports have been limited, because of tight fiscal space and a constrained supply of vaccines. A leading reason for limited fiscal space for these countries is their precarious access to international financial markets, often paired with underdeveloped domestic markets. We study quantitatively the consequences of vaccine scarcity and its interaction with financial markets access and use our findings to evaluate international assistance.

As in Arellano, Bai, and Mihalache (2020a), we integrate standard epidemiological dynamics into a model of a small open economy that borrows internationally to study the roll-out of vaccines and their impact on epidemic and economic outcomes. The epidemic exhibits multiple waves of infections that trigger ongoing health crises, with associated time paths of infected and deceased individuals. In our model, the economy responds to the epidemic with endogenous social distancing measures and vaccination campaigns, while the government issues debt in an attempt to smooth the impact of mitigation measures and vaccine expenditure on consumption. The economy faces financial frictions as borrowing is subject to constraints. These financial frictions increase the welfare cost of the epidemic because, by constraining consumption, they increase the cost of social distancing measures and the usefulness of vaccines that arrive too late. With lower vaccination, death rates are higher which increase the cost of the epidemic. We find that financial assistance programs can increase vaccinations and lower deaths, because they provide a lifeline before the vaccines arrive.

The epidemiological block of the model is the standard Susceptible-Infected-Recovered (SIR) framework, as in Atkeson (2020). New infections are the result of contact between individuals who are susceptible to the disease and those currently infected. All infected individuals eventually transition to either a recovered or deceased state. Social distancing limits infections because it temporarily reduces the contact between individuals who might be infected. Vaccinations reduce permanently the measure of susceptible individuals that can become infected and thus risk death from the epidemic. The international borrowing block of the model follows a standard incomplete markets framework, with a small open bond economy subject to a borrowing constraint. We consider a centralized problem with a sovereign that values the lives and consumption of its population. The sovereign decides borrowing, social distancing measures, and vaccine acquisitions to support consumption and to manage the dynamics of infection, with a goal of preventing deaths. Importantly, the economy faces constraints on vaccine supplies.

In the baseline results, we find that the epidemic leads to multiple waves of social distancing cycles that are associated with reductions in consumption. These outcomes occur because the availability of vaccines is delayed by a year from the start of the epidemic, with a slow ramps up of capacity. Interestingly, we find that not all the vaccine supplies are used, as a large fraction of the population is already immune from past infections when vaccines become available. To tease out the role of financial frictions in these outcomes, we compare these baseline results with financial constraints to an environment with perfect financial markets. As in Arellano, Bai, and Mihalache (2020a), better access to financial markets allows the economy to engage in more intense social distancing measures to manage the epidemic, because these costs do not translate contemporaneously to consumption. With the possibility of vaccines, we also find that better access to financial markets results in more vaccinations. The *complementarity* between financial market access and vaccinations arises because financial resources early in the epidemic reduces early infections and allows a larger fraction of the population to need a vaccine when capacity ramps up. The time-buying role of financial market access can be quite powerful quantitatively increasing vaccinations by about over 40% and reducing the welfare cost of the epidemic by half.

We evaluate how the supply of vaccines, encoded in the vaccine price and quantity constraints the economy faces, affects the country's outcomes and its interactions with financial market conditions. A restricted supply, with higher prices and tighter quantity constraints, worsens epidemic and economic outcomes. With limited options for vaccination, the economy manages the epidemic mainly through social distancing policies which are associated with deeper recessions and more sizable reductions in consumption. In contrast, faced with an ample supply of vaccines, the epidemic is resolved quicker and the economic crisis from a late wave of infections can be avoided or substantially shortened.

We also find that epidemic outcomes, such as fatalities, are more sensitive to vaccine capacity the more constrained financial market conditions are. In our baseline economy, fatalities drop by almost 29 percent if vaccines are widely available after a year, as opposed to a lengthy two years ramp up in the quantity of available vaccines. The same acceleration of vaccine deliveries is associated with a more modest 2.2 percent reduction in fatalities under perfect financial markets. This experiment suggests that expediting the ramp up in vaccine capacity can support a much quicker end to the pandemic and a much shallower recession, especially in countries that face more severe financial frictions.[1] These results again highlight the time-buying role of financial market access: with perfect financial markets what matters most is the eventual availability of vaccines, with financial frictions the timing of the vaccines shapes outcomes.

Finally, we use our framework to evaluate counterfactual international financial assistance loans. We consider long-term loans extended upon the outbreak of the epidemic. These additional loans relax financial constraints for the small open economy. We find that such international assistance tends to increase vaccinations by allowing more robust mitigation measures before vaccines are widely available. With less infections, vaccines are more useful later on, and endogenously employed more heavily. The quantitative effects can be sizable: a loan of 7% of output increase vaccinations by 14 %, reduce deaths by 19%, and lower the welfare costs of the epidemic by 32%. We also evaluate loans extended later, during the outbreak of the second wave. These late loans have limited impact on vaccinations, but also improve welfare substantially because they are well timed, to help support consumption during unexpected waves of infection.

Our paper contributes to the fast-growing literature that studies the COVID-19 epidemic and its economic impact. Alvarez, Argente, and Lippi (2021) and Eichenbaum, Rebelo, and Trabandt (2021) study optimal mitigation policies in simple production economies, in which the epidemic dynamics follow a SIR model. Their results highlight the trade-off inherent in social distancing: they save lives but are costly in terms of economic output. Our framework contains a similar trade-off but emphasizes the role of financial frictions and vaccine constraints.

A few papers share our focus on the impact of COVID-19 on emerging markets. Hevia and Neumeyer (2020) highlight the multifaceted nature of the pandemic, a tremendous external shock for emerging markets that includes collapsing export demand, tourism, remittances, and capital flows. Çakmaklı et al. (2020) focus on international input-output linkages as well as sectoral heterogeneity, by constructing a SIR-macro model calibrated to the Turkish input-output structure. Arellano, Bai, and Mihalache (2020a) focus instead on the interaction between financial market conditions and epidemic outcomes by explicitly modeling default risk as a source of financial frictions, while abstracting from vaccination policies. We share with this work the emphasis on financial frictions, but we uncover a new channel: better financial market access increases the benefits from and use of delayed vaccine availability.

Our paper is also related to the literature studying optimal social distancing and

1. Our work supports the emphasis of the World Health Organization's COVAX program, which aims to provide vaccines to developing countries funded by donor contributions, as discussed by, e.g., Wouters et al. (2021).

vaccination using extended SIR models. Makris and Toxvaerd (2020) argue that social distancing measures are optimally tightened in anticipation of the arrival of a vaccine. Glover et al. (2021) focus on the optimal allocation of vaccines across a population heterogeneous in age. In line with our results, they also find that vaccine and social distancing are complements, as early social distancing increases the benefits of late vaccinations. In contrast, Garriga, Manuelli, and Siddhartha (2020) find that the possibility of vaccine arrival matters little for early social distancing. When available, vaccines substitute for social distancing, as is the case in our paper too. Most of the existing literature focuses on the United States and assumes costless vaccination. Our work, on the other hand, studies emerging markets and highlights the importance of financial frictions for vaccination policies.

2 Model

We study a small open economy with a continuum of agents and a government that borrows from internationally subject to constraints. The economy is unexpectedly hit by an epidemic, COVID-19, which results in time paths of infections and deaths. The epidemic dynamics follow a standard epidemiological Susceptible-Infected-Recovered (SIR) model augmented with endogenous social distance measures and, eventually, a vaccination program. During the epidemic, a subset of the population endogenously transitions from being susceptible to infected or vaccinated. In the model, the vaccine transitions susceptible individuals directly to the recovered state, without a spell of infection, which also implies that they are henceforth immune. All infected individuals eventually either recover or die. The fatality rate is endogenous, to reflect limited healthcare capacity, an especially critical feature for emerging markets. The eventual outcome of the epidemic can be altered with social distancing measures and with the timing and size of the vaccination program.

2.1 Preferences, Technology, and Borrowings

We consider preferences over consumption and lives. As in Alvarez, Argente, and Lippi (2021) and Arellano, Bai, and Mihalache (2020a), the flow payoff which increases in consumption per capita c_t and decreases in fatalities $\phi_{D,t}$. We assume each fatality imposes a loss of value χ. The lifetime value is given by

$$v_0 = \sum_{t=0}^{\infty} \beta^t \left[u(c_t) - \chi \phi_{D,t} \right], \tag{1}$$

where β is the discount factor. The utility from consumption is concave and equals $u(c) = (c^{1-1/\gamma} - 1)/(1 - 1/\gamma)$, with γ controlling the intertemporal elasticity of substitution.

Output in the economy Y_t is produced using labor, possibly constrained by social distancing measures. Agents are endowed with one unit of time, and hence total labor supply equals population N_t. Social distance measures of intensity L_t, reduce each agent's labor input to $(1 - L_t)$.[2] The economy's output equals

$$Y_t = [(1 - L_t)N_t]^{\alpha}, \tag{2}$$

where the parameter α is between 0 and 1.

The country has an international debt level B_t and can borrow at the international rate r up to a borrowing limit $\overline{B}$. The country uses its output resources Y_t and new borrowing B_{t+1} for paying its debt, consumption c_t, and vaccines X_t. The country faces a time-varying quota or capacity constraint $\overline{X}_t$ on its vaccine roll-out and a unit price for each vaccine course of p, both of which are determined in world markets. The resource constraint for the economy is given by

$$N_t c_t + (1 + r)B_t + pX_t \leq [N_t(1 - L_t)]^{\alpha} + B_{t+1}. \tag{3}$$

2.2 Epidemic, Social Distancing, and Vaccination

The epidemic dynamics are modeled using the classic SIR setup of Kermack and McKendrick (1927). Following the outbreak of the disease, a subset of the population transitions endogenously from being susceptible to being infected and, eventually, to being either recovered or deceased. Thus, during the epidemic, the population N_t is partitioned in three epidemiological groups: susceptible, infected, and recovered. The mass of each group is denoted by μ_t^S, μ_t^I, and μ_t^R, respectively. We assume that the initial population size is 1. The total mass of the deceased is $\mu_t^D = 1 - N_t$. The epidemic starts when an initial subset of the population becomes infected exogenously, $\mu_0^I > 0$. The rest are susceptible, except possibly for a measure of agents already recovered $\mu_0^R \geq 0$, so that $\mu_0^S = 1 - \mu_0^I - \mu_0^R$. The presence of some already recovered individuals captures the idea that policymakers become aware of the infection after it has already spread to some extent through the population.

The spread of the epidemic can be mitigated with social distancing L_t and vaccination

2. As in Arellano, Bai, and Mihalache (2020a), we assume that all individuals work, whether they are infected or not. It would be straightforward to consider an extension where the infected are less productive or unable to work. The key maintained assumption is that the infected cannot be targeted with more narrow social distancing measures.

X_t. As in Alvarez, Argente, and Lippi (2021), social distancing L_t reduce labor input by a fraction L_t and social interactions by θL_t, where the parameter θ controls the imperfect effectiveness of social distancing measures for prevention of infection. Eventually the country will be able to buy vaccine courses X_t with a unit price p.[3] Each course can render one susceptible individual immune to the disease. The country faces a time-varying quota or capacity constraint $\overline{X}_t$ on its vaccine roll-out.

In modeling how transmissible the disease is, we follow the standard approach according to which the probability of infection of the currently susceptible depends on the mass of infected individuals μ_t^I and effective social distancing measures θL_t. The mass of newly infected individuals is denoted by μ_t^n and we assume that it is determined by

$$\mu_t^n = \pi_n \left[(1-\theta L_t)\mu_t^I\right] \left[(1-\theta L_t)\mu_t^S\right]. \tag{4}$$

The presence of $1-\theta L_t$ twice in this expression reflects the idea that reduced social interactions are in effect for both the infected and the susceptible. The parameter π_n captures the degree to which the disease is contagious. The mass of susceptible individuals in period $t+1$ is that of period t minus any new infections and individuals vaccinated in period t, X_t

$$\mu_{t+1}^S = \mu_t^S - \mu_t^n - X_t. \tag{5}$$

Individuals remain infected with probability π_I each period. The mass of infected individuals in period $t+1$ equals a π_I share of the infected in period t plus any new infections. The resulting law of motion is

$$\mu_{t+1}^I = \pi_I \mu_t^I + \mu_t^n. \tag{6}$$

With complementary probability $1-\pi_I$ the infection resolves and the individual either recovers or dies. Like Alvarez, Argente, and Lippi (2021), we assume that the probability of death, conditional on being infected, $\pi_D(\mu_t^I)$ is a function of current infections, resulting in $\phi_{D,t} = \pi_D(\mu_t^I)\mu_t^I$ fatalities every period. We assume that $\pi_D(\mu_t^I)$ is an increasing function, to capture the role of health care capacity for the fatality rate; a large number of simultaneous infections puts a strain on the health care system, reducing its ability to successfully treat cases. The resolution of infections into recoveries or deaths induces the

3. For tractability we assume that vaccination requires a one-time dose, thereby abstracting from vaccine courses requiring multiple doses with some time lag between them. Allowing for such a lag would require us to keep track of at least another state variable, the measure of agents with an incomplete vaccine course.

following laws of motion for these latter two groups:

$$\mu^R_{t+1} = \mu^R_t + X_t + \left[1 - \pi_I - \pi_D(\mu^I_t)\right]\mu^I_t, \tag{7}$$

$$\mu^D_{t+1} = \mu^D_t + \pi_D(\mu^I_t)\mu^I_t. \tag{8}$$

The above evolution of types induces a law of motion for population N_t,

$$N_{t+1} = \mu^S_{t+1} + \mu^I_{t+1} + \mu^R_{t+1}. \tag{9}$$

2.3 Dynamic Problem

We study a centralized problem where a government makes all choices for this economy. The government learns about the epidemic in period 0. The outbreak changes the prospects for the economy, since the epidemic will lead to loss of life as well as disruptions in production and consumption. The government borrows from international financial markets B_{t+1}, and chooses social distance policies L_t and vaccine purchases X_t, to maximize the lifetime value (1).

The state variables consist of population measures $\mu_t = (\mu^S_t, \mu^I_t, \mu^R_t)$ and the debt level B_t.[4] The value function $V_t(\mu_t, B_t)$ for the government depends on these states and on time. The problem is inherently time-dependent because of the time path vaccine capacity constraints $\overline{X}_t$. The government can borrow from international lenders at an interest rate r subject to a borrowing limit $\overline{B}$. The government chooses optimal borrowing B_{t+1}, social distancing L_t, and vaccines X_t to maximize its objective, given by

$$V_t(\mu_t, B_t) = \max_{B_t,\, X_t,\, L_t \in [0,1]} \left[u(c_t) - \chi\phi_{D,t}\right] + \beta V_{t+1}\left(\mu_{t+1}(\mu_t, L_t, X_t), B_{t+1}\right), \tag{10}$$

subject to the resource constraint (3), the borrowing and vaccine limits,

$$B_{t+1} \leq \overline{B}, \qquad X_t \leq \overline{X}_t, \tag{11}$$

and the SIR laws of motion (4)–(8), which map current population measures, social distance and vaccination policies to future measures $\mu_{t+1}(\mu_t, L_t, X_t)$, and overall population N_t in (9).

When choosing L_t and X_t the government trades off the potential benefits from saving lives against the costs of social distance policies and vaccinations in terms of output and consumption. Consumption is lowered by production disruptions from social distancing

4. Fatalities can always be computed as residual, $\mu^D_t = 1 - \mu^S_t - \mu^I_t - \mu^R_t$, given initial population $N_0 = 1$.

measures and from spending on vaccines, and this response is amplified by financial frictions. If financing opportunities are ample, under a loose $\overline{B}$ limit, any reduction in current income from social distancing and vaccine purchases matter for consumption only through a reduction in lifetime income. Consumption adjusts modestly to this lower permanent income, but the period-by-period consumption decline need not necessarily mirror the contemporaneous declines in output. With tight borrowing limits in contrast, the consumption costs from social distancing and vaccine purchases cannot be smoothed out.

To emphasize the role of financial frictions in vaccine and social distance policies, we will compare our baseline model with financial frictions to a setup with *perfect financial markets*, in which the government makes choices subject to a lifetime budget constraint for the country

$$\sum_{t=0}^{\infty} \frac{1}{(1+r)^t}(N_t c_t + pX_t) \leq -(1+r)B_0 + \sum_{t=0}^{\infty} \frac{1}{(1+r)^t}[N_t(1-L_t)]^{\alpha}. \tag{12}$$

where B_0 is the initial level of debt for the country upon the outbreak of the epidemic, as well as the vaccine constraints and the SIR laws of motion.

3 Quantitative Analysis

We proceed to the quantitative analysis of our model. We first discuss the choice of parameters, including those controlling the SIR dynamics and supply conditions for vaccines. We then describe the time paths of the baseline economy and compare it to those under perfect financial markets. Next we evaluate how the evolution of the supply of vaccines impacts the epidemic outcomes and its interdependence with financial markets. Finally, we study counterfactual financial assistance programs and show that these can greatly enhance the usefulness of vaccination.

3.1 Parameterization

The period length is one week, to capture the fast dynamics of infection. We use the parameter values in Arellano, Bai, and Mihalache (2020a) except for those controlling the vaccination program, which we discuss shortly. Table 1 collects all parameter values and their interpretation.

Preferences/Technology		
γ	0.5	Intertemporal Elasticity of Substitution
β	$\sqrt[52]{0.98}$	Discounting
χ	4025	Value of Statistical Life
α	0.67	Labor Share
Epidemics and Vaccination		
π_I	0.67	18 days to expected infection resolution
$\pi^{D,0}$	0.0016	Baseline fatality rate
$\pi^{D,1}$	0.0824	Healthcare infrastructure congestion
$\mathcal{R}_{0,\text{init}}$	2.6	Initial $\mathcal{R}_0$
$\mathcal{R}_{0,\text{first}}$	1.2	Asymptotic $\mathcal{R}_0$
ρ	0.9	Decay rate of $\mathcal{R}_0$
$\mathcal{R}_{0,\text{second}}$	1.6	Second wave $\mathcal{R}_0$
$\pi_{n,t}$	$(1-\pi_I)\mathcal{R}_{0,t}$	Time-varying
θ	0.5	Effectiveness of social distancing
T^V	12	Months until the start of vaccine distribution
T^R	12	Months to ramp up to full vaccine capacity
$\overline{X}$	0.035	Maximum weekly vaccine capacity
p	0.2	Vaccine unit price
Financial Markets		
r	$\sqrt[52]{1.01}-1$	Interest rate
B_0	31.2	60% initial debt-to-GDP level

Table 1: Parameters

Note: The parameterization of the model follows Arellano, Bai, and Mihalache (2020a). The additional parameters, governing the availability and cost of vaccines, are discussed in the main text.

Epidemiological parameters. Infections resolve in 18 days on average, implying a value of 0.67 for π_I. Fatalities are quadratic in the measure of infected, $\pi_D(\mu_t^i) = (\pi^{D,0} + \pi^{D,1}\mu_t^I)\mu_t^I$, where $\pi^{D,0} = 0.0016$ is consistent with the baseline fatality rate of 0.5% and $\pi^{D,1}$ captures healthcare infrastructure congestion. Arellano, Bai, and Mihalache (2020a) uses a value of $\pi^{D,1} = 0.0824$ to match the time paths of deaths in the 2020 Latin America data. The rate $\pi_{n,t}$, at which new infections result from the interactions between the currently infected and susceptible, varies over time and depends on the reproduction number $\mathcal{R}_{0,t}$ with $\pi_{n,t} = (1 - \pi_I)\mathcal{R}_{0,t}$.

Arellano, Bai, and Mihalache (2020a) allow for a time-varying $\mathcal{R}_0$ to reproduce the otherwise-puzzling disconnect between the timing of fatalities and social distancing measures in the data and also to introduce the second wave. $\mathcal{R}_0$ starts at $\mathcal{R}_{0,\text{init}} = 2.6$ at the outbreak of the epidemic in April 2020. This number is from early studies of COVID-19 based on the cases on the Diamond Princess ship. During this first wave of infections, $\mathcal{R}_0$ decays at rate $\rho = 0.9$ towards a lower level of $\mathcal{R}_{0,\text{first}} = 1.2$, as a result of heightened awareness and behavioral changes in the population such as mask-wearing and hygiene practices. Formally, $\mathcal{R}_{0,t} = \mathcal{R}_{0,\text{init}}\,\rho^t + \mathcal{R}_{0,\text{first}}\,(1 - \rho^t)$ during the first wave. An unexpected second wave of infections, plausibly caused by a new variant of the virus, raises $\mathcal{R}_0$ permanently to $\mathcal{R}_{0,\text{second}} = 1.6$ about one year from the start of the epidemic. See Appendix A for the time path of $\mathcal{R}_0$. Concerning the effectiveness of social distancing measures, we set $\theta = 0.5$, to reflect the possibility of infection away from work, school, or travel, which dampens the impact of social distance policies on the spread of the epidemic, in line with the evidence in Mossong et al. (2008).

Preferences, production, and debt. Preferences exhibit a constant elasticity of intertemporal substitution in consumption with a standard value of $\gamma = 0.5$, while the parameter χ is set to 4025, based on the value of statistical life measures for emerging markets in Viscusi and Masterman (2017) and the calculations in Arellano, Bai, and Mihalache (2020a). The coefficient α in the production is set to the a standard labor share value of 0.67. The discount factor β is consistent with a 2% domestic real rate in emerging markets and the international rate r is 1% annualized, as in Arellano, Bai, and Mihalache (2020b). Initial debt to annual output at the outbreak of the epidemic is 60%, which is the average government debt to output ratio in Latin American in 2019. We also set the borrowing constraint for this economy equal to the initial level of debt.

The vaccination program. The vaccine program is characterized by its start date, T^V months after the epidemic outbreak, the length of time required for the program to ramp up to full capacity, T^R months, the peak weekly capacity $\overline{X}$. The vaccination can be therefore summarized by the following function

$$\overline{X}_t = \begin{cases} 0, & \text{unavailable, if } t < T^V \\ \frac{t - T^V}{T^R}\overline{X}, & \text{ramp up, if } t \in [T^V, T^V + T^R - 1] \\ \overline{X}, & \text{peak capacity reached, if } t \geq T^V + T^R. \end{cases} \tag{13}$$

We assume that the vaccination of the general population starts one year into the epidemic, $T^V = 12$, broadly in line with the timing of programs in Latin America. We set the peak weekly capacity to 3.5% of the population, based on the high achieved in the U.S. in early April 2021 when over 2 million people were completing their vaccination daily, as reported by CDC (2021). The speed with which emerging markets can reach the capacity observed in the U.S. is uncertain. Our baseline assumes that it takes $T^R = 12$ months for countries to ramp up their capacity, and we perform comparative statics over this timing.

The price for vaccines varies across time and countries, as documented by Dyer (2021) and UNICEF (2021).[5] We use a value of \$40 for two doses, which is within the range of estimates. We then set $p = 0.2$ by expressing the price relative to weekly output per capita, using the 2019 value for Mexico. In Section 3.3, we explore the impact of varying vaccine relative prices, as observed in cross country data.

3.2 Vaccination and Financial Markets Conditions

The epidemic in our model exhibits two waves of infections: the first wave is caused by the initial outbreak in April 2020, while the second wave is due to the unexpected emergence of a new, variant one year later, in April 2021. We assume that upon the outbreak of the epidemic, agents are aware of the eventual availability of vaccines and the speed at which vaccine capacity will be ramped up, but that they do not expect the second wave.

Figure 1 plots time paths for vaccination, social distancing policies, consumption, and population measures by infection status for our baseline economy with constrained financial markets. We also plot the same paths for the reference economy facing perfect financial markets. We start by discussing the paths of the baseline economy, depicted using solid blue lines in Figure 1. Panel (a) captures vaccination outcomes. Vaccines are not available before April 2021, following which capacity ramps up, reaching a peak of 3.5 percent of population weekly in June 2022. The country chooses to use all of its

5. According to UNICEF (2021), the average price per dose is \$14 for Pfizer, \$25 for Moderna, \$5 for AstraZeneca, \$18 for Sinovac, and \$21 for Sinopharm.

available vaccines before September 2021, and then to halt vaccination once the measure of susceptible individuals has reached herd immunity and infections are vanishing. The country uses social distancing measures to battle the outbreak of the first wave, without immunization options. It starts with an aggressive 40 percent reduction in activity and gradually loosens restrictions. Given the limited availability of vaccines, the country begins a renewed set of social distancing measures when the second wave of infections arrives in April 2021. When vaccination becomes more readily available, social distancing is phased out. In Panel (c) we plot the consumption path relative to the consumption level prior to the epidemic. Consumption closely resembles a mirror image of social distancing, with two big declines during both the first and second waves because the country faces tight borrowing constraints throughout. In the second wave, consumption falls slightly more than labor input alone would entail, i.e., beyond the output losses associated with social distance measures, owing to expenditure on vaccine purchases.

Both social distance measures and vaccinations help the country fight against the epidemic. The measure of susceptible individuals decrease over time and reach around 27 percent in October 2021. Between July and October 2021, vaccination significantly reduces the number of susceptible people, in danger of infection. Social distance measures, on the other hand, are less effective than vaccination, as shown by the flatter slope in the first wave in Panel (d). The evolution of infections is plotted in Panel (e). The two humps in the picture reflect the two waves of the pandemic. Panel (f) depicts the cumulative death tolls in this economy. It grows over time, reaching 0.2 percent of the population by the end of the episode.

The red-dashed lines in Figure 1 show the corresponding time paths for the case of perfect financial markets. The government adopts more severe social distance measures for both the first and second waves than the baseline, owing to ample access to international borrowing. Prior to the availability of vaccines, stricter social distance measures significantly lower infection rates. However, before the second wave, the number of susceptible individuals remains high, as fewer people underwent infection and recovery by this time. While the country cannot ramp up its vaccine purchases faster than the baseline economy, it administers vaccinations for a longer period of time. Consumption is not constrained to follow the path of output and social distance measures in this case: over time the country can maintain a smoother path of consumption by aggressively relying on international borrowing.[6] The end result is that the country experiences fewer fatalities than the financially constrained baseline economy, due to its stricter social distance

6. With perfect financial markets, consumption has a slight downward trend, even absent shocks, because in our baseline parameterization the country is relatively more impatient than its lenders, $\beta(1+r) < 1$.

measures and additional vaccinations.

We summarize the health and economic outcomes for these two economies in Table 2. For the baseline economy, about 45 percent of people receive a vaccine. The country chooses social distance measures that cumulatively depress output by about 15 percent of its annual level.[7] In contrast, the present value of expenditure on vaccines is substantially smaller, accounting for only 0.2 percent of annual output. Although they are inexpensive, vaccine are delayed and in limited supply. The epidemic is costly, it lowers welfare by 0.7 percent in terms of consumption equivalence: the country would be willing to forego 0.7 percent of pre-pandemic consumption every period forever to avoid the outbreak entirely.

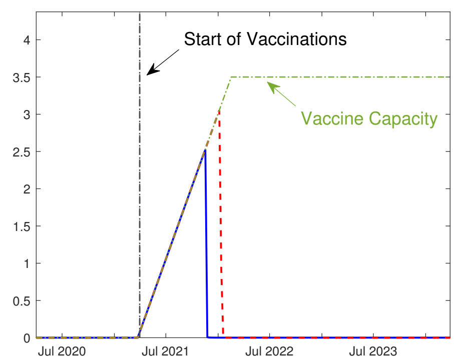
With perfect financial market, outcomes are better. The economy can afford more social distancing and immunizations, with vaccines reaching 65% of the overall population. The cost of social distancing is about 30% of output from more intense and longer social distancing. The resulting epidemic welfare cost is approximately half that of the baseline, with a 0.38 percent consumption equivalent welfare cost relative to the case of no epidemic under perfect financial markets.

For additional context, we compare our results to the case of a second wave without access to vaccines, as in Arellano, Bai, and Mihalache (2020a, Section 4.6). Without vaccination, the only option for the country to contain the outbreak is to impose harsher social distance measures. The financially constrained economy enforces prolonged but less severe measures, to strike a balance between lowering the mortality toll and to smooth consumption, but on net the present value costs are similar to the economy with vaccines. Mortality rates are higher without vaccination, around 0.36 percent in the constrained economy and 0.29 percent for the case of perfect financial markets. Vaccines reduce deaths, but this reduction is much greater for the economy with perfect financial markets: 0.05 percent versus 0.29 percent, a decrease of more than 80 percent. In the baseline financially constrained economy, the decrease in the death toll is half that, about 40 percent. Vaccines can reduce the welfare cost of the pandemic by 0.21 percent for the financially constrained economy, and by 0.42 percent for the one with perfect financial markets.

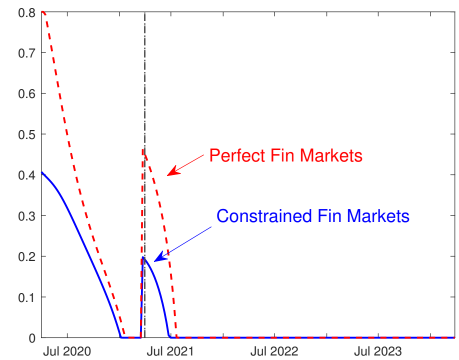
In summary, financial frictions reduce the benefits of vaccination because they increase the costs of early social distance measures needed to take advantage of the delayed vaccines. Access to perfect financial markets enables the country to implement more aggressive social distance measures prior to the availability of the vaccine and therefore to administer more vaccines later. This strategy saves more lives and leads to a lower welfare cost of the pandemic. The lesson is that access to vaccines is especially valuable when paired with favorable financial conditions, as it results in a greater reduction in mortality

7. The decline in output is the present value of output contractions as of the start of the epidemic.

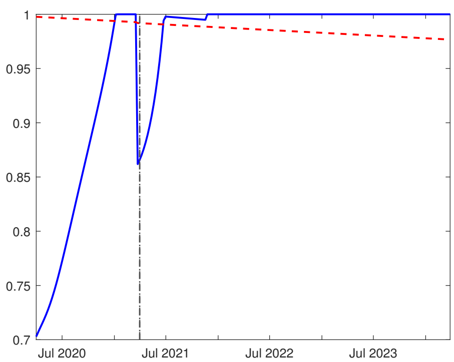
Figure 1: Time Paths: Baseline and Perfect Financial Markets



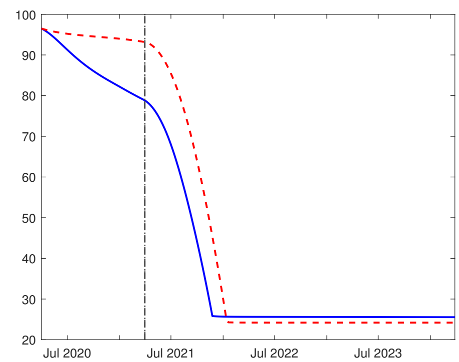
(a) Vaccinations, X



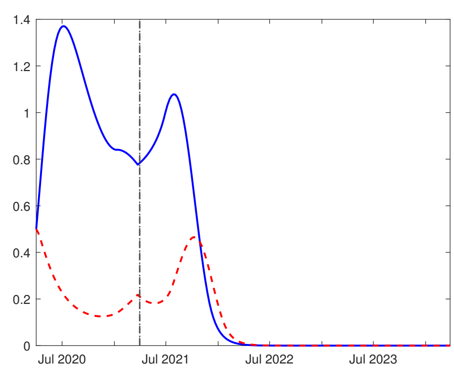
(b) Social Distancing, L



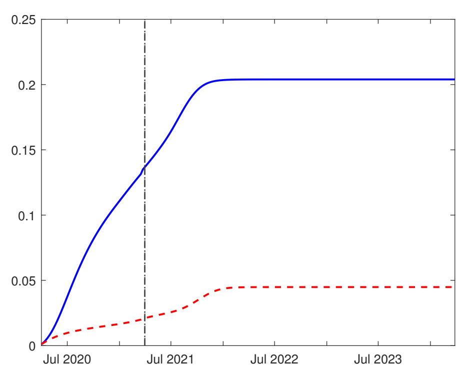
(c) Consumption, C



(d) Susceptible, μ_S



(e) Infected, μ_I



(f) Deceased, μ_D

Note: Simulated time paths for the baseline economy with constrained financial markets (solid, blue) and the economy with perfect financial markets (dashed, red). The epidemic outbreak is timed at the start of April 2020. The second wave and vaccinations begin at April 2021. The vertical dashed black line marks the start of the second wave.

and better welfare.

	With Vaccines		No Vaccines	
	Constrained	Perfect	Constrained	Perfect
Health				
Vaccinations	45	65	–	–
Fatalities	0.20	0.05	0.36	0.29
Mitigation Costs (% output)				
Social Distancing	15	30	16	31
Vaccine Expenditure	0.2	0.3	–	–
Welfare Cost of Pandemic				
Consumption Equivalent	−0.70	−0.38	−0.91	−0.80

Table 2: Vaccination and Financial Markets

Note: The columns "Constrained" are our baseline model with financial frictions while the columns "Perfect" are the model with perfect financial markets. The "No Vaccines" is implemented as $\overline{X}_t = 0$ for all t and corresponds to the results in Arellano, Bai, and Mihalache (2020a, Section 4.6) augmented with a second wave.

3.3 Vaccine Ramp Up, Prices, and Financial Markets

Having established the importance of vaccine availability and its interaction with financial market conditions, we now examine the effect of vaccine ramp up speed and pricing on pandemic outcomes. The top panel of Table 3 summarizes the health and economic consequences of alternative vaccine scenarios. We considers two additional ramp up timings: in the "Quick" case, we assume vaccinations are immediately available at their peak capacity of 3.5 percent, while the "Slow" case takes 24 months to reach this level. With a "Quick" ramp up, the government chooses to max out its capacity for three months when facing constrained financial markets, resulting in an increase in total immunization from 44 to 56 percent. This reduces total fatalities from 0.2 to 0.16 percent, despite the fact that the country engages in less aggressive social distance policies. Additionally, it results in a smaller output costs from social distancing and welfare losses. In comparison, the "Slow" scenario, with a more gradual ramp up, exhibits reduced immunization rates, increased mortality, and lower welfare.

With perfect financial markets, the ramp up speed has qualitatively similar effects. In this case, the country benefits less from the faster ramp up because the increase in immunizations, the reduction in fatalities, and savings in terms of output are all smaller, owing in large part to better outcome in the baseline scenario.

	Constrained Fin Markets			Perfect Fin Markets		
Quantity ramp up	Quick	Baseline	Slow	Quick	Baseline	Slow
Vaccinations	56	44	37	70	65	61
Fatalities	0.16	0.20	0.22	0.045	0.05	0.05
Social Distance Cost	13	15	16	22	30	35
Welfare (CE)	−0.59	−0.70	−0.74	−0.30	−0.38	−0.43
Price	Low	Baseline	High	Low	Baseline	High
Vaccinations	60	44	18	81	65	39
Fatalities	0.20	0.20	0.24	0.05	0.05	0.05
Social Distance Cost	15	15	14	30	30	31
Welfare (CE)	−0.70	−0.70	−0.76	−0.38	−0.38	−0.44

Table 3: Vaccination Scenarios

Note: Quantity ramp up: "Quick" corresponds to $T^R = 0$, our baseline has $T^R = 12$, while "Slow" reports $T^R = 24$ months. Vaccine price comparison: "Low" is $p = 0.035$, our baseline has $p = 0.2$, while "High" corresponds to $p = 7$. The price is expressed in weekly income per capita. The consumption equivalent ("CE") measure reports the welfare comparison of the various vaccine scenarios to a timeline without the epidemic.

In the bottom panel of Table 3, we examine the impact of vaccine prices on health and economic outcomes. We set out baseline price to 0.2 in line with our calculation based on a $40 unit price relative to a weekly income per capita in Mexico in 2019. We consider two alternative prices, a "Low" price of $p = 0.035$ based on a country with weekly income per capita in the range of that of the United States, and a "High" price of $p = 7$ based on weekly income per capita in the range of Burundi.[8] The "Low" price is also consistent with Mexico weekly income and purchases of AstraZeneca at about $4 per dose.

With a higher vaccine price and constrained financial markets, the relevant case for many highly impoverished countries, the epidemic outcomes are significantly worse: fatalities increase by 20 percent and the number of vaccinated individuals is 60 percent lower than in our baseline. Access to perfect financial markets dampens the consequences of high vaccine prices: fatalities increase only from 0.05% to 0.054%, a roughly 7 percent increase. The reduction in vaccinations is also smaller, about 40%, from 65 to 39 percent of the population. The ability to borrow against future income allows the country to smooth out costly vaccine expenditures, enabling a better mix of consumption and a more aggressive vaccination campaign. If instead we consider lower vaccine prices than in the

8. For these calculations the relevant measure of income per capita is not the purchasing power parity (PPP) adjusted one, but rather the income expressed in U.S. Dollars at the current exchange rate.

baseline, the country acquires and administers a greater number of vaccines. However, this has negligible effect on deaths and welfare, for both the constrained economy and the perfect financial markets. The reason is that the country is always subject to a binding capacity constraint early in the vaccination campaign. Even if the country were to inoculate more people later, once capacity is slack, these extra vaccines would come too late to save additional lives.

In summary, based on the comparisons reported in this section, we find that the speed with which a country can obtain and administer vaccines is far more critical than their acquisition price, except for highly impoverished countries. We also find that outcomes for the financially constrained economy are more responsive to both prices and ramp up speed than under perfect financial markets, where outcomes are quite favorable even under baseline conditions.

3.4 International Financial Assistance

We now examine the impact of international financial assistance programs on the vaccination efforts and epidemic outcomes.[9] We consider programs that take the form of long-term loans. We assume that international organizations extend a loan of size F that is repaid with perpetual coupons of size rF. The international organization, therefore, breaks even in present value. We analyze the implications of an early loan that is extended upon the outbreak of the epidemic and a late loan that is extended at the beginning of the second wave. We consider a loan of 7 percent of the economy's annual output and will perform comparative statics for other loan sizes.

When the economy receives the loan, it can choose to either consume it or save it, by reducing its debt towards private lenders. In equilibrium, the economy saves most of it because the inflow from the financial assistance loan is large compared to income or consumption in that week. By adjusting its debt, the economy makes flexible use of this financial assistance. Importantly these funds effectively enable the country to move away from its borrowing constraint and, as we saw in previous sections, such forces potentially have great implications for vaccination, fatalities, and welfare.

Table 4 compares outcomes across financial assistance scenarios.[10] The early loan increases the vaccination rate from 44% to 50% and reduces fatalities by 15%. The economy uses the early loan to engage in more aggressive social distancing policies and

9. This analysis complements the one of Arellano, Bai, and Mihalache (2020a, Section 4.5), which studied debt relief programs for addressing the health crisis through social distance measures only.

10. See Figure 6 in Appendix B for the time paths of vaccination, social distancing, SIR dynamics, and consumption under the early and late loan programs.

		Loan	
	Baseline	Early	Late
Health			
Vaccinations	44	50	44
Fatalities	0.204	0.166	0.189
Mitigation Costs (% output)			
Social Distancing	15	19	16
Vaccine Expenditure	0.17	0.19	0.17
Welfare Cost of Pandemic			
Consumption Equivalent	−0.70	−0.47	−0.37

Table 4: International Financial Assistance Programs

Note: The loans are perpetuity loans of 7% of pre-pandemic annual output. The "Early Loan" is given upon the outbreak of the epidemic while "Late Loan" is timed with the beginning of the second wave.

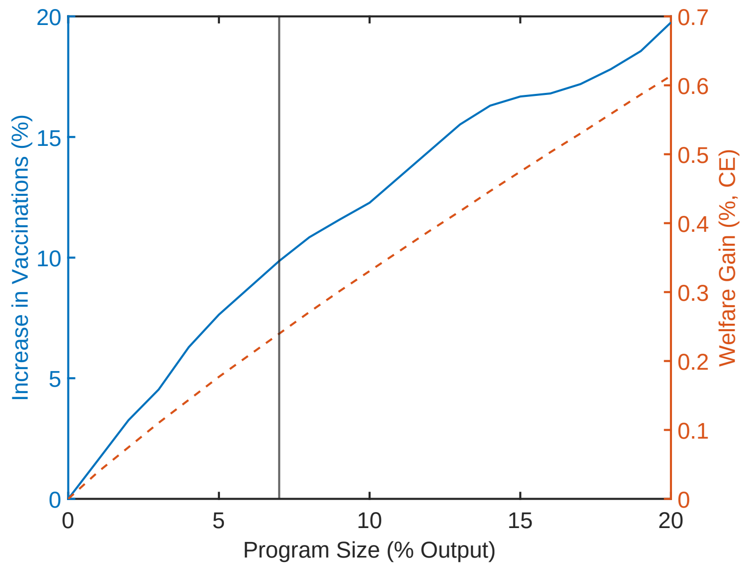
prevent early infections. With fewer early infections, vaccines are more useful when they eventually arrive, and the economy can vaccinate more people, resulting in fewer fatalities. The welfare costs from the epidemic are substantially reduced from 0.7% to 0.47% in terms of consumption equivalence. Hence the welfare gain from the financial assistance is 0.23%. These welfare gains come from both smoother consumption and fewer deaths.[11]

The late loan program, disbursed during the second wave in April 2021, is also beneficial to the economy. The economy uses this late loan to support consumption during the second wave and implement more stringent social distance measures, which help reduce fatalities. Even though it generates smaller reductions in deaths than the early program, the late program cuts the welfare costs from the epidemic more than the early one. The reason is that the second wave is unexpected in our exercises; the late financial assistance loan is useful as it helps support consumption around this unexpected shock.

The impact of the late loan on vaccinations, however, does depend on the timing of the supply of vaccines. We find that such a late loan can in fact increase vaccinations for economies that face higher vaccine prices or tighter quantity constraints. For example, the late loan increases vaccination rates by 1% in our high price economy and by 2% in the low ramp up case. Nevertheless, the more potent effects from financial assistance loans on vaccinations occur by allowing better mitigation before vaccines become available, and this is most important during the first wave.

11. Without the epidemic, the country would also gain from financial assistance because it relaxes the borrowing constraints, but by about half of our baseline gain.

Figure 2: Loan Size, Vaccination, Welfare



We now perform comparative statics to the size of the financial assistance loan, and we focus on the early loan, extended at the outbreak of the epidemic. In Figure 2, we plot the change in vaccinations and welfare gains induced by loans of varying sizes, expressed as percentages of pre-pandemic annual output. Welfare is reported relative to the baseline economy with no financial assistance. The vertical line corresponds to the 7% loan that we analyzed above. Larger loans are associated with a greater increase in vaccinations and higher welfare. For example, the loan of 20% of output increases vaccination rate by 20% and welfare by 0.6% relative to no financial assistance. In summary, bigger loan programs are always weakly better because they increasingly eliminate the constraints imposed by financial frictions and allows the better outcomes previously discussed in the perfect financial markets reference.

4 Conclusion

Vaccination is an essential component of the worldwide fight against the COVID-19 epidemic. We have integrated standard epidemiological dynamics into a small open economy that borrows internationally subject to financial frictions to study the roll-out of vaccines and their impact on epidemic and economic outcomes. We have shown that financial frictions impede the usefulness of vaccines that arrive too late because they limit the early social distancing policies needed to buy time. With financial frictions the welfare cost of the epidemic is higher because of less vaccinations, higher death rates, and more severe declines in consumption. We find that financial assistance programs can increase vaccinations because they provide a lifeline before the vaccines arrive. Our work, therefore, supports the emphasis of many international organizations on the importance of ample vaccine availability for developing countries and on financial assistance programs.

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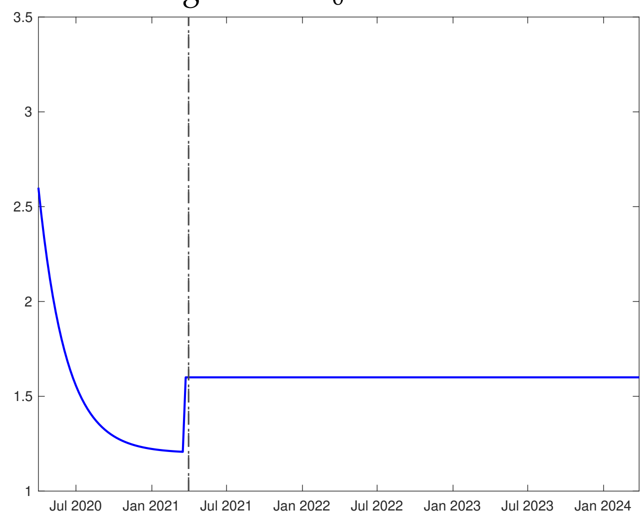
Appendix

A Time Path of Reproduction Number $\mathcal{R}_0$

Figure 3 plots the time path of $\mathcal{R}_0$ taken from Arellano, Bai, and Mihalache (2020a). It features two waves. In the first wave, $\mathcal{R}_0$ starts with 2.6 and then decays at the rate of 0.9 until it reaches 1.2 on March 2021, when the second wave ensues.

Figure 3: $\mathcal{R}_0$ Time Path

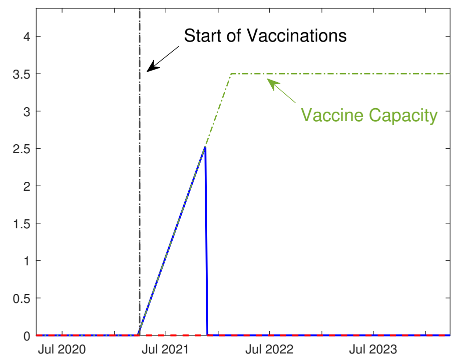


B Time Paths under Various Scenarios

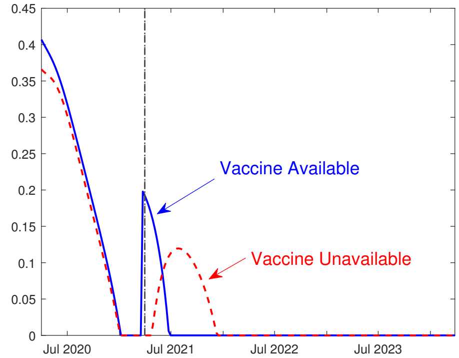
Figure 4 documents the impact of vaccine available under constraint financial markets while Figure 5 reports the case of perfect financial markets. Under both scenarios, vaccines prevent a large share of eventual fatalities and hasten the end of the epidemic.

Figure 6 compares the time paths resulting from the early versus the late loan programs.

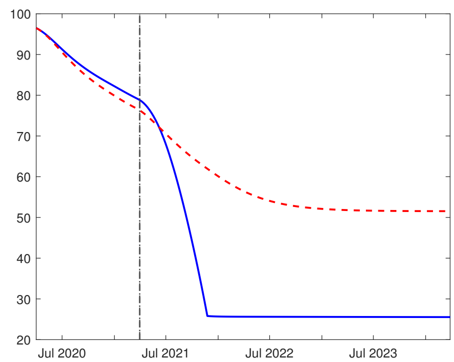
Figure 4: Constrained Fin Markets: Vaccine Availability



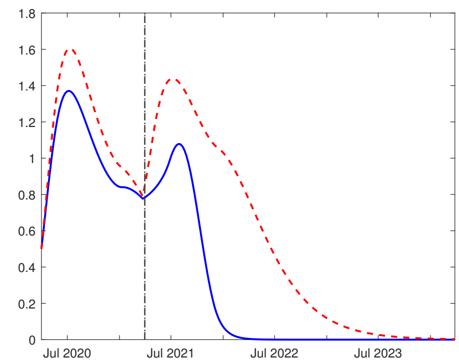
(a) Vaccinations, X



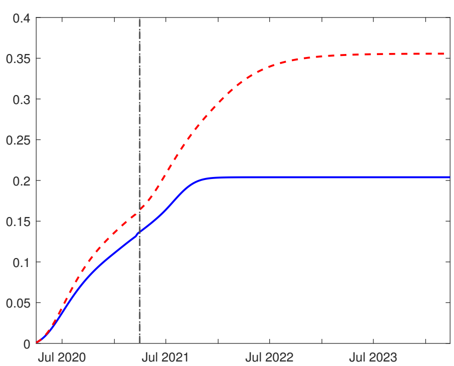
(b) Social distancing, L



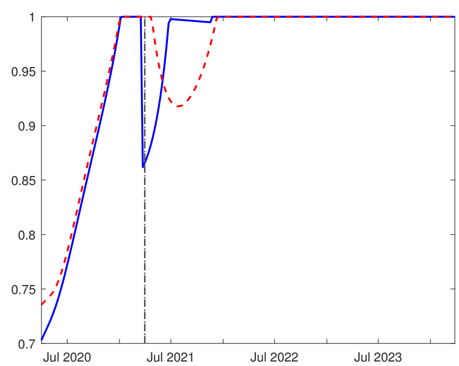
(c) Susceptible, μ_S



(d) Infected, μ_I



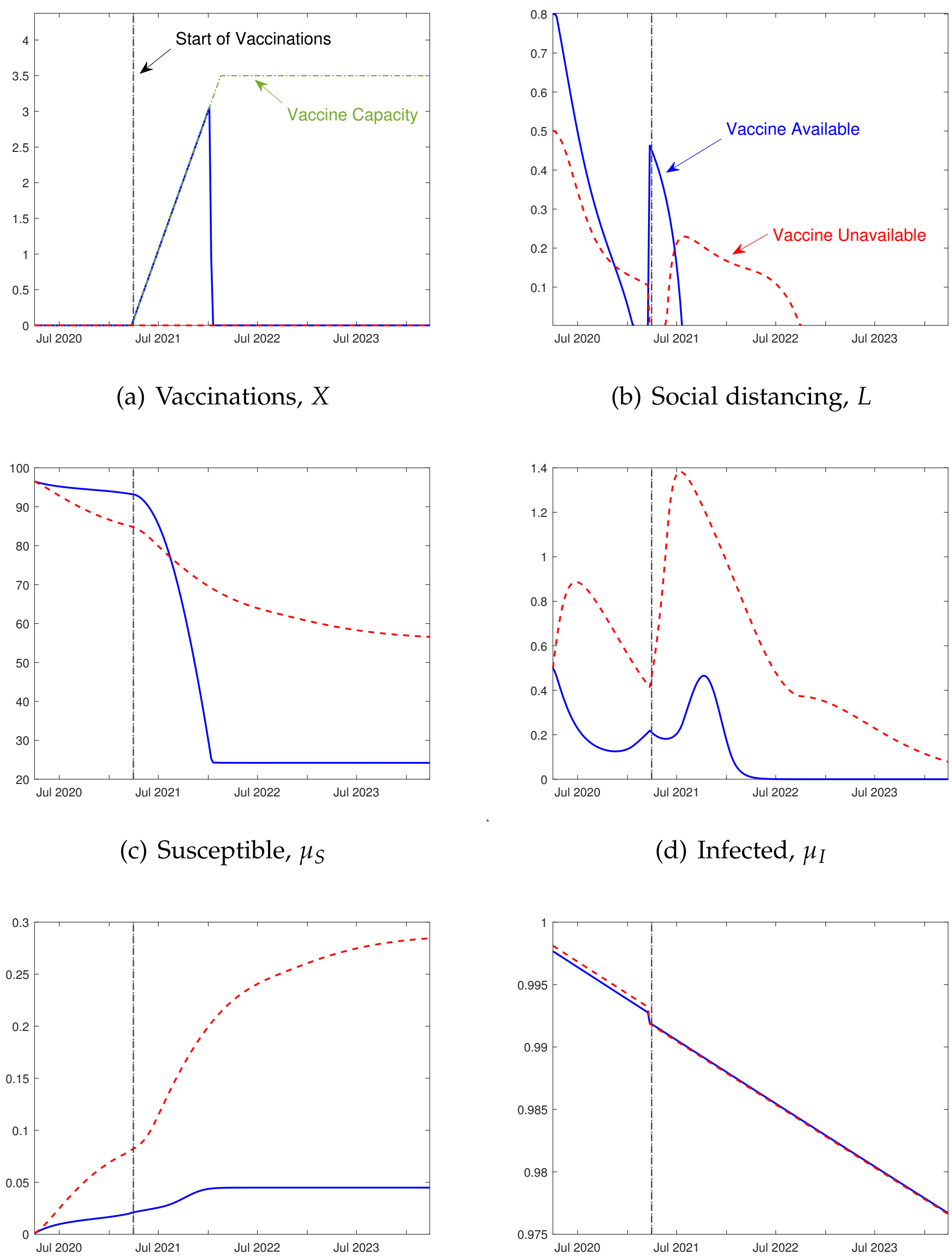
(e) Deceased, μ_D



(f) Consumption, C

Note: Simulated time paths for the economy with vaccination (solid, blue) and without (dashed, red), for the equilibrium of the economy facing constrained financial markets, i.e., a comparison of the baseline parameters with the case of $\overline{X}_t = 0$ for all t.

Figure 5: Perfect Fin Markets: Vaccine Availability



(a) Vaccinations, X

(b) Social distancing, L

(c) Susceptible, μ_S

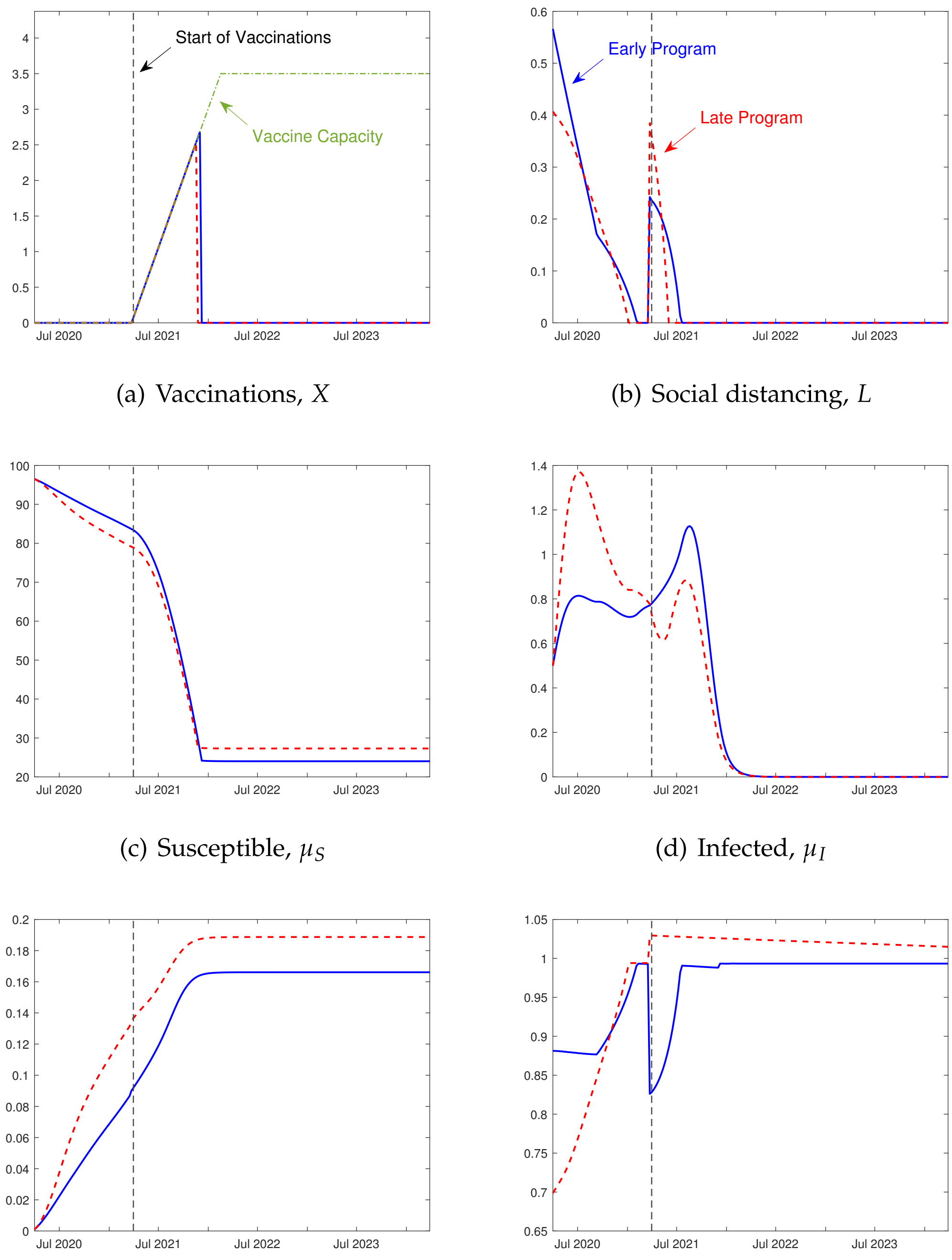
(d) Infected, μ_I

(e) Deceased, μ_D

(f) Consumption, C

Note: Simulated time paths for the economy with vaccination (solid, blue) and without (dashed, red), for the equilibrium of the economy facing perfect financial markets, i.e., a comparison of the baseline parameters with the case of $\overline{X}_t = 0$ for all t.

Figure 6: International Financial Assistance



(a) Vaccinations, X

(b) Social distancing, L

(c) Susceptible, μ_S

(d) Infected, μ_I

(e) Deceased, μ_D

(f) Consumption, C

Note: Simulated time paths for the economy receiving either an early international loan program (solid, blue) or a late program (dashed, red).