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The COVID epidemic and the economic activity with acquired immunity

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Abstract

We calibrate a macroeconomic model with epidemiological restrictions using Colombian data. The key feature of our model is that a portion of the population is immune and cannot transmit the virus, which improves substantially the fit of the model to the observed contagion and economic activity data. The model implies that government restrictions and the endogenous changes in individual behavior saved around 15,000 lives and decreased consumption in 2020 by about 4.7%. The results suggest that most of this effect was the result of the government policies.

Keywords: Colombia, Epidemic, COVID-19, recessions, containment policies, SIR macro model.
JEL Classification: E1, I1, H0

La epidemia de COVID y la actividad económica con inmunidad adquirida

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Resumen

Calibramos un modelo macroeconómico con restricciones epidemiológicas utilizando datos colombianos. La característica clave de nuestro modelo es que una parte de la población es inmune y no puede transmitir el virus, lo cual mejora sustancialmente el ajuste del modelo a los datos de contagio y actividad económica observados. El modelo implica que las restricciones gubernamentales y los cambios endógenos en el comportamiento individual salvaron alrededor de 15,000 vidas y redujeron el consumo en 2020 en aproximadamente un 4.7 %. Los resultados sugieren que la mayor parte de este efecto fue el resultado de las políticas gubernamentales.

Palabras clave: Colombia, epidemia, COVID-19, recesiones, políticas de confinamiento, Modelo macro SIR.
Clasificación JEL: E1, I1, H0

1 Introduction

In this paper we formulate and calibrate a dynamic macroeconomic model in which optimizing agents respond to the risk of contagion and the restrictions imposed by the government during the recent public health crisis. Our model is similar to the model by Eichenbaum et al. (2020) except for the inclusion a modified epidemiological model that incorporates the possibility of exogenous immunity to contagion. We calibrate the model with Colombian data and use it to simulate counterfactual policies.

The original Eichembaum et al. (2020; henceforth ERT) model was the first of a wave of new papers using variations of a simple SIR (Susceptible-Infected-Recovered) epidemiological model to account for the endogenous risk of contagion faced by economic agents. Other papers with similar approaches include Acemoglu et al. (2020); Alvarez et al. (2020); Atkeson (2020); Berger et al. (2020). In these models, both contagion and economic activity are the results of a dynamic programming problem in which agents maximize their intertemporal utility accounting for the risk of contagion over the course of the epidemic.

In the SIR model or its variations (based on seminal work by Kermack and McKendrick (1927)), an epidemic runs its course as it infects individuals who then become immune. The epidemic ends when the population reaches "herd immunity" which occurs when enough people are immune and the virus cannot spread anymore. The main drawback of these models is the difficulty that the models have fitting the observed COVID contagion data. In particular, the standard model predicts very high numbers of both infected and dead people compared to the relatively low numbers observed in the data.

Our main contribution to the understanding of the epidemic is the modification of the SIR model to allow for the presence of individuals who are unaffected by the virus and who become immune immediately after exposure to it. As our results show, the presence of this "immune" population helps fitting the observed data. In particular, the model replicates well the rapid decline of observed deaths after the infection of a relatively low portion of the population.

In contrast with ERT, we calibrate the model in order to match measures of both the epidemic and the economic activity. We follow ERT modeling the government restrictions as a consumption tax, that induces consumers to cut back in their consumption activities, but we can actually calibrate the parameterization of this tax.

The calibrated model predicts that almost all infections in Colombia will have already occurred by December 2020 and that the economy will be back in its long term path by mid-2021. Our simulations suggest that the government restrictions decreased yearly 2020 consumption by around 3% and saved around 10,000 lives. Without government restrictions, the economy would have still faced a 1% contraction, generated by consumers cutting back consumption and labor to avoid contagion.

The paper is organized as follows. In the second section, we describe the model and its calibration. The third section contains the baseline results and counterfactual simulations. The fourth section concludes.

2 The macro-SIOD model

2.1 Description of the model

The model of the epidemic with endogenous contagion

As we indicated above, we follow closely ERT and formulate a model with infinitely lived consumers who choose to allocate time into labor and consumption in order to maximize their lifetime expected utility. Their choices determine both the level of observed economic activity and the probability of contagion.

There are four types of agents in the model, depending on their exposure to the infection: susceptible (S), infected (I), survivor (O) and dead (D). A survivor agent can in turn be immune (M) or recovered (R). Notice that, in contrast to the standard SIR model embedded in ERT, we add the additional immune type (M) which is a type of patient that develops no symptoms and is not infectious.

The existence of this type of "immune" agent is consistent with the increasing evidence of preexisting immunity to the SARS-CoV-2 virus among a significant part of the population (for a review of the evidence see https://www.bmj.com/content/370/bmj.m3563). More broadly, our definition of immunity is consistent with other biological mechanisms that are not well understood yet, the details of which fall beyond the scope of this paper. For example, this "immunity" is equivalent to situations in which individuals become infected but transmit the virus at variable rates (cite https://www.nature.com/articles/d41586-020-02009-w). If some infected individuals do not transmit the virus after infection they are "immune" according to our definition.

Denote T_t as the flow of new infected individuals at time t which depends on the probability that the stock of susceptible agents S_t become infected while interacting with the stock of infected agents I_t during consumption activities, at work, or elsewhere, denoted π_1, π_2 and π_3, respectively:

$$T_t = \pi_1(S_t C_t^S)(I_t C_t^I) + \pi_2(S_t N_t^S)(I_t N_t^I) + \pi_3(S_t I_t), \tag{1}$$

where C_t^k and N_t^k correspond to the consumption and work hours of k-type agents for $k = S, I$.

The stock of infected agents evolves over time depending on (1) as follows:

$$I_{t+1} = I_t(1 - \pi_{dt} - \pi_r) + T_t, \tag{2}$$

where π_{dt} and π_r are the probabilities of death and recovery, conditional on being I. The probability of death changes over time depending on the capacity restrictions of the health system, denoted as λ in the following equation:

$$\pi_{dt} = \pi_d + 1_{\{I_t > \lambda\}} \kappa I_t^2, \tag{3}$$

where the probability increases in a quadratic way when the number of infected individuals surpasses the capacity λ.

The main innovation of our work is the inclusion of a type M of agents who become immune over time without being infected and whose stock evolves as follows:

$$M_{t+1} = M_t + \pi_m S_t, \tag{4}$$

where π_m is the exogenous probability of becoming immune. Notice that we assume that agents become immune over time at a constant rate, probably as a result of their exposure to the virus through their interactions with infected agents. This simplifying assumption recognizes the fact that this immunity is not yet well understood. Notice that setting $M_0 = 0$ and $\pi_m = 0$ yields the standard SIR model, which we can also calibrate as a particular case of our model.

To complete the description of the epidemiological model, the following equations describe the evolution of the stock of agents of type D, R and S:

$$D_{t+1} = D_t + \pi_{dt} I_t, \tag{5}$$

$$R_{t+1} = R_t + \pi_r I_t,$$

$$S_{t+1} = S_t(1 - \pi_m) - T_t,$$

where we asume that the initial stock of susceptible agents is the initial population $S_0 = Pop_0$ and the initial stock of infected agents is nil, $I_0 = \epsilon$.

The economic model

The economic problem of agents is the maximization of their lifetime utility through consumption and work decisions. Their choices determine the total number of hours devoted to consumption C_t and work N_t, which in turn determine the transition across types described above and the endogenous probability of contagion faced by a susceptible agent:

$$\tau_t = \pi_1(c_t^S)(I_t C_t^I) + \pi_2(n_t^S)(I_t N_t^I) + \pi_3(I_t). \tag{6}$$

On the supply side, we assume that there is a continuum of competitive identical firms that use only labor and maximize period-by-period profits:

$$\Pi_t = AN_t - w_t N_t, \tag{7}$$

where A is a productivity parameter, and w_t is the competitive wage. In this closed economy, in equilibrium total production must be equal to total consumption.

At each time t, agents are identified by their infection status $j \in S, I, O$. The problem of each agent j at $t = 0$ is given by:

$$\max_{c,n} U^j = \sum_{t=0}^{\infty} \beta^t u(c_t^j, n_t^j), \tag{8}$$

where

$$u(c_t^j, n_t^j) = \ln c_t^j - \frac{\theta}{2}(n_t^j)^2.$$

The agent faces a budget constraint given by:

$$c_t^j = \phi^j w_t n^j - \mu_t c_t^j + \Gamma_t, \tag{9}$$

where w_t is the hourly wage, μ_t is an exogenous consumption tax rate and Γ_t is a government transfer that does not depend on the type of agent and that balances government finances. The parameter ϕ_t^j is a measure of the work ability of agent j due to infection, with the assumption that $\phi^S = \phi^O = 1$ and $\phi^I \leq 1$.

Thus, the probability of contagion, τ_t, affects the economic decisions of susceptible agents through their lifetime utility up to period t

$$U_t^S = u(c_t^S, n_t^S) + \beta[(1-\tau_t)U_t^S + \tau_t U_t^I]. \tag{10}$$

The tax rate μ_t plays an important role in the model, because it absorbs all the restrictions imposed by the government. Policies like quarantines and limits to the gathering of people are rationalized in the model as a consumption tax. In our application we will use information about the timing of these restrictions to calibrate a path for this parameter over time.

In equilibrium, it must hold that all agents are maximizing their expected lifetime utility, firms maximize profits, the government balances its budget and both labor and goods markets clear:

$$\begin{aligned} S_t C_t^S + I_t C_t^I + O_t C_t^O &= A(S_t N_t^S + I_t N_t^I \phi^o + O_t N_t^O) \\ N_t &= S_t N_t^S + I_t N_t^I \phi^o + O_t N_t^O \end{aligned} \tag{11}$$

2.2 Calibration

We calibrate the model using Colombian data matching the observed path of the COVID epidemic throughout 2020. For any parametrization of the model, it is solved using a backwards induction algorithm which involves finding the optimal sequence of working hours for every type of agent along 250 weeks and then, similarly to ERT, computing the rest of equilibrium sequences using the first order conditions of the model.

We follow closely the criteria in ERT to choose the parameters of the economic model, which we show in Table 1. We then calibrate the parameters $\boldsymbol{\pi} = \{\pi_1, \pi_2, \pi_3, \pi_d, \pi_r, \pi_m\}$ which determine the dynamics of the epidemic. Moreover, we also calibrate the maximum percentage of the population that gets infected, after which there is "herd immunity".

As pointed out, another difference between our model and ERT is the treatment of the tax rate which, as we pointed out, reflects the restrictions imposed by the government to contain the epidemic. We set $\mu_t = \mu$ for $t = 1$ until $t = 19$ which corresponds to August 31 when officially the national lockdown imposed by the government was ended. This policy was in place since March 23 ($t = -4$). For $t \geq 20$ we set $\mu_t = 0.9\mu_{t-1}$, so that restrictions decrease gradually toward zero.

As indicated above, we need to calibrate the parameters $\boldsymbol{\pi}$ and μ. In order to identify $\boldsymbol{\pi}$, we match the number of deaths that are predicted by the model with the observed deaths reported by the Colombian health authorities. We focus on the deaths in order to avoid the problems associated with the underreporting of detected cases.

In order to identify μ we match the weekly consumption predicted by the model to a proxy of economic activity that we observe in real time. Specifically, we use electricity consumption which historically matches roughly the economic cycle, under the understanding that electricity is an input that is used in any type of consumption activity and is difficult to substitute in the short run.

Table 1: Calibrated parameters

Parameter	Value
Calibrated with minimum distance algorithm	
π_1	1.5403×10^{-6}
π_2	1.0014×10^{-5}
π_3	0.9703
π_d	0.0061
π_r	0.7141
π_m	0.0185
μ	0.3783
Calibrated a la ERT	
A	19.2308
θ	0.0015
ϕ^I	0.8000
β	0.9992
κ	1.5000

The model is calibrated over 31 weeks, starting during the 2nd week of April, which is eight weeks after the presumed beginning of the epidemic in Colombia. As occurs almost anywhere, there is very substantial underreporting of contagion, since most infections are asymptomatic. On the other hand, the Colombian health system collects death data with accuracy. Therefore, instead of using reported cases as in ERT, we calibrate the model matching the predicted and the observed weekly deaths. Our proxy of consumption is the gap between observed weekly electricity consumption and a simulated trend estimated from historic data. The electricity consumption is reported by the operator of national electricity transmission network.

Specifically, we minimize the following loss function:

$$\Lambda = \sum_{t=1}^{t=31} \left[\lambda(D_t - \hat{D}_t)^2 + (1-\lambda)(E_t - \hat{E}_t)^2 \right] \tag{12}$$

where D_t and $\hat{D}_t$ are the observed and predicted deaths, respectively; similarly E_t and $\hat{E}_t$ are the realized and predicted electricity consumption gap. The initial time period $t = 1$ corresponds to the 13th week of the year.

As mentioned previously, we use electricity consumption as a proxy to measure economic activity. However, to compute E_t, we need a measure of the average electricity consumption that would have been observed in a scenario without an epidemic. We do so by projecting the trend of electricity consumption implied by the data observed up to March/2020.[1]

As for the weighting scalar, λ, we use a backtesting approach to choose the value which minimizes the average out of sample prediction error.[2]

3 Results

3.1 Baseline

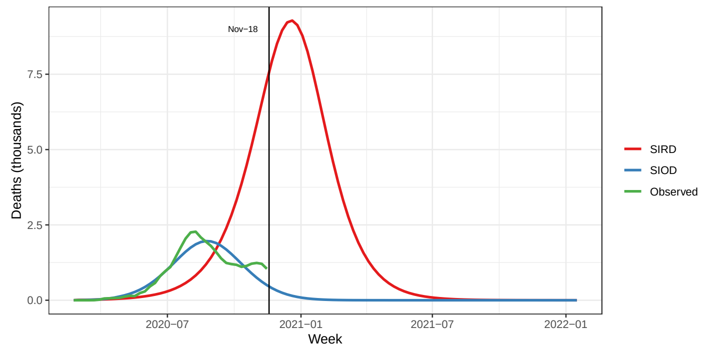
In figures 1 and 2 we show the simulated and observed measures of the epidemics and the economic activity, respectively. The data correspond to the weekly number of COVID related deaths and the weekly gap in electricity consumption. We also show the results of a calibration with no immune individuals ($M_t = 0, \ \forall t$) which is equivalent to the standard macro-SIRD model *a la* ERT.

As shown, the macro-SIOD model is able to predict well the pattern of both variables. Relative to the observed deaths, the model predicts a later peak at a level of around 2,000 weekly deaths which is slightly lower than the observed peak deaths. The number of observed deaths experienced a slight acceleration during the month of September/2020 that the model cannot replicate.

On the other hand, the model predicts well the collapse of economic activity observed during the strict quarantine that was in place during the month of April/2020. The observed recovery afterwards is much bumpier than the prediction of the model. In any

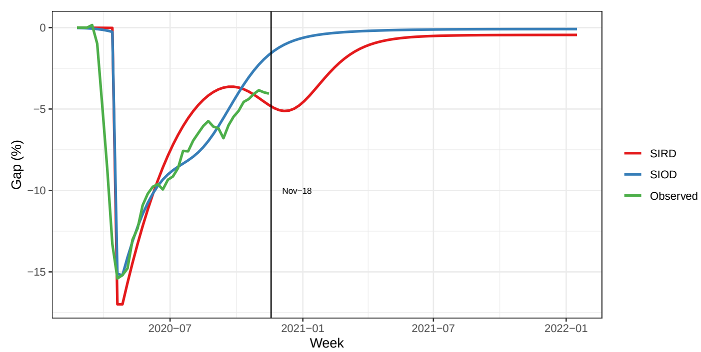
[1]Particularly, we estimate such trend , which can be used as an accurate predictor of such a variable.
[2]After standarizing scales, we find $\lambda = 0.55$.

Figure 1: Simulated against observed deaths



Source: Authors calculations based on data from INS.

Figure 2: Simulated against observed deaths



Source: Authors calculations based on data from INS.

case, the model predicts well the rapid recovery of economic activity, as measured by the electricity consumption gap.

The macro-SIOD model predicts that the COVID epidemics will be mostly over by the beginning of 2021. This prediction is relatively optimistic compared to the standard epidemiological models that have been used to forecast the progress of the epidemics in Colombia. It should also be said that these standard models have consistently predicted much higher deaths than observed. Moreover, currently a substantial portion of the country, which includes big cities on the Pacific and Caribbean coasts, is already experiencing low death rates and low mobility restrictions that are arguably consistent with collective immunity.

On the other hand, the macro-SIOD model predicts that the economic activity will converge to its long run path by mid-2021. The model predicts that consumption falls 4.5% below its long-run level in 2020 and recovers almost fully in 2021. We should note that our calibration is based on electricity consumption which is an imperfect measure of consumption, and economic activity in general. In particular, there are sectors of the economy that might be permanently affected, such as tourism and entertainment activities, that are not intensive in electricity use. It should not be a surprise, then, that the model predicts a full recovery, whereas most probably a portion of the economy is going to be underperforming for a long while.

In contrast with our macro-SIOD model, the calibrated macro-SIRD model has more difficulties matching the data. As shown in Figure 1, this model predicts a much later and higher peak in weekly deaths than what we observe in the data. The model predicts a total of almost 200,000 deaths, whereas the preferred macro-SIOD model predicts no more than 36,000 deaths. A common feature of the standard epidemiological models to predict a much higher than observed number of deaths.

As shown in Figure 2, the macro-SIRD model has also difficulties predicting the path of economic activity. The model replicates well the initial dip of consumption, but then shows a second dip in early 2021. In this model, the second dip is a result of the relaxation of the government restrictions which increase substantially the risk of contagion, which in turn induces consumers to reduce consumption and labor. The contrast between the calibrated SIRD and SIOD models suggest that the addition of immune/non-contagious agents allows the model to replicate the data much better than the standard model.

We should say a word about the shortcomings of our preferred macro-SIOD model. As pointed out above, the epidemiological predictions are optimistic, in the sense that the predicted deaths are relatively low and the epidemics disappears rapidly by the beginning of 2021. We believe that the main reason for this is the fact that there is a portion of the population that is exogenously being kept isolated (e.g. children, college students) and that is gradually coming back into interaction with other people.

In the analysis that follows we will use the preferred macro-SIOD model to evaluate counterfactual scenarios.

3.2 Counterfactual analysis: the impact of government restrictions and individual choices

We will use the calibrated macro-SIOD model to evaluate the impact of the imposed government measures and individual self-regulation on the epidemics and the performance of the economy. Specifically, we simulate the model assuming that there are no government restrictions, and under the assumption that individuals do not account for the contagion risk when consuming or working. We call this last assumption "suboptimal consumption". We perform three counterfactual simulations under combinations of these counterfactual assumptions.

More specifically, each counterfactual simulation can be described as follows:

1. No government restrictions & suboptimal consumption: $\mu_t = 0$, and consumers ignoring the additional risk of contagion associated with c_t and n_t. This simulation assesses the joint effect of government restrictions and individual behavior. It provides an upper bound on deaths relative to the baseline model.

2. No government restrictions & optimal consumption decisions: $\mu_t = 0$. In other words, there are no limits to consumption activities and therefore individuals freely maximize their welfare accounting for the risk of contagion.

3. Observed government restrictions & suboptimal consumption: individuals ignore the additional risk of contagion associated with c_t and n_t.

We describe each simulation below. A common feature of all the simulations is that they all predict that the epidemics will be over in early 2021. As pointed out above, this is an optimistic forecast that is very robust in the model.

We should also reiterate that our consumption calculations are based on the use of electricity which is not a precise measure of total consumption. In particular, activities intensive in personal interactions, such as restaurants and entertainment, are less intensive in electricity use than the production and consumption of, for example, manufactured goods. Therefore, the demand for electricity has shown a faster recovery than the overall economy and our models predict a fast recovery as well and full convergence to the long run equilibrium path by the middle of 2021.

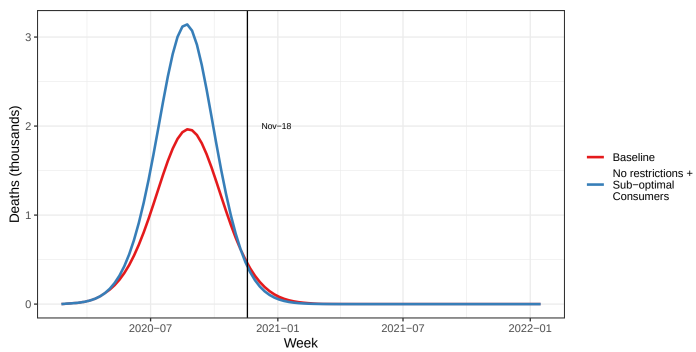
The impact of both government restrictions and individual behavior

We first simulate the model, assuming that there were no restrictions, setting $\mu_t = 0,\ \forall t$, and assuming that consumers perceive the probabilities of contagion in (6) not to be related to consumption and labor activities, i.e. individuals believe $\pi_1 = \pi_2 = 0$ in (6).

In this this fully unrestricted model, individuals behave as if the epidemics follows the standard epidemiological model that assumes an exogenous probability of contagion. Nevertheless, the actual probability of contagion in (1) is still affected by the behavior of individuals. Under our assumption, individuals are irrational in the sense that they believe that contagion risk is exogenous and given solely by π_3. Therefore, in this model the effect of the epidemics on economic activity is very low and driven only by the number of individuals who die, which is a small share of total population.

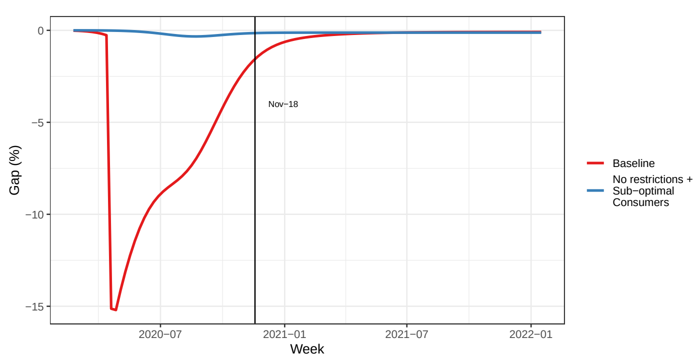
The results of the simulation are shown in figures 3 and 4. The predicted number of deaths in this simulation is 50,506 which is almost 42% higher than in the baseline. Recall that this number of deaths is what would result if the government had imposed no restrictions and individuals would not have changed their behavior endogenously. In that sense, this figure is the upper bound in the number of deaths according to the calibrated model.

Figure 3: Simulated deaths: baseline vs. no restrictions and suboptimal consumption.



Source: Model's predictions.

Figure 4: Simulated consumption gap: baseline vs. no restrictions and sub-optimal consumers.



Source: Authors calculations based on data from XM.

Notice that the consumption path is almost constant, which is a reflection of the fact that behavior is not affected by the epidemics in this simulation.[3] The baseline

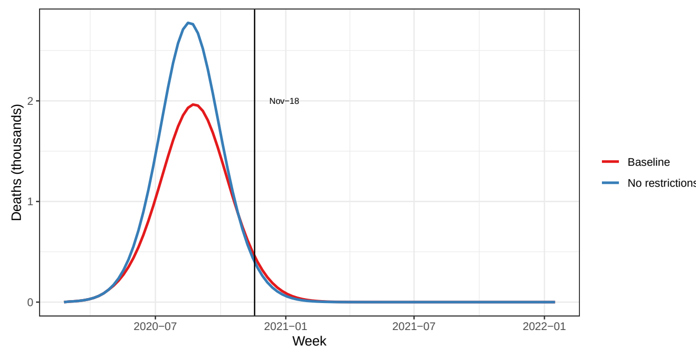
[3] It is worth noting that the slight drop in consumption of this counterfactual is due to the lower

consumption in 2020 is 4.7% lower than this unrestricted consumption level. This figure is a rough estimate of the economic cost of the epidemic in the model.

The role of government restrictions

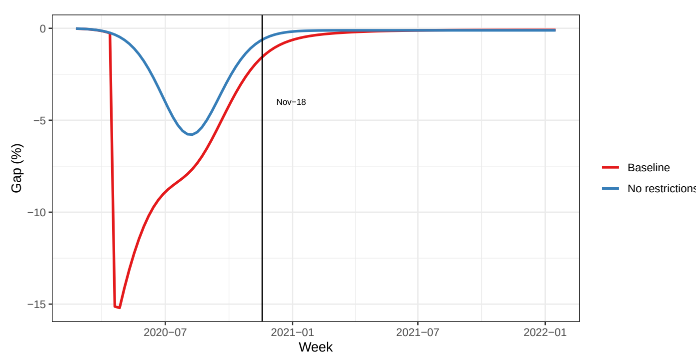
We now simulate the model, assuming that there were no restrictions, but individuals fully account for the effects of their behavior on the risk of contagion. In other words, we set $\mu_t = 0$, $\forall t$ and keep the remaining parameters of the model as in the baseline simulation. The results of this simulation are shown in figures 5 and 6.

Figure 5: Simulated deaths: baseline vs. no restrictions and fully optimal consumers.



Source: Model's predictions.

Figure 6: Simulated consumption gap: baseline vs. no restrictions and fully optimal consumers.



Source: Authors calculations based on data from XM.

As shown in Figure 5 and as expected, the imposed quarantine did have a substantial effect on the number of deaths. Without the restrictions, the model predicts a total of

productivity faced by infected workers, which directly affects consumption in the equilibrium.

45,654 deaths by the end of the epidemics. The model implies that the excess deaths would have occurred mostly around the peak. The restrictions delayed the peak for several weeks and decreased its level by around 1,000 deaths per week.

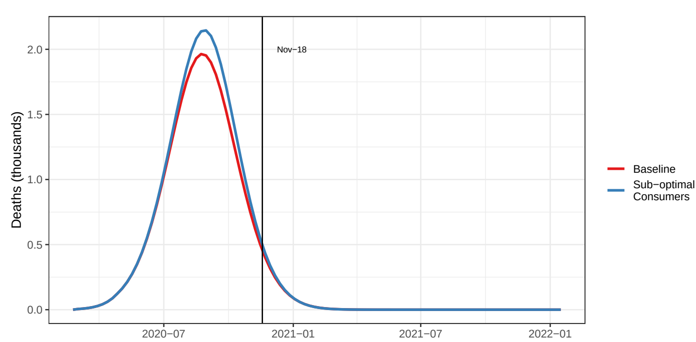
As shown in figure 6, the model without government restrictions shows a much smaller dip in consumption than observed, which coincides in time with the predicted peak in deaths. In the model, this decrease in consumption is a result of consumers' efforts to avoid contagion. In other words, the restrictions had an immediate and substantial effect on economic activity.

The role of individual behavior

Finally, we isolate the impact on contagion and economic activity of the efforts of individuals to self-regulate their behavior. We fix the government restrictions as in the baseline calibration, but set the perceived probabilities of contagion in (6) equal to zero, i.e. $\pi_1 = \pi_2 = 0$. As explained above, in this model individuals believe that contagion risk is given by π_3. Since contagion is perceived to be unaffected by behavior, the simulated dip in consumption is entirely a result of the government restrictions.

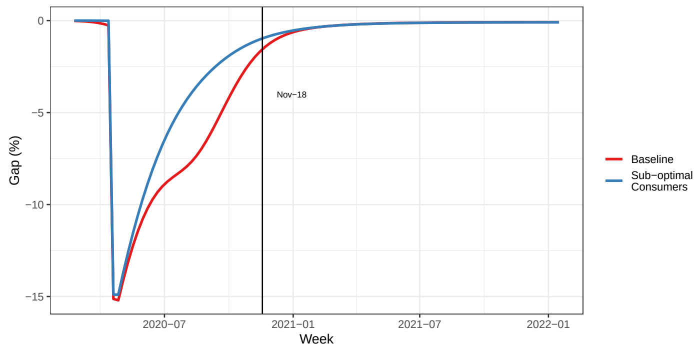
We show the results of this simulation in Figure 7 and Figure 8. As shown, there are around 2,800 more deaths in this scenario than in the baseline simulation. Compared with the results of the previous simulation, the model suggests that individual self-regulation had less an effect on deaths than the government restrictions. The effect on economic activity is an increase of around 1.4% relative to the 2020 baseline value. In other words, the change in individual behavior explains a relatively small portion of the decrease in economic activity.

Figure 7: Simulated deaths: baseline vs. sub-optimal consumers with restrictions.



Source: Model's predictions.

Figure 8: Simulated consumption gap: baseline vs. sub-optimal consumers with restrictions.



Source: Authors calculations based on data from XM.

We show a summary of the results of these simulations in Table 2. We show consumption and deaths in 2020 and 2021 for the baseline and each simulation. As pointed out above, without government restrictions and the behavioral response of individuals, the total number of deaths would have been 50,506 which is 42% higher than in the baseline simulation. Consumption in 2020 would have been 4.7% higher than in the baseline simulation, and would have grown less than 1% in 2021. These figures are a measure of the total cost of the epidemics, in terms of both deaths and economic activity.

Without government restrictions, the behavioral response of individuals would have resulted in 45,458 deaths. Therefore, the government restrictions saved 10,060 lives, which is 28% of the baseline deaths. In this scenario, consumption would have been 3% higher in 2020 and then would have fully recovered in 2021.

The role of the behavioral response of individuals is more limited. Without the rational response of individuals to the risk of contagion, the number of deaths would have been 38,458, which is 2,864 more than in the baseline simulation. Therefore, the behavioral response of individuals saved 8% of deaths, relative to the baseline. In this scenario, 2020 consumption would have been only 1.4% higher than in the baseline simulation, and then would almost fully recover in 2021.

These results imply that the combination of policy and individual behavior saved around 42% of baseline deaths, with an economic cost of around 4.7% of consumption in the year 2020. The simulations imply that the government restrictions had a bigger impact than the endogenous changes in individual behavior.

Table 2: Summary results of simulated scenarios

Baseline	
- Deaths up to a Dic-2020:	35,311
- Deaths up to a Jun-2021:	35,594
- Deaths total:	35,594
- Consumption 2020 (trillions COP):	979.6
- Consumption 2021 (trillions COP):	1,027.3
No restrictions & sub-optimal consumers	
- Deaths up to a Dic-2020:	50,323
- Deaths up to a Jun-2021:	50,506
- Deaths total:	50,506
- Consumption 2020 (trillions COP):	1,027.9
- Consumption 2021 (trillions COP):	1,027.9
No government restrictions	
- Deaths up to a Dic-2020:	45,458
- Deaths up to a Jun-2021:	45,654
- Deaths total:	45,654
- Consumption 2020 (trillions COP):	1,009.6
- Consumption 2021 (trillions COP):	1,027.9
Sub-optimal consumers	
- Deaths up to a Dic-2020:	38,172
- Deaths up to a Jun-2021:	38,458
- Deaths total:	38,458
- Consumption 2020 (trillions COP):	993.2
- Consumption 2021 (trillions COP):	1,027.3

4 Concluding remarks

We have calibrated a model of economic behavior during the COVID epidemic, applied to the Colombian economy. Our model incorporates an "immune" type of agent that helps fitting the data better than the standard epidemiological models. In the model, the epidemic falls rapidly and disappears during early 2021. Consumption falls substantially during 2020 but recovers fully by mid-2021.

The model implies that government restrictions and consumers' self regulation helped averting around 15,000 deaths, or around 42% of baseline deaths. Government restrictions account for more than 67% of this effect. The model predicts a very rapid suppression of the epidemic, which is the result of its simplifying assumptions. In particular, the model lacks agents who return gradually to interaction with other agents, and who don't respond to economic incentives.

Another simplifying assumption of the model is that some agents are "immune" and implies that some individuals become fully infectious after contagion, while others are not contagious at all. This is an extreme version of a model in which virus transmission rates are heterogeneous. Incorporating heterogeneity in both behavior and biology along these lines would enrich the model and is left for future research.

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