Globalization and Pandemics

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Online Appendix (Not for Publication)

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A Introduction

In this Online Appendix, we report additional theoretical results, the proofs of propositions, and further empirical evidence, as discussed in the main paper.

In Section B, we report additional theoretical derivations for our baseline economic model from Section 3 of the paper.

In Section C, we develop a number of extensions of our baseline theoretical specification in the paper, as discussed in Section 3 of the paper. In Section C.1 we work out extensions of our framework in which households have access to two alternative technologies for procuring consumption goods, one involving travel, and the other one involving importing goods remotely. In Section C.2 we develop a dynamic version of our framework in which face-to-face interactions are only necessary to initiate a commercial link between a buyer and a seller.

In Section C.3, we develop a multi-sector version of the model in which the number of international face-to-face interactions varies across sectors, and is shaped by trade costs, mobility costs, and also the relative advantage of in-person versus remote interactions. In Section C.4, we derive our key equilibrium conditions for a world economy with multiple countries, including in the case of a continuum of locations. In Section C.5 we show that the predictions of our baseline model continue to hold if travel costs in equation (1) in the paper are specified in terms of labor rather than being modelled as a utility cost. In Section C.6, we also show that it is straightforward to re-interpret the differentiated varieties produced by households as intermediate inputs, which all households combine into a non-traded homogeneous final good.

We next explore two alternative environments with a distinct market structure from the one in our baseline model. Instead of our Armington framework in which goods are differentiated at the household level, Section C.7 considers an environment à la Eaton and Kortum (2002), in which the measure of final good varieties is fixed at one, and all households worldwide compete to be the least-cost supplier of those goods to other households. In Section C.8, we explore a final variant of our model featuring scale economies, monopolistic competition and fixed costs of exporting, as in the literature on selection into exporting emanating from the seminal work of Melitz (2003).

In Section D, we provide additional theoretical results for our baseline open-economy SIR model from Section 4 of the paper. In Section E, we report further derivations for our generalization of our open-economy SIR model with general equilibrium social distancing from Section 5 of the paper. In Section F, we present additional theoretical results for our generalization of our open-economy SIR model with behavioral responses from Section 6 of the paper.

In Section G, we provide empirical support for the relationship between disease diffusion and globalization in our model. In Subsection G.1, we report econometric estimates of this relationship using data on (i) the Black Death during the 14th century; (ii) the 1957 flu pandemic; (iii) the Covid-19 pandemic. In a robustness test, we also report empirical results for the 1967 flu pandemic, for which less data are available. We omit the 1918 flu because it predates the foundation of the World Health Organization (WHO) from which our data are obtained, and because the geographic diffusion of the 1918 flu pandemic was heavily influenced by troop movements in the closing stages of the First World War, as discussed in Vaughan (1921). In Subsection G.2, we review the wider economic and epidemiological evidence that provides support for this relationship between disease diffusion and globalization.

In Section H, we provide empirical support for the relationship between trade and business travel in our model. In Subsection H.1, we report econometric estimates of this relationship using panel data on bilateral passenger flows, bilateral trade and bilateral tariffs. In Subsection H.2, we review the wider economic literature that provides support for this relationship between trade and business travel.

In Section I, we provide theoretical and empirical support for our assumption that domestic interactions and foreign interactions are substitutes for one another, in the sense that a reduction in international trade costs leads to an increase in foreign interactions relative to domestic interactions. First, we show that this substitutability is a generic property of a constant elasticity gravity model of spatial interactions. Second, we provide empirical evidence that such a constant elasticity gravity model provides a good approximation to observed data on international travel. Third, we review evidence of substitutability from empirical studies of spatial interactions that have directly estimated the substitutability between domestic and foreign locations.

In Section J, we provide evidence on the evolution of the trade to output ratio over the course of the COVID-19 pandemic.

In Section K, we describe the choice of parameter values and the algorithms that we use for the numerical simulations in each section of the paper. In Section L, we provide further details on the data sources and definitions.

B Theoretical Appendix for Economic Model

In this section, we report additional theoretical derivations for our baseline economic model from Section 3 of the paper.

B.1 Second-Order Conditions for Choice of n_{ij}

From equation (6) in the main text, we obtain, for all $j \in \mathcal{J}$,

$$\begin{aligned}
\frac{\partial W(i)}{\partial n_{ij}} &= \frac{w_i}{(\sigma-1)}\left(\sum\nolimits_{j\in\mathcal{J}} n_{ij}\left(\frac{\tau_{ij}w_j}{Z_j}\right)^{1-\sigma}\right)^{\frac{1}{(\sigma-1)}-1}\left(\frac{\tau_{ij}w_j}{Z_j}\right)^{1-\sigma} - c\mu_{ij}\left(d_{ij}\right)^{\rho}\left(n_{ij}\right)^{\phi-1}\;; \\
\frac{\partial W(i)}{\partial\left(n_{ij}\right)^2} &= \frac{w_i}{(\sigma-1)}\left(\frac{2-\sigma}{\sigma-1}\right)\left(\sum\nolimits_{j\in\mathcal{J}} n_{ij}\left(\frac{\tau_{ij}w_j}{Z_j}\right)^{1-\sigma}\right)^{\frac{1}{(\sigma-1)}-2}\left(\frac{\tau_{ij}w_j}{Z_j}\right)^{1-\sigma}\left(\frac{\tau_{ij}w_j}{Z_j}\right)^{1-\sigma} \\
&\quad -(\phi-1)\,c\mu_{ij}\left(d_{ij}\right)^{\rho}\left(n_{ij}\right)^{\phi-2} \\
&= \left(\frac{2-\sigma}{\sigma-1}\right)\left(\sum\nolimits_{j\in\mathcal{J}} n_{ij}\left(\frac{\tau_{ij}w_j}{Z_j}\right)^{1-\sigma}\right)^{-1}\left(\frac{\tau_{ij}w_j}{Z_j}\right)^{1-\sigma} c\mu_{ij}\left(d_{ij}\right)^{\rho}\left(n_{ij}\right)^{\phi-1} \\
&\quad -(\phi-1)\,c\mu_{ij}\left(d_{ij}\right)^{\rho}\left(n_{ij}\right)^{\phi-2} \\
&= c\mu_{ij}\left(d_{ij}\right)^{\rho}\left(n_{ij}\right)^{\phi-2}\left[\left(\frac{1}{(\sigma-1)}-1\right)\left(\frac{n_{ij}\frac{\tau_{ij}w_j}{Z_j}}{\sum_{j\in\mathcal{J}} n_{ij}\left(\frac{\tau_{ij}w_j}{Z_j}\right)^{1-\sigma}}\right)^{1-\sigma}-(\phi-1)\right]; \\
\frac{\partial^2 W(i)}{\partial n_{ij}\partial n_{ii}} &= \frac{w_i}{(\sigma-1)}\left(\frac{2-\sigma}{\sigma-1}\right)\left(\sum\nolimits_{j\in\mathcal{J}} n_{ij}\left(\frac{\tau_{ij}w_j}{Z_j}\right)^{1-\sigma}\right)^{\frac{1}{(\sigma-1)}-2}\left(\frac{\tau_{ij}w_j}{Z_j}\right)^{1-\sigma}\left(\frac{\tau_{ii}w_i}{Z_i}\right)^{1-\sigma}.
\end{aligned}$$

Notice that $\frac{\partial W(i)}{\partial(n_{ij})^2} < 0$ if only if:

$$\left(\frac{2-\sigma}{\sigma-1}\right)\left(\frac{n_{ij}\frac{\tau_{ij}w_j}{Z_j}}{\sum_{j\in\mathcal{J}} n_{ij}\left(\frac{\tau_{ij}w_j}{Z_j}\right)^{1-\sigma}}\right)^{1-\sigma} < (\phi-1)\,,$$

so this condition could be violated for large enough τ_{ij}, unless $\sigma > 2$, in which case the condition is surely satisfied as long as $\phi(\sigma-1) > 1$.

Next, note that

$$\left(\frac{\partial^2 W(i)}{\partial n_{ij}\partial n_{ii}}\right)^2 = \left(\frac{w_i}{\sigma-1}\frac{2-\sigma}{\sigma-1}\left(\sum\nolimits_{j\in\mathcal{J}} n_{ij}\left(\frac{\tau_{ij}w_j}{Z_j}\right)^{1-\sigma}\right)^{\frac{1}{(\sigma-1)}-2}\left(\frac{\tau_{ij}w_j}{Z_j}\right)^{1-\sigma}\left(\frac{\tau_{ii}w_i}{Z_i}\right)^{1-\sigma}\right)^2 = \Xi^2$$

and

$$
\begin{aligned}
\frac{\partial W(i)}{\partial (n_{ii})^2}\frac{\partial W(i)}{\partial (n_{ij})^2} &= \left(\begin{array}{c} \frac{1}{(\sigma-1)}\frac{2-\sigma}{\sigma-1}w_i\left(\sum_{j\in\mathcal{J}} n_{ij}\left(\frac{\tau_{ij}w_j}{Z_j}\right)^{1-\sigma}\right)^{\frac{1}{(\sigma-1)}-2}\left(\frac{\tau_{ii}w_i}{Z_i}\right)^{1-\sigma}\left(\frac{\tau_{ii}w_i}{Z_i}\right)^{1-\sigma} \\ -(\phi-1)\,c\mu_{ii}\,(d_{ii})^{\rho}\,(n_{ii})^{\phi-2} \end{array}\right) \\
&\quad \left(\begin{array}{c} \frac{1}{(\sigma-1)}\frac{2-\sigma}{\sigma-1}w_i\left(\sum_{j\in\mathcal{J}} n_{ij}\left(\frac{\tau_{ij}w_j}{Z_j}\right)^{1-\sigma}\right)^{\frac{1}{(\sigma-1)}-2}\left(\frac{\tau_{ij}w_j}{Z_j}\right)^{1-\sigma}\left(\frac{\tau_{ij}w_j}{Z_j}\right)^{1-\sigma} \\ -(\phi-1)\,c\mu_{ij}\,(d_{ij})^{\rho}\,(n_{ij})^{\phi-2} \end{array}\right) \\
&= \Xi^2-\chi_{ij}^{i}-\chi_{ij}^{j}+\varpi_{ij},
\end{aligned}
$$

where $\chi_{ij}^{i}<0$ and $\chi_{ij}^{j}<0$, and $\varpi_{ij}>0$, whenever $\sigma>2$ and $\phi>1$.

In sum, when $\sigma>2$ and $\phi(\sigma-1)>0$, we have

$$
\frac{\partial W(i)}{\partial (n_{ii})^2}\frac{\partial W(i)}{\partial (n_{ij})^2} > \left(\frac{\partial^2 W(i)}{\partial n_{ij}\partial n_{ii}}\right)^2,
$$

and the second-order conditions are met.

B.2 Price Index and Welfare

In this subsection, we solve for the price index and household welfare in each country. Working with equations (4)-(7) in the main text and the budget constraint, and simplifying delivers

$$
P_i = \left(\frac{w_i}{c(\sigma-1)}\right)^{-\frac{1}{\phi(\sigma-1)-1}}\left(\sum_{j\in\mathcal{J}}(\Upsilon_{ij})^{-\varepsilon}(w_j/Z_j)^{-\frac{(\sigma-1)\phi}{\phi-1}}\right)^{-\frac{(\phi-1)}{\phi(\sigma-1)-1}}. \tag{B.1}
$$

Going back to the expression for welfare in (2), and plugging (7) and (B.1), we then find

$$
W_i = \frac{\phi(\sigma-1)-1}{\phi(\sigma-1)}\frac{w_i}{P_i}, \tag{B.2}
$$

which combined with (9) implies that aggregate welfare is given by

$$
W_iL_i = \frac{\phi(\sigma-1)-1}{\phi(\sigma-1)}(\pi_{ii})^{-\frac{(\phi-1)}{\phi(\sigma-1)-1}}\left(\frac{(Z_i)^{\phi(\sigma-1)}}{c(\sigma-1)}(\Upsilon_{ii})^{-\varepsilon(\phi-1)}\right)^{\frac{1}{\phi(\sigma-1)-1}}L_i. \tag{B.3}
$$

This formula is a variant of the Arkolakis et al. (2012) welfare formula indicating that, with estimates of ϕ and σ at hand, one could compute the change in welfare associated with a shift to autarky only with information on the domestic trade share π_{ii}. A key difference relative to their contribution is that the combination of ϕ and σ relevant for welfare cannot easily be backed out from estimation of a 'trade elasticity' (see equation (10) in the main text). When we allow trade to affect the transmission of disease and this disease to affect mortality, a further difference will be that the effect of trade on aggregate welfare will also depend on its effect on mortality (via changes in L_i).

B.3 Existence and Uniqueness

Note that the general-equilibrium condition in (11) in the paper is identical to that obtained in standard gravity models. Therefore, from the results in Alvarez and Lucas (2007), Allen and Arkolakis (2014), or Allen et al. (2020), we obtain:

Proposition B.1 *As long as trade frictions Υ_{ij} are bounded, there exists a unique vector of equilibrium wages $\mathbf{w}^* = (w_i, w_j) \in \mathbb{R}^2_{++}$ that solves the system of equations in (11).*

Recall that in Alvarez and Lucas (2007), uniqueness requires some additional (mild) assumptions due to the existence of an intermediate-input sector. However, since our model features no intermediate inputs, we just need to assume that trade frictions remain bounded.

Using the implicit-function theorem, it is also straightforward to see that the relative wage w_j/w_i will be increasing in L_i, Υ_{ii}, Υ_{ji}, and Z_j, while it will be decreasing in L_j, Υ_{jj}, Υ_{ij}, and Z_i.

B.4 Comparative Statics for Bilateral Interactions

We now establish the comparative statics of bilateral interactions with respect to international trade or travel frictions.

Proposition B.2 *A decline in any international trade or travel friction $(d_{ij}, t_{ij}, t_{ji}, \mu_{ij}, \mu_{ji})$ leads to: (a) a decline in the rates (n_{ii} and n_{jj}) at which individuals will meet individuals in their own country; and (b) an increase in the rates at which individuals will meet individuals from the other country (n_{ij} and n_{ji}).*

Proof of part a):

From equation (7) in the main text, we can write

$$n_{ii}(\mathbf{w}) = (c(\sigma-1)\mu_{ii})^{-1/(\phi-1)} (d_{ii})^{-\frac{\rho+(\sigma-1)\delta}{\phi-1}} \left(\frac{t_{ii}}{Z_i}\right)^{-\frac{\sigma-1}{(\phi-1)}} \left(\frac{w_i}{P_i}\right)^{-\frac{\sigma-2}{\phi-1}},$$

but remember from (B.3) that

$$\frac{w_i}{P_i} = (\pi_{ii})^{-\frac{(\phi-1)}{\phi(\sigma-1)-1}} \left(\frac{(Z_i)^{\phi(\sigma-1)}}{c(\sigma-1)} (\Upsilon_{ii})^{-\varepsilon(\phi-1)}\right)^{\frac{1}{\phi(\sigma-1)-1}}.$$

This implies that, in order to study the effect of international trade frictions on $n_{ii}(\mathbf{w})$, it suffices to study their effect on π_{ii}, with the dependence of n_{ii} on π_{ii} being monotonically positive. Now from

$$\pi_{ii} = \frac{(w_i/Z_i)^{-\frac{\phi(\sigma-1)}{\phi-1}} (\Upsilon_{ii})^{-\varepsilon}}{\sum_{\ell\in\mathcal{J}} (w_\ell/Z_\ell)^{-\frac{\phi(\sigma-1)}{\phi-1}} (\Upsilon_{i\ell})^{-\varepsilon}},$$

it is clear that the *direct* effect (holding w_i constant) of a lower $\Upsilon_{i\ell}$ is to decrease π_{ii} and thus to decrease n_{ii}. To take into account general-equilibrium forces, we can write equation (11) in the main text as

$$\frac{(Z_i)^{\frac{\phi(\sigma-1)}{\phi-1}}(\Upsilon_{ii})^{-\varepsilon}}{(Z_i)^{\frac{\phi(\sigma-1)}{\phi-1}}(\Upsilon_{ii})^{-\varepsilon}+(Z_j/\omega)^{\frac{\phi(\sigma-1)}{\phi-1}}(\Upsilon_{ij})^{-\varepsilon}}L_i+\frac{(Z_i)^{\frac{\phi(\sigma-1)}{\phi-1}}(\Upsilon_{ji})^{-\varepsilon}}{(Z_j/\omega)^{\frac{\phi(\sigma-1)}{\phi-1}}(\Upsilon_{jj})^{-\varepsilon}+(Z_i)^{\frac{\phi(\sigma-1)}{\phi-1}}(\Upsilon_{ji})^{-\varepsilon}}\omega L_j=L_i, \tag{B.4}$$

where $\omega \equiv 1/w_i$ is the relative wage in country j. From this equation, it is easy to see that if Υ_{ij} falls, ω cannot possibly decrease. If it did, both terms in the left-hand side of (B.4) would fall. But if ω goes up, then the second term in (B.4) must increase, which implies that the first term (i.e., π_{ii}) must decrease. In sum, a decrease in Υ_{ij} necessarily leads to a decline in n_{ii}.

Consider now a decline in Υ_{ji}. From equation (7) in the main text, equation (B.3) and the expression for π_{ii} above, we see that the effect will work only via relative wages. Turning to equation (B.4), note that π_{ji} increases on impact when Υ_{ji} falls, so ω needs to decrease to re-equilibrate the labor market, which leads to a decline in π_{ii}, and thus in n_{ii}.

Because the results above hold for Υ_{ij} and Υ_{ji}, they must hold for any of the constituents of those composite parameters.

Proof of part b):

Note from equation (2) in the paper and equation (B.2) that

$$\frac{c}{\phi}\sum\nolimits_{j\in\mathcal{J}}\mu_{ij}\left(d_{ij}\right)^{\rho}\left(n_{ij}\right)^{\phi}=\frac{1}{\phi\left(\sigma-1\right)}\frac{w_i}{P_i}.$$

In part a) of the proof, we have established that when any international trade friction decreases, π_{ii} goes down, and from (B.3), w_i/P_i goes up. Thus, $\mu_{ii}\left(d_{ii}\right)^{\rho}\left(n_{ii}\right)^{\phi}+\mu_{ij}\left(d_{ij}\right)^{\rho}\left(n_{ij}\right)^{\phi}$ goes up when any international trade friction decreases. But because n_{ii} goes down, and μ_{ij} and d_{ij} (weakly) go down, it must be the case that n_{ij} increases.

B.5 Comparative Statics for Overall Interactions

We now establish the comparative statics of the overall number of interactions with respect to international trade or travel frictions.

Proposition B.3 *Suppose that countries are symmetric, in the sense that $L_i = L$, $Z_i = Z$, and $\Upsilon_{ij} = \Upsilon$ for all i. Then, a decline in any (symmetric) international trade frictions leads to an overall increase in human interactions (n_{ii}+n_{ij}) experienced by both household buyers and household sellers.*

We begin by considering the case with general country asymmetries. Consider the sum

$$\mu_{ii}\left(d_{ii}\right)^{\rho}\left(n_{ii}\right)^{\phi}+\mu_{ij}\left(d_{ij}\right)^{\rho}\left(n_{ij}\right)^{\phi}.$$

Differentiating:

$$\phi\left[\mu_{ii}\left(d_{ii}\right)^{\rho}\left(n_{ii}\right)^{\phi-1}\underbrace{dn_{ii}}_{<0}+\mu_{ij}\left(d_{ij}\right)^{\rho}\left(n_{ij}\right)^{\phi-1}dn_{ij}\right]+\underbrace{d\left(\mu_{ij}\left(d_{ij}\right)^{\rho}\right)}_{\leq 0}\left(n_{ij}\right)^{\phi}>0, \tag{B.5}$$

where the inequalities follow from ours result in Proposition 2.

Clearly, we must have

$$\mu_{ii}\left(d_{ii}\right)^{\rho}\left(n_{ii}\right)^{\phi-1}dn_{ii}+\mu_{ij}\left(d_{ij}\right)^{\rho}\left(n_{ij}\right)^{\phi-1}dn_{ij}>0.$$

So if

$$\mu_{ii}\left(d_{ii}\right)^{\rho}\left(n_{ii}\right)^{\phi-1}>\mu_{ij}\left(d_{ij}\right)^{\rho}\left(n_{ij}\right)^{\phi-1},$$

we must have

$$dn_{ij}>-dn_{ii},$$

which would prove the Proposition.

Now, from the FOC for the choice of n_{ii} and n_{ij} in equation (7), we have

$$\begin{aligned}\mu_{ii}\left(d_{ii}\right)^{\rho}\left(n_{ii}\right)^{\phi-1} &= \left(\frac{w_i}{P_i}\right)^{1/(\phi-1)}\frac{\left(P_i\right)^{\frac{\sigma-1}{(\phi-1)}}}{\left(\sigma-1\right)c}\left(\frac{\left(d_{ii}\right)^{\delta}t_{ii}w_i}{Z_i}\right)^{-\frac{\sigma-1}{(\phi-1)}}\\ \mu_{ij}\left(d_{ij}\right)^{\rho}\left(n_{ij}\right)^{\phi-1} &= \left(\frac{w_i}{P_i}\right)^{1/(\phi-1)}\frac{\left(P_i\right)^{\frac{\sigma-1}{(\phi-1)}}}{\left(\sigma-1\right)c}\left(\frac{\left(d_{ij}\right)^{\delta}t_{ij}w_j}{Z_j}\right)^{-\frac{\sigma-1}{(\phi-1)}},\end{aligned}$$

so a sufficient condition for the result is

$$\frac{\left(d_{ii}\right)^{\delta}t_{ii}w_i}{Z_i}<\frac{\left(d_{ij}\right)^{\delta}t_{ij}w_j}{Z_j}.$$

This condition is implied by prices for domestic varieties being lower than prices for foreign varieties. This makes sense since, for that price difference, desired quantities of domestic varieties will be higher, and the marginal benefit of getting more of them will be higher as well.

Note finally that with full symmetry, we must have $w_i = w_j$ and $Z_j = Z_i$, and the condition above trivially holds since $t_{ij} > t_{ii}$ and $d_{ij} > d_{ii}$.

C Extensions of Economic Model

In this section, we flesh out some of the details of the various extensions of our framework discussed in Section 3 of the main text.

C.1 In-Person versus Remote Purchases

In the baseline version of our model, households *must* travel to consume each variety. We now consider a generalization, in which households have access to two alternative technologies for sourcing varieties: one of them involves travel, while the other one involves importing goods remotely, without travel. To incorporate a trade off between these options, we let the fixed utility cost of sourcing a variety from each location depend on which of these two technologies is used. It seems natural to suppose that, *on average*, sourcing a variety through travel is more costly than doing so without travel, but for certain buyers, personal contacts with foreign sellers may be particularly important (see Startz, 2021). We capture this by introducing agent-specific idiosyncratic shocks to these sourcing costs. As we show below, for a suitable parameterization of these idiosyncratic shocks to sourcing costs, we obtain an aggregation of our trade model that is isomorphic to the one in our baseline model. The main innovation is that the number of personal interactions is now shaped by both the measure of varieties consumed as well as by the share of these varieties that are sourced by traveling.

We next provide the mathematical details of the new features of this extension. The rest of the assumptions are as in our baseline model.

C.1.1 Sourcing Decision

For a household h in country i, the fixed utility cost of sourcing a variety k from country j through travel is:

$$\tilde{c}_{ij}^{P}\left(h,k,n_{ij}\right)=\frac{c^{P}}{\phi}\mu_{ij}\left(d_{ij}\right)^{\rho}\left(n_{ij}\right)^{\phi-1}\epsilon\left(h,k\right)^{P},$$

where the superscript P is a mnemonic for in-**P**erson transactions; recall that μ_{ij} is the mobility cost and d_{ij} is distance; $\epsilon^{P}\left(h,k\right)$ is an idiosyncratic shock to the fixed utility cost of sourcing a variety k through in-person trade, which is specific to each variety k, household h and pair of countries (i,j).

In contrast, the fixed utility cost of sourcing a variety from country j through remote trade is:

$$\tilde{c}_{ij}^{R}\left(h,k,n_{ij}\right)=\frac{c^{R}}{\phi}\left(d_{ij}\right)^{\rho}\left(n_{ij}\right)^{\phi-1}\epsilon\left(h,k\right)^{R},$$

where the superscript R is a mnemonic for **R**emote trade; $\epsilon\left(h,k\right)^{R}$ is an idiosyncratic shock to the fixed utility cost of sourcing a variety through remote trade, which is specific to each variety k, household h and pair of countries (i,j). Remote trade does not involve mobility costs (μ_{ij}) and we allow the fixed utility cost for remote trade to be small relative to that for trade with face-to-face interactions ($c^{R}<c^{P}$). For now, we assume that all households share a common value for c^{P} and c^{R}.

We assume that individuals choose the measure of varieties n_{ij} to source from each location *before* observing the realizations for the idiosyncratic shocks to the fixed utility costs (ϵ^{P}, ϵ^{R}). We assume that all households draw these idiosyncratic shocks independently from the following

Fréchet distributions:

$$F\left(\epsilon^{P}\right)=e^{-\left(\epsilon^{P}\right)^{-\kappa}}, \qquad F\left(\epsilon^{R}\right)=e^{-\left(\epsilon^{R}\right)^{-\kappa}}.$$

Using the monotonic relationship between sourcing costs and idiosyncratic shocks, the fixed utility costs of sourcing a variety through each sourcing mode also have Fréchet distributions:

$$F_{ij}^{P}\left(\tilde{c}_{ij}^{P}\right)=e^{-\left(c_{ij}^{P}/\Phi_{ij}^{P}\right)^{-\kappa}}, \qquad F_{ij}^{R}\left(\tilde{c}_{ij}^{R}\right)=e^{-\left(c_{ij}^{R}/\Phi_{ij}^{R}\right)^{-\kappa}},$$

where

$$\Phi_{ij}^{P}\equiv\frac{\tilde{c}^{P}}{\phi}\mu_{ij}\left(d_{ij}\right)^{\rho}\left(n_{ij}\right)^{\phi-1}, \qquad \Phi_{ij}^{R}\equiv\frac{\tilde{c}^{R}}{\phi}\left(d_{ij}\right)^{\rho}\left(n_{ij}\right)^{\phi-1}.$$

Using the properties of extreme value distributions, the minimum fixed utility cost across these two possible sourcing modes also has a Fréchet distribution:

$$F_{ij}\left(\tilde{c}_{ij}\right)=e^{-\left(\tilde{c}_{ij}/\Phi_{ij}\right)^{-\kappa}}, \qquad \left(\Phi_{ij}\right)^{\kappa}\equiv\left(\Phi_{ij}^{P}\right)^{\kappa}+\left(\Phi_{ij}^{R}\right)^{\kappa}.$$

The expected cost of sourcing a variety from country j is then given by

$$\mathbb{E}\left[\tilde{c}_{ij}\right]=\Gamma\left(\frac{\kappa-1}{\kappa}\right)\frac{1}{\phi}\left(d_{ij}\right)^{\rho}\left(n_{ij}\right)^{\phi-1}\left[\left(c^{P}\mu_{ij}\right)^{\kappa}+\left(c^{R}\right)^{\kappa}\right]^{\frac{1}{\kappa}},$$

where $\Gamma(\cdot)$ denotes the Gamma function. It thus follows that the expected total fixed cost of sourcing n_{ij} varieties can be written in the following form that is isomorphic to our baseline specification:

$$\mathbb{E}\left[c_{ij}\right]=n_{ij}\mathbb{E}\left[\tilde{c}_{ij}\right]=\frac{\widetilde{c}}{\phi}\widetilde{\mu}_{ij}\left(d_{ij}\right)^{\rho}\left(n_{ij}\right)^{\phi},$$

where

$$\widetilde{c}\equiv\Gamma\left(\frac{\kappa-1}{\kappa}\right), \qquad \widetilde{\mu}_{ij}\equiv\left[\left(c^{P}\mu_{ij}\right)^{\kappa}+\left(c^{R}\right)^{\kappa}\right]^{\frac{1}{\kappa}}.$$

Therefore, this generalization yields the same predictions for trade flows as in our baseline specification, except that (i) households make decisions about the measure of varieties to consume based on the adjusted mobility costs ($\widetilde{\mu}_{ij}$) and (ii) households only end up traveling for a fraction of the varieties that they decide to consume. The probability that a household in country i sources a variety from country j through in-person interactions is

$$\pi_{ij}^{P}=\frac{\left(c^{R}\right)^{\kappa}}{\left(c^{P}\mu_{ij}\right)^{\kappa}+\left(c^{R}\right)^{\kappa}}, \tag{C.1}$$

and the corresponding probability that the household sources the variety through remote trade is given by

$$\pi_{ij}^{R}=\frac{\left(c^{P}\mu_{ij}\right)^{\kappa}}{\left(c^{P}\mu_{ij}\right)^{\kappa}+\left(c^{R}\right)^{\kappa}}. \tag{C.2}$$

We also define the number of personal and remote contacts between agents in i and in j as follows

$$
\begin{aligned}
n_{ij}^P &\equiv n_{ij}\pi_{ij}^P; \\
n_{ij}^R &\equiv n_{ij}\pi_{ij}^R.
\end{aligned}
$$

C.1.2 Propositions of Trade Model

We are now ready to state and prove results analogous to those in Propositions B.1 through B.3 in Sections B.3 through B.5 of this Online Appendix, but applying to the objects that are relevant for the dynamics of the SIR model.

Proposition 1': *As long as trade frictions (Υ_{ij}) are bounded, there exists a unique vector of equilibrium wages $\mathbf{w}^* = (w_i, w_j) \in \mathbb{R}^2_{++}$ that solves the system of equations above.*

Proof. The general equilibrium aspects of the model have not changed, so this follows again from results in standard gravity models in Alvarez and Lucas (2007), Allen and Arkolakis (2014), and Allen et al. (2020), and the fact that if there exists a unique wage vector, the remaining equilibrium variables in this single-sector economy are uniquely determined. ■

Proposition 2': *A decline in any international trade or mobility friction $(d_{ij}, t_{ij}, t_{ji}, \mu_{ij}, \mu_{ji})$ leads to: (a) a decline in the rates (n_{ii}^P and n_{jj}^P) at which individuals will meet individuals in their own country; and (b) an increase in the rates at which individuals will meet individuals from the other country (n_{ij}^P and n_{ji}^P).*

Proof. Due to the isomorphism outlined above, it should be clear from Proposition B.2 in the main text that the above statement (a) applies to $n_{ii} = n_{ii}^P + n_{ii}^R$ and $n_{jj} = n_{jj}^P + n_{jj}^R$, while statement (b) applies to $n_{ij} = n_{ij}^P + n_{ij}^R$ and $n_{ji} = n_{ji}^P + n_{ji}^R$. We next note that π_{ii}^P and π_{jj}^R are independent of international trade or mobility frictions, and thus, if n_{ii} and n_{jj} increase in these frictions, it must be the case that n_{ii}^P and n_{jj}^P increase with them as well. This proves part (a). As for part (b), we note that, from equation (C.1), π_{ij}^P is decreasing in μ_{ij} and independent of d_{ij}, t_{ij}. Thus, because n_{ij} decreases in d_{ij}, t_{ij}, and μ_{ij}, it must be the case that $n_{ij}^P \equiv n_{ij}\pi_{ij}^P$ decreases in these frictions as well. The result for n_{ji}^P is analogous, which completes the proof of part (b). ■

Proposition 3': *Suppose that countries are symmetric, in the sense that $L_i = L$, $Z_i = Z$, and $\Upsilon_{ij} = \Upsilon$ for all i. Then a decline in any (symmetric) international trade frictions leads to an overall increase in human interactions ($n_{dom}^P + n_{for}^P$) experienced by both household buyers and household sellers.*

Proof. Due to the isomorphism outlined above, it should be clear from Proposition B.3 in the main text that the statement in the Proposition applies to $n_{dom} + n_{for} = n_{dom}^P + n_{for}^P + n_{dom}^R + n_{for}^R$.

Next note that π_{ii}^P and π_{jj}^P are independent of international trade or mobility frictions, while π_{ij}^P and π_{ji}^P are both declining in trade frictions. For the purposes of the Proposition we can thus write

$$n_{dom}^P + n_{for}^P = n_{dom} A + n_{for} B,$$

where A is independent of trade frictions, and B is declining in trade frictions. It is then trivial that if $n_{dom} + n_{for}$ declines in trade frictions, it must also be the case that $n_{dom}^P + n_{for}^P$ declines in trade frictions. ∎

C.1.3 Jet Setters versus Homebodies

In the above extension, households faced idiosyncratic shocks to the fixed utility cost of sourcing a variety k via in-person or remote means. Because these shocks are independently drawn across the continuum of varieties from a common distribution, all households ended up purchasing an identical share of varieties via travel. Thus, although an arbitrary large share of transactions happens remotely, it is still the case that half of the population engages in international business travel. We next outline an extension of our framework in which the share of personal contacts varies across households, so that the model can distinguish between households that are particularly prone to travel ('jet setters') and households that are particularly prone to buy goods without traveling ('homebodies').

The simplest way to capture this is by assuming that the shocks $\epsilon(h,k)^P$ and $\epsilon(h,k)^R$ in the previous extension are common for all varieties (and thus independent of k), so that households only choose one of the two possible modes (in-person or remote trade) for all varieties. Denote by 'jet setter' the set of households purchasing all varieties (from j) in person, and by 'homebodies' the set of households purchasing all varieties (from j) remotely. Following the same steps as before, and noting that all countries are inhabited by a continuum of households, it is then straightforward to show that the share of 'jet setter' households in i's population (when buying goods from j) is given by π_{ij}^P in equation (C.1), while the share of 'homebody' households in i's population (when buying goods from j) is given by π_{ij}^R in equation (C.2). The rest of the equilibrium is then identical to the one described above (when all households sourcing personally a common share of varieties), and thus Propositions 1' through 4' are again preserved.

Although this extension is pretty stark and features full segmentation between jet setters and homebodies, it is straightforward to develop an alternative extension in which all households source some varieties via in-person interactions and the remaining varieties remotely, but the shares would vary across households. For instance, one can imagine a situation in which the shocks $\epsilon(h,k)^P$ and $\epsilon(h,k)^R$ are i.i.d. across varieties, but they are drawn from two possible distributions, one for jet-setters and one for homebodies, with $c_{jet}^P < c_{hb}^P$ and $c_{jet}^R \geq c_{hb}^R$, where the subscript jet denotes jet setters, and the subscript hb denotes homebodies. These would generate distinct measures of personal contacts $n_{ij,jet}^P$ and $n_{ij,hb}^P$ for jet setters and homebodies, somewhat complicating the general-equilibrium aspects of the model, but it should not impact the key comparative statics we obtain in the static version of our model.[1]

C.1.4 Implications for SIR Disease Dynamics

So far, we have focused on the implications of these extensions for the properties of our static general equilibrium model of trade. Let us now consider their implications for the SIR model in our paper. For simplicity, we focus on the baseline version of our model, in which population, technology and relative wages are time-invariant, so that we can treat the rates of personal contacts n_{ii}^P, n_{ij}^P, n_{ji}^P and n_{jj}^P as parameters (though their constant level is of course shaped by the primitives of the model, including in particular trade and mobility frictions).

We assume that a buyer who sources a variety through remote trade is *not* exposed to infection by the seller, and a seller who supplies a variety through remote trade is *not* exposed to infection by the buyer. Under these assumptions, disease dynamics take a similar form as in the baseline specification of the model in the paper, except that only a fraction π_{ij}^P of the varieties that households in country i source from county j expose buyers from i and sellers in j to infection, and only a fraction π_{ji}^P of the varieties that households in country j source from country i expose buyers from j and sellers in i to infection. Analogously, in the extension with jet setters versus homebodies, π_{ij}^P and π_{ji}^P denote the share of households purchasing goods in-person (and thus being subject to contagion). Next, if we assume that the idiosyncratic shocks $\epsilon\left(h,k\right)^R$ and $\epsilon\left(h,k\right)^P$ are drawn independently each period, we do not need to keep track of the precise identity of the agents who source varieties through in-person interactions, but only the probability each period that a variety is sourced through personal interactions.

The share of households of **S**usceptible, **I**nfected and **R**ecovered households thus evolves according to the following laws of motion:

$$\begin{aligned}
\dot{S}_i &= -2n_{ii}^P\alpha_i S_i I_i - n_{ij}^P\alpha_j S_i I_j - n_{ji}^P\alpha_i S_i I_j; \\
\dot{I}_i &= 2n_{ii}^P\alpha_i S_i I_i + n_{ij}^P\alpha_j S_i I_j + n_{ji}^P\alpha_i S_i I_j - \gamma_i I_i; \\
\dot{R}_i &= \gamma_i I_i,
\end{aligned}$$

which are identical to those in our baseline model with n_{ij}^P replacing n_{ij} for any i and j. Given the comparative statics in Propositions 2' and 3', it is clear that the rest of the results in our paper related to disease dynamics will continue to hold.

A diametrically opposed case to the one in which idiosyncratic shocks are independently drawn over time would be the case in which the type of households (say whether they are jet setters or homebodies) is fixed over time. In such a case, the SIR dynamics would get more complicated because we would need to distinguish between six types of agents in the population: susceptible jet setters and homebodies, infectious jet setters and homebodies, and recovered jet setters and

[1] One could also extend the model along the lines of the work of Lind and Ramondo (2021) to allow for idiosyncratic but *correlated* shocks across varieties.

homebodies. More specifically, in such a case, we would have

$$
\begin{aligned}
\dot{S}_{i,jet} &= -\alpha_i \left(2n^P_{ii,jet} I_{i,jet} + \left(n^P_{ii,jet} + n^P_{ii,hb}\right) I_{i,hb}\right) S_{i,jet} - n^P_{ij,jet}\alpha_j S_{i,jet}\left(I_{i,jet} + I_{i,hb}\right) \\
&\quad -n^P_{ji,jet}\alpha_i S_{i,jet} I_{j,jet} - n^P_{ji,hb}\alpha_i S_{i,jet} I_{j,hb}; \\
\dot{I}_{i,jet} &= \alpha_i \left(2n^P_{ii,jet} I_{i,jet} + \left(n^P_{ii,jet} + n^P_{ii,hb}\right) I_{i,hb}\right) S_{i,jet} + n^P_{ij,jet}\alpha_j S_{i,jet}\left(I_{i,jet} + I_{i,hb}\right) \\
&\quad +n^P_{ji,jet}\alpha_i S_{i,jet} I_{j,jet} + n^P_{ji,hb}\alpha_i S_{i,jet} I_{j,hb} - \gamma_i I_{i,jet}; \\
\dot{R}_{i,jet} &= \gamma_i I_{i,jet}; \\
\dot{S}_{i,hb} &= -\alpha_i \left(2n^P_{ii,hb} I_{i,hb} + \left(n^P_{ii,hb} + n^P_{ii,jet}\right) I_{i,jet}\right) S_{i,hb} - n^P_{ij,hb}\alpha_j S_{i,hb}\left(I_{i,hb} + I_{i,jet}\right) \\
&\quad -n^P_{ji,jet}\alpha_i S_{i,hb} I_{j,jet} - n^P_{ji,hb}\alpha_i S_{i,hb} I_{j,hb}; \\
\dot{I}_{i,hb} &= \alpha_i \left(2n^P_{ii,hb} I_{i,hb} + \left(n^P_{ii,hb} + n^P_{ii,jet}\right) I_{i,jet}\right) S_{i,hb} + n^P_{ij,hb}\alpha_j S_{i,hb}\left(I_{i,hb} + I_{i,jet}\right) \\
&\quad +n^P_{ji,jet}\alpha_i S_{i,hb} I_{j,jet} + n^P_{ji,hb}\alpha_i S_{i,hb} I_{j,hb} - \gamma_i I_{i,jet}; \\
\dot{R}_{i,hb} &= \gamma_i I_{i,hb}.
\end{aligned}
$$

Note that in the special case where the shocks $\epsilon(h,k)^P$ and $\epsilon(h,k)^R$ are common for all varieties, we have that $n^P_{ii,hb} = n^P_{ij,hb} = n^P_{ji,hb} = 0$ since homebodies never source by traveling. We leave the analysis of such a multi-group SIR model for future research.

C.2 New versus Old Contacts

In this subsection, we develop a dynamic version of our framework in which face-to-face interactions are only necessary to initiate a commercial link between a buyer and a seller. The stock of buyer-seller links is thus increased by personal contacts, but we also let it depreciate at some constant rate δ. In particular, denoting by m_{ii} and m_{ij} the measures of *new links* established by a representative household in i in countries i and j, respectively, we can write the dynamic problem faced by a household as

$$
\begin{aligned}
W_i(0) = \max_{m_{ii}(\cdot), m_{ij}(\cdot)} \quad & \int_0^\infty e^{-\xi t}\left[Q_i\left(n_{ii}(t), n_{ij}(t)\right) - C_i\left(m_{ii}(t), m_{ij}(t)\right)\right] dt \\
\text{s.t.} \quad & \dot{n}_{ii}(t) = m_{ii}(t) - \delta n_{ii}(t) \\
& \dot{n}_{ij}(t) = m_{ij}(t) - \delta n_{ij}(t)
\end{aligned}
$$

given $n_{ii}(0)$ and $n_{ij}(0)$, where

$$
Q_i\left(n_{ii}(t), n_{ij}(t)\right) = w_i(t)\left(\sum\nolimits_{j\in\mathcal{J}} n_{ij}(t)\left(\frac{\tau_{ij} w_j(t)}{Z_j}\right)^{1-\sigma}\right)^{\frac{1}{(\sigma-1)}},
$$

and

$$
C_i\left(m_{ii}(t), m_{ij}(t)\right) = \frac{c}{\phi}\sum\nolimits_{j\in\mathcal{J}} \mu_{ij}\left(d_{ij}\right)^{\rho}\left(m_{ij}(t)\right)^{\phi},
$$

and where ξ is the rate of time preference. Notice that we assume the exact same cost function associated with in-person purchases as in our baseline model, but this cost function now applies *only* to the creation of *new* links. The only other novelty is that buyer-seller links $n_{ii}(t)$ and $n_{ij}(t)$ are now state variables of a dynamic optimization problem.

We can write the present-value Hamiltonian of this problem as

$$\begin{aligned} H\left(n_{ii}, n_{ij}, m_{ii}, m_{ij}, \theta_{ii}, \theta_{ij}\right) &= \left[Q_i\left(n_{ii}(t), n_{ij}(t)\right) - C_i\left(m_{ii}(t), m_{ij}(t)\right)\right] e^{-\xi t} \\ &\quad + \theta_{ii}\left[m_{ii}(t) - \delta n_{ii}(t)\right] + \theta_{ij}\left[m_{ij}(t) - \delta n_{ij}(t)\right], \end{aligned}$$

with associated first-order conditions

$$\begin{aligned} \frac{\partial H(\cdot)}{\partial m_{ii}} &= -\frac{\partial C_i\left(m_{ii}(t), m_{ij}(t)\right)}{\partial m_{ii}} e^{-\xi t} + \theta_{ii} = 0 \\ \frac{\partial H(\cdot)}{\partial m_{ij}} &= -\frac{\partial C_i\left(m_{ii}(t), m_{ij}(t)\right)}{\partial m_{ij}} e^{-\xi t} + \theta_{ij} = 0 \\ \frac{\partial H(\cdot)}{\partial n_{ii}} &= \frac{\partial Q_i\left(n_{ii}(t), n_{ij}(t)\right)}{\partial n_{ii}} e^{-\xi t} - \delta\theta_{ii} = -\dot{\theta}_{ii} \\ \frac{\partial H(\cdot)}{\partial n_{ij}} &= \frac{\partial Q_i\left(n_{ii}(t), n_{ij}(t)\right)}{\partial n_{ij}} e^{-\xi t} - \theta_{ij}\delta = -\dot{\theta}_{ij}, \end{aligned}$$

as well as the transversality conditions

$$\begin{aligned} \lim_{t\to\infty} n_{ii}(t)\,\theta_{ii}(t) &= 0; \\ \lim_{t\to\infty} n_{ij}(t)\,\theta_{ij}(t) &= 0. \end{aligned}$$

Manipulating these first-order conditions, we obtain

$$\frac{\partial Q_i\left(n_{ii}(t), n_{ij}(t)\right)}{\partial n_{ii}} = \left(\xi + \delta - (\phi - 1)\frac{\dot{m}_{ii}(t)}{m_{ii}(t)}\right)\frac{\partial C_i\left(m_{ii}(t), m_{ij}(t)\right)}{\partial m_{ii}}; \tag{C.3}$$

$$\frac{\partial Q_i\left(n_{ii}(t), n_{ij}(t)\right)}{\partial n_{ij}} = \left(\xi + \delta - (\phi - 1)\frac{\dot{m}_{ij}(t)}{m_{ij}(t)}\right)\frac{\partial C_i\left(m_{ii}(t), m_{ij}(t)\right)}{\partial m_{ij}}. \tag{C.4}$$

Because there is no underlying source of growth in the model, it seems natural to focus on a steady state in which $\dot{m}_{ii}(t) = \dot{m}_{ij}(t) = 0$, and thus

$$\begin{aligned} m_{ii}^*(t) &= \delta n_{ii}^*(t); \\ m_{ij}^*(t) &= \delta n_{ij}^*(t). \end{aligned}$$

In such a case, the optimality conditions (C.3) and (C.4) collapse to

$$\begin{aligned}
\frac{\partial Q_i\left(n_{ii}^*(t), n_{ij}^*(t)\right)}{\partial n_{ii}^*} &= (\xi+\delta)\frac{\partial C_i\left(\delta n_{ii}^*(t), \delta n_{ij}^*(t)\right)}{\partial\left(\delta n_{ii}^*(t)\right)};\\
\frac{\partial Q_i\left(n_{ii}^*(t), n_{ij}^*(t)\right)}{\partial n_{ij}^*} &= (\xi+\delta)\frac{\partial C_i\left(\delta n_{ii}^*(t), \delta n_{ij}^*(t)\right)}{\partial\left(\delta n_{ij}^*(t)\right)}.
\end{aligned}$$

Plugging in the functional forms for $C_i(m_{ii}(t), m_{ij}(t))$ and $Q_i(n_{ii}(t), n_{ij}(t))$, finally delivers

$$\begin{aligned}
n_{ii}^*(t) &= (\hat{c}(\sigma-1)\mu_{ii})^{-1/(\phi-1)}(d_{ii})^{-\frac{\rho+(\sigma-1)\delta}{\phi-1}}\left(\frac{t_{ii}w_i}{Z_iP_i}\right)^{-\frac{\sigma-1}{(\phi-1)}}\left(\frac{w_i}{P_i}\right)^{1/(\phi-1)};\\
n_{ij}^*(t) &= (\hat{c}(\sigma-1)\mu_{ij})^{-1/(\phi-1)}(d_{ij})^{-\frac{\rho+(\sigma-1)\delta}{\phi-1}}\left(\frac{t_{ij}w_j}{Z_jP_i}\right)^{-\frac{\sigma-1}{(\phi-1)}}\left(\frac{w_i}{P_i}\right)^{1/(\phi-1)},
\end{aligned}$$

where

$$\hat{c} = (\xi+\delta)(\delta)^{\phi-1}c.$$

Comparing these expressions to equation (7) in the main text, it is then clear that, in the steady state of this dynamic version of our model, the number of face-to-face interactions between buyers in country i and sellers in country j is equal to $\delta n_{ij}^*(t)$, where $n_{ij}^*(t)$ takes a value identical to its value in our baseline model up to a constant. It is then clear that the same comparative statics we derived in our baseline model would continue to hold in the steady state of this model.

Relative to our baseline model, this dynamic extension would obviously generate transitional dynamics when the number of links in the world economy is distinct from its steady state value. We focus on steady-state comparisons here, because the transition dynamics of face-to-face interactions during a pandemic are likely to be heavily influenced by behavioral responses, and we provide a characterization of transition dynamics with behavioral responses in Section 6 in the main text.

C.3 Multiple Sectors: Heterogeneity in Need of Travel

In this subsection, we consider a multi-sector version of our model that allows for cross-sectoral heterogeneity in trade costs, mobility costs, and also the relative advantage of in-person versus remote interactions.

C.3.1 Baseline Model with Cross-Sectoral Heterogeneity

We now let preferences of a representative household be given by

$$W_i = \prod_{s=1}^{S}\left(\frac{1}{\chi_s}\left(\sum\nolimits_{j\in\mathcal{J}}\int_0^{n_{ijs}} q_{ijs}(k)^{\frac{\sigma_s-1}{\sigma_s}}dk\right)^{\frac{\sigma_s}{\sigma_s-1}}\right)^{\chi_s} - \sum_{s=1}^{S}\frac{c_s}{\phi_s}\sum\nolimits_{j\in\mathcal{J}}\mu_{ijs}(d_{ij})^{\rho_s}(n_{ijs})^{\phi_s},$$

where s indexes sectors and where χ_s denotes the share of spending in sector s varieties. As in our baseline model, we assume that households are endowed with the ability to produce a differentiated variety in a given sector s. They therefore need to procure all varieties from all sectors (except for their own variety) from other households. For now, we assume that purchasing varieties from other households requires in-person contacts, but we will relax this assumption below.

Following the same exact steps as in our baseline model, households in i consume an amount of a representative variety in sector s produced in country j given by

$$q_{ijs} = \frac{\chi_s w_i}{(P_{is})^{1-\sigma}} \left(\frac{\tau_{ijs} w_j}{Z_{js}} \right)^{-\sigma_s},$$

where w_i is household income, w_j/Z_{js} is the common free-on-board price of all varieties produced in location j, τ_{ijs} are sector-specific trade costs when shipping from j to i, and P_{is} is a price index in sector s given by

$$P_{is} = \left(\sum\nolimits_{j \in \mathcal{J}} n_{ijs} \left(\frac{\tau_{ijs} w_j}{Z_{js}} \right)^{1-\sigma_s} \right)^{1/(1-\sigma_s)}.$$

With these expressions at hand, we can again follow the same steps as in the main text to derive the following expression for welfare for given contacts n_{ijs} in all countries and sectors:

$$W_i = w_i \prod_{s=1}^{S} \left(\sum\nolimits_{j \in \mathcal{J}} n_{ijs} \left(\frac{\tau_{ijs} w_j}{Z_{js}} \right)^{1-\sigma_s} \right)^{\frac{\chi_s}{(\sigma_s - 1)}} - \sum_{s=1}^{S} \frac{c_s}{\phi_s} \sum\nolimits_{j \in \mathcal{J}} \mu_{ijs} (d_{ij})^{\rho_s} (n_{ijs})^{\phi_s}.$$

Choosing those contacts to maximize welfare delivers a first-order condition for the choice of n_{ijs} that can be manipulated to deliver:

$$n_{ijs} = (c_s (\sigma_s - 1) \mu_{ijs})^{-1/(\phi_s - 1)} (d_{ijs})^{-\frac{\rho_s + (\sigma_s - 1)\delta_s}{\phi_s - 1}} \left(\frac{t_{ijs} w_j}{Z_{js} P_{is}} \right)^{-\frac{\sigma_s - 1}{(\phi_s - 1)}} \left(\frac{\chi_s w_i}{P_i} \right)^{1/(\phi_s - 1)}, \tag{C.5}$$

which is completely analogous to expression (7) in the main text except for the term χ_s and the sectoral heterogeneity in parameters.

Sectoral bilateral import flows by country i from country j are in turn given by:

$$\begin{aligned} X_{ijs} &= n_{ijs} p_{ijs} q_{ijs} L_i \\ &= \chi_s (c_s (\sigma_s - 1) \mu_{ijs})^{-\frac{1}{\phi_s - 1}} (d_{ij})^{-\frac{\rho_s + \phi_s(\sigma_s - 1)\delta_s}{\phi_s - 1}} \left(\frac{t_{ijs} w_j}{Z_{js} P_{is}} \right)^{-\frac{\phi_s(\sigma_s - 1)}{(\phi_s - 1)}} \left(\frac{\chi_s w_i}{P_i} \right)^{\frac{1}{\phi_s - 1}} \chi_s w_i L_i, \end{aligned}$$

so that *sectoral* trade shares can be written as:

$$\pi_{ijs} = \frac{X_{ijs}}{\sum_{\ell \in \mathcal{J}} X_{i\ell s}} = \frac{(\mu_{ijs})^{-\frac{1}{\phi_s - 1}} (d_{ij})^{-\frac{\rho_s + \phi_s(\sigma_s - 1)\delta_s}{\phi_s - 1}} (t_{ijs} w_j / Z_{js})^{-\frac{\phi_s(\sigma_s - 1)}{(\phi_s - 1)}}}{\sum_{\ell \in \mathcal{J}} (\mu_{i\ell s})^{-\frac{1}{\phi_s - 1}} (d_{i\ell})^{-\frac{\rho_s + \phi_s(\sigma_s - 1)\delta_s}{\phi_s - 1}} (t_{i\ell s} w_\ell / Z_{\ell s})^{-\frac{\phi_s(\sigma_s - 1)}{(\phi_s - 1)}}},$$

or simply

$$\pi_{ijs} = \frac{(\Upsilon_{ijs})^{-\varepsilon_s} (w_j/Z_{js})^{-\frac{\phi_s(\sigma_s-1)}{(\phi_s-1)}}}{\sum_{\ell\in\mathcal{J}} (\Upsilon_{i\ell s})^{-\varepsilon_s} (w_\ell/Z_{\ell s})^{-\frac{\phi_s(\sigma_s-1)}{(\phi_s-1)}}}, \tag{C.6}$$

in a manner analogous to that in the main text, except for the heterogeneity in the sectoral parameters.

The sectoral price index P_{is} can be written as:

$$P_{is} = \left((c_s(\sigma_s-1))^{-1/(\phi_s-1)} \left(\frac{1}{P_{is}}\right)^{-\frac{\sigma_s-1}{(\phi_s-1)}} \left(\frac{\chi_s w_i}{P_i}\right)^{1/(\phi_s-1)} \sum_{\ell\in\mathcal{J}} (\Upsilon_{i\ell s})^{-\varepsilon_s} (w_\ell/Z_{\ell s})^{-\frac{\phi_s(\sigma_s-1)}{(\phi_s-1)}} \right)^{1/(1-\sigma_s)}. \tag{C.7}$$

We next note that welfare can be written as

$$\begin{aligned} W_i &= w_i \prod_{s=1}^{S} \left(\sum_{j\in\mathcal{J}} n_{ijs} \left(\frac{\tau_{ijs} w_j}{Z_{js}}\right)^{1-\sigma_s} \right)^{\frac{\chi_s}{(\sigma_s-1)}} - \sum_{s=1}^{S} \frac{c_s}{\phi_s} \sum_{j\in\mathcal{J}} \mu_{ijs} (d_{ij})^{\rho_s} (n_{ijs})^{\phi_s} \\ &= w_i \prod_{s=1}^{S} (P_i^s)^{-\chi_s} - \sum_{s=1}^{S} \frac{c_s}{\phi_s} \sum_{j\in\mathcal{J}} \mu_{ijs} (d_{ij})^{\rho_s} (n_{ijs})^{\phi_s}. \end{aligned}$$

Plugging the value of n_{ijs} in equation (C.5), using (C.7), and manipulating produces this expression relating welfare to a constant times the real wage, or:

$$W_i = \left(1 - \sum_{s=1}^{S} \frac{\chi_s}{\phi_s(\sigma_s-1)}\right) \frac{w_i}{\prod_{s=1}^{S} (P_i^s)^{\chi_s}}. \tag{C.8}$$

We next seek to express welfare as a function of sectoral domestic shares. To do so, begin using (C.7) to note that

$$\begin{aligned} P_i &= \prod_{s=1}^{S} (P_i^s)^{\chi_s} \\ &= \prod_{s=1}^{S} \left(\frac{1}{P_i}\right)^{\frac{\chi_s}{\phi_s(\sigma_s-1)}} \left((c_s(\sigma_s-1))^{-\frac{1}{\phi_s-1}} (\chi_s w_i)^{\frac{1}{\phi_s-1}} \sum_{\ell\in\mathcal{J}} (\Upsilon_{i\ell s})^{-\varepsilon_s} (w_\ell/Z_{\ell s})^{-\frac{\phi_s(\sigma_s-1)}{(\phi_s-1)}} \right)^{\frac{\chi_s(\phi_s-1)}{\phi_s(1-\sigma_s)}} \end{aligned}$$

so we can write

$$(P_i)^{1-\sum_{s=1}^{S}\frac{\chi_s}{\phi_s(\sigma_s-1)}} = \prod_{s=1}^{S} \left((c_s(\sigma_s-1))^{-\frac{1}{\phi_s-1}} (\chi_s w_i)^{\frac{1}{\phi_s-1}} \sum_{\ell\in\mathcal{J}} (\Upsilon_{i\ell s})^{-\varepsilon_s} (w_\ell/Z_{\ell s})^{-\frac{\phi_s(\sigma_s-1)}{(\phi_s-1)}} \right)^{\frac{\chi_s(\phi_s-1)}{\phi_s(1-\sigma_s)}}. \tag{C.9}$$

Next, note that from the sectoral trade share equation (C.6), we have

$$\sum_{\ell\in\mathcal{J}} (\Upsilon_{i\ell s})^{-\varepsilon_s} (w_\ell/Z_{\ell s})^{-\frac{\phi_s(\sigma_s-1)}{(\phi_s-1)}} = (\Upsilon_{iis})^{-\varepsilon_s} (w_i/Z_{is})^{-\frac{\phi_s(\sigma_s-1)}{(\phi_s-1)}} (\pi_{iis})^{-1},$$

and thus, plugging back into (C.9), and manipulating, delivers

$$W_i = \Lambda \frac{w_i}{P_i} = \Lambda \prod_{s=1}^{S} \left(c_s \left(\sigma_s - 1\right)/\chi_s\right)^{-\frac{\chi_s}{\phi_s(\sigma_s-1)}\frac{1}{\Lambda}} \left(\Upsilon_{iis}\right)^{-\frac{\chi_s(\phi_s-1)}{\phi_s(\sigma_s-1)}\frac{1}{\Lambda}\varepsilon_s} \left(Z_{is}\right)^{\chi_s \frac{1}{\Lambda}} \left(\pi_{iis}\right)^{-\frac{\chi_s(\phi_s-1)}{\phi_s(\sigma_s-1)}\frac{1}{\Lambda}}, \quad \text{(C.10)}$$

where

$$\Lambda = 1 - \sum_{s=1}^{S} \frac{\chi_s}{\phi_s\left(\sigma_s - 1\right)}.$$

This formula again resonates with those derived in Arkolakis et al. (2012).

We conclude our description of the equilibrium of this variant of the model by discussing the determination of equilibrium wages. For that, it is simplest to just invoke the equality between income and spending in each country, that is $\sum_{s=1}^{S} \pi_{iis} w_i L_i + \sum_{s=1}^{S} \pi_{jis}^{s} w_j L_j = w_i L_i$, which plugging in (C.6), can be written as

$$\sum_{s=1}^{S} \pi_{iis}\left(w_i, w_j\right) w_i L_i + \sum_{s=1}^{S} \pi_{jis}\left(w_i, w_j\right) w_j L_j = w_i L_i. \quad \text{(C.11)}$$

C.3.2 Main Propositions of Trade Model

We are now ready to state and prove results analogous to those in Propositions B.2-B.3 in Sections B.4-B.5 of this Online Appendix, but applying in our multi-sectoral environment. Unfortunately, there does not exist a proof of existence and uniqueness for standard multi-sector models of trade featuring gravity (see Allen et al., 2020), so we cannot prove an analogue of Proposition B.1 in our baseline model.

Turning to the effects of trade integration on the number of in-person interactions, we now derive results analogous to those in Propositions B.2 and B.3. In order, to avoid complications arising from cross-sectoral general-equilibrium effects of reductions in trade frictions in specific sectors, we focus on a situation in which trade and mobility frictions Υ_{ijs}, as well as the parameters Z_{is}, σ_s, and ϕ_s are all common for all sectors.

Proposition 2': *Let trade and mobility frictions Υ_{ijs}, as well as the parameters Z_{is}, σ_s, and ϕ_s be common for all sectors. A decline in any international trade or mobility friction $(d_{ij}, t_{ij}, t_{ji}, \mu_{ij}, \mu_{ji})$ leads to: (a) a decline in the rates (n^P_{iis} and n^P_{jjs}) at which individuals will meet individuals in their own country when purchasing goods in* any *sector; and (b) an increase in the rates at which individuals will meet individuals from the other country (n^P_{ijs} and n^P_{jis}) when purchasing goods in* any *sector.*

Proof. Part (a). From equation (C.5), we can write

$$n_{iis} = \left(c_s\left(\sigma - 1\right)\mu_{ii}/\chi_s\right)^{-1/(\phi_s-1)} \left(d_{ii}\right)^{-\frac{\rho+(\sigma-1)\delta}{\phi-1}} \left(\frac{t_{ii}}{Z_i}\right)^{-\frac{\sigma-1}{(\phi-1)}} \left(\frac{P_{is}}{P_i}\right)^{\frac{\sigma-1}{\phi-1}} \left(\frac{w_i}{P_i}\right)^{-\frac{\sigma-2}{\phi-1}},$$

but remember from (C.10) that

$$\frac{w_i}{P_i} = \prod_{s=1}^{S} \left(c_s\left(\sigma-1\right)/\chi_s\right)^{-\frac{\chi_s}{\phi(\sigma-1)}\frac{1}{\Lambda}} \left(\Upsilon_{ii}\right)^{-\frac{\chi_s(\phi-1)}{\phi(\sigma-1)}\frac{1}{\Lambda}\varepsilon} \left(Z_i\right)^{\chi_s\frac{1}{\Lambda}} \left(\pi_{iis}\right)^{-\frac{\chi_s(\phi-1)}{\phi(\sigma-1)}\frac{1}{\Lambda}},$$

where $\Lambda = \left(\phi\left(\sigma-1\right)-1\right)/\phi\left(\sigma-1\right)$. Furthermore, given equation (C.7), we have

$$\frac{P_{is}}{P_{is'}} = \left(\frac{\chi_{s'}}{\chi_s}\frac{c_s}{c_{s\prime}}\right)^{1/\phi(\sigma-1)},$$

and thus the ratio P_{is}/P_s is independent of changes in trade frictions.

In order to study the effect of international trade frictions on n_{iis}, it then suffices to study their effect on the domestic trade expenditure shares π_{iis}, with the dependence of n_{iis} on any π_{iis} being monotonically positive. Next, we note that from (C.6),

$$\pi_{iis} = \frac{\left(\Upsilon_{ii}\right)^{-\varepsilon}\left(w_i/Z_i\right)^{-\frac{\phi(\sigma-1)}{(\phi-1)}}}{\sum_{\ell\in\mathcal{J}}\left(\Upsilon_{i\ell}\right)^{-\varepsilon}\left(w_\ell/Z_\ell\right)^{-\frac{\phi(\sigma-1)}{(\phi-1)}}},$$

it is clear that the direct impact effect of a lower $\Upsilon_{i\ell}$ is to decrease π_{iis} and thus to decrease n_{iis} as well. To take into account general-equilibrium forces, we can write equation (C.11) as

$$\begin{aligned} L_i &= \sum_{s=1}^{S}\frac{\left(Z_i\right)^{\frac{\phi(\sigma-1)}{(\phi-1)}}\left(\Upsilon_{ii}\right)^{-\varepsilon}}{\left(Z_i\right)^{\frac{\phi(\sigma-1)}{(\phi-1)}}\left(\Upsilon_{ii}\right)^{-\varepsilon}+\left(Z_j/\omega\right)^{\frac{\phi(\sigma-1)}{(\phi-1)}}\left(\Upsilon_{ij}\right)^{-\varepsilon}}L_i \\ &+ \sum_{s=1}^{S}\frac{\left(Z_i\right)^{\frac{\phi(\sigma-1)}{\phi-1}}\left(\Upsilon_{ji}\right)^{-\varepsilon}}{\left(Z_j/\omega\right)^{\frac{\phi(\sigma-1)}{\phi-1}}\left(\Upsilon_{jj}\right)^{-\varepsilon}+\left(Z_i\right)^{\frac{\phi(\sigma-1)}{\phi-1}}\left(\Upsilon_{ji}\right)^{-\varepsilon}}\omega L_j, \end{aligned}$$

where $\omega \equiv w_j/w_i$ is the relative wage in country j. From this equation, it is easy to see that if Υ_{ij} falls in all sectors, ω cannot possibly decrease. If it did, both terms in the left-hand side of (B.4) would fall. But if ω goes up, the second term goes up for all sectors, and thus it must be the case that $\left(\omega\right)^{-\frac{\phi(\sigma-1)}{(\phi-1)}}\left(\Upsilon_{ij}\right)^{-\varepsilon}$ in the denominator of the first term must go up in all sectors, which implies that π_{iis} must decline in all sectors, and thus does n_{iis}.

Consider now a decline in Υ_{ji}. From equations (C.5), (C.10) and the expression for π_{iis} above, we see that the effect will work only via relative wages. Turning to equation (C.11), note that π_{jis} increases on impact when trade costs Υ_{ji} fall in all sectors, so ω needs to decrease to re-equilibrate the labor market, which leads to a decline in π_{iis}, and thus in n_{iis}.

Because the results above hold for Υ_{ij} and Υ_{ji}, they must hold for any of the constituents of those composite parameters.

Part (b). Note from equation (C.8) that

$$\frac{c_s}{\phi}\sum_{j\in\mathcal{J}}\mu_{ij}\left(d_{ij}\right)^{\rho}\left(n_{ijs}\right)^{\phi} = \frac{\chi_s}{\phi\left(\sigma-1\right)}\frac{w_i}{P_i}.$$

In part (a) of the proof, we have established that when any international trade friction decreases proportionately across sectors, π_{iis} goes down in all sectors, while from equation (C.10), w_i/P_i goes up. Thus, $\mu_{ij}\left(d_{ij}\right)^{\rho}\left(n_{ijs}\right)^{\phi}$ goes up in all sectors, and because n_{iis} goes down, and μ_{ij} and d_{ij} (weakly) go down, it must be the case that n_{ijs} increases. ■

Proposition 3': *Let trade and mobility frictions Υ_{ijs}, as well as the parameters Z_{is}, σ_s, and ϕ_s be common for all sectors. Furthermore, suppose that countries are symmetric, in the sense that $L_i = L$, $Z_i = Z$, and $\Upsilon_{ij} = \Upsilon$ for all i. Then a decline in any (symmetric) international trade frictions leads to an overall increase in human interactions ($\sum_s n^P_{dom,s} + \sum_s n^P_{for,s}$) experienced by both household buyers and household sellers.*

Proof. We begin by considering the case with general country asymmetries. Consider the sum

$$\mu_{ii}\left(d_{ii}\right)^{\rho}\left(n_{ijs}\right)^{\phi} + \mu_{ij}\left(d_{ij}\right)^{\rho}\left(n_{ijs}\right)^{\phi}.$$

Differentiating:

$$\phi_s\left[\mu_{ii}\left(d_{ii}\right)^{\rho}\left(n_{iis}\right)^{\phi-1}\underbrace{dn_{iis}}_{<0} + \mu_{ij}\left(d_{ij}\right)^{\rho}\left(n_{ijs}\right)^{\phi-1}dn_{ijs}\right] + \underbrace{d\left(\mu_{ij}\left(d_{ij}\right)^{\rho}\right)}_{\leq 0}\left(n_{ijs}\right)^{\phi} > 0,$$

where the inequalities follow from our result in Proposition 2'.

Clearly, we must have

$$\mu_{ii}\left(d_{ii}\right)^{\rho}\left(n_{iis}\right)^{\phi-1}dn_{iis} + \mu_{ij}\left(d_{ij}\right)^{\rho}\left(n_{ijs}\right)^{\phi-1}dn_{ijs} > 0.$$

So, if

$$\mu_{ii}\left(d_{ii}\right)^{\rho}\left(n_{iis}\right)^{\phi-1} > \mu_{ij}\left(d_{ij}\right)^{\rho}\left(n_{ijs}\right)^{\phi-1},$$

we must have

$$dn_{ijs} > -dn_{iis},$$

which would prove the Proposition.

Now, from the FOC for the choice of n's, we can derive

$$\frac{\mu_{ij}\left(d_{ij}\right)^{\rho}\left(n_{ijs}\right)^{\phi-1}}{\mu_{ii}\left(d_{ii}\right)^{\rho}\left(n_{iis}\right)^{\phi-1}} = \left(\frac{\left(d_{ij}\right)^{\delta}t_{ij}w_j}{\left(d_{ii}\right)^{\delta}t_{ii}w_i}\frac{Z_{is}}{Z_{js}}\right)^{1-\sigma}$$

so a sufficient condition for the result is

$$\frac{\left(d_{ii}\right)^{\delta}t_{ii}w_i}{Z_{is}} < \frac{\left(d_{ij}\right)^{\delta}t_{ij}w_j}{Z_{js}}.$$

This amounts to prices for domestic varieties being lower than prices for foreign varieties. Note finally that with full symmetry, we must have $w_i = w_j$ and $Z_j = Z_i$, and the condition above trivially holds since $t_{ij} > t_{ii}$ and $d_{ij} > d_{ii}$. Finally, because the result holds for all sectors s, it must hold for their sum too. ■

C.3.3 Remote Versus In-Person Purchases

It is also straightforward to extend this multi-sector model to incorporate a tradeoff between in-person and remote purchases, similarly to how we did in the main text. In particular, we can let the fixed utility cost of sourcing a variety k in sector s from country j in person be given by

$$\tilde{c}_{ijs}^{P}\left(h,k,n_{ij}\right)=\frac{c_{s}^{P}}{\phi_{s}}\mu_{ijs}\left(d_{ij}\right)^{\rho_{s}}\left(n_{ijs}\right)^{\phi_{s}-1}\epsilon_{s}\left(h,k\right)^{P},$$

and the fixed utility cost of sourcing a variety in sector s from country j through remote trade be given by

$$\tilde{c}_{ijs}^{R}\left(h,k,n_{ij}\right)=\frac{c_{s}^{R}}{\phi_{s}}\left(d_{ij}\right)^{\rho_{s}}\left(n_{ijs}\right)^{\phi_{s}-1}\epsilon_{s}\left(h,k\right)^{R}.$$

The shocks $\epsilon_s\left(h,k\right)^P$ and $\epsilon\left(h,k\right)^R$ are specific to each variety k, sector s, household h and pair of countries (i,j). Note that remote trade does not involve mobility costs (μ_{ij}) and we allow the fixed utility cost for remote trade to be small relative to that for trade with face-to-face interactions $(c_s^R < c_s^P)$.

Assuming that individuals choose the measure of varieties n_{ijs} to source from each location *before* observing the realizations for the idiosyncratic shocks to the fixed utility costs (ϵ^P, ϵ^R), and that these idiosyncratic shocks are drawn from Fréchet distributions, it is straightforward to follow the same steps as in Online Appendix C.1 to characterize the equilibrium of this multi-sectoral variant of our model in which the share of remote and in-person interactions can vary across countries, across sectors, and across households.

C.4 Multi-Country Model

We next consider a version of our model with a world economy featuring multiple countries. It should be clear that all our equilibrium conditions, except for the labor-market clearing condition (11) apply to that multi-country environment once the set of countries $\mathcal{J}$ is redefined to include multiple countries. The equality between income and expenditure on the goods produced by a country is in turn given by

$$\sum\nolimits_{j\in\mathcal{J}}\pi_{ij}\left(\mathbf{w}\right)w_{j}L_{j}=w_{i}L_{i},$$

where $\pi_{ij}\left(\mathbf{w}\right)$ is defined in equation (9) in the main text for an arbitrary set of countries $\mathcal{J}$. Similarly, the model is also easily adaptable to the case in which there is a continuum of locations $i \in \Omega$, where Ω is a closed and bounded set of a finite-dimensional Euclidean space. The equilibrium conditions are again unaltered, with integrals replacing summation operators throughout.

From the results in Alvarez and Lucas (2007), Allen and Arkolakis (2014), and Allen et al. (2020), it is clear that Proposition B.1 in Section B.3 of this Online Appendix on existence and uniqueness will continue to hold. In the presence of arbitrary asymmetries across countries, it is hard however to derive crisp comparative static results of the type in Proposition B.2 in Section B.4 of this Online Appendix. Nevertheless, our result in Proposition B.3 in Section B.5 of this Online Appendix regarding the positive effect of declines of trade and mobility barriers on the overall level of human interactions between symmetric countries is generalizes to the case of many countries.

C.5 Traveling Costs in Terms of Labor

If traveling costs are specified in terms of labor (rather than utility), welfare at the household level depends only on consumption

$$W_i = \left(\sum_{j \in \mathcal{J}} \int_0^{n_{ij}} q_{ij}(k)^{\frac{\sigma-1}{\sigma}} dk \right)^{\frac{\sigma}{\sigma-1}},$$

and the implied demand (for a given n_{ii} and n_{ij}) is given by

$$q_{ij}(k) = \left(\frac{p_{ij}}{P_i} \right)^{-\sigma} \frac{\mathcal{I}_i}{P_i},$$

where $\mathcal{I}_i$ is household income, which is given by

$$\mathcal{I}_i = w_i \left(1 - \frac{c}{\phi} \sum_{j \in \mathcal{J}} \mu_{ij} d_{ij}^{\rho} n_{ij}^{\phi} \right),$$

since the household now needs to hire labor to be able to secure final-good differentiated varieties, and where

$$P_i = \left(\sum_{j \in \mathcal{J}} n_{ij} p_{ij}^{1-\sigma} \right)^{\frac{1}{1-\sigma}}.$$

Welfare can therefore be rewritten as

$$W_i = \frac{\mathcal{I}_i}{P_i} = w_i \left(1 - \frac{c}{\phi} \sum_{j \in \mathcal{J}} \mu_{ij} d_{ij}^{\rho} n_{ij}^{\phi} \right) \left(\sum_{j \in \mathcal{J}} n_{ij} p_{ij}^{1-\sigma} \right)^{\frac{1}{\sigma-1}}.$$

The first-order condition for the choice of n_{ij} delivers:

$$n_{ij} = (c(\sigma-1))^{-\frac{1}{\phi-1}} \left(\frac{\mathcal{I}_i}{w_i} \right)^{\frac{1}{\phi-1}} \left(\frac{t_{ij} w_j}{Z_j P_i} \right)^{-\frac{\sigma-1}{\phi-1}} \mu_{ij}^{-\frac{1}{\phi-1}} d_{ij}^{-\frac{\rho+\delta(\sigma-1)}{\phi-1}}.$$

Bilateral import flows by country i from country j are given by

$$X_{ij} = n_{ij} p_{ij} q_{ij} L_i = (c(\sigma-1))^{-\frac{1}{\phi-1}} \left(\frac{\mathcal{I}_i}{w_i} \right)^{\frac{1}{\phi-1}} \left(\frac{t_{ij} w_j}{Z_j P_i} \right)^{-\frac{\phi(\sigma-1)}{\phi-1}} \mu_{ij}^{-\frac{1}{\phi-1}} d_{ij}^{-\frac{\rho+\phi\delta(\sigma-1)}{\phi-1}} \mathcal{I}_i L_i,$$

and the trade share can be written as

$$\pi_{ij} = \frac{X_{ij}}{\sum_{l\in\mathcal{J}} X_{il}} = \frac{\left(\frac{w_j}{Z_j}\right)^{-\frac{\phi(\sigma-1)}{\phi-1}} \mu_{ij}^{-\frac{1}{\phi-1}} d_{ij}^{-\frac{\rho+\phi\delta(\sigma-1)}{\phi-1}} t_{ij}^{-\frac{\phi(\sigma-1)}{\phi-1}}}{\sum_{l\in\mathcal{J}} \left(\frac{w_l}{Z_l}\right)^{-\frac{\phi(\sigma-1)}{\phi-1}} \mu_{il}^{-\frac{1}{\phi-1}} d_{il}^{-\frac{\rho+\phi\delta(\sigma-1)}{\phi-1}} t_{il}^{-\frac{\phi(\sigma-1)}{\phi-1}}} = \frac{S_j}{\Phi_i}\Upsilon_{ij}^{-\varepsilon},$$

where

$$\Upsilon_{ij}^{-\varepsilon} = \mu_{ij}^{-\frac{1}{\phi-1}} d_{ij}^{-\frac{\rho+\phi\delta(\sigma-1)}{\phi-1}} t_i^{-\frac{\phi(\sigma-1)}{\phi-1}},$$

which is identical to equation (9) for our baseline model with traveling costs in terms of labor in the main text.

The price index is in turn given by

$$P_i = (c(\sigma-1))^{\frac{1}{\phi(\sigma-1)}} \left(\frac{\mathcal{I}_i}{w_i}\right)^{-\frac{1}{\phi(\sigma-1)}} \left(\sum_{j\in\mathcal{J}} \left(\frac{w_j}{Z_j}\right)^{-\frac{\phi(\sigma-1)}{\phi-1}} \Upsilon_{ij}^{-\varepsilon}\right)^{-\frac{\phi-1}{\phi(\sigma-1)}},$$

and using this expression together for the one for π_{ij}, one can verify that we can write

$$n_{ij} = \left(\frac{t_{ij} d_{ij}^{\delta} w_j}{Z_j P_i}\right)^{\sigma-1} \pi_{ij},$$

just as in equation (12) of the main text.

Plugging this expression back into the budget constraint yields

$$\mathcal{I}_i = \frac{\phi(\sigma-1)}{\phi(\sigma-1)+1} w_i,$$

and a resulting price index equal to

$$P_i = \left(\frac{c\phi}{\phi(\sigma-1)+1}\right)^{\frac{1}{\phi(\sigma-1)}} \left(\sum_{j\in\mathcal{J}} \left(\frac{w_j}{Z_j}\right)^{-\frac{\phi(\sigma-1)}{\phi-1}} \Upsilon_{ij}^{-\varepsilon}\right)^{-\frac{\phi-1}{\phi(\sigma-1)}},$$

which is only slightly different than expression (B.1) in the main text.

The condition equating income and expenditure on the goods produced by a country is

$$\pi_{ii}\mathcal{I}_i L_i + \pi_{ji}\mathcal{I}_j L_j = \mathcal{I}_i L_i$$

or, equivalently,

$$\pi_{ii} w_i L_i + \pi_{ji} w_j L_j = w_i L_i,$$

just as in the main text, and remember that the expressions for π_{ii} and π_{ji} are also left unchanged.

We next turn to verifying that Propositions B.1 through B.3 in Sections B.3 through B.5 of this Online Appendix continue to hold whenever travel costs in equation (1) are specified in terms of labor rather than being modelled as a utility cost.

Proposition 1': *As long as trade frictions (Υ_{ij}) are bounded, there exists a unique vector of equilibrium wages $w^* = (w_i, w_j) \in R^2_{++}$ that solves the system of equations above.*

Proof. By results in standard gravity models in Alvarez and Lucas (2007), Allen and Arkolakis (2014), and Allen et al. (2020). ■

Proposition 2': *A decline in any international trade or mobility friction ($d_{ij}, t_{ij}, t_{ji}, \mu_{ij}, \mu_{ji}$) leads to: (a) a decline in the rates (n_{ii} and n_{jj}) at which individuals will meet individuals in their own country; and (b) an increase in the rates at which individuals will meet individuals from the other country (n_{ij} and n_{ji}).*

Proof. (a) Given that $\mathcal{I}_i = \frac{\phi(\sigma-1)}{\phi(\sigma-1)+1} w_i$,

$$n_{ii} = (c(\sigma-1))^{-\frac{1}{\phi-1}} \left(\frac{\mathcal{I}_i}{w_i}\right)^{\frac{1}{\phi-1}} \left(\frac{t_{ii}w_i}{Z_i P_i}\right)^{-\frac{\sigma-1}{\phi-1}} \mu_{ii}^{-\frac{1}{\phi-1}} d_{ii}^{-\frac{\rho+\delta(\sigma-1)}{\phi-1}} = const \left(\frac{P_i}{w_i}\right)^{\frac{\sigma-1}{\phi-1}}$$

Then

$$\frac{P_i}{w_i} = \left(\frac{c\phi}{\phi(\sigma-1)+1}\right)^{\frac{1}{\phi(\sigma-1)}} \left(Z_i^{\frac{\phi(\sigma-1)}{\phi-1}} \Upsilon_{ii}^{-\varepsilon} + \left(\frac{Z_j}{\omega}\right)^{\frac{\phi(\sigma-1)}{\phi-1}} \Upsilon_{ij}^{-\varepsilon}\right)^{-\frac{\phi-1}{\phi(\sigma-1)}},$$

where $\omega = w_j/w_i$ is the relative wage in country j.

Note that the equality between income and expenditure on the goods produced by a country can be rewritten as

$$\frac{Z_i^{\frac{\phi(\sigma-1)}{\phi-1}} \Upsilon_{ii}^{-\varepsilon}}{Z_i^{\frac{\phi(\sigma-1)}{\phi-1}} \Upsilon_{ii}^{-\varepsilon} + \left(\frac{Z_j}{\omega}\right)^{\frac{\phi(\sigma-1)}{\phi-1}} \Upsilon_{ij}^{-\varepsilon}} L_i + \frac{Z_i^{\frac{\phi(\sigma-1)}{\phi-1}} \Upsilon_{ji}^{-\varepsilon}}{Z_i^{\frac{\phi(\sigma-1)}{\phi-1}} \Upsilon_{ji}^{-\varepsilon} + \left(\frac{Z_j}{\omega}\right)^{\frac{\phi(\sigma-1)}{\phi-1}} \Upsilon_{jj}^{-\varepsilon}} \omega L_j = L_i.$$

Consider a case when Υ_{ij} decreases, while other Υ_{kl} remain constant. That means that the first term in the sum goes down, while the second term is constant. For the equality to hold, ω should increase. After re-equilibration, the second term in the sum increased, which means that the first term decreased. This means that P_i/w_i decreased, and n_{ii} as well.

Consider now a case when Υ_{ji} decreases, while other Υ_{kl} remain constant. The second term increases, so ω needs to go down to equilibrate the model. That means that the first term decreases, and P_i/w_i and n_{ii} decrease by extension.

Therefore, whenever one decreases any international friction ($d_{ij}, t_{ij}, t_{ji}, \mu_{ij}, \mu_{ji}$), Υ_{ij} or Υ_{ji} goes down, and, hence, n_{ii} and n_{jj} go down.

(b) Note that

$$\frac{\mathcal{I}_i}{w_i} = 1 - \frac{c}{\phi} \sum_{j \in \mathcal{J}} \mu_{ij} d_{ij}^{\rho} n_{ij}^{\phi}$$

Since $\mathcal{I}_i = \frac{\phi(\sigma-1)}{\phi(\sigma-1)+1} w_i$, the left-hand side is constant. Since n_{ii} and n_{jj} decrease, n_{ij} and n_{ji} must increase. ■

Proposition 3': *Suppose that countries are symmetric, in the sense that $L_i = L$, $Z_i = Z$, and $\Upsilon_{ij} = \Upsilon$ for all i. Then a decline in any (symmetric) international trade frictions leads to an overall increase in human interactions ($n_{dom} + n_{for}$) experienced by both household buyers and household sellers.*

Proof. We begin by considering the case with general country asymmetries. Consider the sum

$$\mu_{ii} d_{ii}^{\rho} n_{ii}^{\phi} + \mu_{ij} d_{ij}^{\rho} n_{ij}^{\phi} = \frac{1}{\phi(\sigma-1)+1}.$$

Differentiating yields

$$\phi \mu_{ii} d_{ii}^{\rho} n_{ii}^{\phi-1} dn_{ii} + \phi \mu_{ij} d_{ij}^{\rho} n_{ij}^{\phi-1} dn_{ij} + \phi n_{ij}^{\phi} \underbrace{d\left(\mu_{ij} d_{ij}^{\rho}\right)}_{\leq 0} = 0.$$

Hence,

$$\phi \mu_{ii} d_{ii}^{\rho} n_{ii}^{\phi-1} dn_{ii} + \phi \mu_{ij} d_{ij}^{\rho} n_{ij}^{\phi-1} dn_{ij} \geq 0,$$

and if $\mu_{ii} d_{ii}^{\rho} n_{ii}^{\phi-1} > \mu_{ij} d_{ij}^{\rho} n_{ij}^{\phi-1}$, then $dn_{ij} > -dn_{ii}$.

From the FOC for the choice of n_{ii} and n_{ij}, we obtain

$$\mu_{ii} d_{ii}^{\rho} n_{ii}^{\phi-1} = \frac{1}{c(\sigma-1)} \frac{\mathcal{I}_i}{w_i} \left(\frac{p_{ii}}{P_i}\right)^{1-\sigma}$$

$$\mu_{ij} d_{ij}^{\rho} n_{ij}^{\phi-1} = \frac{1}{c(\sigma-1)} \frac{\mathcal{I}_i}{w_i} \left(\frac{p_{ij}}{P_i}\right)^{1-\sigma}$$

Therefore, $\mu_{ii} d_{ii}^{\rho} n_{ii}^{\phi-1} > \mu_{ij} d_{ij}^{\rho} n_{ij}^{\phi-1}$ is satisfied if and only if $p_{ii} < p_{ij}$.

When countries are symmetric, this holds trivially because of international trade costs $t_{ij} > t_{ii}$ and $d_{ij} > d_{ii}$. Hence, $dn_{ij} > -dn_{ii}$, and $n_{dom} + n_{for}$ increases. ■

C.6 International Sourcing of Inputs

The assumption that households travel internationally to procure consumption goods may seem unrealistic. Perhaps international travel is better thought as being a valuable input when firms need specialized inputs and seek potential providers of those inputs in various countries. It is straightforward to re-interpret our model along those lines. In particular, suppose now that all households in country i produce a homogeneous final good but also produce differentiated intermediate input varieties. The household's final good is produced combining a bundle of the intermediate inputs produced by other households. Technology for producing the final good is given by

$$Q_i = \left(\sum\nolimits_{j \in \mathcal{J}} \int_0^{n_{ij}^I} q_{ij}^I \left(k\right)^{\frac{\sigma-1}{\sigma}} dk \right)^{\frac{\sigma}{\sigma-1}}$$

and this final good is not traded (this is without loss of generality if households are homogeneous in each country and trade costs for final goods are large enough). Household welfare is linear in consumption of the final good and is reduced by the disutility cost of a household's member having to travel to secure intermediate inputs. In particular, we have

$$W_i = \left(\sum\nolimits_{j \in \mathcal{J}} \int_0^{n_{ij}^I} q_{ij}^I \left(k\right)^{\frac{\sigma-1}{\sigma}} dk \right)^{\frac{\sigma}{\sigma-1}} - \frac{c}{\phi} \sum\nolimits_{j \in \mathcal{J}} \mu_{ij} \left(d_{ij}\right)^{\rho} \left(n_{ij}^I\right)^{\phi}.$$

Under these assumptions, this model is isomorphic to the one above, except that trade will be in intermediate inputs rather than in final goods.

C.7 Ricardian Sourcing

In this subsection, we consider an environment à la Eaton and Kortum (2002), in which the measure of final good varieties is fixed at one, and all households worldwide compete to be the least-cost supplier of those goods to other households. As we shall see, this delivers expressions isomorphic to those in our baseline model.

The world consists of a discrete number of countries indexed by $i, j \in \{1, \ldots, \mathcal{J}\}$. Each country contains a large number L_i of households (which we will approximate by a continuum at times). Each household is endowed with one unit of labor and the ability to produce any good from a continuum of final goods $k \in [0, 1]$. Household preferences are defined over this same continuum of goods produced by households:

$$W_i = \left(\int_0^1 q_i(k)^{\frac{\sigma-1}{\sigma}} dk \right)^{\frac{\sigma}{\sigma-1}},$$

with $\sigma > 1$. Goods are produced by labor according to a linear technology, such that the cost to a household h in country j to deliver consumption goods to households in i is given by

$$p_{ij}\left(k\right) = \frac{\tau_{ji} w_j}{z_j^h\left(k\right)},$$

where $z_j^h\left(k\right)$ is the productivity of household h in j in the production of variety k. We assume that the production technology of each household is perfectly contestable, such that pricing is competitive. We assume that the idiosyncratic productivity $z_j^h\left(k\right)$ is drawn independently across households and across varieties from the following Fréchet distribution:

$$F\left(z\right) = e^{-\left(z/Z_j\right)^{-\theta}}, \qquad \theta > \sigma - 1,$$

where Z_j^θ is the Fréchet scale parameter for country j.

For a household to be able to consume from other households, it is necessary for one of the household members – the buyer – to travel to other households. We assume that the number of other households in i and j that a household in i chooses to visit is decided *before* the shocks $z_j^h(k)$ for all households are realized. Suppose that a household from i decides to visit n_{ij} households in each other country $j \in \{1, \ldots, \mathcal{J}\}$ (including i). Using the properties of the Fréchet distribution (see Eaton and Kortum, 2002), one can verify that this household will spend a share

$$\pi_{ij} = \frac{n_{ij}\left(\tau_{ji} w_j / Z_j\right)^{-\theta}}{\sum_{\ell \in \mathcal{J}} n_{ij}\left(\tau_{ji} w_j / Z_j\right)^{-\theta}}, \tag{C.12}$$

of their income on goods provided by country j households. Furthermore, such consumption choices will deliver a level of utility to this household equal to

$$Q_i = \frac{w_i}{P_i} = \Psi w_i \left(\sum_{j \in \mathcal{J}} n_{ij} \left(\frac{\tau_{ij} w_j}{Z_j} \right)^{-\theta} \right)^{1/\theta},$$

where Ψ is a constant and w_i is the wage rate in country i (note that household's income is purely labor income, as markets are competitive and households sell at marginal cost).[2] As in the main text, we assume that households derive disutility from the buyer spending time away from home, and capture this with the following cost function:

$$c_{ij}\left(n_{ij}\right) = \frac{c}{\phi} \mu_{ij} \left(d_{ij}\right)^{\rho} \left(n_{ij}\right)^{\phi},$$

whenever the household's buyer secures n_{ij} varieties from location j, at a distance $d_{ij} \geq 1$ from i.

As a result, households in i will set n_{ij} for each $j \in \{1, \ldots, \mathcal{J}\}$ to maximize

$$W_i = \Psi w_i \left(\sum\nolimits_{j \in \mathcal{J}} n_{ij} \left(\frac{\tau_{ij} w_j}{Z_j} \right)^{-\theta} \right)^{1/\theta} - \frac{c}{\phi} \sum\nolimits_{j \in \mathcal{J}} \mu_{ij} \left(d_{ij}\right)^{\rho} \left(n_{ij}\right)^{\phi}.$$

It is apparent that this expression is isomorphic to equation (6) in the main text (up to a constant) after replacing θ with $\sigma - 1$. Ignoring integer constraints (i.e., treating the number of households as a continuous variable), this model will thus deliver identical choices for the number of in-person contacts n_{ii} and n_{ij}. Furthermore, replacing again θ with $\sigma - 1$, it is straightforward to verify that this specification delivers the exact same implication for bilateral trade flows as our baseline model. Naturally, this isomorphism applies as well to the equality between income and expenditure on the goods produced by a country. In sum, the equilibrium conditions of this variant of the model are

[2] More specifically,

$$\Psi = \left[\Gamma \left(\frac{\theta + 1 - \phi}{\theta} \right) \right]^{1/(\sigma - 1)},$$

where Γ is the Gamma function.

isomorphic to those derived in our baseline model, and thus they carry the same implications, as summarized by Propositions B.1 through B.3 in Sections B.3 through B.5 of this Online Appendix.

C.8 Scale Economies and Imperfect Competition

We finally explore a variant of our model in which it is the household's seller rather than the buyer who travels to other locations. We model this via a framework featuring scale economies, monopolistic competition and fixed cost of exporting, as in the literature on selection into exporting emanating from the seminal work of Melitz (2003), except that the fixed costs of selling are defined at the buyer level rather than at the country level, as in the work of Arkolakis (2010).

On the consumption side, households maximize their utility, given by

$$W_i = \left(\sum_{j \in \mathcal{J}} \int_0^{\nu_{ij}} q_{ij}(k)^{\frac{\sigma-1}{\sigma}} dk \right)^{\frac{\sigma}{\sigma-1}},$$

where ν_{ij} is the measure of varieties available to them, subject to the household budget constraint. This yields

$$q_{ij}(k) = \left(\frac{p_{ij}}{P_i} \right)^{-\sigma} \frac{\mathcal{I}_i}{P_i},$$

where $\mathcal{I}_i$ is household income and the price index is

$$P_i = \left(\sum_{j \in \mathcal{J}} \nu_{ij} p_{ij}^{1-\sigma} \right)^{\frac{1}{1-\sigma}}.$$

Household sellers in country j produce N_j varieties and make them available to n_{ij} consumers. Both N_j and n_{ij} are endogenous and pinned down as part of the equilibrium. Note that because there are L_i and L_j households in i and j, respectively, the measure of varieties available from j to consumers in i is given by $\nu_{ij} = n_{ij} N_j L_j / L_i$ (where implicitly we assume that which precise consumers in j get access to a seller's varieties is chosen at random).

The level of output and price of each variety, as well as the measure of consumers n_{ij} sellers reach out to follows from profit maximization:

$$\max_{n_{ij}, p_{ij}} n_{ij} \left(p_{ij} - \frac{\tau_{ij} w_j}{Z_j} \right) q_{ij} - w_j \frac{c}{\phi} \mu_{ij} d_{ij}^{\rho} n_{ij}^{\phi},$$

where again n_{ij} is the number of customers served, and where the remaining parameters are analogous to those in our baseline model.

Sellers naturally charge a constant markup over marginal cost,

$$p_{ij} = \frac{\sigma}{\sigma - 1} \frac{\tau_{ij} w_j}{Z_j},$$

so the choice of n_{ij} boils down to

$$\max_{n_{ij}} \frac{n_{ij}}{\sigma} p_{ij} q_{ij} - w_j \frac{c}{\phi} \mu_{ij} d_{ij}^{\rho} n_{ij}^{\phi}.$$

The first-order condition of this problem yields

$$\frac{p_{ij} q_{ij}}{\sigma} = w_j c \mu_{ij} d_{ij}^{\rho} n_{ij}^{\phi-1} \Rightarrow n_{ij} = \left(\frac{p_{ij} q_{ij}}{c\sigma \mu_{ij} d_{ij}^{\rho} w_j} \right)^{\frac{1}{\phi-1}}.$$

Developing a new variety costs $w_i f$. Hence, by free entry, $\sum_k \Pi_{ki} = w_i f$, and the zero-profit condition also entails $\mathcal{I}_i = w_i$. As a result, we can express n_{ij} as

$$n_{ij} = (c\sigma)^{-\frac{1}{\phi-1}} \mu_{ij}^{-\frac{1}{\phi-1}} d_{ij}^{-\frac{\rho+(\sigma-1)\delta}{\phi-1}} \left(\frac{\sigma}{\sigma-1} \frac{t_{ij} w_j}{P_i Z_j} \right)^{-\frac{\sigma-1}{\phi-1}} \left(\frac{w_i}{w_j} \right)^{\frac{1}{\phi-1}}.$$

With this expression at hand, we can compute the import volume of country i from country j:

$$\begin{aligned}
X_{ij} &= \nu_{ij} p_{ij} q_{ij} L_i = n_{ij} p_{ij} q_{ij} N_j L_j \\
&= w_j c\sigma \mu_{ij} d_{ij}^{\rho} n_{ij}^{\phi} N_j L_j \\
&= (c\sigma)^{-\frac{1}{\phi-1}} \mu_{ij}^{-\frac{1}{\phi-1}} d_{ij}^{-\frac{\rho+\phi(\sigma-1)\delta}{\phi-1}} \left(\frac{\sigma}{\sigma-1} \frac{t_{ij} w_j}{P_i Z_j} \right)^{-\frac{\phi(\sigma-1)}{\phi-1}} \left(\frac{w_i}{w_j} \right)^{\frac{1}{\phi-1}} w_i N_j L_j \\
&= (c\sigma)^{-\frac{1}{\phi-1}} \Upsilon_{ij}^{-\varepsilon} \left(\frac{\sigma}{\sigma-1} \frac{w_j}{P_i Z_j} \right)^{-\frac{\phi(\sigma-1)}{\phi-1}} \left(\frac{w_i}{w_j} \right)^{\frac{1}{\phi-1}} w_i N_j L_j
\end{aligned}$$

Hence, the share of country j in country i's import is

$$\pi_{ij} = \frac{\Upsilon_{ij}^{-\varepsilon} \left(\frac{w_j}{Z_j} \right)^{-\frac{\phi(\sigma-1)}{\phi-1}} w_j^{-\frac{1}{\phi-1}} N_j L_j}{\sum_k \Upsilon_{ik}^{-\varepsilon} \left(\frac{w_k}{Z_k} \right)^{-\frac{\phi(\sigma-1)}{\phi-1}} w_k^{-\frac{1}{\phi-1}} N_k L_k}.$$

Solving for price index yields

$$\begin{aligned}
w_i L_i &= \sum_j X_{ij} \\
w_i L_i &= \sum_j (c\sigma)^{-\frac{1}{\phi-1}} \Upsilon_{ij}^{-\varepsilon} \left(\frac{\sigma}{\sigma-1} \frac{w_j}{P_i Z_j} \right)^{-\frac{\phi(\sigma-1)}{\phi-1}} \left(\frac{w_i}{w_j} \right)^{\frac{1}{\phi-1}} w_i N_j L_j \\
P_i &= \frac{\sigma}{\sigma-1} (c\sigma)^{\frac{1}{\phi(\sigma-1)}} L_i^{\frac{\phi-1}{\phi(\sigma-1)}} \left(\sum_j \Upsilon_{ij}^{-\varepsilon} \left(\frac{w_j}{Z_j} \right)^{-\frac{\phi(\sigma-1)}{\phi-1}} \left(\frac{w_i}{w_j} \right)^{\frac{1}{\phi-1}} N_j L_j \right)^{-\frac{\phi-1}{\phi(\sigma-1)}}.
\end{aligned}$$

We can next study the choice of the number of varieties N_j produced by sellers. Profits of sellers are given by

$$\Pi_{ij} = \frac{\phi - 1}{\phi} \frac{n_{ij} p_{ij} q_{ij}}{\sigma} = \frac{\phi - 1}{\phi} \frac{X_{ij}}{\sigma N_j L_j},$$

so the zero-profit condition implies

$$\sum_k \Pi_{ki} = w_i f \Rightarrow \frac{\phi - 1}{\phi} \frac{1}{\sigma N_i L_i} \sum_k X_{ki} = w_i f.$$

Since $\sum_k X_{ki} = w_i L_i$,

$$\frac{\phi - 1}{\phi} \frac{w_i L_i}{\sigma N_i L_i} = w_i f \Rightarrow N_i = \frac{\phi - 1}{\phi \sigma f}.$$

Hence, the number of varieties is constant and independent of many of the parameters of the model.

We finally turn to the general equilibrium of the model, which is associated with the condition:

$$\pi_{ii} w_i L_i + \pi_{ji} w_j L_j = w_i L_i.$$

Plugging in the expressions for trade shares yields

$$\frac{\Upsilon_{ii}^{-\varepsilon} \left(\frac{w_i}{Z_i}\right)^{-\frac{\phi(\sigma-1)}{\phi-1}} w_i^{-\frac{1}{\phi-1}} L_i}{\sum_k \left(\Upsilon_{ik}^{-\varepsilon} \frac{w_k}{Z_k}\right)^{-\frac{\phi(\sigma-1)}{\phi-1}} w_k^{-\frac{1}{\phi-1}} L_k} w_i L_i + \frac{L_i \left(\frac{w_i}{Z_i}\right)^{-\frac{\phi(\sigma-1)}{\phi-1}} w_i^{-\frac{1}{\phi-1}} \Upsilon_{ji}^{-\varepsilon}}{\sum_k L_k \left(\frac{w_k}{Z_k}\right)^{-\frac{\phi(\sigma-1)}{\phi-1}} w_k^{-\frac{1}{\phi-1}} \Upsilon_{jk}^{-\varepsilon}} w_j L_j = w_i L_i.$$

We are now ready to state and proof results analogous to those in Propositions B.1 through B.3 in Sections B.3 through B.5 of this Online Appendix.

Proposition 1": *As long as trade frictions (Υ_{ij}) are bounded, there exists a unique vector of equilibrium wages $\mathbf{w}^* = (w_i, w_j) \in \mathbb{R}^2_{++}$ that solves the system of equations above.*

Proof. This follows again from results in standard gravity models in Alvarez and Lucas (2007), Allen and Arkolakis (2014), and Allen et al. (2020), and the fact that if there exists a unique wage vector, the remaining equilibrium variables in this single-sector economy are uniquely determined. ■

Proposition 2": *A decline in any international trade or mobility friction ($d_{ij}, t_{ij}, t_{ji}, \mu_{ij}, \mu_{ji}$) leads to: (a) a decline in the rates (n_{ii} and n_{jj}) at which individuals will meet individuals in their own country; and (b) an increase in the rates at which individuals will meet individuals from the other country (n_{ij} and n_{ji}).*

Proof. (a) First, note that

$$n_{ii} = \xi \mu_{ii}^{-\frac{1}{\phi-1}} d_{ii}^{-\frac{\rho+(\sigma-1)\delta}{\phi-1}} \left(\frac{t_{ii} w_i}{P_i Z_i}\right)^{-\frac{\sigma-1}{\phi-1}} = const \left(\frac{P_i}{w_i}\right)^{\frac{\sigma-1}{\phi-1}}.$$

Then

$$\frac{P_i}{w_i} = const L_i^{\frac{\phi-1}{\phi(\sigma-1)}} \left(L_i \Upsilon_{ii}^{-\varepsilon} Z_i^{\frac{\phi(\sigma-1)}{\phi-1}} + L_j \Upsilon_{ij}^{-\varepsilon} \left(\frac{Z_j}{\omega} \right)^{\frac{\phi(\sigma-1)}{\phi-1}} \omega^{-\frac{1}{\phi-1}} \right)^{-\frac{\phi-1}{\phi(\sigma-1)}},$$

where $\omega = w_j/w_i$ is the relative wage in country j .

Note that the equilibrium equations can be rewritten as

$$\frac{L_i Z_i^{\frac{\phi(\sigma-1)}{\phi-1}} \Upsilon_{ii}^{-\varepsilon}}{L_i Z_i^{\frac{\phi(\sigma-1)}{\phi-1}} \Upsilon_{ii}^{-\varepsilon} + L_j \left(\frac{Z_j}{\omega} \right)^{\frac{\phi(\sigma-1)}{\phi-1}} \omega^{-\frac{1}{\phi-1}} \Upsilon_{ij}^{-\varepsilon}} L_i \tag{C.13}$$

$$+ \frac{L_i Z_i^{\frac{\phi(\sigma-1)}{\phi-1}} \Upsilon_{ji}^{-\varepsilon}}{L_i Z_i^{\frac{\phi(\sigma-1)}{\phi-1}} \Upsilon_{ji}^{-\varepsilon} + L_j \left(\frac{Z_j}{\omega} \right)^{\frac{\phi(\sigma-1)}{\phi-1}} \omega^{-\frac{1}{\phi-1}} \Upsilon_{jj}^{-\varepsilon}} \omega L_j = L_i. \tag{C.14}$$

Consider a case when Υ_{ij} decreases, while other Υ_{kl} remain constant. That means that the first term in the sum goes down, while the second term is constant. For the equality to hold, ω should increase. After re-equilibration, the second term in the sum increased, which means that the first term decreased. This means that P_i/w_i decreased, and n_{ii} as well.

Consider now a case when Υ_{ji} decreases, while other Υ_{kl} remain constant. The second term increases, so ω needs to go down to equilibrate the model. That means that the first term decreases, and P_i/w_i and n_{ii} decrease by extension.

Therefore, whenever one decreases any international friction $(d_{ij}, t_{ij}, t_{ji}, \mu_{ij}, \mu_{ji})$, Υ_{ij} or Υ_{ji} goes down, and, hence, n_{ii} and n_{jj} go down.

(b) Note that $\Pi_{ii} + \Pi_{ji} = w_i f$. That can be rewritten as

$$\frac{\phi-1}{\phi} \frac{n_{ii} p_{ii} q_{ii}}{w_i \sigma} + \frac{\phi-1}{\phi} \frac{n_{ji} p_{ji} q_{ji}}{w_i \sigma} = f.$$

Using the FOC for n_{ij}, that yields

$$\frac{\phi-1}{\phi} c \mu_{ii} d_{ii}^{\rho} n_{ii}^{\phi} + \frac{\phi-1}{\phi} c \mu_{ji} d_{ji}^{\rho} n_{ji}^{\phi} = f.$$

Since n_{ii} and n_{jj} decrease and frictions do not increase, n_{ij} and n_{ji} have to increase. ■

Proposition 3": *Suppose that countries are symmetric, in the sense that $L_i = L$, $Z_i = Z$, and $\Upsilon_{ij} = \Upsilon$ for all i. Then a decline in any (symmetric) international trade frictions leads to an overall increase in human interactions ($n_{dom} + n_{for}$) experienced by both household buyers and household sellers.*

Proof. We begin by considering the case with general country asymmetries. Consider the sum

$$\mu_{ii} d_{ii}^{\rho} n_{ii}^{\phi} + \mu_{ji} d_{ji}^{\rho} n_{ji}^{\phi} = const.$$

Differentiating yields

$$\phi\mu_{ii}d_{ii}^{\rho}n_{ii}^{\phi-1}dn_{ii}+\phi\mu_{ji}d_{ji}^{\rho}n_{ji}^{\phi-1}dn_{ji}+n_{ji}^{\phi}\underbrace{d\left(\mu_{ji}d_{ji}^{\rho}\right)}_{\leq 0}=0.$$

Hence,

$$\mu_{ii}d_{ii}^{\rho}n_{ii}^{\phi-1}dn_{ii}+\mu_{ji}d_{ji}^{\rho}n_{ji}^{\phi-1}dn_{ji}\geq 0,$$

and if $\mu_{ii}d_{ii}^{\rho}n_{ii}^{\phi-1}>\mu_{ji}d_{ji}^{\rho}n_{ji}^{\phi-1}$, then $dn_{ji}>-dn_{ii}$.

From the FOC for the choice of n_{ii} and n_{ji},

$$\mu_{ii}d_{ii}^{\rho}n_{ii}^{\phi-1}=const\frac{p_{ii}q_{ii}}{w_i}=const\left(\frac{p_{ii}}{P_i}\right)^{1-\sigma}$$

$$\mu_{ji}d_{ji}^{\rho}n_{ji}^{\phi-1}=const\frac{p_{ji}q_{ji}}{w_i}=const\left(\frac{p_{ji}}{P_j}\right)^{1-\sigma}\left(\frac{w_j}{w_i}\right).$$

Since the countries are symmetric, $P_i=P_j$ and $w_i=w_j$, so the inequality is satisfied if and only if $p_{ii}<p_{ji}$.

When countries are symmetric, this holds trivially because of international trade costs $t_{ji}>t_{ii}$ and $d_{ji}>d_{ii}$. Hence, $dn_{ji}>-dn_{ii}$, and $n_{dom}+n_{for}$ increases. ■

D Theoretical Appendix for Open-Economy SIR Model

In this section of the Online Appendix, we report additional details and derivations for our baseline open-economy SIR model from Section 4 of the paper.

D.1 Comparative Statics of Pandemic Equilibrium

In this subsection of the Online Appendix, we analyze the comparative statics of the steady-state share of susceptible households in each country ($S_i(\infty)$, $S_j(\infty)$) in the system of equations (17)-(18) in Section 4.3 of the paper. We examine the change in the steady-state share of susceptible households ($S_i(\infty)$, $S_j(\infty)$) with respect to bilateral interactions (n_{ii}, n_{jj}, n_{ij}, n_{ji}), where we already determined these bilateral interactions as a function of bilateral trade and travel frictions in Section 3 of the paper.

We begin with the law of motion for susceptible agents in each country in equation (13) in the main text:

$$\begin{aligned}\dot{S}_i &= -2\alpha_i n_{ii}S_iI_i-\alpha_j n_{ij}S_iI_j-\alpha_i n_{ji}S_iI_j\\ \dot{S}_j &= -2\alpha_j n_{jj}S_jI_j-\alpha_j n_{ij}S_jI_i-\alpha_i n_{ji}S_jI_i\end{aligned}$$

Dividing by the own share of susceptibles, and plugging the expression for $\dot{R}_i$ and $\dot{R}_j$ in equation

(15) in the main text, we obtain

$$\begin{aligned}
\frac{\dot{S}_i}{S_i} &= -\frac{2\alpha_i n_{ii}}{\gamma_i}\dot{R}_i - \frac{\alpha_j n_{ij} + \alpha_i n_{ji}}{\gamma_j}\dot{R}_j \\
\frac{\dot{S}_j}{S_j} &= -\frac{2\alpha_j n_{jj}}{\gamma_j}\dot{R}_j - \frac{\alpha_j n_{ij} + \alpha_i n_{ji}}{\gamma_i}\dot{R}_i.
\end{aligned}$$

Turning the growth rate in the left-hand side to a log-difference, and integrating we get

$$\begin{aligned}
\ln S_i(t) - \ln S_i(0) &= -\frac{2\alpha_i n_{ii}}{\gamma_i}\left(R_i(t) - R_i(0)\right) - \frac{\alpha_j n_{ij} + \alpha_i n_{ji}}{\gamma_j}\left(R_j(t) - R_j(0)\right) \\
\ln S_j(t) - \ln S_j(0) &= -\frac{2\alpha_j n_{jj}}{\gamma_j}\left(R_j(t) - R_j(0)\right) - \frac{\alpha_j n_{ij} + \alpha_i n_{ji}}{\gamma_i}\left(R_i(t) - R_j(0)\right).
\end{aligned}$$

Finally, noting $S_i(0) \simeq 1$ and $R_i(0) \simeq 1$, and $R_i(\infty) = 1 - S_i(\infty)$ (since $I_i(\infty) = 0$), we obtain the system in equations (17)-(18) in the main text, that is:

$$\begin{aligned}
\ln S_i(\infty) &= -\frac{2\alpha_i n_{ii}}{\gamma_i}\left(1 - S_i(\infty)\right) - \frac{\alpha_j n_{ij} + \alpha_i n_{ji}}{\gamma_j}\left(1 - S_j(\infty)\right) \\
\ln S_j(\infty) &= -\frac{2\alpha_j n_{jj}}{\gamma_j}\left(1 - S_j(\infty)\right) - \frac{\alpha_j n_{ij} + \alpha_i n_{ji}}{\gamma_i}\left(1 - S_i(\infty)\right).
\end{aligned}$$

Although we cannot solve the system in closed-form, we can derive some comparative statics. In particular, total differentiating we find

$$\begin{aligned}
&\frac{1}{S_i(\infty)}dS_i(\infty) - \frac{2\alpha_i n_{ii}}{\gamma_i}dS_i(\infty) + \left(1 - S_i(\infty)\right)d\left(\frac{2\alpha_i n_{ii}}{\gamma_i}\right) \\
=\ &\left(\frac{\alpha_j n_{ij} + \alpha_i n_{ji}}{\gamma_j}\right)dS_j(\infty) - d\left(\frac{\alpha_j n_{ij} + \alpha_i n_{ji}}{\gamma_j}\right)\left(1 - S_j(\infty)\right) \\
&\frac{1}{S_j(\infty)}dS_j(\infty) - \frac{2\alpha_j n_{jj}}{\gamma_j}dS_j(\infty) + \left(1 - S_j(\infty)\right)d\left(\frac{2\alpha_j n_{jj}}{\gamma_j}\right) \\
=\ &\left(\frac{\alpha_j n_{ij} + \alpha_i n_{ji}}{\gamma_i}\right)dS_i(\infty) - d\left(\frac{\alpha_j n_{ij} + \alpha_i n_{ji}}{\gamma_i}\right)\left(1 - S_i(\infty)\right).
\end{aligned}$$

Solving

$$\begin{aligned}
dS_i(\infty) &= -\frac{\left[\begin{array}{c} \frac{\alpha_j n_{ij}+\alpha_i n_{ji}}{\gamma_j}\left(d\left(\frac{\alpha_j n_{ij}+\alpha_i n_{ji}}{\gamma_i}\right) + \left(1 - S_j(\infty)\right)d\left(\frac{2\alpha_j n_{jj}}{\gamma_j}\right)\right) \\ + \left(\frac{1}{S_j(\infty)} - \frac{2\alpha_j n_{jj}}{\gamma_j}\right)\left(d\left(\frac{\alpha_j n_{ij}+\alpha_i n_{ji}}{\gamma_j}\right)\left(1 - S_j(\infty)\right) + \left(1 - S_i(\infty)\right)d\left(\frac{2\alpha_i n_{ii}}{\gamma_i}\right)\right) \end{array}\right]}{\left(\frac{1}{S_i(\infty)} - \frac{2\alpha_i n_{ii}}{\gamma_i}\right)\left(\frac{1}{S_j(\infty)} - \frac{2\alpha_j n_{jj}}{\gamma_j}\right) - \frac{\left(\alpha_j n_{ij}+\alpha_i n_{ji}\right)^2}{\gamma_i\gamma_j}} \\
dS_j(\infty) &= -\frac{\left[\begin{array}{c} \frac{\alpha_j n_{ij}+\alpha_i n_{ji}}{\gamma_i}\left(d\left(\frac{\alpha_j n_{ij}+\alpha_i n_{ji}}{\gamma_j}\right) + \left(1 - S_i(\infty)\right)d\left(\frac{2\alpha_i n_{ii}}{\gamma_i}\right)\right) \\ + \left(\frac{1}{S_i(\infty)} - \frac{2\alpha_i n_{ii}}{\gamma_i}\right)\left(d\left(\frac{\alpha_j n_{ij}+\alpha_i n_{ji}}{\gamma_i}\right)\left(1 - S_i(\infty)\right) + \left(1 - S_j(\infty)\right)d\left(\frac{2\alpha_j n_{jj}}{\gamma_j}\right)\right) \end{array}\right]}{\left(\frac{1}{S_j(\infty)} - \frac{2\alpha_j n_{jj}}{\gamma_j}\right)\left(\frac{1}{S_i(\infty)} - \frac{2\alpha_i n_{ii}}{\gamma_i}\right) - \frac{\left(\alpha_j n_{ij}+\alpha_i n_{ji}\right)^2}{\gamma_i\gamma_j}}.
\end{aligned}$$

Next, note that because new infections eventually go to zero, there have to be (at least) two peaks of infection (t_i^* and t_j^*) defined by $\dot{I}_i(t_i^*) = \dot{I}_j\left(t_j^*\right) = 0$. Whenever there are more than two peaks in one country, one should set t_i^* and t_j^* to the latest periods for which $\dot{I}_i(t_i^*) = \dot{I}_j\left(t_j^*\right) = 0$.

Now we have two cases to consider:

- **Case 1: $t_i^* \geq t_j^*$.** Then $\dot{I}_i(t_i^*) = 0 > \dot{I}_j\left(t_j^*\right)$ and

$$\begin{aligned} \frac{2\alpha_i n_{ii}}{\gamma_i} S_i(t_i^*) + \frac{\alpha_j n_{ij} + \alpha_i n_{ji}}{\gamma_i} S_i(t_i^*) \frac{I_j(t_i^*)}{I_i(t_i^*)} &= 1 \\ \frac{2\alpha_j n_{jj}}{\gamma_j} S_j(t_i^*) + \frac{\alpha_j n_{ij} + \alpha_i n_{ji}}{\gamma_j} S_j(t_i^*) \frac{I_i(t_i^*)}{I_j(t_i^*)} &\leq 1 \end{aligned}$$

and thus

$$\left(\frac{1}{S_i(t_i^*)} - \frac{2\alpha_i n_{ii}}{\gamma_i}\right)\left(\frac{1}{S_j(t_i^*)} - \frac{2\alpha_j n_{jj}}{\gamma_j}\right) \geq \frac{(\alpha_j n_{ij} + \alpha_i n_{ji})^2}{\gamma_i \gamma_j} \frac{I_j(t_i^*)}{I_i(t_i^*)} \frac{I_i(t_i^*)}{I_j(t_i^*)} = \frac{(\alpha_j n_{ij} + \alpha_i n_{ji})^2}{\gamma_i \gamma_j}$$

But as $S_i(t_i^*) > S_i(\infty)$ and $S_j(t_i^*) > S_i(\infty)$, so we must have $\frac{2\alpha_i n_{ii}}{\gamma_i} S_i(\infty) \leq 1$ and $\frac{2\alpha_j n_{jj}}{\gamma_j} S_j(\infty) \leq 1$, as well as

$$\left(\frac{1}{S_i(\infty)} - \frac{2\alpha_i n_{ii}}{\gamma_i}\right)\left(\frac{1}{S_j(\infty)} - \frac{2\alpha_j n_{jj}}{\gamma_j}\right) \geq \frac{(\alpha_j n_{ij} + \alpha_i n_{ji})^2}{\gamma_i \gamma_j}.$$

- **Case 2: $t_j^* \geq t_j^*$.** Then $\dot{I}_j\left(t_j^*\right) = 0 > \dot{I}_i(t_i^*)$ and

$$\begin{aligned} \frac{2\alpha_i n_{ii}}{\gamma_i} S_i\left(t_j^*\right) + \frac{\alpha_j n_{ij} + \alpha_i n_{ji}}{\gamma_i} S_i\left(t_j^*\right) \frac{I_j\left(t_j^*\right)}{I_i\left(t_j^*\right)} &\leq 1 \\ \frac{2\alpha_j n_{jj}}{\gamma_j} S_j\left(t_j^*\right) + \frac{\alpha_j n_{ij} + \alpha_i n_{ji}}{\gamma_j} S_j\left(t_j^*\right) \frac{I_i\left(t_j^*\right)}{I_j\left(t_j^*\right)} &= 1 \end{aligned}$$

and thus

$$\left(\frac{1}{S_i\left(t_j^*\right)} - \frac{2\alpha_i n_{ii}}{\gamma_i}\right)\left(\frac{1}{S_j\left(t_j^*\right)} - \frac{2\alpha_j n_{jj}}{\gamma_j}\right) \geq \frac{(\alpha_j n_{ij} + \alpha_i n_{ji})^2}{\gamma_i \gamma_j} \frac{I_j\left(t_j^*\right)}{I_i\left(t_j^*\right)} \frac{I_i\left(t_j^*\right)}{I_j\left(t_j^*\right)} = \frac{(\alpha_j n_{ij} + \alpha_i n_{ji})^2}{\gamma_i \gamma_j}.$$

But $S_i\left(t_j^*\right) > S_i(\infty)$ and $S_j\left(t_j^*\right) > S_i(\infty)$, so we must again have $\frac{2\alpha_i n_{ii}}{\gamma_i} S_i(\infty) \leq 1$ and $\frac{2\alpha_j n_{jj}}{\gamma_j} S_j(\infty) \leq 1$, as well as

$$\left(\frac{1}{S_i(\infty)} - \frac{2\alpha_i n_{ii}}{\gamma_i}\right)\left(\frac{1}{S_j(\infty)} - \frac{2\alpha_j n_{jj}}{\gamma_j}\right) \geq \frac{(\alpha_j n_{ij} + \alpha_i n_{ji})^2}{\gamma_i \gamma_j}.$$

Going back to the system, this means that an increase in any n or a decrease in any γ will decrease the steady-state values for $S_i(\infty)$ and $S_j(\infty)$, and thus increase infections everywhere.

D.2 Proof of Proposition 1

Proposition 5: *Assume that there is trade between the two countries (i.e., $\alpha_j n_{ij} + \alpha_i n_{ji} > 0$), which implies that the next generation matrix FV^{-1} is irreducible. If $\mathcal{R}_0 \leq 1$, the no-pandemic equilibrium is the unique stable equilibrium. If $\mathcal{R}_0 > 1$, the no-pandemic equilibrium is unstable, and there exists a unique stable endemic equilibrium.*

Proof. The proof of existence and uniqueness, depending on whether $\mathcal{R}_0 \leq 1$ or $\mathcal{R}_0 > 1$, follows standard arguments for a two-group SIR model, as in Magal et al. (2016). We proceed in the following steps.

(A) The system of dynamic equations for susceptibles, infected and recovered is given by:

$$\dot{S}_i(t) = -2\alpha_i n_{ii} S_i(t) I_i(t) - \alpha_j n_{ij} S_i(t) I_j(t) - \alpha_i n_{ji} S_i(t) I_j(t), \tag{D.1}$$

$$\dot{S}_j(t) = -2\alpha_j n_{jj} S_j(t) I_j(t) - \alpha_i n_{ji} S_j(t) I_i(t) - \alpha_j n_{ij} S_j(t) I_i(t), \tag{D.2}$$

$$\dot{I}_i(t) = 2\alpha_i n_{ii} S_i(t) I_i(t) + \alpha_j n_{ij} S_i(t) I_j(t) + \alpha_i n_{ji} S_i(t) I_j(t) - \gamma_i I_i(t), \tag{D.3}$$

$$\dot{I}_j(t) = 2\alpha_j n_{jj} S_j(t) I_j(t) + \alpha_i n_{ji} S_j(t) I_i(t) + \alpha_j n_{ij} S_j(t) I_i(t) - \gamma_j I_j(t), \tag{D.4}$$

$$\dot{R}_i(t) = \gamma_i I_i(t), \tag{D.5}$$

$$\dot{R}_j(t) = \gamma_j I_j(t). \tag{D.6}$$

Note that we can re-write the dynamic equations for infections (D.3) and (D.4) as:

$$\begin{bmatrix} \dot{I}_i(t) \\ \dot{I}_j(t) \end{bmatrix} = \left\{ \begin{bmatrix} \frac{2\alpha_i n_{ii}}{\gamma_i} S_i(t) & \frac{\alpha_j n_{ij} + \alpha_i n_{ji}}{\gamma_j} S_i(t) \\ \frac{\alpha_j n_{ij} + \alpha_i n_{ji}}{\gamma_i} S_j(t) & \frac{2\alpha_j n_{jj}}{\gamma_j} S_j(t) \end{bmatrix} - \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \right\} \begin{bmatrix} \gamma_i I_i(t) \\ \gamma_j I_j(t) \end{bmatrix}. \tag{D.7}$$

The properties of this dynamic system depend crucially on the properties of the matrix B:

$$B \equiv \begin{bmatrix} \frac{2\alpha_i n_{ii}}{\gamma_i} S_i(t) & \frac{\alpha_j n_{ij} + \alpha_i n_{ji}}{\gamma_j} S_i(t) \\ \frac{\alpha_j n_{ij} + \alpha_i n_{ji}}{\gamma_i} S_j(t) & \frac{2\alpha_j n_{jj}}{\gamma_j} S_j(t) \end{bmatrix}.$$

We assume that there is trade between the two countries:

$$\frac{\alpha_j n_{ij} + \alpha_i n_{ji}}{\gamma_i} > 0, \qquad \frac{\alpha_j n_{ij} + \alpha_i n_{ji}}{\gamma_j} > 0,$$

which implies that the matrix B is irreducible for all strictly positive susceptibles $S_i(t), S_j(t) > 0$.
(B) Re-writing equations (D.1) and (D.2) in proportional changes, and using equations (D.5) and

(D.6), we have:

$$\frac{\dot{S}_i(t)}{S_i(t)} = -\frac{2\alpha_i n_{ii}}{\gamma_i}\dot{R}_i(t) - \frac{\alpha_j n_{ij} + \alpha_i n_{ji}}{\gamma_j}\dot{R}_j(t),$$
$$\frac{\dot{S}_j(t)}{S_j(t)} = -\frac{2\alpha_j n_{jj}}{\gamma_j}\dot{R}_j(t) - \frac{\alpha_i n_{ji} + \alpha_j n_{ij}}{\gamma_i}\dot{R}_i(t).$$

Integrating from 0 to t, we have:

$$\log S_i(t) - \log S_i(0) = -\frac{2\alpha_i n_{ii}}{\gamma_i}(R_i(t) - R_i(0)) - \frac{\alpha_j n_{ij} + \alpha_i n_{ji}}{\gamma_j}(R_j(t) - R_j(0)),$$

$$\log S_j(t) - \ln S_j(0) = -\frac{2\alpha_j n_{jj}}{\gamma_j}(R_j(t) - R_j(0)) - \frac{\alpha_i n_{ji} + \alpha_j n_{ij}}{\gamma_i}(R_i(t) - R_i(0)).$$

Using the accounting identities, $S_i(t) + I_i(t) + R_i(t) = 1$ and $S_j(t) + I_j(t) + R_j(t) = 1$, we obtain:

$$\log S_i(t) - \log S_i(0) = \frac{2\alpha_i n_{ii}}{\gamma_i}[(S_i(t) + I_i(t)) - (S_i(0) + I_i(0))] + \frac{\alpha_j n_{ij} + \alpha_i n_{ji}}{\gamma_j}[(S_j(t) + I_j(t)) - (S_j(0) + I_j(0))],$$

$$\log S_j(t) - \ln S_j(0) = \frac{2\alpha_j n_{jj}}{\gamma_j}[(S_j(t) + I_j(t)) - (S_j(0) + I_j(0))] + \frac{\alpha_i n_{ji} + \alpha_j n_{ij}}{\gamma_i}[(S_i(t) + I_i(t)) - (S_i(0) + I_i(0))].$$

In the steady state as $t \to \infty$, we have $I_i(\infty) = I_j(\infty) = 0$, and hence:

$$S_i(\infty) = S_i(0)\exp\left[\frac{2\alpha_i n_{ii}}{\gamma_i}[S_i(\infty) - V_i] + \frac{\alpha_j n_{ij} + \alpha_i n_{ji}}{\gamma_j}[S_j(\infty) - V_j]\right], \tag{D.8}$$

$$S_j(\infty) = S_j(0)\exp\left[\frac{2\alpha_j n_{jj}}{\gamma_j}[S_j(\infty) - V_j] + \frac{\alpha_i n_{ji} + \alpha_j n_{ij}}{\gamma_i}[S_i(\infty) - V_i]\right], \tag{D.9}$$

where $V_i \equiv S_i(0) + I_i(0)$ and $V_j(0) \equiv S_j(0) + I_j(0)$. We now define the following notation:

$$X \leq Y \quad \Leftrightarrow \quad X_k \leq Y_k \text{ for all } k \in \{i, j\},$$

$$X < Y \quad \Leftrightarrow \quad X \leq Y \text{ and } X_k < Y_k \text{ for some } k \in \{i, j\},$$

$$X \ll Y \quad \Leftrightarrow \quad X_k < Y_k \text{ for all } k \in \{i, j\},$$

and represent the system (D.8)-(D.9) as the following map:

$$X = T(X),$$

$$\begin{pmatrix} x_i \\ x_j \end{pmatrix} = T\begin{pmatrix} x_i \\ x_j \end{pmatrix} = \begin{pmatrix} T_i(x_i, x_j) \\ T_j(x_i, x_j) \end{pmatrix},$$

with

$$T_i(x_i, x_j) = S_i(0)\exp\left[\frac{2\alpha_i n_{ii}}{\gamma_i}[x_i - V_i] + \frac{\alpha_j n_{ij} + \alpha_i n_{ji}}{\gamma_j}[x_j - V_j]\right],$$

$$T_j(x_i, x_j) = S_j(0) \exp\left[\frac{\alpha_i n_{ji} + \alpha_j n_{ij}}{\gamma_i}[x_i - V_i] + \frac{2\alpha_j n_{jj}}{\gamma_j}[x_j - V_j]\right].$$

(C) Using this notation, we begin by establishing that all the fixed points of T in $[0, S(0)]$ are contained in the smaller interval $[S^-, S^+]$. To establish this result, note that T is monotonically increasing, which implies that:

$$X \leq Y \quad \Rightarrow \quad T(X) \leq T(Y).$$

Using our assumption of positive trade, $\frac{\alpha_i n_{ji} + \alpha_j n_{ij}}{\gamma_i} > 0$ and $\frac{\alpha_j n_{ij} + \alpha_i n_{ji}}{\gamma_j} > 0$, this implies:

$$X \ll Y \quad T(X) \ll T(Y).$$

For $S(0) \gg 0$, and using the definitions of V_i and V_j above, this implies:

$$0 \ll T(0) < T(S(0)) < S(0).$$

Therefore, by induction arguments, we have the following result for each $n \geq 1$:

$$0 \ll T(0) \cdots \ll T^n(0) \ll T^{n+1}(0) \leq T^{n+1}(S(0)) < \cdots T^n(S(0)) < S(0).$$

By taking the limit as n does to $+\infty$, we obtain:

$$0 \ll \lim_{n \to +\infty} T^n(0) =: S^- \leq S^+ := \lim_{n \to +\infty} T^n(S(0)) < S(0).$$

Then, by continuity of T, we have:

$$T\left(S^-\right) = S^- \quad \text{and} \quad T\left(S^+\right) = S^+.$$

(D) We next establish that if $S^- < S^+$ then $S^- \ll S^+$. This property follows from our assumption that the matrix B above is irreducible. Assume, for example, that $S_i^- < S_i^+$. Then, since $\frac{\alpha_i n_{ji} + \alpha_j n_{ij}}{\gamma_i} > 0$, we have:

$$S_j^- = T_j\left(S_i^-, S_j^-\right) \leq T_j\left(S_i^-, S_j^+\right) < T_2\left(S_i^+, S_j^+\right) = S_j^+.$$

Hence,

$$S_i^- < S_i^+ \Rightarrow S_j^- < S_j^+.$$

By the same argument, $\frac{\alpha_j n_{ij} + \alpha_i n_{ji}}{\gamma_j} > 0$ implies,

$$S_j^- < S_j^+ \Rightarrow S_i^- < S_i^+.$$

(E) We now establish the following result for $\lambda > 1$ and $X \gg 0$:

$$T\left(\lambda X + S^{-}\right) - T\left(S^{-}\right) \gg \lambda\left[T\left(X + S^{-}\right) - T\left(S^{-}\right)\right].$$

Note that we can write the left-hand side of this inequality as follows:

$$T\left(\lambda X + S^{-}\right) - T\left(S^{-}\right) = \int_0^1 DT\left(l\lambda X + S^{-}\right)(\lambda X)\, dl = \lambda \int_0^1 DT\left(l\lambda X + S^{-}\right) X dl,$$

where the differential of T is given by:

$$DT(X) = \begin{pmatrix} \frac{2\alpha_i n_{ii}}{\gamma_i} T_i(x_i, x_j) & \frac{\alpha_j n_{ij} + \alpha_i n_{ji}}{\gamma_j} T_i(x_i, x_j) \\ \frac{\alpha_i n_{ji} + \alpha_j n_{ij}}{\gamma_i} T_j(x_i, x_j) & \frac{2\alpha_j n_{jj}}{\gamma_j} T_j(x_i, x_j) \end{pmatrix}. \tag{D.10}$$

Since $\lambda > 1$ and $X \gg 0$, we have:

$$DT\left(l\lambda X + S^{-}\right) X \gg DT\left(lX + S^{-}\right) X \qquad \forall \quad l \in [0, 1].$$

It follows that:

$$\begin{aligned} T\left(\lambda X + S^{-}\right) - T\left(S^{-}\right) &\gg \lambda \int_0^1 DT\left(lX + S^{-}\right) X dl, \\ &= \lambda\left[T\left(X + S^{-}\right) - T\left(S^{-}\right)\right], \end{aligned}$$

which establishes the result.

(F) We now show that the map T has at most two equilibria such that either:

(i) $S^{-} = S^{+}$ and T has only one equilibrium in $[0, S(0)]$;

(ii) $S^{-} \ll S^{+}$ and the only equilibria of T in $[0, S(0)]$ are S^{-} and S^{+}.

We prove this result by contradiction. Assume that $S^{-} \neq S^{+}$. Then $S^{-} < S^{+}$, which implies $S^{-} \ll S^{+}$. Now suppose that there exists $\bar{X} \in [S^{-}, S^{+}]$ a fixed point T such that:

$$S^{-} \neq \bar{X} \qquad \text{and} \qquad \bar{X} \neq S^{+}.$$

Then, by using the same arguments as in **(D)** above, we have:

$$S^{-} \ll \bar{X} \ll S^{+}.$$

Now define:

$$\gamma := \sup\left\{\lambda \geq 1 : \lambda\left(\bar{X} - S^{-}\right) + S^{-} \leq S^{+}\right\}. \tag{D.11}$$

Since $\bar{X} \ll S^{+}$ this implies that

$$\gamma > 1.$$

We have

$$\gamma\left(\bar{X}-S^{-}\right)+S^{-}\leq S^{+},$$

and, by applying T to both sides of this inequality, we obtain:

$$T\left(\gamma\left(\bar{X}-S^{-}\right)+S^{-}\right)\leq S^{+}.$$

Now, using **(E)**, we have:

$$\begin{aligned}
T\left(\gamma\left(\bar{X}-S^{-}\right)+S^{-}\right)-T\left(S^{-}\right) &\gg \gamma\left[T\left(\left(\bar{X}-S^{-}\right)+S^{-}\right)-T\left(S^{-}\right)\right],\\
&= \gamma\left[T\left(\bar{X}\right)-T\left(S^{-}\right)\right],\\
&= \gamma\left[\bar{X}-S^{-}\right].
\end{aligned}$$

Therefore we have shown that:

$$S^{+}\geq T\left(\gamma\left(\bar{X}-S^{-}\right)+S^{-}\right)\gg\gamma\left[\bar{X}-S^{-}\right],$$

which contradicts the definition of gamma as the supremum of the set in equation (D.11), since $S^{-}\geq 0$. Therefore we cannot have another fixed point $\bar{X}\in\left[S^{-},S^{+}\right]$.

(G) Now consider the case where:

$$S^{-}\ll S^{+}.$$

In this case of two equilibria, the differential of T can be written as:

$$DT\left(S^{\pm}\right)=B\left(S_i^{\pm}\right)=\begin{pmatrix} \frac{2\alpha_i n_{ii}}{\gamma_i}S_i^{\pm} & \frac{\alpha_j n_{ij}+\alpha_i n_{ji}}{\gamma_j}S_i^{\pm} \\ \frac{\alpha_i n_{ji}+\alpha_j n_{ij}}{\gamma_i}S_j^{\pm} & \frac{2\alpha_j n_{jj}}{\gamma_j}S_j^{\pm} \end{pmatrix}.$$

(H) We now establish the following property of the spectral radius of the matrices $DT\left(S^{-}\right)$ and $DT\left(S^{+}\right)$:

$$\rho\left(DT\left(S^{-}\right)\right)<1<\rho\left(DT\left(S^{+}\right)\right).$$

To prove this result, note that:

$$\begin{aligned}
S^{+}-S^{-} &= T\left(S^{+}\right)-T\left(S^{-}\right),\\
&= T\left(\left(S^{+}-S^{-}\right)+S^{-}\right)-T\left(S^{-}\right),\\
&= \int_0^1 DT\left(l\left(S^{+}-S^{-}\right)+S^{-}\right)\left(S^{+}-S^{-}\right)dl.
\end{aligned}$$

Since $S^{+}-S^{-}\gg 0$, we also have:

$$\begin{aligned}
DT\left(S^{+}\right)\left(S^{+}-S^{-}\right) &\gg \int_0^1 DT\left(l\left(S^{+}-S^{-}\right)+S^{-}\right)\left(S^{+}-S^{-}\right)dl,\\
&\gg DT\left(S^{-}\right)\left(S^{+}-S^{-}\right).
\end{aligned}$$

Combining these two results, we obtain:

$$DT\left(S^{+}\right)\left(S^{+}-S^{-}\right) \gg \left(S^{+}-S^{-}\right) \gg DT\left(S^{-}\right)\left(S^{+}-S^{-}\right). \tag{D.12}$$

which can be equivalently written as:

$$\left[DT\left(S^{+}\right)-I\right]\left(S^{+}-S^{-}\right)>0,$$

$$\left[DT\left(S^{+}\right)-\xi^{+}I\right]\left(S^{+}-S^{-}\right)=0, \qquad \xi^{+}>1,$$

and

$$\left[DT\left(S^{-}\right)-I\right]\left(S^{+}-S^{-}\right)<0,$$

$$\left[DT\left(S^{-}\right)-\xi^{-}I\right]\left(S^{+}-S^{-}\right)=0, \qquad \xi^{-}<1,$$

where I is the identity matrix. Noting that the matrices $DT\left(S^{+}\right)$ and $DT\left(S^{-}\right)$ are non-negative and irreducible, the Perron-Frobenius theorem implies:

$$\xi^{-}=\rho\left(DT\left(S^{-}\right)\right)<1<\rho\left(DT\left(S^{+}\right)\right)=\xi^{+}.$$

(I) We now solve explicitly for the spectral radius of the matrices $DT\left(S^{\pm}\right)$. We find the eigenvalues of the matrix $DT\left(S^{\pm}\right)$ by solving the characteristic equation:

$$\left|DT\left(S^{\pm}\right)-\xi^{\pm}I\right|=\left|\left[\begin{array}{cc} \frac{2\alpha_i n_{ii}}{\gamma_i}S_i^{\pm} & \frac{\alpha_j n_{ij}+\alpha_i n_{ji}}{\gamma_j}S_j^{\pm} \\ \frac{\alpha_j n_{ij}+\alpha_i n_{ji}}{\gamma_i}S_i^{\pm} & \frac{2\alpha_j n_{jj}}{\gamma_j}S_j^{\pm} \end{array}\right]-\left[\begin{array}{cc} \xi^{\pm} & 0 \\ 0 & \xi^{\pm} \end{array}\right]\right|=0.$$

The characteristic polynomial is:

$$\left(\xi^{\pm}\right)^2-\left(\frac{2\alpha_i n_{ii}}{\gamma_i}S_i^{\pm}+\frac{2\alpha_j n_{jj}}{\gamma_j}S_j^{\pm}\right)\xi^{\pm}+\left(\frac{2\alpha_i n_{ii}}{\gamma_i}\frac{2\alpha_j n_{jj}}{\gamma_j}S_i^{\pm}S_j^{\pm}-\frac{\left(\alpha_j n_{ij}+\alpha_i n_{ji}\right)^2}{\gamma_i\gamma_j}S_i^{\pm}S_j^{\pm}\right)=0.$$

The spectral radius is the largest eigenvalue:

$$\rho\left(DT\left(S^{\pm}\right)\right)=\frac{1}{2}\left(\frac{2\alpha_i n_{ii}}{\gamma_i}S_i^{\pm}+\frac{2\alpha_j n_{jj}}{\gamma_j}S_j^{\pm}\right)+\frac{1}{2}\sqrt{\left(\frac{2\alpha_i n_{ii}}{\gamma_i}S_i^{\pm}-\frac{2\alpha_j n_{jj}}{\gamma_j}S_j^{\pm}\right)^2+4\frac{\left(\alpha_j n_{ij}+\alpha_i n_{ji}\right)^2}{\gamma_i\gamma_j}S_i^{\pm}S_j^{\pm}}.$$

(J) We now use the results in **(H)** and **(I)** to examine the local stability of the two steady-state equilibria. From the dynamics of infections in equation (D.7), we have:

$$\left[\begin{array}{c} \dot{I}_i^{\pm} \\ \dot{I}_j^{\pm} \end{array}\right]=\left\{\left[\begin{array}{cc} \frac{2\alpha_i n_{ii}}{\gamma_i}S_i^{\pm} & \frac{\alpha_j n_{ij}+\alpha_i n_{ji}}{\gamma_j}S_j^{\pm} \\ \frac{\alpha_j n_{ij}+\alpha_i n_{ji}}{\gamma_i}S_i^{\pm} & \frac{2\alpha_j n_{jj}}{\gamma_j}S_j^{\pm} \end{array}\right]-\left[\begin{array}{cc} 1 & 0 \\ 0 & 1 \end{array}\right]\right\}\left[\begin{array}{c} I_i^{\pm} \\ I_j^{\pm} \end{array}\right]. \tag{D.13}$$

Therefore the spectral radius of the matrix $DT\left(S^{\pm}\right)$ corresponds to the global $\mathcal{R}_0$ that determines the local stability of the two steady-state equilibria. As we have shown that $\rho\left(DT\left(S^{+}\right)\right)>1$, the steady state S^+ is locally unstable. As we have shown that $\rho\left(DT\left(S^-\right)\right) < 1$, the steady state S^- is locally stable.

■

D.3 Local Stability of Pandemic-Free Equilibrium

In Section 4.3 of the main text, we characterize the stability of the non-pandemic equilibrium using the next generation matrix, as defined immediately above equation (16), following Diekmann et al. (1990). In this section of the Online Appendix, we show that an analogous result can be derived using the Jacobian of the SIR system of equations.

In particular, we consider the laws of motion for (S_i, S_j, I_i, I_j) evaluated at the pandemic-free equilibrium, in which $S_i = S_j \simeq 1$ and $I_i = I_j \simeq 0$. The Jacobian of this system is given by

$$J = \begin{bmatrix} 0 & 0 & -2\alpha_i n_{ii} & -\left(\alpha_j n_{ij} + \alpha_i n_{ji}\right) \\ 0 & 0 & -\left(\alpha_j n_{ij} + \alpha_i n_{ji}\right) & -2\alpha_j n_{jj} \\ 0 & 0 & 2\alpha_i n_{ii} - \gamma_i & \alpha_j n_{ij} + \alpha_i n_{ji} \\ 0 & 0 & \alpha_j n_{ij} + \alpha_i n_{ji} & 2\alpha_j n_{jj} - \gamma_j \end{bmatrix},$$

and the largest positive eigenvalue of this matrix is given by

$$\lambda_{\max} = \frac{1}{2}\left(2\alpha_i n_{ii} - \gamma_i\right) + \frac{1}{2}\left(2\alpha_j n_{jj} - \gamma_j\right) + \frac{1}{2}\sqrt{4\left(\alpha_j n_{ij} + \alpha_i n_{ji}\right)^2 + \left(\left(2\alpha_i n_{ii} - \gamma_i\right) - \left(2\alpha_j n_{jj} - \gamma_j\right)\right)^2}.$$

Since we are interested in finding necessary conditions for local stability of this equilibrium (i.e., $\lambda_{\max} < 0$), and noting that $\lambda_{\max}$ is increasing in n_{ij} and n_{ji}, we have that

$$\lambda_{\max} \geq \lambda_{\max}|_{n_{ij}=n_{ji}=0} = \max\left\{2\alpha_i n_{ii} - \gamma_i, 2\alpha_j n_{jj} - \gamma_{jj}\right\}. \tag{D.14}$$

As a result, a pandemic-free equilibrium can only be stable whenever $2\alpha_i n_{ii}/\gamma_i \leq 1$ and $2\alpha_j n_{jj}/\gamma_{jj} \leq 1$. This confirms that if the reproduction number $\mathcal{R}_{0i}$ based only on domestic interactions (but evaluated at the world equilibrium value of n_{ii}) is higher than 1 in *any* country, the pandemic-free equilibrium is necessarily unstable.

D.4 Open Economy Equilibrium with Many Countries

In this subsection of the Online Appendix, we show that the epidemiological externality illustrated for two countries in Section 4.3 of the paper extends to the general case of $N \geq 2$ countries with arbitrary country asymmetries. If any country has a reproduction number $\mathcal{R}_{0i}$ of greater than one based on its domestic interactions, there is a global pandemic.

In the general case N countries, the global $\mathcal{R}_{0i}$ again corresponds to the spectral radius of the next generation matrix $A = (FV)^{-1}$. Assume that this matrix A is positive. Denote its spectral radius by $\rho(A)$. Let x be the Perron vector. By the Perron-Frobenius Theorem, we have:

$$Ax = \rho(A)\, x.$$

Consider the i-th row of the above matrix system. We have:

$$\sum_j a_{ij} x_j = \rho(A)\, x_i.$$

Since A is positive, we also know:

$$a_{ii} x_i < \sum_j a_{ij} x_j.$$

Combining these last two results, we have:

$$a_{ii} x_i < \sum_j a_{ij} x_j = \rho(A)\, x_i,$$

which establishes that $a_{ii} < \rho(A)$. Therefore, the spectral radius $\rho(A)$ is always larger than the largest diagonal element of the matrix A. It follows that a sufficient condition for the spectral radius of the next generation matrix to be greater than 1 is that $\mathcal{R}_{0i}$ based on *any* country's domestic rate of infections is strictly greater than 1.

Note, however, that the intensity of domestic interactions is lower in the open economy than in the closed economy, and is decreasing in the number of trade partners, because of substitution in interactions across destinations. Additionally, even if one country has a reproduction number $\mathcal{R}_{0i}$ of greater than one based on its domestic interactions, the resulting global pandemic can be small if that country is small relative to other countries.

D.5 Multiple Waves of Infection

In this Appendix, we show that another implication of the interaction between trade and disease dynamics in our model is that multiple waves of infection can occur in the open economy, even though a single wave of infection would occur in the closed economy. Remember that for values of the global reproduction rate ($\mathcal{R}_0$) greater than one, a pandemic occurs in the open economy. Integrating the dynamics of infections in each country using the initial conditions $S_i(0) = S_j(0) = 1$ and $R_i(0) = R_j(0) = 0$, we obtain the following closed-form solutions for infections in each country at each point in time (I_{it}, I_{jt}) as a function of susceptibles in each country ($S_i(t)$, $S_j(t)$):

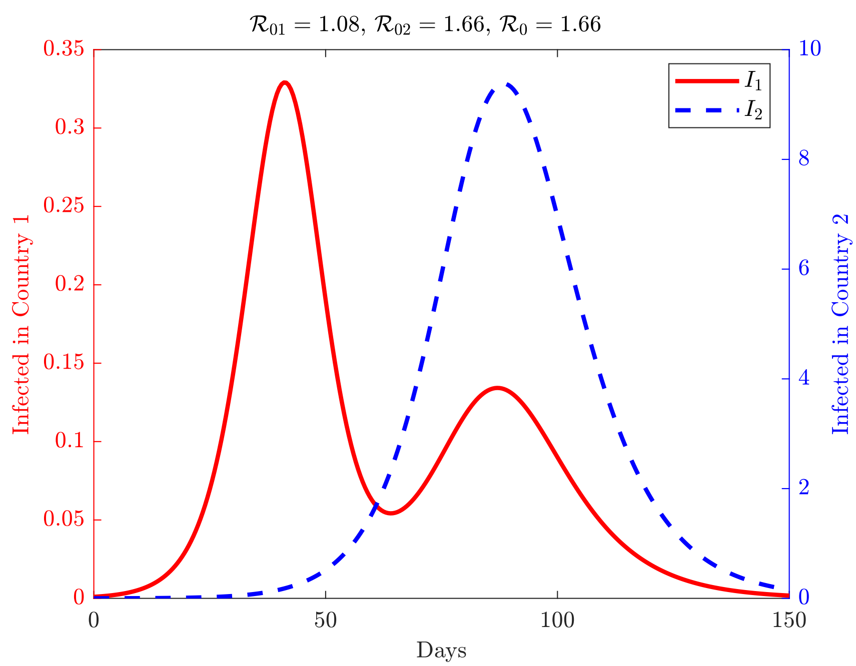
$$I_i(t) = 1 - S_i(t) + \frac{\log S_i(t) - \frac{\alpha_j n_{ij} + \alpha_i n_{ji}}{2\alpha_j n_{jj}} \log S_j(t)}{\frac{2\alpha_i n_{ii}}{\gamma_i} - \frac{\alpha_j n_{ij} + \alpha_i n_{ji}}{2\alpha_j n_{jj}} \frac{\alpha_i n_{ji} + \alpha_j n_{ij}}{\gamma_i}}, \tag{D.15}$$

$$I_j(t) = 1 - S_j(t) + \frac{\log S_j(t) - \frac{\alpha_i n_{ji} + \alpha_j n_{ij}}{2\alpha_i n_{ii}} \log S_i(t)}{\frac{2\alpha_j n_{jj}}{\gamma_j} - \frac{\alpha_i n_{ji} + \alpha_j n_{ij}}{2\alpha_i n_{ii}} \frac{\alpha_j n_{ij} + \alpha_i n_{ji}}{\gamma_j}}. \tag{D.16}$$

Although there is necessarily a single wave of infections in the closed economy, multiple waves of infection can occur in the open economy, because infections in each country in equations (D.15) and (D.16) depend on the stock of susceptibles in both countries. Multiple waves of infection occur when a country has a wham-bam epidemic that is over very quickly in the closed economy, whereas its trade partner has an epidemic that builds slowly in the closed economy. The first peak reflects the country's rapid explosion of infections, which dissipates quickly. The second peak, which is in general smaller, reflects the evolution of the pandemic in its trade partner.

In Figure D.1 we provide an example, in which Country 1 experiences two waves of infections in the open economy, whereas Country 2 experiences a single, more prolonged and severe wave. Country 1 features a large value of α_1, but also a large value of γ_1. Thus, although the infection rate is large, people remain contagious only briefly (perhaps because of a good contact tracing program). The resulting domestic reproduction rate $\mathcal{R}_{01} = 1.08$ and the first peak of the pandemic is relatively small and quick. Since Country 1 is assumed ten times smaller than Country 2, its small initial pandemic has no significant effect on Country 2. There, the infection rate is much smaller, but the disease remains contagious for much longer, leading to a larger $\mathcal{R}_{01} = 1.66$, which also results in a global reproduction number $\mathcal{R}_0 = 1.66$.[3] The result is a more protracted but also much longer singled-peaked pandemic in Country 2. This large pandemic does affect the smaller country through international interactions. The large country amounts for many of the interactions of the small country, which leads to the second wave of the pandemic in Country 2.

Figure D.1: Multiple Waves of Infection in the Open Economy



Note: See Online Appendix K for further details on the parameters and algorithms used in these numerical simulations.

[3] The parameter values used in the exercise are $\sigma = 4.5$, $L_1 = 2$, $L_2 = 20$, $d_{12} = d_{11}$, $c = 0.12$, $\alpha_1 = 0.69$, $\alpha_2 = 0.09$, $\gamma_1 = 2.1$ and $\gamma_2 = 0.18$. All other values are identical to the baseline case. See Online Appendix K for more details.

Essential for this example is that countries have very different timings for their own pandemics in autarky, but also that in the open economy the relationship is very asymmetric, with the small country having little effect on the large country but the large country influencing the small country significantly. If the interactions are large enough in both directions, both countries will end up with a synchronized pandemic with only one peak. This property of multiples waves of infections was observed during the Covid-19 pandemic. While these multiple waves in part reflected time-varying policies such as lockdowns, there was also much discussion of countries (or states in large countries such as the United States) becoming reinfected from one another.[4]

D.6 Proof of Proposition 2

See main text. In particular, the result is an immediate corollary of Proposition B.3 in Section B.5 of this Online Appendix.

D.7 Proof of Proposition 3

See main text.

E Theoretical Appendix for GE Social Distancing

In this section of the Online Appendix, we report additional theoretical derivations for our generalization of our open-economy SIR model with general equilibrium social distancing from Section 5 of the paper.

E.1 Comparative Statics with Respect to Labor Supply

We begin by establishing comparative statics with respect to labor supply.

Proposition E.1 *A decrease in the population of country i relative to that in country j leads to a decrease in the rates n_{ii} and n_{ji} at which individuals meet in country i, and to an increase in the rates n_{jj} and n_{ij} at which individuals meet in country j.*

Note from equation (B.1), that we can write

$$
\begin{aligned}
\frac{w_i}{P_i} &= const \times \left(\left(\frac{1}{Z_i}\right)^{-\frac{\phi(\sigma-1)}{\phi-1}} (\Upsilon_{ii})^{-\varepsilon} + \left(\frac{\omega}{Z_j}\right)^{-\frac{\phi(\sigma-1)}{\phi-1}} (\Upsilon_{ij})^{-\varepsilon} \right)^{\frac{(\phi-1)}{\phi(\sigma-1)-1}} \\
\frac{w_j}{P_i} &= const \times \omega \left(\left(\frac{1}{Z_i}\right)^{-\frac{\phi(\sigma-1)}{\phi-1}} (\Upsilon_{ii})^{-\varepsilon} + \left(\frac{\omega}{Z_j}\right)^{-\frac{\phi(\sigma-1)}{\phi-1}} (\Upsilon_{ij})^{-\varepsilon} \right)^{\frac{(\phi-1)}{\phi(\sigma-1)-1}}
\end{aligned}
$$

[4] See, for example, the discussion of U.S. regional patterns of infection in the Covid -19 pandemic in the New York Times: "What Previous Covid-19 Waves Tell Us About the Virus Now".

where $\omega = w_j/w_i$. Plugging in equation (7) in the main text, we have

$$n_{ii} = const \times \left(\frac{w_i}{P_i}\right)^{-\frac{\sigma-2}{\phi-1}} \left(\left(\frac{1}{Z_i}\right)^{-\frac{\phi(\sigma-1)}{\phi-1}} (\Upsilon_{ii})^{-\varepsilon} + \left(\frac{\omega}{Z_j}\right)^{-\frac{\phi(\sigma-1)}{\phi-1}} (\Upsilon_{ij})^{-\varepsilon}\right)^{-\frac{\sigma-2}{\phi(\sigma-1)-1}},$$

and thus n_{ii} increases in ω. Next, note

$$\begin{aligned} n_{ij} &= const \times \left(\frac{w_j}{P_i}\right)^{-\frac{\sigma-1}{(\phi-1)}} \left(\frac{w_i}{P_i}\right)^{1/(\phi-1)} \\ &= const \times \omega^{-\frac{\sigma-1}{(\phi-1)}} \left(\left(\frac{1}{Z_i}\right)^{-\frac{\phi(\sigma-1)}{\phi-1}} (\Upsilon_{ii})^{-\varepsilon} + \left(\frac{\omega}{Z_j}\right)^{-\frac{\phi(\sigma-1)}{\phi-1}} (\Upsilon_{ij})^{-\varepsilon}\right)^{-\frac{\sigma-2}{\phi(\sigma-1)-1}}. \end{aligned}$$

The effect of ω may look ambiguous, but in fact we have that n_{ij} decreases if ω goes up. To see this, note that

$$\frac{\partial \omega^{-a} \left(b + c\omega^{-d}\right)^{-g}}{\partial \omega} = -\frac{(a-dg)\,c + ab\omega^d}{\left(\frac{1}{\omega^d}\,(c + b\omega^d)\right)^g \omega^a \omega \,(c + b\omega^d)},$$

which is negative if $a - dg > 0$. But here we have

$$a - dg = \frac{\sigma - 1}{(\phi - 1)} - \frac{\phi\,(\sigma - 1)}{\phi - 1} \frac{\sigma - 2}{\phi\,(\sigma - 1) - 1} = \frac{\sigma - 1}{\phi\,(\sigma - 1) - 1} > 0.$$

In sum, n_{ij} decreases in ω. Because an increase in L_i/L_j increases in ω (from straightforward use of the implicit function theorem to equation (11) in the main text), the Proposition follows.

Notice also that

$$\begin{aligned} n_{ji} &= const \times \left(\frac{w_i}{P_j}\right)^{-\frac{\sigma-1}{(\phi-1)}} \left(\frac{w_j}{P_j}\right)^{1/(\phi-1)} \\ &= const \times \omega^{\frac{\sigma-1}{(\phi-1)}} \left(\left(\frac{\omega}{Z_j}\right)^{-\frac{\phi(\sigma-1)}{\phi-1}} (\Upsilon_{jj})^{-\varepsilon} + \left(\frac{1}{Z_i}\right)^{-\frac{\phi(\sigma-1)}{\phi-1}} (\Upsilon_{ji})^{-\varepsilon}\right)^{-\frac{\sigma-2}{\phi(\sigma-1)-1}}, \end{aligned}$$

and by an analogous argument above, we have that n_{ji} increases in ω, and thus an increase in population in i leads to an increase in n_{ji} (while also decreasing n_{jj}).

E.2 Proof of Proposition 4

Building on the comparative statics with respect to labor supply in the previous subsection, we now provide a proof of Proposition 4 in the paper. The goods market clearing condition with deaths defines the following implicit function:

$$\Lambda_i = \left[\begin{array}{c} \frac{(Z_i)^{\frac{\phi(\sigma-1)}{\phi-1}}(\Upsilon_{ii})^{-\varepsilon}}{(Z_i)^{\frac{\phi(\sigma-1)}{\phi-1}}(\Upsilon_{ii})^{-\varepsilon}+(Z_j/\omega)^{\frac{\phi(\sigma-1)}{\phi-1}}(\Upsilon_{ij})^{-\varepsilon}}\left(1-D_i\right)L_i \\ +\frac{(Z_i)^{\frac{\phi(\sigma-1)}{\phi-1}}(\Upsilon_{ji})^{-\varepsilon}}{(Z_j/\omega)^{\frac{\phi(\sigma-1)}{\phi-1}}(\Upsilon_{jj})^{-\varepsilon}+(Z_i)^{\frac{\phi(\sigma-1)}{\phi-1}}(\Upsilon_{ji})^{-\varepsilon}}\omega\left(1-D_j\right)L_j-\left(1-D_i\right)L_i \end{array} \right] = 0.$$

Taking partial derivatives of this implicit function, we have:

$$\frac{\partial \Lambda_i}{\partial D_i} > 0, \qquad \frac{\partial \Lambda_i}{\partial D_j} < 0, \qquad \frac{\partial \Lambda_i}{\partial \omega} > 0.$$

Therefore, from the implicit function theorem, we have the following comparative statics of the relative wage with respect to deaths in the two countries:

$$\frac{d\omega}{dD_i} = -\frac{\partial \Lambda_i/\partial D_i}{\partial \Lambda_i/\partial \omega} < 0, \qquad \frac{d\omega}{dD_j} = -\frac{\partial \Lambda_i/\partial D_j}{\partial \Lambda_i/\partial \omega} > 0. \tag{E.1}$$

We now combine these results above with the comparative statics of bilateral interactions with respect to the relative wage (ω) from Proposition E.1 in the previous subsection. In particular, from the proof of that proposition, we have the following results:

$$\frac{dn_{ii}}{d\omega} > 0, \qquad \frac{dn_{ij}}{d\omega} < 0. \tag{E.2}$$

Combining these two sets of relationships (E.1) and (E.2), we have the following results stated in the proposition:

$$\frac{dn_{ii}}{dD_i} = \underbrace{\frac{dn_{ii}}{d\omega}}_{>0}\underbrace{\frac{d\omega}{dD_i}}_{<0} < 0, \qquad \frac{dn_{ii}}{dD_j} = \underbrace{\frac{dn_{ii}}{d\omega}}_{>0}\underbrace{\frac{d\omega}{dD_j}}_{>0} > 0.$$

$$\frac{dn_{ij}}{dD_i} = \underbrace{\frac{dn_{ij}}{d\omega}}_{<0}\underbrace{\frac{d\omega}{dD_i}}_{<0} > 0, \qquad \frac{dn_{ij}}{dD_j} = \underbrace{\frac{dn_{ij}}{d\omega}}_{<0}\underbrace{\frac{d\omega}{dD_j}}_{>0} < 0.$$

E.3 Elasticity of Wages with Respect to Labor Supply

In this subsection of the Online Appendix, we provide an analytical characterization of the elasticity of a country's relative wage with respect to its own population in our baseline open-economy SIR model from Sections 3-4 of the main text. The general equilibrium of this open-economy SIR model is characterized by the following trade share and market clearing condition:

$$\pi_{ji} = \frac{(\Upsilon_{ji})^{-\epsilon}(w_i/Z_i)^{-\frac{\phi(\sigma-1)}{\phi-1}}}{(\Upsilon_{ji})^{-\epsilon}(w_i/Z_i)^{-\frac{\phi(\sigma-1)}{\phi-1}} + (\Upsilon_{jj})^{-\epsilon}(w_j/Z_j)^{-\frac{\phi(\sigma-1)}{\phi-1}}},$$

$$w_i L_i = \pi_{ii} w_i L_i + \pi_{ji} w_j L_j,$$

where recall that the first subscript is the country of consumption and the second subscript is the country of production. We focus on comparative statics with respect to population (L_i), where the deaths considered in Section 5.1 of the main text correspond to a reduction in population (L_i). We start by totally differentiating the market clearing condition:

$$\frac{dw_i}{w_i}w_iL_i + \frac{dL_i}{L_i}w_iL_i = \left[\begin{array}{c} \pi_{ii}w_iL_i\frac{dw_i}{w_i} + \pi_{ii}w_iL_i\frac{dL_i}{L_i} + \pi_{ii}w_iL_i\frac{d\pi_{ii}}{\pi_{ii}} \\ +\pi_{ji}w_jL_j\frac{dw_j}{w_j} + \pi_{ji}w_jL_j\frac{dL_j}{L_j} + \pi_{ji}w_jL_j\frac{d\pi_{ji}}{\pi_{ji}} \end{array} \right].$$

We choose the wage in country j as the numéraire: $w_j = 1$ and hence $dw_j/w_j = 0$. Using this choice of numéraire, and dividing through by w_iL_i, we get:

$$\frac{dw_i}{w_i} + \frac{dL_i}{L_i} = \left[\begin{array}{c} \xi_{ii}\frac{dw_i}{w_i} + \xi_{ii}\frac{dL_i}{L_i} + \xi_{ii}\frac{d\pi_{ii}}{\pi_{ii}} \\ +\xi_{ij}\frac{dL_j}{L_j} + \xi_{ij}\frac{d\pi_{ji}}{\pi_{ji}} \end{array} \right],$$

where we have defined ξ_{ij} as the share of country i's income that comes from market j:

$$\xi_{ij} \equiv \frac{\pi_{ji}w_jL_j}{w_iL_i}.$$

Dividing through by dL_i/L_i, and assuming for simplicity that country j's population is constant ($dL_j/L_j = 0$), we get:

$$\frac{dw_i/w_i}{dL_i/L_i} + 1 = \left[\xi_{ii}\frac{dw_i/w_i}{dL_i/L_i} + \xi_{ii} + \xi_{ii}\frac{d\pi_{ii}/\pi_{ii}}{dL_i/L_i} + \xi_{ij}\frac{d\pi_{ji}/\pi_{ji}}{dL_i/L_i}\right].$$

Noting that wages are the only endogenous variable that affects the trade share, and using our choice of numéraire, we can re-write this equation as:

$$\frac{dw_i/w_i}{dL_i/L_i} + 1 = \left[\xi_{ii}\frac{dw_i/w_i}{dL_i/L_i} + \xi_{ii} + \xi_{ii}\frac{d\pi_{ii}/\pi_{ii}}{dw_i/w_i}\frac{dw_i/w_i}{dL_i/L_i} + \xi_{ij}\frac{d\pi_{ji}/\pi_{ji}}{dw_i/w_i}\frac{dw_i/w_i}{dL_i/L_i}\right].$$

Re-arranging this relationship, we have:

$$\frac{dw_i/w_i}{dL_i/L_i}\left[1 - \xi_{ii} - \xi_{ii}\frac{d\pi_{ii}/\pi_{ii}}{dw_i/w_i} - \xi_{ij}\frac{d\pi_{ji}/\pi_{ji}}{dw_i/w_i}\right] = -\left(1 - \xi_{ii}\right),$$

and hence:

$$\frac{dw_i/w_i}{dL_i/L_i} = -\frac{1 - \xi_{ii}}{\left[1 - \xi_{ii} - \xi_{ii}\frac{d\pi_{ii}/\pi_{ii}}{dw_i/w_i} - \xi_{ij}\frac{d\pi_{ji}/\pi_{ji}}{dw_i/w_i}\right]}. \tag{E.3}$$

Totally differentiating the trade share, holding productivity (Z_i, Z_j) and trade costs (Υ_{ii}, Υ_{jj}, Υ_{ij}, Υ_{ji}) constant, and using our choice of numéraire, we have:

$$d\pi_{ji} = -\left(\frac{\phi(\sigma-1)}{\phi-1}\right)\frac{dw_i}{w_i}\frac{(\Upsilon_{ji})^{-\epsilon}(w_i/Z_i)^{-\frac{\phi(\sigma-1)}{\phi-1}}}{(\Upsilon_{ji})^{-\epsilon}(w_i/Z_i)^{-\frac{\phi(\sigma-1)}{\phi-1}}+(\Upsilon_{jj})^{-\epsilon}(1/Z_j)^{-\frac{\phi(\sigma-1)}{\phi-1}}}$$
$$+\left(\frac{\phi(\sigma-1)}{\phi-1}\right)\frac{dw_i}{w_i}\frac{(\Upsilon_{ji})^{-\epsilon}(w_i/Z_i)^{-\frac{\phi(\sigma-1)}{\phi-1}}}{(\Upsilon_{ji})^{-\epsilon}(w_i/Z_i)^{-\frac{\phi(\sigma-1)}{\phi-1}}+(\Upsilon_{jj})^{-\epsilon}(1/Z_j)^{-\frac{\phi(\sigma-1)}{\phi-1}}}\frac{(\Upsilon_{ji})^{-\epsilon}(w_i/Z_i)^{-\frac{\phi(\sigma-1)}{\phi-1}}}{(\Upsilon_{ji})^{-\epsilon}(w_i/Z_i)^{-\frac{\phi(\sigma-1)}{\phi-1}}+(\Upsilon_{jj})^{-\epsilon}(1/Z_j)^{-\frac{\phi(\sigma-1)}{\phi-1}}},$$

which can be written as:

$$\frac{d\pi_{ji}/\pi_{ji}}{dw_i/w_i} = -\left(\frac{\phi(\sigma-1)}{\phi-1}\right)(1-\pi_{ji}),$$

where $\frac{\phi(\sigma-1)}{\phi-1}$ is the elasticity of trade flows with respect to trade frictions t_{ji}.

Using this result in equation (E.3) above, we obtain the following closed-form solution for the elasticity of a country's wage with respect to its population:

$$\frac{dw_i/w_i}{dL_i/L_i} = -\frac{1-\xi_{ii}}{\left[(1-\xi_{ii})+\xi_{ii}\left(\frac{\phi(\sigma-1)}{\phi-1}\right)(1-\pi_{ii})+\xi_{ij}\left(\frac{\phi(\sigma-1)}{\phi-1}\right)(1-\pi_{ji})\right]} < 0. \tag{E.4}$$

We can equivalently write this expression as:

$$\frac{dw_i/w_i}{dL_i/L_i} = -\frac{1}{\left[1+\frac{\xi_{ii}}{1-\xi_{ii}}\left(\frac{\phi(\sigma-1)}{\phi-1}\right)(1-\pi_{ii})+\frac{\xi_{ij}}{1-\xi_{ii}}\left(\frac{\phi(\sigma-1)}{\phi-1}\right)(1-\pi_{ji})\right]},$$

and hence:

$$\frac{dw_i/w_i}{dL_i/L_i} = -\frac{1}{\left[1+\left(\frac{\phi(\sigma-1)}{\phi-1}\right)\left[\frac{\xi_{ii}}{1-\xi_{ii}}(1-\pi_{ii})+(1-\pi_{ji})\right]\right]},$$

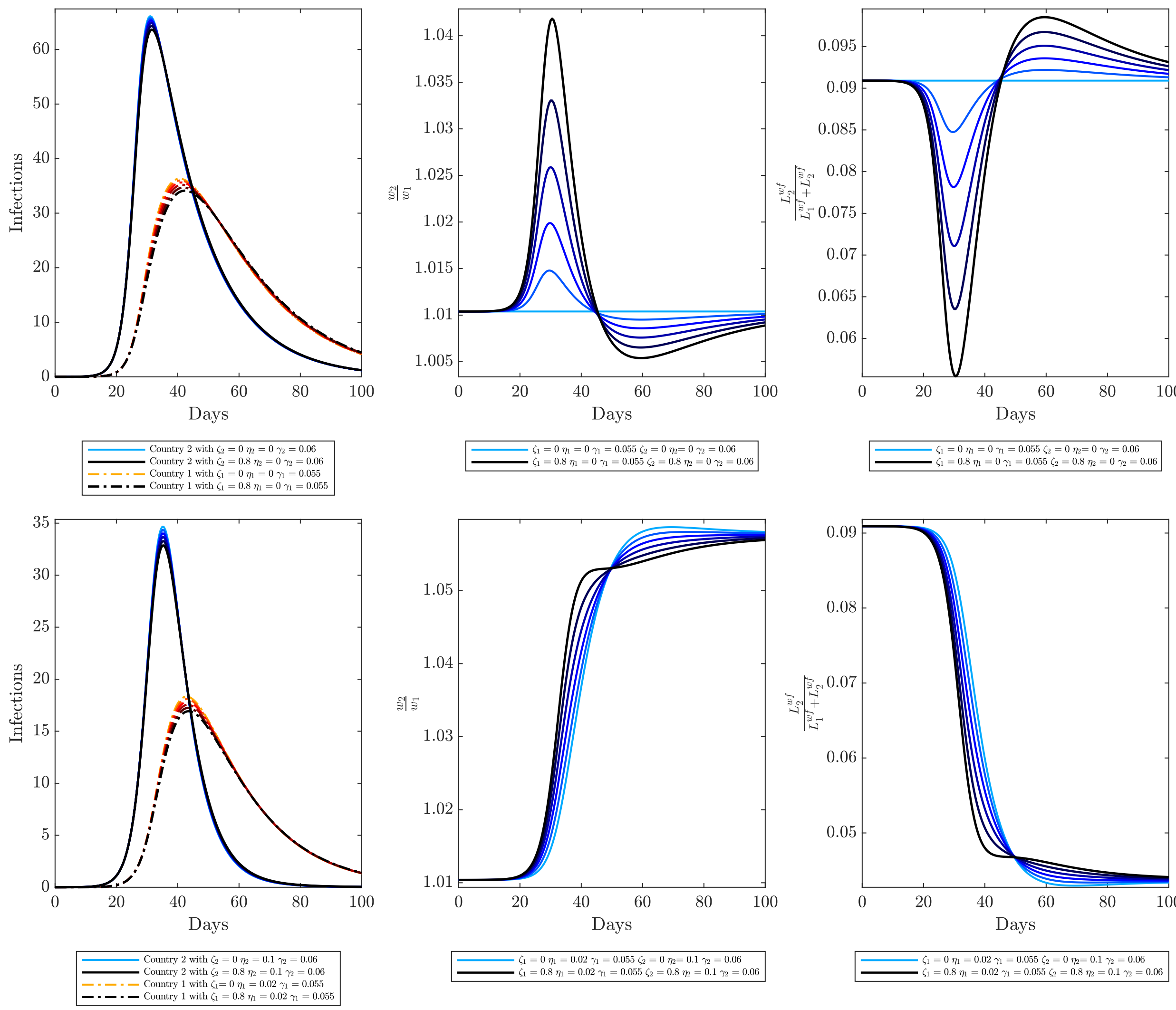
Therefore, this wage elasticity is larger in absolute value for smaller $\frac{\phi(\sigma-1)}{\phi-1}$ (as $\frac{\phi(\sigma-1)}{\phi-1}$ approaches zero from above), such that a larger change in relative wages and the international terms of trade is required to restore goods market equilibrium. Additionally, this wage elasticity becomes larger in absolute value as the share of country i's income that it derives from itself (ξ_{ii}) becomes smaller, such that country i becomes more dependent on foreign markets. Finally, this wage elasticity is bounded above in absolute value by one, and converges to this largest absolute value as $\frac{\phi(\sigma-1)}{\phi-1}$ converges to zero from above.

E.4 Reduced Labor Supply without Isolation

In Section 5.2 of the paper we extended our baseline model to have infected individuals supply less labor and isolate. We now study the case in which infected individuals supply less labor (or are less productive), but where they do not isolate. Specifically, we assume that infected agents only provide $1-\varsigma_i > 0$ units of labor. While they work, we assume that they still interact with other agents such that the system of differential equations for $\dot{S}_i, \dot{I}_i, \dot{R}_i$, and $\dot{D}_i$ remains the one in equations (20)-(23). This case allows us to showcase more clearly the general equilibrium implications of reductions in labor supply due to illness.

In Figure E.1 we present a set of numerical simulations of our model to illustrate some of these implications. The top row of figures presents a set of exercises in which we set $\eta_i = 0$ in both countries and so there are no deaths. The example isolates the effect of the reduced labor supply by the infected. We present simulations for six values of ς_i between 0 and 0.8. The bottom row of figures presents the case when there are deaths as well. In both cases we let Country 1 be ten times larger than country two and we assume that it has a much healthier environment in which local contagion is rare. Contagion is much more common in Country 2. The large difference in size makes the general equilibrium wage effects particularly large in Country 2. The difference in health environments helps us make the infection wave asynchronous across countries.[5]

Figure E.1: Evolution of Infections, Relative Wages, and Labor Supply Share with Reduced Labor Supply by the Infected without Isolation



Note: See Online Appendix K for further details on the parameters and algorithms for these numerical simulations.

[5] See Online Appendix K for a description of the full set of parameters used in the figure.

Consider first the exercise in the top row. The worse health environment in Country 2 implies that it goes through its wave of infections early, which (see the graph in the first column of the first row) reduces its effective labor supply and increases its wage (as can be appreciated in the second and third columns of Figure E.1). Naturally, the effects are more pronounced the higher is ς_i, represented with darker curves. Perhaps interestingly, the reduced labor supply of infected individuals also has an effect on infections in both countries through the general equilibrium social distancing effect. For high ς_i, agents in both countries interact less with individuals in Country 2, due to the initial increase in relative wages. This reduces interactions with the infected population there, and lowers the peak of infections. The figure in the right panel of the top row illustrates this effect.

As Country 2 gains heard immunity and the number of infections in Country 2 declines, these effects disappear and eventually reverse, with higher numbers of infected people, lower relative labor supply, and higher relative wages in Country 1. Again, there is a general equilibrium social distancing effect, but because the health environment in the country is so much better, it is not perceivable in the figure.

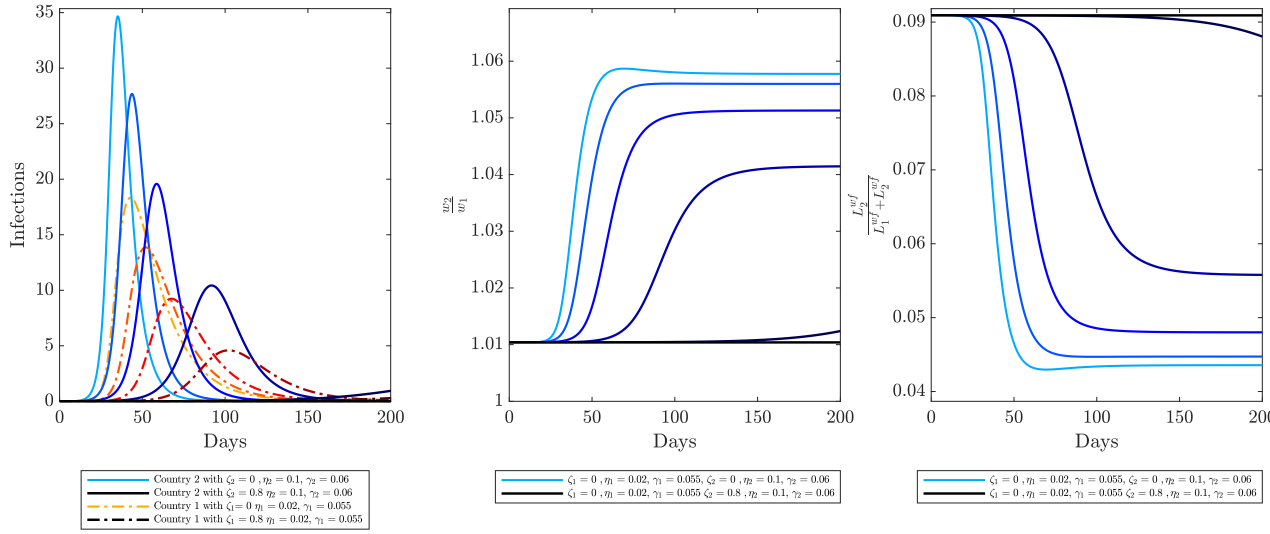
The second row of Figure E.1 presents a case in which there are also deaths, as in Section 5. The same effects discussed above are present, but all of them relative to the overall pattern of labor supply and wages caused by deaths. As in Figure 6 (in the main text), we assume that mortality is higher in Country 2, so relative labor supply decreases and wages increase even when $\varsigma_i = 0$ in both countries. Note that the general equilibrium social distancing effect on the number of infected people implies that more people die in Country 2 when $\varsigma_i > 0$ and so there is an effect of the reduction in labor supply by the infected on relative wages even when the pandemic ends.

In the example above, we assumed that even though infected individuals only work part-time, they still meet and infect others at the same rate. Instead, as in the main text, we can assume that for a fraction ς_i of the time, infected individuals 'isolate' and thus cannot infect other individuals. We continue to assume that there are no behavioral responses. As described in Section 5.2, this effect reduces the magnitude and importance of the general equilibrium social distancing effects that we underscored above. In the limit, when $\varsigma_1 = 1$ in all countries, there is no pandemic since the initially infected isolate completely and infections do not spread. Figure E.2 introduces isolation to the example in the bottom row of Figure E.1 and illustrates the reduction and flattening of the resulting infection wave in both countries.

F Theoretical Appendix for Behavioral Responses

In this section of the online appendix, we provide additional theoretical derivations for our generalization of our open-economy SIR model with behavioral responses from Section 6 of the paper.

Figure E.2: Evolution of Infections, Relative Wages, and Labor Supply Share with Reduced Labor Supply and Isolation by the Infected



Note: See Online Appendix K for further details on the parameters and algorithms for these numerical simulations.

F.1 Proof of Lemma 1

Proof. Because $Q_i(n_{ii}(t), n_{ij}(t)) \geq C_i(n_{ii}(t), n_{ij}(t))$, from equation (28) in the paper, we must have $\dot{\theta}_i^k(t) \geq 0$ at all t. This in turn implies that we must have $\theta_i^k(t) \leq 0$ at all t for the transversality condition to be met (i.e., convergence to 0 from below).

We next show that $\dot{\theta}_i^i(t) \geq 0$ and $\theta_i^i(t) \leq 0$ for all t. First note that we must have

$$\eta_i \theta_i^k(t) < (\gamma_i + \eta_i)\, \theta_i^i(t)$$

and thus (from equation (27) in the paper) $\dot{\theta}_i^i(t) > 0$ for all t. To see this, note that if instead we had

$$\eta_i \theta_i^k(t_0) > (\gamma_i + \eta_i)\, \theta_i^i(t_0),$$

at any time t_0, then $\dot{\theta}_i^i(t_0) < 0 < \dot{\theta}_k^i(t_0)$ so this inequality would continue to hold for all $t_0 > t$. But then we would have $\dot{\theta}_i^i(t) < 0$ for all $t > t_0$, and for $\theta_i^i(t)$ to meet its transversality condition, we would need to have $\theta_i^i(t) > 0$ at all $t > t_0$. But if $\theta_i^i(t) > 0$ and $\theta_i^k(t) \leq 0$ for $t > t_0$, it is clear from equation (27) in the paper that $\dot{\theta}_i^i(t) > 0$ for $t > t_0$, which is a contradiction. In sum, $\dot{\theta}_i^i(t) > 0$ for all t. But then for $\theta_i^i(t)$ to meet its transversality condition (from below), we need $\theta_i^i(t) \leq 0$ for all t.

Finally, to show that $\theta_i^s(t) > \theta_i^i(t)$ for all t, suppose that $\theta_i^s(t_0) < \theta_i^i(t_0)$ for some t_0. From equation (26) in the paper, this would imply $\dot{\theta}_i^s(t_0) < 0$. But because $\dot{\theta}_i^i(t) > 0$ for all t, we would continue to have $\theta_i^s(t) < \theta_i^i(t)$ for all $t > t_0$, and thus $\dot{\theta}_i^s(t) < 0$ for all $t > t_0$. This would imply that, for $t > t_0$, $\theta_i^s(t)$ would converge to its steady-state value of 0 from above, i.e., $\theta_i^s(t) > 0$ for $t > t_0$. But because $\theta_i^i(t) \leq 0$ for all t, from equation (26) in the paper, we would have $\dot{\theta}_i^s(t) > 0$

for $t > t_0$, which is a contradiction. In sum, we must have $\theta_i^s(t) > \theta_i^i(t)$ for all t. ■

F.2 Adjustment Costs and the Risk of a Pandemic

Despite the potential for significant disruptions in international trade during a pandemic, a clear implication of the first-order condition (25) in the paper is that as long as $I_i(t) = I_j(t) = 0$, human interactions are at the same level as in a world without the potential for pandemics. In other words, although there are rich dynamics of international trade during a pandemic, as soon as this pandemic is over (via herd immunity or the arrival of a vaccine), life immediately goes back to normal. We next explore an extension of our model that explores the robustness of this notion of a rapid V-shape recovery in economic activity and international trade flows after a global pandemic.

The main novel feature we introduce is adjustment costs associated with changes in the measures of human contacts $n_{ii}(t)$ and $n_{ij}(t)$. More specifically, we assume that whenever a household wants to change the measure of contacts $n_{ij}(t)$, it needs to pay a cost $\psi_1 |\dot{n}_{ij}(t)|^{\psi_2}$, where $\psi_1 > 0$ and $\psi_2 > 1$. An analogous adjustment cost function applies to changes in domestic interactions n_{ii}. Notice that this formulation assumes that the cost of reducing or increasing the number of contacts are symmetric. This leads to the following modified first-order condition for the choice of n_{ij} at any point in time t_0 (an analogous condition holds for n_{ii}):

$$\int_{t_0}^{\infty} e^{-\xi t}\left[\frac{\partial Q_i(n_{ii}(t), n_{ij}(t))}{\partial n_{ij}} - \frac{\partial C_i(n_{ii}(t), n_{ij}(t))}{\partial n_{ij}}\right](1 - k_i(t))dt$$
$$= \int_{t_0}^{\infty} e^{-\xi t}\left[\theta_i^s(t_0) - \theta_i^i(t_0)\right] s_i(t_0)\, a_j I_j(t_0)\, dt + e^{-\xi t_0}\psi_1\psi_2 |\dot{n}_{ij}(t_0)|^{\psi_2 - 1}(1 - k_i(t_0)).$$

Since dead individuals do not pay adjustment costs, equation (28) in the paper becomes

$$-\dot{\theta}_i^k(t) = -\left[Q_i(n_{ii}(t), n_{ij}(t)) - C_i(n_{ii}(t), n_{ij}(t)) - \psi_1(|\dot{n}_{ii}(t)|^{\psi_2} + |\dot{n}_{ij}(t)|^{\psi_2})\right] e^{-\xi t}.$$

The rest of the system is as before with the added feature that the values of $n_{ii}(t)$ and $n_{ij}(t)$ are now state variables, with exogenous initial conditions $n_{ii}(0)$ and $n_{ij}(0)$.[6]

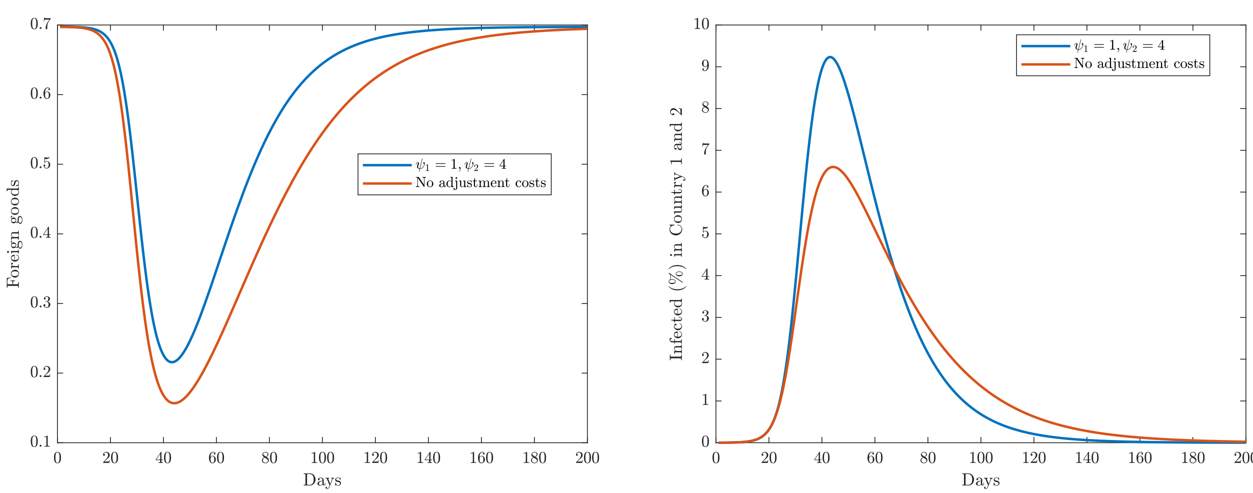
As the first-order condition makes evident, the choice of $\dot{n}_{ij}(t_0)$ now affects the values of $n_{ii}(t)$ and $n_{ij}(t)$ in the future directly and not only through its impact on the pandemic (and the corresponding co-state variables $\theta_i^s(t_0)$ and $\theta_i^i(t_0)$). This has two important implications. First, adjustment costs imply that agents will react less aggressively to a pandemic and overall their reaction will be smoother. Of course, the counterpart is that their endogenous response will attenuate the flattening of the curve of infections associated with behavioral responses. Second, if households anticipate that the probability of a future pandemic is $\lambda > 0$, the growth in the resurgence of human interactions will be slower than in the world in which the perceived probability of a future pandemic is 0, and the more so the larger is λ. As a result, if due to recency effects, households

[6] Alternatively we can use terminal conditions. This is what we do in the numerical exercise below where we assume that a pandemic ends, and never happens again, after some large time period T.

perceive a particularly high risk of future pandemics in the aftermath of a pandemic, this could slow the recovery of international trade flows after a pandemic occurs.

Figure F.1 presents a numerical example of an economy with symmetric countries, behavioral responses, and adjustment costs. The figure uses the baseline parameters from the previous section for symmetric countries, together with $\psi_1 = 1$ and $\psi_2 = 4$ for the adjustment cost parameters. The left-panel shows the evolution of foreign varieties consumed, $n_{ij}(t)$, and compares it with the case with no adjustment costs ($\psi_1 = 0$). Clearly, adjustment costs reduce the magnitude of the behavioral response. Not only do agents take longer to start the adjustment, but the adjustment is substantially smaller. In computing this example we assume that the pandemic never repeats itself. Hence, eventually the number of varieties consumed is the same as in the behavioral case without adjustment costs. We use this value as the terminal condition and compare the resulting initial $n_{ij}(1)$. Anticipatory effects, namely agents adjusting their behavior in anticipation of a pandemic, imply that the initial value should be smaller than the terminal one. Figure F.1 shows no indication that these effects are significant. Although $n_{ij}(1) < n_{ij}(T)$, the effect is negligible and cannot be perceived in the graph. This is the case, even though the effect on the evolution of domestic and foreign contacts is fairly large. This pattern of results is consistent with the view that economies will quickly return to normal after the pandemic, although with the caveat that we have here assumed that adjustment costs are symmetric and that the pandemic does not affect agents' beliefs of the probability of future pandemics. The right panel of Figure F.1 presents the corresponding evolution of infections with and without adjustment costs. As discussed above, the milder and delayed behavioral response in the case with adjustment costs leads to a faster increase in the number of infections. It also leads to a corresponding faster decline, since herd immunity starts reducing the number of infections earlier. The result is a faster, but more severe, pandemic with more overall deaths, but less pronounced temporary reductions in real income and trade.

Figure F.1: Behavioral Responses with Adjustment Costs



Note: See Online Appendix K for further details on the parameters and algorithms for these numerical simulations.

G Globalization and Disease Diffusion

In this section of the Online Appendix, we both provide new econometric evidence on the role of globalization in the spread on infectious diseases, and briefly review the related literature on globalization and disease diffusion in economics and epidemiology.

For most of human history, regional and continental populations were relatively isolated from one another. Large-scale improvements in air, sea and land transportation across the centuries have dramatically increased the globalization of the world economy, and the associated movements of people and goods around the world. Perhaps the most dramatic example of international trade spreading infectious disease comes from Christopher Columbus's discovery of the New World in 1492, during his search for a more direct trade route with China and the Spice Islands. As argued in Diamond (1998), the Americas were populated with relatively few of the domesticated animals from which many Old World infectious diseases are derived (e.g., smallpox, measles and influenza). As a result, the inhabitants of the Americas had no accumulated immunity to these Old World infectious diseases. Therefore, following the arrival of Europeans, native populations were decimated by disease epidemics, with estimates of mortality rates of up to 80-95 percent.[7]

In examining the relationship between globalization and the spread of disease, we distinguish two main categories of disease based on the existing epidemiological literature: (i) Human infectious diseases that can be directly transmitted between humans (e.g., influenza, coronavirus, smallpox, measles); (ii) Vector-borne diseases (e.g., Malaria and Yellow Fever, which are carried by the vector of mosquitos). In principle, our theoretical model could be applied to either human infectious diseases (trade induces human movements) or vector-borne diseases (trade induces movements of the disease vector).[8] Throughout our analysis, we focus mainly on diseases that can be directly transmitted between humans, as in our Susceptible-Infected-Recovered (SIR) model. Although for one of the infectious disease that we consider (the plague), there is evidence of both direct human transmission and vector-borne transmission (through fleas on rats).

Throughout this section, we provide evidence on the role of globalization in speeding the diffusion of infectious disease. Therefore, we focus on the time lag between the first outbreak of an infectious disease in each location and the first outbreak anywhere. We refer to the difference between these two dates as the *arrival time* of the infectious disease in each location.

We examine the relationship between globalization and the spread of infectious disease, rather than the relationship between globalization and mortality from infectious disease, because mortality can be heavily influenced by public health improvements. In particular, the globalization of the world economy over time has occurred alongside sanitation and medical revolutions that have drastically reduced mortality from infectious diseases, as discussed in Kenny (2021). The sanitation revolution includes innovations such as clean drinking water, sewers, flushing toilets, soap, disinfec-

[7] See, for example, Newson (2001), Mann (2005), and Nunn and Qian (2010). According this historical literature, deaths in the New World from Old World infectious diseases far outnumbered those from military conflict.

[8] Examples of international trade spreading vector-borne diseases include Yellow Fever (spread to the Caribbean from Africa through the Atlantic Slave Trade) and Malaria (spread into North-Eastern Brazil in the 1930s), as discussed for example in de la Rocque et al. (2011).

tant and hand washing. The medical revolution includes antibiotics (which can help treat or cure infectious diseases) and vaccinations against infectious diseases (including for example smallpox and polio). Indeed in the specification of our theoretical model with behavioral responses, improvements in public health (reductions in the death rate) can generate increased globalization (through less social distancing), a more rapid spread of infectious diseases around the world (through increased human interaction), and reduced mortality (through a lower death rate) during a pandemic. Some scholars argue that it is only because of the sanitation and medical revolutions that today's high levels of urbanization and globalization are sustainable, as discussed further in Kenny (2021).

In Subsection G.1, we present our econometric evidence on the role of globalization in the spread of infectious diseases. We report empirical results for (i) The plague, using existing historical data sources; (ii) The 1957-8 Influenza pandemic, using newly-digitized data from the Weekly Epidemiological Record of the World Health Organization (1957, 1958); and (iii) Covid-19, using data from the Center for Systems Science and Engineering (CSSE) at Johns Hopkins University. In Subsection G.2, we briefly review the related literature in economics and epidemiology that provides further support for the role of globalization in the spread of infectious diseases.

G.1 Empirical Evidence on Globalization and Disease Diffusion

In Subsection G.1.1, we discuss the historical background to our three infectious diseases, and present some descriptive evidence on their speed of diffusion around the world. In Subsection G.1.2, we introduce the econometric specification that we use to examine the relationship between the speed of diffusion of these diseases and globalization. In Subsection G.1.3, we report our main empirical results for these three diseases. In Subsection G.1.4, we provide further evidence for Covid-19 using the additional data available for this pandemic.

G.1.1 Historical Background and Data

We begin by discussing the historical background and data sources for each of our three infectious diseases and presenting some descriptive evidence on their diffusion over time.

Plague One of the most devastating outbreaks of infectious disease in human history was the Black Death (plague) from 1347-51, in which around one third of Europe's population is estimated to have died. Symptoms included fever, headache, chills, and weakness, and swollen, painful lymph nodes (called buboes). Debate continues about the exact origin, nature and mode of transmission of the plague. The consensus is that the Black Death (plague) was initiated by the flea-borne bacterium *Yersina pestis*, which circulates mainly on rodents and other mammal hosts through fleas.[9] Existing scholarship suggests that the Black Death pandemic originated in Mongolia in present-day China in 1331, and then spread Westwards along Maritime trade routes through Constantinople, Messina, Sardinia, Genoa and Marseilles.[10]

[9] The discussion in this subsection draws on Benedictow (2004).

[10] See McNeil (1996) and Benedictow (2004).

Existing research also suggests that *Yersina pestis* is transmitted through bloodsucking fleas on an infected mammal. The bacterium quickly multiplies and clusters, leading to a blockage of the alimentary canal in the fleas' guts. When the infected flea jumps on to another mammal, it transmits the bacterium to the new host by regurgitating the clotted blood from the blockage of its alimentary canal. If an infected flea attempts to feed on a human, it transmits *Yersina pestis* to that person, and induces either bubonic or pulmonary plague.

Traditionally, it was thought that the clustering of *Yersina pestis* rarely happened on human fleas. However, recent evidence suggests that not only rodent fleas (e.g., *Xenopsylla cheopis*) but also human fleas (*Pulex irritans*) and cat fleas (*Ctenocephalides felis*) play a role in the transmission of the bacterium.[11] Furthermore, laboratory studies have suggested the possibility of oral transmission of plague between humans, and epidemiological records suggest plague transmission through the consumption of contaminated meat.[12]

We use existing historical data on plague outbreaks from Büntgen et al. (2019). The data cover 6,735 plague outbreaks from 1347-1760 across European cities. The first plague outbreak recorded in the data is in Messina in 1347. From that point onwards, Europe experienced a succession of plague epidemics, with particularly severe subsequent outbreaks occurring in 1563, 1593, 1625 and 1665. We define the arrival time for each city as the difference in years between the first plague outbreak in that city and the first European plague outbreak in Messina in 1347. In Figure G.1, we show the distribution of these arrival times in years across European cities. Given the relatively low economic integration in this historical time period, some cities were infected early on, whereas others escaped earlier epidemics, only to be infected in a later plague outbreak.

To provide evidence on the role of international trade in the spread of the plague, we use information on cities' proximity to major historical trading routes, since representative data on bilateral trade between cities are not available for the medieval era. In particular, we use Geographical Information Systems (GIS) data on the route of eighteen old world trade routes from the Old World Trade Routes (OWTRAD) database, including for example the main trade routes of the Holy Roman Empire and the Anatolian Silk Road.[13] For each of the cities in our dataset, we compute the shortest geographical distance to the nearest point on an old world trade route.

Influenza Influenza (commonly called the flu) is an infectious disease characterized by the symptoms of fever, muscles aches, sore throat, headache, and fatigue. Most people infected with influenza feel ill for several days and then recover. However, in some instances, influenza can lead to pneumonia, other complications, and even death.[14]

Influenza is caused by influenza viruses, which are part of the Orthomyxoviridae family of viruses. Four types of the virus exist: A and B, which are responsible for seasonal flu epidemics in people; C, which is relatively rare, causes a mild respiratory illness, and is not thought to cause

[11] See Laudisoit (2007) and Eisen (2008).

[12] Evidence on oral transmission is provided in Butler et al. (1982). Evidence on transmission through contaminated meat is given in Seed et al. (2016) and Malek et al. (2016).

[13] See `http://www.ciolek.com/OWTRAD/DATA/tmcTRm1200a.html`.

[14] For classic textbook treatments of influenza, see Stuart-Harris and Schild (1976) and Pyle (1986).

Figure G.1: Distribution of Arrival Times in Years for the Plague Across European Cities

Note: First European outbreak of the plague in Messina in 1347; data on plague outbreaks from 1347-1760 across European cities from the digitizing historical plague dataset (Büntgen et al. 2019).

epidemics; and D, which primarily infects cattle and is not known to affect people.

Influenza A virus, which also infects birds, pigs, horses, and other animals, is further divided into subtypes based on two antigens (proteins) on the virus's surface: hemagglutinin (H), of which there 18 subtypes, and neuraminidase (N), of which there 11 subtypes. The specific virus is recognized by these antigens. For example, H1N1 refers to influenza A virus with hemagglutinin subtype 1 and neuraminidase subtype 1. Similarly, H3N2 refers to influenza A virus with hemagglutinin subtype 3 and neuraminidase subtype 2. Influenza B, on the other hand, is recognized by lineages and strains. The influenza B viruses commonly seen in people belong to one of two lineages: B/Yamagata or B/Victoria.

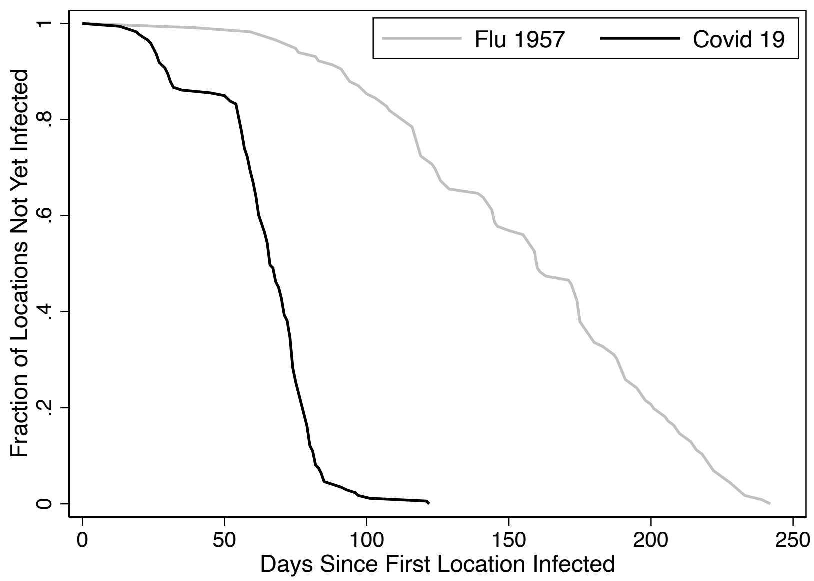
An influenza pandemic occurs when a new subtype or strain of influenza virus develops from antigenic shift and spreads globally. The three influenza pandemics of the 20th century were all caused by an antigenic shift in influenza A strains: (i) 1918-9 Influenza Pandemic (H1N1); (ii) 1957-8 Influenza Pandemic (H2N2); (iii) The 1968-9 Influenza Pandemic (H3N2).

We construct newly-digitized data on the global diffusion of the 1957-8 Influenza Pandemic. We focus on this pandemic, because comprehensive data on its diffusion are available from the Weekly Epidemiological Reports of the World Health Organization (1957, 1958). For each country, we record the date of the first outbreak of this disease. We define the influenza arrival time for each country as the difference in days between the first outbreak in that country and the first outbreak worldwide in China in February 1957. We also report some robustness checks for the 1968-9 Influenza pandemic, although the number of countries for which data are available in the Weekly Epidemiological Reports is smaller for this later pandemic. We abstract from the 1918-19 Influenza Pandemic, because it predates the 1948 foundation of the World Health Organization

(WHO) from which we obtain our data, and the global diffusion of the 1918-19 Influenza was heavily influenced by troop movements towards the end of the First World War, which are unlikely to mimic the economic forces in our model.

In Figure G.2, we show the distribution of these arrival times in days for the 1957-8 Influenza Pandemic across countries around the world. We find a much more rapid diffusion of this disease around the world, consistent with the higher levels of economic integration of more recent decades. To examine the role of international trade in the spread of the 1957-8 influenza, we combine these diffusion data with the Historical Bilateral Trade and Gravity Dataset (TRADHIST) from CEPII (Fouquin and Hugot 2017) for the year 1956 immediately before the pandemic.

Figure G.2: Distribution of Arrival Times in Days for the 1957-8 Influenza and Covid-19



Note: arrival time for each country defined as the difference in days between the first outbreak in that country and the first outbreak of the disease worldwide; data on the 1957-8 influenza pandemic for 120 countries from the World Epidemiological Reports of the World Health Organization (WHO); data on the Covid-19 pandemic for 208 countries from the Center for Systems Science and Engineering (CSSE) at Johns Hopkins University.

Covid-19 Coronavirus disease 2019 (Covid-19 or simply Covid) is an infectious disease caused by severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2). Symptoms of Covid-19 include fever, cough, headache, fatigue, breathing difficulties, and loss of smell and taste. Symptoms may begin one to fourteen days after exposure to the virus. At least a third of people who are infected do not develop noticeable symptoms. Of those people who develop symptoms noticeable enough to be classed as patients, around 80 percent develop mild to moderate symptoms (up to mild pneumonia), while around 15 percent develop severe symptoms (including dyspnea and hypoxia), and 5 percent suffer critical symptoms (respiratory failure or multiorgan dysfunction).

There are many thousands of variants of the SARS-CoV-2 virus, which are grouped by the World Health Organization (WHO) into either clades or lineages. As of December 2021, the five dominant variants of SARS-CoV-2 were as follows: Alpha variant (B.1.1.7); Beta variant (B.1.351);

Gamma variant (P.1); Delta variant (B.1.617.2); and Omicron variant (B.1.1.529).

We use data on the global diffusion of the Covid-19 Pandemic from the Center for Systems Science and Engineering (CSSE) at Johns Hopkins University. For each country, we record the date of the first outbreak of this disease. We define the Covid-19 arrival time for each country as the difference in days between the first outbreak in that country and the first outbreak worldwide in China in December 2019. In Figure G.2, we also show the distribution of these arrival times in days across countries around the world. Again we find a rapid diffusion of Covid-19 around the world, consistent with the high levels of integration of the world economy in recent decades.

We examine the role of international trade and other international linkages in the spread of Covid-19 using data on bilateral trade in 2019 before the pandemic from the United Nations COMTRADE database; bilateral migrant stocks in 2017 from the World Bank; total arrivals and departures of people in China (including migrants, business travelers and tourists) from China's Census and Population Sampling Survey Database for 2010; bond security flows with China (inflows + outflows) and equity and mutual fund security flows with China (inflows + outflows) for 2015-7 from the Global Capital Allocation Project (Maggiori et al. 2021); outward Foreign Direct Investment (FDI) from China for 2010-2 from UNCTAD; and the total value of debt and equity assets held by a country in China for 2018-9 from the International Monetary Fund (IMF).

G.1.2 Econometric Specification

A key prediction of our model is that the initial diffusion of infectious diseases across countries is shaped by the gravity equation of human interactions and international trade. Once agents and policymakers within each country become aware of the infection, our model implies that these gravity equation predictions are modified by behavioral responses and public policy interventions. To abstract from these behavioral responses and public policy interventions, we focus in our empirical analysis on the model's gravity equation predictions for the initial diffusion of infectious diseases.

In particular, we consider a multi-country version of our baseline theoretical model. Starting from a no-pandemic equilibrium, in which all agents in each country i are susceptible ($S_i = 1$), we consider a small initial infection in one country j at time t ($\epsilon_j(t) > 0$ and $\epsilon_k(t) = 0$ for all $k \neq j$). Given this small initial infection, our model implies that the growth of infections in each country i at time t depends on the gravity equation structure of its interactions with country j:

$$\frac{\dot{I}_i(t)}{I_i(t)} = \left[\alpha_j n_{ij}(t) + \alpha_i n_{ji}(t)\right] \epsilon_j(t), \tag{G.1}$$

where recall that α_j is the contact rate in country j (as determined by the epidemiological characteristics of the disease and social norms regarding human interaction) and $n_{ij}(t)$ is the number of agents in country i that travel to country j at time t.

In our theoretical model, there is a continuous measure of agents in each country, which implies that this relationship in equation (G.1) holds deterministically. In reality, population is not a continuum, and hence it may take time an infection to occur, or for the incidence of a disease to rise above the threshold to be detected. Therefore, we interpret equation (G.1) as implying that greater interactions with country j (higher $n_{ij}(t)$ and $n_{ji}(t)$) raise the probability that an infection occurs and is detected, and reduce the arrival time of the disease in each country i.

While equation (G.1) holds exactly at the time of initial infection t, as time elapses since that initial infection, other countries become infected, which creates the possibility of indirect transmission of the disease from those other countries. We focus on each country's direct interactions with the country of first infection, using the fact that the direct and indirect connections to the country of first infection are strongly positively correlated with one another.

We provide evidence on these predictions using our empirical measure of the disease arrival time: the difference in time between the first case in country i and the first case worldwide (in country j). We regress the log arrival time in country i (A_i) on measures of the strength of interactions of country i with country j (Z_{ij}):

$$\ln A_i = a + b \ln Z_{ij} + \ln X_{ij} c + u_i, \tag{G.2}$$

where X_{ij} is a vector of controls that vary bilaterally between country i and country j; and u_i is a stochastic error.

To facilitate comparisons of the economic magnitude of coefficients, we standardize all variables, such that each variable has a mean of zero and a standard deviation of one. Therefore, the estimated coefficients on each variable correspond to conventional beta coefficients: how many standard deviations the left-hand side variables changes in response to a one standard deviation change in each right-hand side variable.

In line with our focus on international trade and pandemics, we use bilateral trade (Z_{ij}) as our baseline measure of the strength of interaction between countries i and j. To abstract from reverse causality from pandemics to international trade, we use bilateral trade data for the year immediately before the 1957-8 Influenza and Covid-19 pandemics, where neither of these pandemics was anticipated in the months leading up to the first disease outbreak. Similarly, for the plague, we use data on Old World Trade Routes that pre-dated the first outbreak of the plague.

In our baseline specification, we regress the arrival time of each disease on these pre-existing trade measures. Much of the variation in these pre-existing trade measures is driven by bilateral geographical distance. But one potential concern is that there could be omitted variables that affect disease diffusion and are correlated with geographical distance (e.g., movements of animals that can act as reservoirs for the disease). To address this concern, we also report specifications, in which we control separately for geographical distance.

Additionally, for Covid-19, we have data on a large number of countries and several different measures of the strength of interactions between each pair of countries, including for example bilateral migration, and total arrivals and departures of people (migrants, business travelers and tourists, where tourism itself can be interpreted as a form of business travel). In our theoretical model, the mechanism through which international trade affects spread of the disease is through movements of people. Therefore, our model implies that there should be no effect of international trade once one conditions on total arrivals and departures of people, a prediction that we are able to examine using these additional data for the Covid-19 pandemic.

Finally, our baseline specification (G.2) posits a log linear relationship between the arrival time (A_i) and the strength of bilateral interactions (Z_{ij}). We estimate this relationship using ordinary least squares (OLS), which can be interpreted as a local approximation to the conditional expectation function, as argued in Angrist and Pischke (2009). To ensure that our results are not sensitive to this functional form specification, we also report non-parametric binscatter specifications, and show that our log linear representation provides a good approximation to the data.

G.1.3 Empirical Results

We now report our main empirical results from estimating our baseline specification (G.2) for our three infectious diseases of the plague, 1957-8 influenza and Covid-19.

Plague In Table G.1, we estimate equation (G.2) using our data on plague arrival times for our sample of 1,149 European cities from 1347-1760. In Column (1), we include only trade access, as measured by the inverse of distance from the nearest old world trading route. Consistent with international trade speeding the spread of disease, we find a negative and statistically significant coefficient, implying that the plague diffused faster to cities with better trade access. In Column (2), we augment this specification with log geographical distance from the first outbreak of the plague in Messina. In line with the idea that it took time for the plague to spread geographically (in part through trade), we find a positive and statistically significant coefficient on geographical distance. Nevertheless, the coefficient on trade access remains negative and statistically significant. Therefore, even after controlling for geographical distance, we find that trade access speeded the diffusion of the plague. This effect of trade access is not only statistically significant but also economically relevant: a one standard deviation increase in log trade access reduces the arrival time of the plague by 0.218 standard deviations, compared an effect of 0.108 standard deviations for log geographical distance.

In Column (3), we restrict attention to cities with below-median arrival times, for which distance from the first outbreak in Messina could be particularly important. We continue to find negative and positive coefficients on our trade access and geographical distance variables, respectively, which remain statistically significant at conventional levels. As a further robustness test, Column (4) returns to our baseline sample, and includes country fixed effects. Even when we focus solely on variation across cities within countries, we find the same pattern of results. Finally, cities are relatively small geographical units, and there could be a correlation in the error terms between nearby cities. To address this concern, Column (5) reports Heteroskedasticity Autocorrelation Consistent (HAC) standard errors following Conley (1999), which allow the error terms for cities to be correlated up to a distance threshold of 100 kilometers. Although the standard errors for both variables increase marginally, we continue to find statistically significant coefficients for both our trade access and geographical distance variables.

Table G.1: Arrival Time for Plague Across European Cities

	(1) Log Arrival	(2) Log Arrival	(3) Log Arrival	(4) Log Arrival	(5) Log Arrival
Log Trade Access	-0.249***	-0.218***	-0.236***	-0.179***	-0.179***
	(0.0335)	(0.0349)	(0.0473)	(0.0323)	(0.0352)
Log Distance		0.108***	0.103**	0.251***	0.251***
		(0.0302)	(0.0505)	(0.0727)	(0.0907)
Sample	All	All	Below-Median Arrival Time	All	All
Country fixed effects				Yes	Yes
Observations	1,149	1,149	575	1,149	1,149
R-squared	0.061	0.072	0.067	0.145	0.145

Note: Cross-section of cities in Europe; all variables are standardized to have a mean of zero and a standard deviation of one; hence the estimated coefficients have an interpretation as beta coefficients (how many standard deviations the left-hand side variable changes with a one standard deviation change in a right-hand side variable); Arrival is the difference in years between the time of the first plague outbreak in a city and the first plague outbreak in Europe (in 1347 in Messina, Italy); Trade Access is the inverse of the shortest distance between a city and an Old World trade route, as defined in Online Appendix L; Distance is the geographical distance between a city and the city with the first plague outbreak in Europe (Messina, Italy in 1347); Columns (1)-(4) report heteroskedasticity robust standard errors in parentheses; Column (5) reports Conley (1999) Heteroskedasticity and Autocorrelation Consistent (HAC) standard errors using a distance cutoff of 100 kilometers in parentheses; *** denotes significance at the 1 percent level; ** denotes significance at the 5 percent level; * denotes significance at the 10 percent level; data on plague outbreaks from the historical plague dataset (Büntgen et al. 2019).

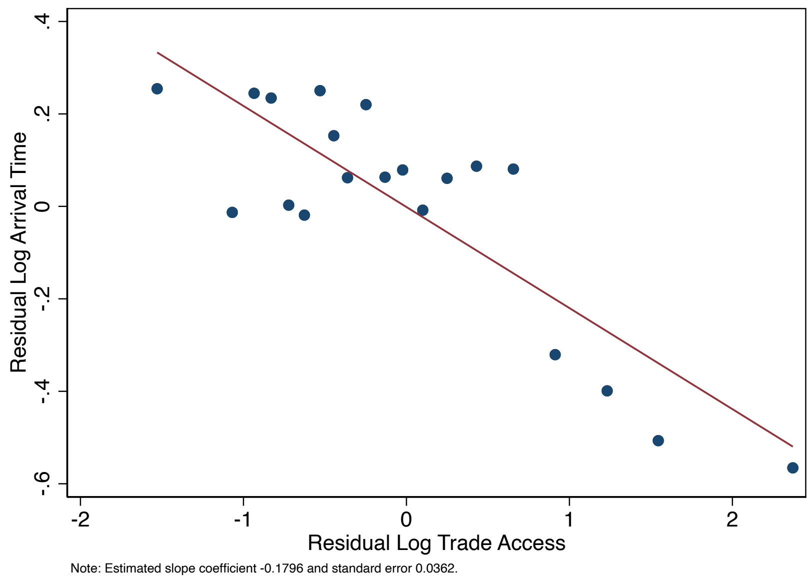
In Figure G.3, we report a specification check on our functional form assumption. We display a binscatter of the conditional correlation between the log arrival time of the plague and log trade access, after controlling for log geographical distance from Messina.[15] We find a strong, negative and approximately linear relationship between the two variables, consistent with our log linear specification providing a reasonable approximation to the data.

These empirical findings in Table G.1 and Figure G.3 are consistent with a large historical literature that has argued that the plague spread along traditional trade routes, including for example McNeil (1996), Benedictow (2004), Harrison (2012) and Kenny (2021). In line with our results, Yue et al. (2017) finds that both proximity to both Old World Trade Routes and major trade ports increased the frequency of plague outbreaks. Using data for African, Asian and European cities, Gómez and Verdú (2017) find that cities with greater connectedness to the trading network (as measured by network centrality and transitivity) were more adversely affected by the plague (had greater mortality and a higher probability of multiple infections).

Taken together, the evidence of this section provides strong support for the idea that international trade played a role in the transmission of the plague, even after controlling for the geographical distance between locations.

[15] Using the Frisch-Waugh-Lovell Theorem, we run separate regressions of the log arrival time and log trade access on log geographical distance from Messina, generate the residuals, and then display a binscatter of the two residuals against one another.

Figure G.3: Binscatter of Conditional Correlation Between Log Arrival Time and Log Trade Access for the Plague from 1347-1760



Note: Residual log arrival time for the plague and residual log trade access after controlling for log geographical distance from the first plague outbreak in Europe in Messina, Italy in 1347; trade access measured by the inverse of distance from the nearest Old World trade route; blue circles correspond to ventiles of the conditional relationship between the two residuals across European cities; red line shows the linear regression fit between the two residuals.

Influenza 1957-8 In Table G.2, we estimate equation (G.2) using our data on arrival times of the 1957-8 influenza for our baseline sample of countries. We have data on arrival times for 117 countries, excluding China as the location of the first outbreak. Of these 117 countries, 52 have positive values of bilateral trade with China in 1956.

In Column (1), we include only log bilateral trade with China. We find a negative and statistically significant coefficient, consistent with international trade speeding the spread of disease. In Column (2), we augment this specification with log geographical distance from China. In line with the idea that it took time for the 1957-8 influenza to spread geographically (in part through international trade), we find a positive and statistically significant coefficient on geographical distance. Since much of the variation in international trade is driven by geographical distance, we find that the coefficient on international trade falls somewhat, but remains significant at the 10 percent level. The estimated effect of international trade is not only statistically significant, but also economically relevant: a one standard deviation increase in log international trade with China reduces the log arrival time of the 1957-8 influenza by 0.176 standard deviations, compared an effect of 0.560 standard deviations for log geographical distance from China. Together these two variables alone explain 44 percent of the variation in influenza arrival times across countries.[16]

In Column (3), we restrict attention to countries with below-median arrival times, for which

[16] In a robustness check, we find a similar pattern of results for the 1968-9 influenza. For example, in the specification in Column (2), we obtain an estimated coefficient (standard error) of -0.393 (0.1010) for log bilateral trade and 0.484 (0.1094) for log geographical distance, with a regression R-squared of 0.50.

bilateral trade and geographical distance from the country with the first outbreak could be particularly important. Although the resulting sample includes only 23 countries, we continue to find a negative and statistically significant coefficient for international trade, and a positive and statistically significant coefficient for geographical distance. In Columns (1)-(3), our choice of a log linear specification restricts attention to countries with positive values of bilateral trade with China, and hence captures only the intensive margin of trade. In Column (4), we consider a robustness test in which we include bilateral trade with China in levels rather than in logs, which expands the sample to include countries with zero trade flows, and hence captures both the extensive and intensive margins of trade. Again we find a similar pattern of results, with a negative and statistically significant coefficient on bilateral trade with China, and a positive and statistically significant coefficient on geographical distance for China. Across Columns (2)-(4), we find that these two variables alone explain around 45 percent of the variation in arrival times of the 1957-8 influenza.

Table G.2: Arrival Time for 1957-8 Influenza Across Countries

	(1) Log Arrival	(2) Log Arrival	(3) Log Arrival	(4) Arrival
Log Trade	-0.365***	-0.176*	-0.328***	
	(0.1175)	(0.1048)	(0.0994)	
Log Distance		0.560***	0.323***	0.654***
		(0.0867)	(0.0854)	(0.0593)
Trade				-0.135***
				(0.0145)
Sample	All	All	Below-Median Arrival Times	All
Observations	52	52	23	117
R-squared	0.148	0.439	0.542	0.461

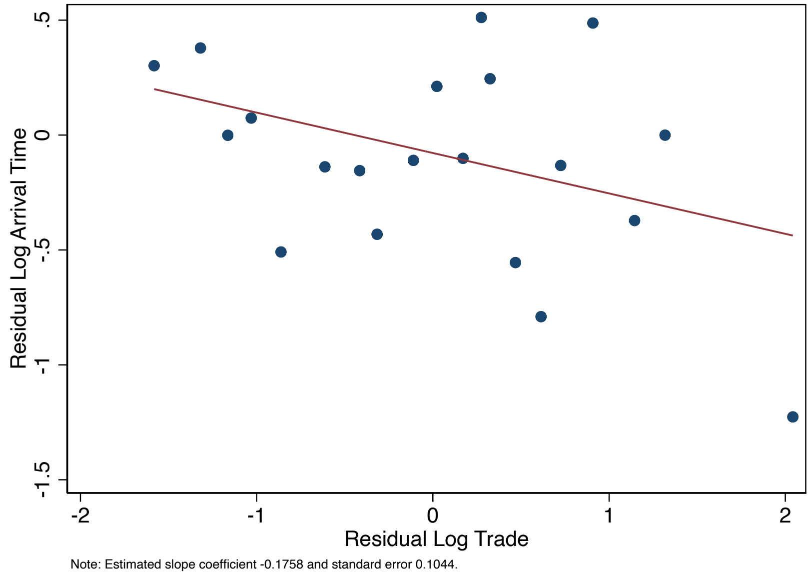
Note: Cross-section of countries; all variables are standardized to have a mean of zero and a standard deviation of one; hence the estimated coefficients have an interpretation as beta coefficients (how many standard deviations the left-hand side variable changes with a one standard deviation change in a right-hand side variable); Arrival is the difference in days between the first outbreak of 1957-8 influenza in a country and the first outbreak worldwide in China in February 1957; Distance is the geographical distance between a country and China; Trade is the sum of the value of exports and imports for each country with China in 1956 before the pandemic; heteroskedasticity robust standard errors in parentheses; *** denotes significance at the 1 percent level; ** denotes significance at the 5 percent level; * denotes significance at the 10 percent level; data on outbreaks of 1957 influenza from the Weekly Epidemiological Report of the World Health Organization (WHO).

As a check on our functional form assumption, Figure G.4 displays a binscatter of the conditional correlation between the log arrival time of the 1957-8 influenza and bilateral trade with China, after controlling for log geographical distance from China.[17] Although there is some noise, we find a negative, significant and approximately linear relationship between the two variables, consistent with our log linear specification providing a reasonable approximation to the data.

Our empirical findings in Table G.2 and Figure G.4 are consistent with the existing empirical

[17] Again we run separate regressions of the log arrival time and log trade on log geographical distance, generate the residuals, and then display a binscatter of the two residuals against one another.

Figure G.4: Binscatter of Conditional Correlation Between Log Arrival Time and Log Bilateral Trade for the 1957-8 Influenza



Note: Residual log arrival time and residual log bilateral trade after controlling for log geographical distance from the first outbreak of 1957-8 influenza in China in February 1957; blue circles correspond to ventiles of the conditional relationship between the two residuals; red line shows the linear regression fit between the two residuals.

literature in economics and epidemiology on the diffusion of influenza. The geographic diffusion of the 1957-8 and the 1968-9 influenza pandemics is discussed in Payne (1957) and Cockburn, Delon and Ferreira (1969), respectively. Using data from the 1968-9 influenza pandemic, Grais et al. (2003) provides evidence on the role of airline travel in shaping the geographic spread of the disease outbreak. Using data on weekly influenza and pneumonia mortality data from 1996 to 2005 in the United States, Brownstein, Wolfe and Mandl (2006) provides evidence that the increase in airline travel around Thanksgiving, and the decline in airline travel after the September 11, 2001 terrorist attacks, are both predictive of the spread of seasonal influenza.

Therefore, taking the findings of this section as whole, we find a similar pattern of results for the 1957-8 influenza as for the plague, with greater bilateral trade reducing the arrival time of the disease, even after controlling for the geographical distance between countries.

Covid-19 In Table G.3, we estimate equation (G.2) using our data on arrival times of Covid-19 for our baseline sample of countries. We have data on arrival times for 173 countries, excluding China as the location of the first outbreak. Of these 173 countries, 172 have positive values of bilateral trade with China in 2019.

In Column (1), we include only log bilateral trade with China. We find a negative and statistically significant coefficient, consistent with international trade speeding the spread of disease. In Column (2), we augment this specification with log geographical distance from China. In line with the idea that it took time for Covid-19 to spread geographically (in part through international trade), we find a positive and statistically significant coefficient on geographical distance. Since much of the variation in international trade is driven by geographical distance, we find that the coefficient on international trade falls somewhat, but it remains statistically significant at conventional levels. The estimated effect of international trade is not only statistically significant, but also economically relevant: a one standard deviation increase in log international trade with China reduces the log arrival time of Covid-19 by 0.525 standard deviations, compared an effect of 0.301 standard deviations for log geographical distance from China

Table G.3: Arrival Time for Covid-19 Across Countries

	(1) Log Arrival	(2) Log Arrival	(3) Log Arrival	(4) Arrival	(5) Log Arrival	(6) Log Arrival
Log Trade	-0.618***	-0.525***	-0.512***		-0.238***	0.0195
	(0.0813)	(0.0742)	(0.1164)		(0.0804)	(0.101)
Log Distance		0.301***	0.501***	0.269***	0.227***	0.0665
		(0.0819)	(0.0880)	(0.0840)	(0.0819)	(0.0897)
Trade				-0.496***		
				(0.1144)		
Log Migrant Stock					-0.440***	-0.279***
					(0.0920)	(0.0945)
Log Arrivals-Departures						-0.512***
						(0.1259)
Observations	172	172	79	173	152	149
Sample	All	All	Below-Median Arrival Time	All	All	All
R-squared	0.380	0.462	0.492	0.398	0.538	0.576

Note: Cross-section of countries; all variables are standardized to have a mean of zero and a standard deviation of one; hence the estimated coefficients have an interpretation as beta coefficients (how many standard deviations the left-hand side variable changes with a one standard deviation change in a right-hand side variable); Arrival is the difference in days between the first outbreak of Covid-19 in a country and the first outbreak worldwide in China; Distance is the geographical distance between a country and China; Trade is the sum of the value of exports and imports for each country with China in 2019 before the pandemic; Migrant stock is the total number of immigrants in a country from China plus the total number of ex-patriots in China from that country in 2017; Arrivals-Departures is the total number of people arriving in a country from China plus the total number of people arriving in China from that country (including migrants, business travellers and tourists) in 2010; heteroskedasticity robust standard errors in parentheses; *** denotes significance at the 1 percent level; ** denotes significance at the 5 percent level; * denotes significance at the 10 percent level; data on outbreaks of Covid-19 from the Center for Systems Science and Engineering (CSSE) at Johns Hopkins University.

In Column (3), we restrict attention to countries with below-median arrival times, for which bilateral trade and geographical distance from the country with the first outbreak could be particularly important. We continue to find statistically significant coefficients for both international trade and geographical distance, which are both marginally larger in absolute value than for the full sample. Our log linear specification in Columns (1)-(3) restricts attention to countries with positive values of bilateral trade with China, which captures only the intensive margin of trade. In Column (4), we consider a robustness test in which we include bilateral trade with China in levels rather than in logs, which includes zero trade flows, and hence captures both the extensive and intensive margins of trade. Again we find a similar pattern of results, with a negative and statistically significant coefficient on bilateral trade with China, and a positive and statistically significant coefficient on geographical distance. Across Columns (2)-(4), we find that these two variables alone explain around 45 percent of the variation in arrival times of Covid-19.

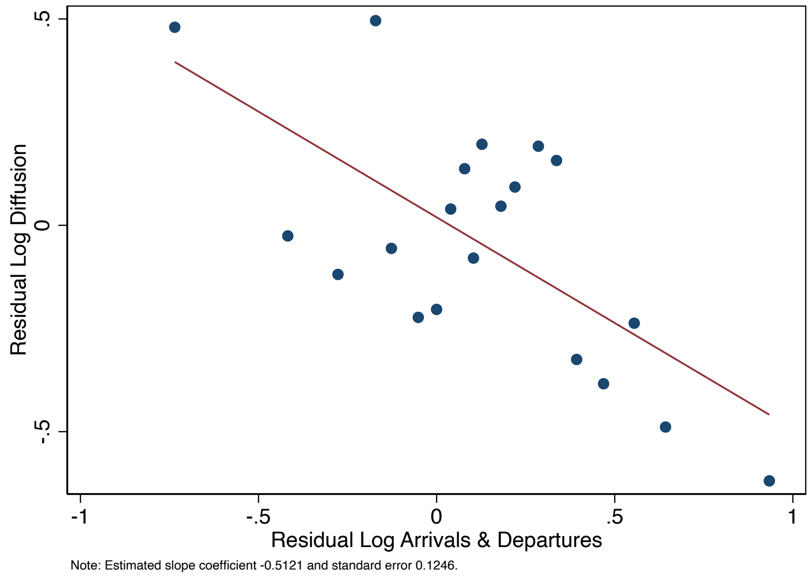
In the remaining columns of the table, we use the additional data available for Covid-19 to examine the mechanisms through which international trade affects the spread of disease and the robustness of our results to including additional measures of international linkages between countries. In Column (5), we augment our baseline specification from Column (2) with the log migrant stock, as measured by the total number of immigrants in a country from China plus the total number of ex-patriots in China from that country. Consistent with the idea that disease can be transmitted through people movements associated with both migration and international trade, we find negative and statistically significant coefficients for both variables. In Column (6), we further augment this specification with the total number of arrivals and departures between each country and China, including migration, business travel and tourism, where tourism can be interpreted within our model as a form of business travel to consume non-traded services. Once we control for total arrivals and departures of people, the estimated coefficients on both trade and distance fall by order of magnitude, and are both close to zero and no longer statistically significant at conventional levels. This pattern of results is consistent with the mechanism in our model and the science underlying the transmission of Covid-19, in which the spread of the disease occurs through face-to-face interactions and the mobility of people. We continue to find a negative and statistically significant coefficient on the migrant stock, which could reflect measurement error in total arrivals and departures of people, such that the migration stock is proxying for unobserved people flows associated with migration.

As a check on our assumed functional form, Figure G.5 displays a binscatter of the conditional correlation between the log arrival time of Covid-19 and the log total number of arrivals and departures in China, after controlling for log geographical distance from China, log bilateral trade with China and the log migrant stock with China.[18] We find a strong, negative andapproximately linear relationship between the two variables, consistent with our log linear specification providing a reasonable approximation to the data.

As a final placebo specification check, we examine the sensitivity of our results to the inclusion of measures of international financial linkages between countries, including log bond security flows with China (inflows plus outflows); log equity and mutual fund security flows with China (inflows plus outflows); log outward FDI from China; log assets held in debt; log assets held in equity; and log total assets held. In Columns (1)-(6) of Table G.4, we augment the specification from Column (6) of Table G.3 with each of these additional measures of international linkages. These variables are either equal to zero or missing for a number of countries, which results in a smaller

[18] We run separate regressions of the log arrival time and log total number of arrivals and departures with China on log trade with China, log geographical distance from China, and log migrant stock with China, generate the residuals, and then display a binscatter of the two residuals against one another.

Figure G.5: Binscatter of Conditional Correlation Between Log Arrival Time and Log Bilateral Trade for COVID-19



Note: Residual log arrival time and residual log total number of arrivals and departures of people with China, after controlling for log trade with China, log geographical distance from China, and log migrant stock with China; blue circles correspond to ventiles of the conditional relationship between the two residuals; red line shows the linear regression fit between the two residuals.

sample size. After controlling for total arrivals and departures of people, our model and the science underlying the transmission of Covid-19 imply that we should not expect any of these measures of international linkages to affect the spread of the disease. In line with this idea, we find that none of these variables are statistically significant, and that the estimated coefficients on the migrant stock and total arrivals and departures of people remain of around the same magnitude and statistically significant at conventional levels.

Taken together, these findings for Covid-19 provide further support for the predictions of our model, and reinforce our conclusions for the plague and the 1957-8 influenza. We find that international trade speeds the diffusion of disease, even after controlling for the geographical distance between locations. Consistent with our model and the science underlying the transmission of infectious diseases, we find that international trade operates through the mechanism of arrivals and departures of people. Therefore, after controlling for total arrivals and departures of people, we find no effect of international trade or other measures of international financial linkages. In Subsections H.1 and H.2 below, we provide further evidence in support of this mechanism, in which reductions in trade costs that increase international trade lead to increased travel between countries.

G.1.4 Additional Empirical Evidence for Covid-19

In our baseline empirical specification in the previous subsection, we provide evidence on the initial diffusion of each infectious disease. We do so to abstract from the possible impact of public policy

Table G.4: Arrival Time for Covid-19 Across Countries (Placebo)

	(1) Log Arrival	(2) Log Arrival	(3) Log Arrival	(4) Log Arrival	(5) Log Arrival	(6) Log Arrival
Log trade	-0.0182	-0.0534	-0.132	-0.256	-0.0378	-0.0155
	(0.154)	(0.231)	(0.189)	(0.322)	(0.161)	(0.176)
Log distance	0.0723	0.146	0.0891	0.155	0.0696	0.0706
	(0.112)	(0.106)	(0.114)	(0.110)	(0.105)	(0.106)
Log migrant stock	-0.270**	-0.444***	-0.202	-0.521**	-0.274**	-0.258**
	(0.123)	(0.160)	(0.126)	(0.198)	(0.125)	(0.128)
Log arrivals-departures	-0.618***	-0.466**	-0.597***	-0.333	-0.578***	-0.581***
	(0.183)	(0.204)	(0.204)	(0.244)	(0.166)	(0.169)
Log bonds	-0.0315					
	(0.132)					
Log equity and funds		0.0743				
		(0.122)				
Log outward FDI			0.0126			
			(0.0846)			
Log assets in debt				0.0264		
				(0.171)		
Log assets in equity					-0.0725	
					(0.0931)	
Log total assets						-0.105
						(0.110)
Observations	106	73	93	57	104	103
R-squared	0.623	0.632	0.580	0.650	0.640	0.641

Note: Cross-section of countries; all variables are standardized to have a mean of zero and a standard deviation of one; hence the estimated coefficients have an interpretation as beta coefficients (how many standard deviations the left-hand side variable changes with a one standard deviation change in a right-hand side variable); bonds is the total value of bond security flows with China (inflows + outflows) from 2015-7; Equity and funds is the total value of equity and mutual fund security flows with China (inflows + outflows) from 2015-7; outward FDI is the outward flow of Foreign Direct Investment from China for 2010-2; assets in debt is the total value of debt assets held by a country in China for 2018-9; assets in equity is the total value of equity assets held by a country in China for 2018-9; all other variables defined as in Table G.3; heteroskedasticity robust standard errors in parentheses; *** denotes significance at the 1 percent level; ** denotes significance at the 5 percent level; * denotes significance at the 10 percent level; data on outbreaks of Covid-19 from the Center for Systems Science and Engineering (CSSE) at Johns Hopkins University.

interventions and behavioral responses. In particular, we provide evidence on the extensive margin of disease diffusion, as measured by arrival time of the disease in each location. This approach has the additional advantage that these arrival times can be computed for a number of different infectious diseases over a long historical time period, because it only requires data on the timing of the first outbreak of the disease in each location.

In this subsection, we provide further evidence on the intensive margin of disease diffusion, as measured by the rate of growth of infections, using additional data that are available for Covid-19. Again we focus on the initial period of the outbreak in order to reduce the impact of public policy interventions and behavioral responses. In the conventional closed-economy SIR model, the rate of growth of infections in the neighborhood of the no-infection equilibrium is exponential, and is separately determined for each country, depending on the epidemiological parameters in that country, which in turn depend on the culture, geography and institutions in that country. In contrast, in our open economy SIR model, this rate of growth of infections in the neighborhood of the no-infection equilibrium is not only exponential, but is interdependent across countries. In particular, the more a country trades with a partner with a high relative level of infections, the more rapid that country's own rate of growth of infections, even after controlling for the time since its own initial infection.

In the remainder of this subsection, we first derive the predictions of the closed economy SIR model for the rate of growth of infections in the neighborhood of the no-infection equilibrium, as used in the epidemiological literature. We next derive the corresponding predictions of our open economy SIR model. Finally, we provide evidence in support of the predictions of our open economy SIR model using data for the Covid-19 pandemic. We show that countries that trade more with partners with high relative levels of infections have more rapid rates of growth of infection, even after controlling for the time since their own initial infection.

Conventional SIR Model In the conventional closed-economy SIR model, the system of dynamic equations for the evolution of Susceptibles ($S_i(t)$), Infected ($I_i(t)$) and Recovered ($R_i(t)$) for country i at time t is as follows:

$$\dot{S}_i\left(t\right) = -\beta_i S_i\left(t\right) I_i\left(t\right),$$

$$\dot{I}_i\left(t\right) = \beta_i S_i\left(t\right) I_i\left(t\right) - \gamma_i I_i\left(t\right),$$

$$\dot{R}_i\left(t\right) = \gamma_i I_i\left(t\right),$$

where a dot above a variable denotes a time derivative; in our baseline model with no behavioral responses and no general equilibrium effects, we have $\beta_i = 2\alpha_i n_{ii}$, where n_{ii} is time-invariant.

A standard approach to estimating this conventional SIR model is to focus on the initial time window of exponential growth in the neighborhood of the no-infection equilibrium, as for example in Ma (2020). In the neighborhood of this no-infection equilibrium, $S_i(t) \approx 1$, and we have:

$$\frac{\dot{I}_i\left(t\right)}{I_i\left(t\right)} \approx \left[\beta_i - \gamma_i\right],$$

Integrating in this neighborhood, we have:

$$\int_t^{t+\tau} \frac{\dot{I}_i\left(s\right)}{I_i\left(s\right)} ds \approx \int_t^{t+\tau} \left[\beta_i - \gamma_i\right] ds,$$

$$\Delta \log I_i(t+\tau) \approx \left[\beta_i - \gamma_i\right] \tau.$$

Therefore, in the conventional SIR model, $[\beta_i - \gamma_i]$ can be estimated from a linear regression of the log change in the share of the population infected ($\Delta \log I_i(t+\tau)$) on the number of days since the first infection (τ), using data over a time window immediately after the first infection. Given separate information on either the contact rate (β_i) or the recovery rate (γ_i) from elsewhere, one can then recover the reproduction rate $R_{i0} = \beta_i/\gamma_i$ from the estimate of $[\beta_i - \gamma_i]$.

Open Economy SIR Model In a multi-country version of our open-economy SIR model, the system of dynamic equations for the evolution of Susceptibles ($S_i(t)$), Infected ($I_i(t)$) and Recovered ($R_i(t)$) in country $i \in \mathcal{J}$ at time t instead takes the following form:

$$\dot{S}_i(t) = -\beta_{ii} S_i(t) I_i(t) - \sum_{j \in \{\mathcal{J} \backslash i\}} \beta_{ij} S_i(t) I_j(t) - \sum_{j \in \{\mathcal{J} \backslash i\}} \beta_{ji} S_i(t) I_j(t),$$

$$\dot{I}_i(t) = \beta_{ii} S_i(t) I_i(t) + \sum_{j \in \{\mathcal{J} \backslash i\}} \beta_{ij} S_i(t) I_j(t) + \sum_{j \in \{\mathcal{J} \backslash i\}} \beta_{ji} S_i(t) I_j(t) - \gamma_i I_i(t),$$

$$\dot{R}_i(t) = \gamma_i I_i(t),$$

where recall that a dot above a variable denotes a time derivative; in our baseline model with no behavioral responses and no general equilibrium effects, we have $\beta_{ii} = 2\alpha_i n_{ii}$, $\beta_{ij} = \alpha_j n_{ij}$, and $\beta_{ji} = \alpha_i n_{ji}$, where $\{n_{ii}, n_{ij}, n_{ji}\}$ are time invariant.

Following an analogous approach as for the conventional SIR model above, we focus on the initial time window of exponential growth in the neighborhood of the no-infection equilibrium. In the neighborhood of this no-infection equilibrium, $S_i(t) \approx 1$, and we have:

$$\frac{\dot{I}_i(t)}{I_i(t)} \approx [\beta_{ii} - \gamma_i] + \sum_{j \in \{\mathcal{J} \backslash i\}} \beta_{ij} \frac{I_j(t)}{I_i(t)} + \sum_{j \in \{\mathcal{J} \backslash i\}} \beta_{ji} \frac{I_j(t)}{I_i(t)}, \qquad \text{for } I_i(t) > 0.$$

Integrating in this neighborhood, we have:

$$\int_t^{t+\tau} \frac{\dot{I}_i(s)}{I_i(s)} ds \approx \int_t^{t+\tau} [\beta_{ii} - \gamma_i] \, ds + \int_t^{t+\tau} \left[\sum_{j \in \{\mathcal{J} \backslash i\}} (\beta_{ij} + \beta_{ji}) \frac{I_j(s)}{I_i(s)} \right] ds, \qquad \text{for } I_i(t) > 0.$$

$$\Delta \log I_i(t+\tau) \approx [\beta_{ii} - \gamma_i] \, \tau + \int_t^{t+\tau} \left[\sum_{j \in \{\mathcal{J} \backslash i\}} (\beta_{ij} + \beta_{ji}) \frac{I_j(s)}{I_i(s)} \right] ds, \qquad \text{for } I_i(t) > 0.$$

We approximate the second term by replacing relative infections at each time $s \in [t, t+\tau]$ ($I_j(s)/I_i(s)$) with relative infections at the time of country i's initial infection ($I_j(t)/I_i(t)$), which yields the following expression:

$$\Delta \log I_i(t+\tau) \approx [\beta_{ii} - \gamma_i] \, \tau + \int_t^{t+\tau} \left[\sum_{j \in \{\mathcal{J} \backslash i\}} (\beta_{ij} + \beta_{ji}) \frac{I_j(t)}{I_i(t)} \right] ds, \qquad \text{for } I_i(t) > 0,$$

Evaluating the integral, we obtain:

$$\Delta \log I_i(t+\tau) \approx [\beta_{ii} - \gamma_i]\,\tau + \sum_{j \in \{\mathcal{J} \backslash i\}} (\beta_{ij} + \beta_{ji}) \left[\frac{I_j(t)}{I_i(t)} \tau \right], \qquad \text{for } I_i(t) > 0, \tag{G.3}$$

where the first term is the same as in the closed-economy SIR model above and the second term captures spillovers of infections from other countries.

Therefore, the rate of growth of a country's infections in the neighborhood of the no-infection equilibrium ($\Delta \log I_i(t+\tau)$) does not only depend on the time since its own initial infection (τ) and the country's own epidemiological parameters ($[\beta_{ii} - \gamma_i]$). It also depends on spillovers from the country's trade partners, as determined by relative infection rates ($I_j(t)/I_i(t)$) interacted with the time since the country's own initial infection (τ), and the parameters β_{ij} and β_{ji}.

Empirical Specification We now provide empirical evidence in support of this prediction of our open-economy SIR model of spillovers of infections between countries. We consider the following empirical specification of equation (G.3) using panel data on countries i across days τ:

$$\Delta \log I_i(t+\tau) = a_0 + b_1 \tau + b_2 \left(J_i(t) \tau \right) + u_i(t+\tau), \tag{G.4}$$

where we assume common epidemiological parameters across countries ($\beta_{ii} = \beta$, $\gamma_i = \gamma$), such that $b_1 = [\beta - \gamma]$; $u_i(t+\tau)$ is a stochastic error; and we model spillovers of infections between countries using observed trade flows, such that $J_i(t)$ is the trade-weighted average of relative infection rates ($I_j(t)/I_i(t)$) in other countries j at the time of country i's initial infection t:

$$J_i(t) \equiv \sum_{j \in \{\mathcal{J} \backslash i\}} \frac{X_{ij}}{X} \frac{I_j(t)}{I_i(t)}, \qquad \text{for } I_i(t) > 0,$$

and:

$$\sum_{j \in \{\mathcal{J} \backslash i\}} (\beta_{ij} + \beta_{ji}) \left[\frac{I_j(t)}{I_i(t)} \tau \right] = b_2 \sum_{j \in \{\mathcal{J} \backslash i\}} \frac{X_{ij}}{X} \left[\frac{I_j(t)}{I_i(t)} \tau \right], \qquad \text{for } I_i(t) > 0.$$

We measure trade between country i and country j (X_{ij}) as the sum of exports and imports, and $X = \sum_{i \in \mathcal{J}} \sum_{j \in \mathcal{J}} X_{ij}$ is the total value of trade. We use 2019 trade values (X_{ij}) to abstract from behavioral responses and public policy interventions, since the first case of Covid-19 worldwide occurred in China in December, 2019.

In a robustness check, we also augment our baseline econometric specification (G.4) with country fixed effects, which control for any main effect of the spillovers term ($J_i(t)$), and for unobserved differences in culture, geography and institutions that affect the growth of infections. To facilitate comparisons of the economic magnitude of coefficients, we again standardize all variables, such that each variable has a mean of zero and a standard deviation of one. Therefore, the estimated coefficients correspond to beta coefficients: how many standard deviations the left-hand side variables changes in response to a one standard deviation change in each right-hand side variable.

Data and Measurement We use data on new Covid-19 cases from the Center for Systems Science and Engineering (CSSE) at Johns Hopkins University. We focus on the first wave of infections of Covid-19 in 2020 by restricting attention to the first 200 days after the first case in China in December 2019. The last country in our sample to be infected experiences its first case 123 days after the first case in China. We construct our baseline measure of the share of the population that are infected ($I_i(s)$) using the structure of the SIR model and the guideline from the Centers for Disease Control and Prevention (CDC) that people with Covid-19 remain infectious for 10 days.[19] Given this infectious period of 10 days, we construct the stock of infected people each day in each country using the perpetual inventory method, based on the number of new cases that day and the lagged number of new cases for the previous 9 days:

$$I_i(s) = \frac{\mathcal{I}_i^{\text{Stock}}(s)}{L_i} = \sum_{k=0}^{9} \mathcal{I}_i^{\text{New}}(s-k),$$

where $I_i(s)$ is the fraction of country i's population infected by Covid-19 at time s; $\mathcal{I}_i^{\text{Stock}}(s)$ is the stock of people infected by Covid-19; $\mathcal{I}_i^{\text{New}}(s)$ is the flow of new cases of Covid-19; and L_i is total population in 2019. In robustness checks, we also report empirical results from specifications in which we instead assume an infectious period of 8 or 9 days.

Empirical Results In Table G.5, we report the estimation results. In our baseline specification assuming an infectious period of 10 days, we have 18,191 country-day observations during our 200-day window for which countries have positive shares of the population infected with Covid-19. In Column (1), we estimate equation (G.4) including only the time since a country's own first infection (τ). We find a positive and statistically significant coefficient, which is consistent with the condition for a pandemic to occur of $\beta - \gamma > 0$. From the regression R-squared, we find that the time since a country's first infection alone explains around 21 percent of the variance in the log change in the share of the population that is infected.

In Column (2), we augment this specification with our spillover interaction term between the trade-weighted average of relative infection rates and the time since a country's own first infection ($J_i(t)\tau$). We find a positive and statistically significant coefficient on this interaction term, consistent with cross-country spillovers of infections through travel induced by trade.[20] These spillovers are not only statistically significant but also economically relevant: a one standard deviation increase in this interaction term raises a country's own rate of infection growth by 0.192 standard deviations, compared with 0.414 standard deviations for the length of time since a country own initial infection. Comparing Columns (1) and (2), we find that allowing for spillovers increases the explanatory power of the regression, with the R-squared increasing by around 20 percent.

In Column (3), we show that these results are robust to including country fixed effects, which

[19] https://www.cdc.gov/coronavirus/2019-ncov/if-you-are-sick/quarantine-isolation-background.html.

[20] We find a similar pattern of results if we further augment this specification with an interaction between log distance from China and time since a country's own first infection: the estimated coefficients (standard errors) on our spillover interaction and the distance interaction are as follows: 0.217 (0.0259) and 0.003 (0.0012), respectively.

Table G.5: Growth in Share of the Population Infected with Covid-19

	(1) Log Growth Share Infected	(2) Log Growth Share Infected	(3) Log Growth Share Infected	(4) Log Growth Share Infected	(5) Log Growth Share Infected
Time Since Infection	0.455***	0.414***	0.396***	0.388***	0.388***
	(0.0436)	(0.0398)	(0.0325)	(0.0326)	(0.0326)
Spillover Interaction		0.192***	0.226***		
		(0.0275)	(0.0330)		
Spillover Interaction				0.227***	
				(0.0338)	
Spillover Interaction					0.227***
					(0.0337)
Infectious Period	10 days	10 days	10 days	9 days	8 days
Country Fixed Effects			Yes	Yes	Yes
Observations	18,191	18,191	18,191	18,116	18,116
R-squared	0.210	0.247	0.659	0.659	0.659

Note: Panel of country-day observations within 200 days of the first Covid-19 case worldwide; all variables are standardized to have a mean of zero and a standard deviation of one; hence the estimated coefficients have an interpretation as beta coefficients (how many standard deviations the left-hand side variable changes with a one standard deviation change in a right-hand side variable); Log growth share infected is the log change in the share of a country's population that is infected relative to the first day in which that country experienced an infection ($\Delta \log I_i(t+\tau)$); Time since infection is the number of days since a country's first Covid-19 case (τ); Spillover interaction ($J_i(t)\tau$) is the interaction between the trade-weighted average of relative infections ($I_j(t)/I_i(t)$) in other countries j at the time t of country i's initial infection: trade weights are calculated as the sum of exports and imports in 2019; Infectious period is the number of days for which people are assumed to remain infectious with Covid-19 when constructing the share of the population infected (I_i) from the data on new cases of Covid-19; the number of observations falls in Columns (4) and (5), because there are fewer country-day observations with a positive share of the population infected with Covid-19 under the assumption of an 8 or 9-day infectious period; Standard errors in parentheses are clustered by country; *** denotes significance at the 1 percent level; ** denotes significance at the 5 percent level; * denotes significance at the 10 percent level; data on outbreaks of Covid-19 from the Center for Systems Science and Engineering (CSSE) at Johns Hopkins University.

control for cross-country differences in culture, geography, institutions and public policy that affect the rate of growth of infections, as well as any main effect of the spillover term ($J_i(t)$). We continue to find positive and statistically significant coefficients on the time since a country's own first infection and our spillover interaction term, which remain of around the same magnitude as in Column (2). The substantial increase in the regression R-squared to around 65 percent when we include the country fixed effects is consistent with the idea that cross-country differences, including differences in public policy, played an important role in shaping the evolution of the pandemic. Nevertheless, we continue to find statistically significant and economically relevant evidence of cross-country spillovers of infections through travel induced by trade, with the estimated coefficient on our spillover interaction term increasing in magnitude.

In Columns (4) and (5), we report robustness tests, in which we assume infectious periods of 8 and 9 days, respectively, instead of the 10 days in our baseline specification. The number of observations falls slightly, because there are fewer country-day observations with a positive share of the population infected with Covid-19 under the assumption of a 8 or 9-day infectious period. Nevertheless, we find a similar pattern of results, with positive and statistically significant coefficients on the time since a country's own first infection and our spillover interaction term, which again remain of around the same magnitude as in Column (3). Therefore, our findings of cross-country spillovers of infections through travel induced by trade are not sensitive to assumptions about the exact number of days for which a person with Covid-19 remains infectious.

In sum, when we consider the intensive margin of infection growth instead of the extensive margin of the arrival time of infections, we again find empirical support for the theoretical predictions of our open-economy SIR model. We find robust evidence of cross-country spillovers of infections mediated through international trade: Countries that trade more with partners with higher relative levels of infection have a more rapid rate of growth of their own infections, even after controlling for the length of time since their own initial infection.

G.2 Existing Literature on Globalization and Disease Diffusion

Our empirical findings for the plague, 1957-8 influenza and Covid-19 are consistent with a wider related literature in economics and epidemiology that argues that globalization plays a central role in shaping the spread of disease around the world.

In particular, the role of global trade and transportation networks in the transmission of infectious diseases is widely accepted in the epidemiological literature, as summarized in the Institute of Medicine (2006) National Academies of Science Conference Volume on *The Impact of Globalization on Infectious Disease Emergence and Control: Exploring the Consequences and Opportunities* and the review in Tatem et al. (2006).[21] This review in Tatem et al. (2006) examines five human-infectious and four vector-borne diseases. The five human infectious diseases are: (i) Plague; (ii) Cholera; (iii) Influenza; (iv) Human Immunodeficiency Virus (HIV) / Acquired Immunodeficiency Syndrome (AIDS); and (v) Severe Acute Respiratory Syndrome (SARS). The four vector-borne diseases are: (i) Yellow Fever; (ii) Dengue; (iii) West Nile Virus; and (iv) Malaria.

As an example from the human infectious diseases, Cholera is caused by an intestinal infection with the bacterium *Vibrio cholerae*, which leads to severe dehydration, shock and often-rapid death. Accounts of cholera-like diseases go back as far as the times of Hippocrates and Buddha. Over the past two centuries, *Vibrio cholerae* has broken out seven times from its endemic heartland in West Bengal, India to cause pandemics (Sack et al. 2004). The first cholera pandemic started in 1817 in India, but soon spread to China, Japan, Indonesia and Southern Russia along trade routes (Reidl and Klose 2002; Karlen 1995). Each successive cholera pandemic increased in geographic extent and severity, with the expanding reach of the global transportation system and the increased movement of people around the world (Rogers 1919; Shah 2001).

As an example from the vector-borne diseases, Yellow Fever is caused by the yellow fever virus, and is spread by the bite of an infected mosquito. Symptoms include fever, chills, loss of appetite, nausea, muscle pains, and can result in death. Yellow Fever originated in Africa and was spread to

[21] The global airline network has received particular attention as a major network for disease transmission, including for example Colizza et al. (2006), Balcan et al. (2009), and Barbosa et al. (2018).

the Americas in the 15th century through the Transatlantic Slave Trade (Oldstone 2009). Either some enslaved people were already infected with yellow fever, or the mosquito vector of the disease survived the voyage across the Atlantic in barrels of drinking water. The first recorded cases of Yellow Fever in the Americas were in Barbados in 1647 (Findlay 1941). By the end of the epidemic in 1649, around 6,000 people had died. From the 1690s, the disease spread northwards, appearing at ports along the Eastern seaboard of North America, with epidemics in Boston, Charleston and Philadelphia in 1693 (Harrison 2012). By the time of the Revolutionary War from 1775-83, it is estimated that there were twenty-five major epidemics in the thirteen colonies that become the United States of America (Patterson 1992). In 1927, yellow fever virus was the first human virus to be isolated. Although a safe and effective vaccine against yellow fever now exists, it remains endemic in tropical areas of Africa and South America.

Further evidence on the role of the international movement of people and goods in the transmission of infectious diseases is provided by Desbordes (2021), using data from the Global Infectious Disease and Epidemiology Online Network (GIDEON) database. The paper considers the top twenty diseases that have caused the largest number of outbreaks in developed or developing countries in recent decades: (i) Influenza; (ii) Measles; (iii) Cholera; (iv) Dengue; (v) Salmonellosis; (vi) Hepatitis A; (vii) Enterovirus infection; (viii) Chikungunya; (ix) Shigellosis; (x) Anthrax; (xi) Meningitis - bacterial; (xii) Typhoid and enteric fever; (xiii) Malaria; (xiv) Leptospirosis; (xv) Orbital and eye infection; (xvi) Gastroenteritis - viral; (xvii) Meningitis - aseptic (viral); (xviii) Tubercolosis; (xix) Conjunctivitis - viral; and (xx) Brucellosis. A spatial autoregressive (SAR) model is estimated for the number of outbreaks of each disease using data on 165 countries from 1995-2015. The weights in the spatial weights matrix are directly estimated using data on bilateral goods trade and migration. The paper finds large, positive and statistically significant coefficients on the contemporaneous spatial lag variables, consistent with disease outbreaks diffusing spatially through goods trade and migration. The estimated spatial dependence is particularly high for the vector-borne diseases of Chikungunya and Dengue; the diarrhoeal disease of Cholera; and the viral disease of Measles. These findings of disease diffusion through spatial networks of goods and people movements provide direct support for the predictions of our theoretical model.

Therefore, in both our empirical work and the wider related literature in economics and epidemiology, we find strong evidence in support of the view that globalization plays a leading role in shaping the diffusion of disease around the world.

H International Travel and Trade

In this section of the Online Appendix, we provide empirical evidence on the assumption in our theoretical model that international travel is closely related to international trade. In Subsection H.1, we report new empirical evidence on the relationship between bilateral travel, trade and tariffs as a direct measure of trade policy. In Subsection H.2, we review the related empirical literature that has used quasi-experimental variation to provide evidence that reductions in travel barriers lead to increased travel and trade.

H.1 Empirical Evidence on International Travel and Trade

First, we establish a strong, positive and statistically significant correlation between international travel and trade. Second, we provide further evidence on the correlations between international travel, trade and tariffs as a direct measure of trade policy barriers.

Data We measure international travel using data on bilateral air passengers from the Origin and Destination (OFOD) Database of the International Civil Aviation Organization (ICAO) for the period from 1982-2019.[22] These data report information on direct flights between each origin and destination, where a direct flight is defined as a flight for which the same flight number is maintained. Therefore, direct flights include both non-stop flights, and flights with one or more intermediate stops as part of the same flight number. We aggregate air traffic between bilateral pairs of origin and destination airports to bilateral pairs of origin and destination countries. We measure international travel using the bilateral number of air passengers, which includes first, business and economy-class travel, and captures both business travelers and tourists. We interpret tourism in terms of our model as a form of business travel to consume non-traded services.

We combine these data on international travel with a variety of other sources of data. We use data on the value of bilateral trade between countries from the CEPII GRAV Database based on the IMF Direction of Trade Statistics from 1982-2019.[23] We measure trade as the sum of exports and imports. We also use data on bilateral trade in goods mainly transported by land and sea, for which air transport accounts for less than 20 percent of the value of trade. We construct this measure by combining COMTRADE data on the value of bilateral trade for each HS 6-digit product from 1988 onwards with EUROSTAT data on the fraction of the total value of trade in each HS 6-digit product that is transported by air.[24] We measure the bilateral distance between countries based on the latitude and longitude coordinates of their capital cities. Finally, we instrument for international trade flows using tariff data, which are available from the United Nations Trade Analysis Information System (TRAINS) from 1988-2019.[25] We measure the bilateral tariff for each origin-destination pair as the unweighted average of the bilateral *ad valorem* tariffs for each HS 6-digit product for the origin and destination countries.

Correlation Between Travel and Trade We begin by considering the following log linear empirical specification that relates bilateral travel (Y_{ijt}) to bilateral trade (X_{ijt}) between origin country j and destination country i in year t:

$$\log Y_{ijt} = \beta \log X_{ijt} + \eta_{ij}^{Y} + \kappa_t^{Y} + \epsilon_{ijt}^{Y}, \tag{H.1}$$

[22] See https://data.icao.int/icads/Product/View/115.

[23] See http://www.cepii.fr/cepii/en/bdd_modele/presentation.asp?id=8.

[24] Direct information on bilateral trade by mode of transportation for each origin-destination-year observation is not reported for our sample period in COMTRADE.

[25] See https://databank.worldbank.org/.

where the origin-destination fixed effects (η_{ij}^{Y}) control for time-invariant characteristics of an origin-destination pair that affect both travel and trade (e.g., geographical distance and contiguity); the year fixed effects (κ_t^Y) capture macro shocks that affect both travel and trade over time; ϵ_{ijt}^{Y} is a stochastic error; we report standard errors clustered by origin-destination pair to allow for serial correlation in the error term over time.

Since this specification includes origin-destination fixed effects, the estimated coefficient β captures the relationship between changes in bilateral travel and changes in bilateral trade within origin-destination pairs. Our theoretical model implies that these two variables are endogenous and jointly determined by trade and mobility frictions. Therefore, equation (H.1) captures a correlation between two endogenous variables. We begin by providing evidence on the strength of this correlation by estimating equation (H.1) using ordinary least squares (OLS).

Table H.1: Correlation Between International Travel and Trade

	(1) Log Air Passengers	(2) Log Air Passengers	(3) Log Air Passengers
Log Trade	0.217***	0.293***	
	(0.0111)	(0.0173)	
Log Trade Land/Sea			0.230***
			(0.0134)
Estimation	OLS	OLS	OLS
Sample	All	$> 3,000$ km	All
Destination FEs	Yes	Yes	Yes
Year FEs	Yes	Yes	Yes
Observations	124,597	65,332	96,197
R-squared	0.763	0.771	0.781

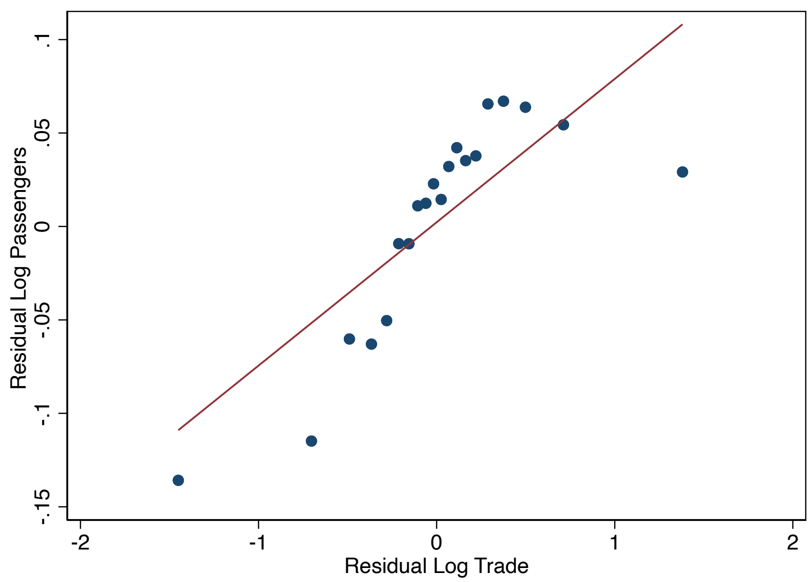
Note: Panel of origin-destination-year observations; Air passengers is total number of airline passengers from an origin to a destination in a given year; Trade is the sum of exports and imports between each origin and destination in a given year; Trade Land/Sea is the sum of exports and imports for Harmonized System (HS) 6-digit products for which air transport accounts for less than 20 percent of the value of trade; Origin-Destination FEs are origin-destination fixed effects; Year FEs are year fixed effects; Sample in Column (2) is restricted to origin-destination pairs with bilateral distances greater than 3,000 kilometers; Standard errors in parentheses are clustered by origin-destination pair; *** denotes significance at the 1 percent level; ** denotes significance at the 5 percent level; * denotes significance at the 10 percent level.

As reported in Column (1) of Table H.1, we find a positive and statistically significant correlation, with a one percent increase in the value of bilateral trade associated with a 0.217 percent increase in the number of air passengers. One potential concern is that our bilateral travel data are based on air passengers, and hence exclude travel by land and sea. This could lead us to underestimate bilateral travel between countries, particularly over short distances, for which air transport is relatively less important. To address this concern, Column (2) reports a robustness test in which we restrict attention to origin-destination pairs more than 3,000 kilometers apart, for which air travel is likely to be the dominant mode of transport. We continue to find a positive and statistically significant correlation, which increases in magnitude compared to Column (1).

Another potential concern is that aircraft are used to transport both people and goods, which could introduce a mechanical correlation between air travel and trade. To address this concern, Column (3) reports a robustness test, in which we restrict attention to trade in goods for which which air transport accounts for less than 20 percent of the value of trade. Even when we focus on trade in these goods that are mainly transported by land and sea, we continue to find a strong, positive and statistically significant correlation between bilateral air travel and trade.

As a final specification check, Figure H.1 displays a binscatter of the conditional correlation between log bilateral air passengers and log bilateral trade, after controlling for origin-destination and year fixed effects.[26] We a strong positive relationship between these two variables throughout the distribution, providing further empirical support for the close relationship between international travel and trade in our theoretical model.

Figure H.1: Binscatter of Conditional Correlation Between Log Bilateral Air Passengers and Log Bilateral Trade



Note: Residual log bilateral air passengers and residual log bilateral trade after controlling for origin-destination fixed effects and year fixed effects; blue circles correspond to ventiles of the conditional relationship between the two residuals; red line shows the linear regression fit between the two residuals.

International Travel and Trade Barriers Our theoretical model suggests that the estimated positive correlation between travel and trade in Table H.1 need not have a causal interpretation, because both variables are jointly determined by trade and travel frictions. To explore further the role of trade frictions, we next consider a direct measure of trade policy barriers in the form of tariffs. In particular, we treat equation (H.1) as a second-stage regression relating bilateral travel (Y_{ijt}) to endogenous bilateral trade (X_{ijt}). We instrument bilateral trade (X_{ijt}) with tariff barriers

[26]Using the Frisch-Waugh-Lovell Theorem, we regress each variable separately on origin-destination fixed effects and year fixed effects, generate the residuals, and then display a binscatter of the two residuals against one another.

$(1 + \tau_{ijt})$ using the following first-stage regression:

$$\log X_{ijt} = \gamma \log (1 + \tau_{ijt}) + \eta_{ij}^X + \kappa_t^X + \epsilon_{ijt}^X, \tag{H.2}$$

where the origin-destination fixed effects (η_{ij}^X) control for time-invariant characteristics of an origin-destination pair that affect both trade and tariffs; the year fixed effects (κ_t^X) control for secular trends in trade and tariffs over time; ϵ_{ijt}^X is a stochastic error; again we report standard errors clustered by origin-destination pair to allow for serial correlation in the error term over time.

The exclusion restriction for the IV estimation is that bilateral tariffs only affect bilateral travel through bilateral trade. This exclusion restriction could be violated if there are other channels through which bilateral tariffs affect bilateral travel (e.g., through the travel of trade negotiators). Therefore, we also report the corresponding reduced-form specification between travel and tariffs, which captures all channels through which bilateral travel and tariffs are related:

$$\log Y_{ijt} = \gamma \log (1 + \tau_{ijt}) + \mu_{ij} + \chi_t + \varepsilon_{ijt}, \tag{H.3}$$

where μ_{ij} are origin-destination fixed effects; χ_t are time fixed effects; and ε_{ijt} is a stochastic error; again we report standard errors clustered by origin-destination pair to allow for serial correlation in the error term over time.

The identifying assumption in this reduced-form specification is that unobserved shocks to travel (ε_{ijt}) in equation (H.3) are uncorrelated with tariffs $(1 + \tau_{ijt})$, after controlling for the origin-destination and year fixed effects. Again this identifying assumption could be violated, because bilateral tariffs are the result of a political economy process, which itself could be endogenous to bilateral travel between countries. Although it is challenging to ever fully address this endogeneity concern, a growing empirical literature has used sources of quasi-experimental variation to provide evidence in support of a causal relationship between bilateral trade and travel, as discussed further in Online Appendix H.2 below.

In Column (1) of Table H.2, we reproduce our OLS estimates of the second-stage regression (H.1) linking travel and trade from Column (1) of Table H.1. In Columns (2)-(4) of Table H.2, we report two-stage least squares (2SLS) estimates of the specifications from Columns (1)-(3) of Table H.1. Across all of these specifications, we find a positive and statistically significant correlation between bilateral travel and the variation in bilateral trade predicted by bilateral tariffs. We find that tariffs are powerful determinants of trade in the first-stage regression, with the first-stage F-statistic reported at the bottom of the column well above the conventional threshold of 10.

In Column (5), we report the results of estimating the reduced-form specification (H.3) that relates bilateral travel directly to bilateral tariiffs. We find a negative and statistically significant coefficient, implying that trade liberalization is correlated with increased bilateral travel. Nevertheless, this correlation is again not necessarily causal, because bilateral tariffs themselves could be endogenous to bilateral travel through the political economy process. In the next subsection, we review a number of recent studies that have sources of quasi-experimental variation to provide

Table H.2: International Travel, Trade and Trade Barriers

	(1) Log Air Passengers	(2) Log Air Passengers	(3) Log Air Passengers	(4) Log Air Passengers	(5) Log Air Passengers
Log Trade	0.217***	0.399**	0.452***		
	(0.0111)	(0.157)	(0.142)		
Log Trade Land/Sea				0.498***	
				(0.159)	
Log Tariff					-1.088***
					(0.368)
Estimation	OLS	IV	IV	IV	OLS
Sample	All	All	$> 3,000$ km	All	All
Origin-Destination FEs	Yes	Yes	Yes	Yes	Yes
Year FEs	Yes	Yes	Yes	Yes	Yes
Observations	124,597	68,734	34,889	65,967	71,376
R-squared	0.763	–	–	–	0.790
First-stage F-statistic	–	100.8	129.7	122.7	–

Note: Panel of origin-destination-year observations; Air passengers is total number of air passengers from an origin to a destination in a given year; Trade is the sum of exports and imports for each origin and destination in a given year; Trade Land/Sea is the sum of exports and imports for Harmonized System (HS) 6-digit products for which air transport accounts for less than 20 percent of the value of trade; Origin-Destination FEs are origin-destination fixed effects; Year FEs are year fixed effects; Log trade is instrumented with log tariff in Columns (2)-(4); Log tariff is the unweighted average of the bilateral *ad valorem* tariffs for each HS 6-digit product for the origin and destination countries; First-stage F-statistic is the F-statistic for the statistical significance of the instrument in the first-stage regression; the R-squared for the second-stage regression is not reported in the IV specifications, because it does not have a meaningful interpretation; Standard errors in parentheses are clustered by origin-destination pair; *** denotes significance at the 1 percent level; ** denotes significance at the 5 percent level; * denotes significance at the 10 percent level.

evidence in support of a causal relationship between bilateral travel and trade.

H.2 Existing Literature on International Travel and Trade

In this section of the Online Appendix, we review the broader empirical literature on the relationship between international travel and trade. A large number of studies find a strong correlation between international travel and trade, including for example Kulendran and Wilson (2000), Shan and Wilson (2001), Poole (2009), Cristea (2011), Alderighi and Gaggero (2017), and Yilmazkuday and Yilmazkuday (2017).[27] In this subsection, we summarize evidence from a small number of studies that have used micro data and sources of quasi-experimental variation to provide evidence that business travel has a causal impact on international trade.

Evidence from Micro Data on Nigerian Traders Startz (2021) examines the role of business travel in international trade using a novel micro dataset on Nigerian importers, which combines

[27] A related empirical literature provides evidence on the role of business and social networks in international trade, including Rauch (2001) and Combes et al. (2005).

information on the type and value of goods traded with variables describing the actual process of firm-to-firm trade (e.g., travel and payment terms) at the transaction level. The data cover 620 importers of differentiated consumer goods, such as clothing and electronics, who were randomly sampled from a census of over 50,000 shops in commercial districts of Lagos. The data captures imports over two years, totaling almost four thousand purchases from over thirty source countries and over a thousand foreign suppliers.

The paper begins by documenting a number of key features of business travel and international trade. First, business travel is common but not universal, and is more likely when importing from countries that are cheap to reach and in sectors in which new products appear frequently. Second, business travel expenditures are large – equivalent to the amounts spent on transportation and regulatory trade costs combined. Third, business travel by importers is persistent over time, and does not decline significantly in experience with particular countries or suppliers, suggesting motives beyond one-time matching or learning.

The paper next develops a theoretical model to account for these features of the observed data. Traders make forward-looking choices about how frequently to restock, and when doing so, whether or not to pay a fixed cost to travel to the source country. Traveling allows importers to search more effectively for new vintages and avoid a contract enforcement problem by conducting a spot transaction. Ordering remotely has a lower fixed cost but yields less up-to-date products as a result of a search friction and incurs higher unit costs as a result of a contracting friction.

The model is structurally estimated using the micro data on Nigerian traders. In the estimated model, importing without traveling yields goods that are on average 1.7 months behind the frontier available in the source country (the search friction) and requires paying a 15.5 percent price premium to induce good behavior from suppliers (the contracting friction). Removing both frictions increases welfare from the traded consumer goods sector by 14 percent – roughly two-thirds of the gains that would come from eliminating physical and regulatory trade costs in this sector. The welfare gains from eliminating the search friction alone would be 4.5 percent, and the gains from eradicating the contracting alone friction would be 7 percent, where the impact of removing both frictions is greater than the sum of removing each individually, because they interact with one another.

Taken together, these findings provide strong evidence that reductions in the costs of business travel have quantitatively relevant effects on the volume of international trade and hence welfare.

Evidence from the Liberalization of Soviet Air Space Söderlund (2020) uses the natural experiment of the liberalization of Soviet airspace in 1985 to provide evidence of the causal impact of business travel on trade. Before this liberalization, almost no airline had permission to overfly the Soviet Union. As part of the broader policies of reform of Glasnost and Perestroika in the Soviet Union from the mid-1980s onwards, and motivated by the need for foreign currency, the Soviet Union began to permit foreign airlines to make non-stop flights over its territory.

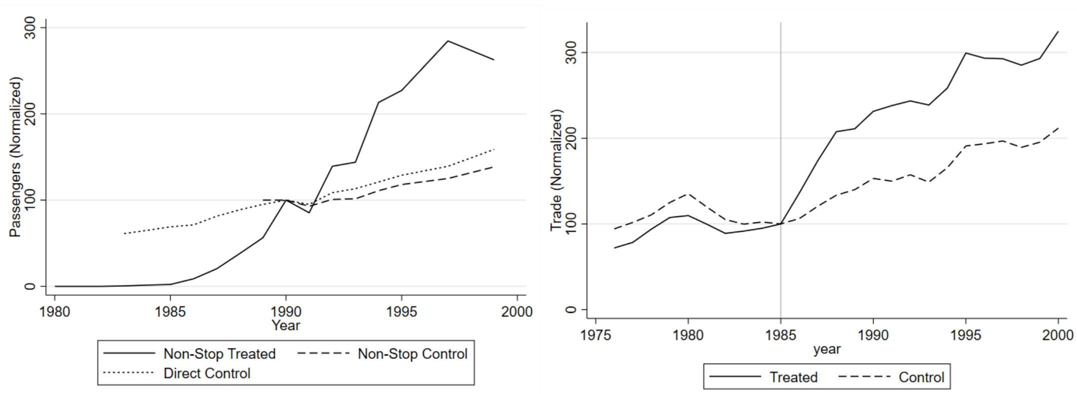
The resulting savings in flight time were substantial for a large number of international routes, particularly those between Europe and Asia. Before the liberalization, nearly every flight from

Europe to East Asia was routed either through Anchorage, Alaska, or the Middle East. After the liberalization, a flight from London to Tokyo, which previously took 18 hours, could be undertaken non-stop in less than 12 hours when routed over Soviet air space.

To estimate the impact of these reductions in travel time on business travel and international trade, Söderlund combines data on airline timetables, passenger traffic data from the International Civil Aviation Organization (ICAO), and international trade data from COMTRADE. The empirical analysis proceeds in a number of steps. First, the paper isolates origin-destination pairs affected by the liberalization, by mapping routes that pass through or close to Soviet airspace. In total, 252 origin-destination pairs are affected, and assigned to the treatment group. The control group consists of all other origin-destination pairs, excluding Eastern Bloc countries that were part of the Soviet Union's sphere of influence, which could have been affected in other ways by the opening up of the Soviet Union.

Second, the paper computes the change in travel times for the affected routes, by comparing the shortest routes for affected pairs before and after the liberalization of Soviet air space, and assuming an average flight speed of 850 km/h. The resulting average reduction in flight time among the treated origin-destination pairs is 3.9 hours or around 19 percent.

Figure H.2: Passengers (Left Panel) and Trade (Right Panel) for Treatment and Control Origin-Destination Pairs



Note: Reproduced from Söderlund (2020); treatment origin-destination pairs are those affected by the liberalization of Soviet airspace in 1985; control origin-destination pairs are all others, excluding Eastern Bloc countries that were part of the Soviet Union's sphere of influence; direct flights differ from non-stop flights in the left panel, because they can include one or more intermediate stops as part of the same flight number.

Third, the paper compares changes in travel and changes in trade over time for treatment and control origin-destination pairs. The left panel of Figure H.2 displays passenger traffic for these two groups, where values are normalized relative to 1990. Following the liberalization of Soviet air space in 1985, there is a sharp increase in passenger traffic for treated non-stop flights compared to either control non-stop flights or control direct flights.[28] The right panel of Figure H.2 shows

[28]Recall that the difference between a non-stop and direct flight is that a direct flight can include one or more intermediate stops as part of the same flight number.

the value of trade for treatment and control origin-destination pairs. Following the liberalization of Soviet air space in the mid 1980s, there is also a sharp increase in international trade for treated origin-destination pairs relative to control origin-destination pairs.

Fourth, the paper uses a gravity equation specification to estimate substantial impacts of these reductions in travel times on international trade flows. Business travel costs are estimated to account for 85.3 percent of the total trade frictions generated by geographical distance. The effect of travel time on trade continues to hold when restricting attention to trade in goods largely transported by land and sea. Therefore, these estimated effects of travel time on trade are not driven by lower transportation costs for goods shipped by air.

Finally, the changes in flight times are found to have a larger estimated impact for more technologically advanced products, consistent with the idea that these products that rely on advanced technology require more physical presence through business travel when traded.

Therefore, using quasi-experimental variation in travel time from the liberalization of Soviet airspace, this paper finds strong evidence that reductions in the costs of business travel lead to increased international travel and trade.

Evidence from High-speed Rail in Japan Bernard, Moxnes and Saito (2019) provides further evidence that business travel has a causal impact on trade using the natural experiment of the opening of a new high-speed (Shinkansen) train line in Japan. Although the route of this new high-speed train line had been planned at least since 1973, the actual construction was subject to substantial timing uncertainty due to numerous budgetary and administrative delays, which limited the scope for anticipation effects. A key feature of these high-speed trains is that they are used only to transport people and not goods. Therefore, the opening of this new line reduced the costs of business travel, while holding constant the costs of trading goods.

The main econometric equation is a triple-differences specification, which compares changes in firm outcomes (first difference) for firms near new Shinkansen stations compared to those further away (second difference), for periods before and after the opening of the new stations (third difference). After the opening of the new high-speed line, firms close to the new stations exhibit larger increases in (i) the number of locations from which they source inputs; (ii) the number of suppliers close to the new stations; and (iii) firm sales, employment, and productivity. Taken together, this pattern of empirical results is consistent with the view that exogenous reductions in the cost of business travel cause increased trade between locations.

Global Evidence from Air Travel Campante and Yanagizawa-Drott (2018) uses quasi-experimental variation in bilateral airline connections between cities to provide evidence on the role of air connections in determining levels of economic activity. In particular, the paper exploits the fact that pairs of cities just under 6,000 miles apart are more likely to have direct connections than those just above this threshold, because of a combination of flight regulations and airplane technology. Regulatory requirements on maximum flight time and crew accommodations increase costs substantially for flights of more than 12 hours, which corresponds to a distance of approximately 6,000 miles - a little over the distance separating Milan from Shanghai, or Istanbul from Jakarta. Although these regulations have been in place for decades, advances in airplane technology from the introduction of new long-range aircraft (Boeing's 747-400 and 777, in 1989 and 1995 respectively, and Airbus's A330 and A340 in 1993-4) reduced the relevance of this discontinuity from 1990 onwards.

The main econometric equation is a regression discontinuity design (RDD), which compares city pairs just below and above the 6,000 mile distance threshold. City pairs just below this threshold are substantially more likely to have direct airline connections than those just above this threshold. Additionally, cities with a higher fraction of potential links below this 6,000 mile threshold have a larger number and higher quality of airline connections, where the quality of a link is measured by its centrality within the airline network. Consistent with these relationships being driven by the interaction of flight regulations and airplane technology, these relationships become weaker after 1990 following the introduction of new long-range aircraft.

The paper next links air connections to economic development using data on the intensity of satellite nighttime lights as a measure of economic activity. Locations close to airports with a larger share of quality-weighted links below the 6,000-mile threshold are found to grow faster over time, after controlling for a number of potential confounders. Finally, the paper explores the mechanism through which airline connections affect economic development using data on business linkages between locations, as measured by foreign direct investment (FDI) ownership links from the Orbis dataset. City pairs just below the 6,000 mile threshold have substantially more business linkages than those just above this threshold. This pattern of results is consistent with the view that face-to-face interactions are particularly important for business linkages, and that more airline connections reduces the cost of business travel for these face-to-face interactions.[29]

Taking the empirical studies reviewed in this section as a whole, there is a strong evidence using a number of different sources of quasi-experimental variation that reductions in the costs of business travel play a causal role in increasing international travel and trade.

I Location Substitutability

In this section of the Online Appendix, we provide theoretical and empirical support for our assumption that domestic and foreign interactions are substitutes for one another, in the sense that a reduction in trade costs increases foreign interactions relative to domestic interactions.

This assumption of substitutability plays a key role in our theoretical result in the paper that a reduction in international trade costs can diminish the severity of the pandemic for both countries (Proposition 3 in the paper). This theoretical result obtains when the two countries have very different levels of infection. Under our assumption of substitutability between domestic and foreign interactions, a reduction in trade costs induces the residents of the unhealthy country to interact

[29] A number of other studies have used quasi-experimental sources of variation to show that increased airline connections lead to increased economic interactions between locations, including Giroud (2013) for headquarter investment in production plants, and Pauly and Stipanicic (2021) for knowledge creation and diffusion.

less in the bad domestic disease environment and more in the good foreign disease environment. With sufficient differences in levels of infection between the two countries, this substitution between the domestic and foreign locations in the unhealthy country can reduce the severity of the epidemic in both countries.

We now provide support for our assumption of substitutability. First, we show theoretically that this substitutability is implied by a constant elasticity gravity equation, in the sense that reductions in international trade costs increase foreign interactions relative to domestic interactions. Second, we provide empirical evidence that a constant elasticity gravity equation provides a good approximation to observed data on international travel. Third, we review evidence of substitutability from empirical studies of spatial interactions that have directly estimated the substitutability between domestic and foreign locations.

Substitutability and the Gravity Equation We consider the class of models of spatial interactions that satisfy a constant elasticity gravity equation. We assume that bilateral spatial interactions (n_{ij}) between origin j and destination i are increasing in an origin characteristic (O_j), increasing in a destination characteristic (D_i), and decreasing in bilateral travel frictions (τ_{ij}):

$$n_{ij} = O_j D_i \tau_{ij}^{-\delta}, \tag{I.1}$$

where we assume a constant elasticity ($-\delta$) of bilateral interactions with respect to bilateral travel frictions.

Our model of human interactions and trade in the paper falls within this class of constant elasticity gravity equation models of spatial interactions. From this gravity equation (I.1), the share of destination i's interactions with origin j is given by:

$$s_{ij} = \frac{n_{ij}}{\sum_{\ell} n_{i\ell}} = \frac{O_j \tau_{ij}^{-\delta}}{\sum_{\ell} O_{\ell} \tau_{i\ell}^{-\delta}}. \tag{I.2}$$

We now consider an increase in bilateral travel frictions between destination i and a given foreign origin $j \neq i$ ($d \ln \tau_{ij} > 0$), holding constant bilateral travel frictions with all other origins ($d \ln \tau_{i\ell} = 0$ for all $\ell \neq j$), including the own location, and holding constant all origin characteristics (O_{ℓ} for all ℓ). Taking the partial derivative with respect to bilateral travel frictions in equation (I.2), the share of interactions with that given foreign origin $j \neq i$ necessarily falls:

$$\frac{\partial s_{ij}}{\partial \tau_{ij}} \frac{\tau_{ij}}{s_{ij}} = -\delta \left(1 - s_{ij}\right) < 0, \qquad j \neq i, \tag{I.3}$$

and the share of interactions with all other origins, including the own location, necessarily rises:

$$\frac{\partial s_{i\ell}}{\partial \tau_{ij}} \frac{\tau_{ij}}{s_{i\ell}} = \delta s_{ij} > 0, \qquad \forall \ell \neq j. \tag{I.4}$$

A closely-related result is that domestic and foreign interactions are necessarily substitutes in the sense of the partial elasticity considered by Arkolakis, Costinot and Rodríguez Clare (2012):

$$\frac{\partial\left(\frac{n_{ij}}{n_{jj}}\right)}{\partial\tau_{ij}}\frac{\tau_{ij}}{\left(\frac{n_{ij}}{n_{jj}}\right)}=\frac{\partial\left(\frac{O_i\tau_{ij}^{-\delta}}{O_j\tau_{jj}^{-\delta}}\right)}{\partial\tau_{ij}}\frac{\tau_{ij}}{\left(\frac{O_i\tau_{ij}^{-\delta}}{O_j\tau_{jj}^{-\delta}}\right)}=-\delta<0. \tag{I.5}$$

Therefore, the class of constant elasticity gravity equations implies that domestic and foreign interactions are necessarily substitutes, in the sense that a reduction in trade costs increases foreign interactions relative to domestic interactions.

Empirical Evidence on the Gravity Equation We now provide empirical evidence on the extent to which the constant elasticity gravity equation (I.1) provides a good approximation to observed data on bilateral travel between countries.

We measure international travel using data on bilateral air passengers from the Origin and Destination (OFOD) Database of the International Civil Aviation Organization (ICAO) for the period from 1982-2019.[30] These data report information on direct flights between an origin and a destination, where a direct flight is defined as a flight for which the same flight number is maintained. Therefore, direct flights include both non-stop flights, and flights with one or more intermediate stops as part of the same flight number. We aggregate air traffic between bilateral pairs of origin and destination airports to bilateral pairs of origin and destination countries. We measure international travel using the bilateral number air passengers, which includes first, business and economy-class travel, and captures both business travelers and tourists. We interpret tourism in terms of our model as a form of business travel to consume non-traded services. We proxy for bilateral travel frictions between countries using the bilateral distance between countries based on the latitude and longitude coordinates of their capital cities.

Taking logarithms in equation (I.1), we obtain the following log linear gravity equation for international air travel:

$$\ln X_{ij}=\eta_j+\mu_i-\phi\ln\mathrm{dist}_{ij}+u_{ij}, \tag{I.6}$$

where X_{ij} is the number of bilateral air passengers from origin j to destination i; $\eta_j\equiv\ln O_j$ is an origin fixed effect; $\mu_i\equiv\ln D_i$ is a destination fixed effect; dist_{ij} is the bilateral distance between origin j and destination i; ϕ is a composite elasticity, which captures the elasticity of travel with respect to travel frictions, and the elasticity of travel frictions with respect to distance; u_{ij} is a stochastic error that captures idiosyncratic travel frictions unrelated to distance.

In Table I.1, we report the estimation results. For brevity, we focus on the year 2019, but find the same pattern of results for each year of our sample period from 1982-2019. In Column (1), we estimate the log linear gravity equation (I.6) using ordinary least squares (OLS), which focuses on origin-destination pairs for which bilateral air passengers are strictly positive. We find a negative and statistically significant coefficient on bilateral distance, consistent with bilateral travel frictions

[30]See https://data.icao.int/icads/Product/View/115.

increasing with bilateral distance. We find a regression R-squared of 0.550, suggesting that the constant elasticity gravity equation has substantial explanatory power for the data. In Column (2), we report a robustness test, in which we restrict attention to origin-destination pairs more than 3,000 kilometers apart, for which air travel is likely to be the dominant mode of transport. Again, we find a negative and statistically significant coefficient on bilateral distance, with an increase in the regression R-squared to 0.665. Therefore, the explanatory power of the model improves when we focus on bilateral origin-destination pairs for which there is likely to be less substitution to other modes of transport that are not captured in our air travel data.

Table I.1: International Travel Gravity Equation

	(1) Log Air Passengers	(2) Log Air Passengers	(3) Air Passengers	(4) Air Passengers
Log Distance	-1.871***	-3.595***	-1.196***	-2.602***
	(0.0493)	(0.151)	(0.0322)	(0.0724)
Estimation	OLS	OLS	PPML	PPML
Sample	All	$> 3,000$ km	All	$> 3,000$ km
Observations	5,368	2,718	29,756	23,971
R-squared	0.550	0.665	–	–

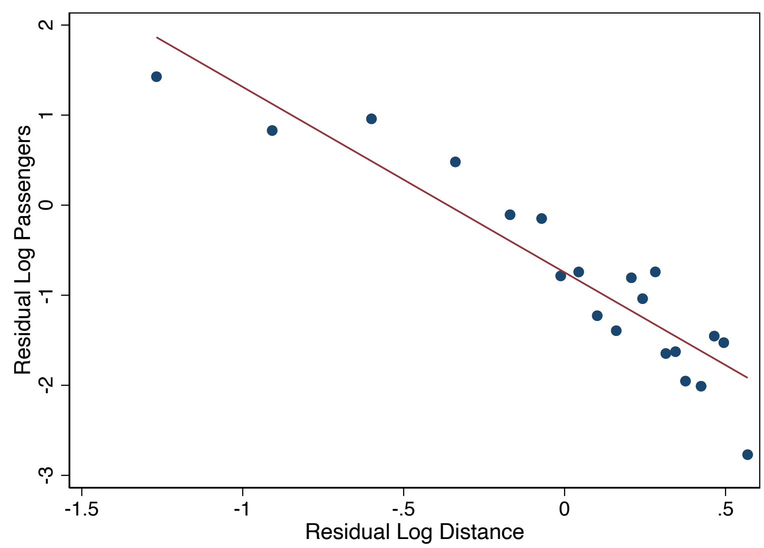
Note: Cross-section of origin-destination pairs for the year 2019; Air passengers is total number of air passengers from an origin country to a destination country in a given year; Distance is the geographical distance between the capital cities of each origin and destination country; Columns (1) and (2) estimated using ordinary least squares (OLS); Columns (3) and (4) estimated using Poisson Pseudo Maximum Likelihood (PPML); Sample in Columns (2) and (4) restricts attention to origin-destination pairs more than 3,000 km apart; heteroskedasticity robust standard errors in parentheses; *** denotes significance at the 1 percent level; ** denotes significance at the 5 percent level; * denotes significance at the 10 percent level.

In Column (3), we re-estimate the gravity equation in levels rather than logs for all origin-destination pairs using the Poisson-Pseudo Maximum Likelihood (PPML) estimator of Santos Silva and Tenreyro (2006). This specification incorporates observations with zero bilateral air passengers. We continue to find the same pattern of results, with a negative and statistically significant coefficient on bilateral distance, confirming that our results are not sensitive to the treatment of zero bilateral flows. In Column (4), we re-estimate this specification, restricting attention to origin-destination pairs more than 3,000 kilometers apart. Again, we continue to find a negative and statistically significant coefficient on bilateral distance, confirming the robustness of our results to focusing our origin-destination pairs for which air travel is likely to be the dominant mode of transport.

As a further specification check, Figure I.1 displays a binscatter of the conditional correlation between the log of bilateral air passengers and the log of bilateral distance, after controlling for origin-destination fixed effects. We show this conditional correlation for origin-destination pairs more than 3,000 kilometers apart, for which air travel is likely to be the dominant mode of transport. We find a strong, negative and approximately linear relationship, consistent with the predictions of a constant elasticity gravity equation.

Taken together, these empirical findings suggest that bilateral travel is well approximated by a constant elasticity gravity equation, which in turn implies substitution between origin-destination pairs, in the sense that a reduction in international trade costs increases foreign travel relative to domestic travel.

Figure I.1: Binscatter of Conditional Correlation Between Log Bilateral Air Passengers and Log Bilateral Distance for Origin-Destination Pairs more than 3,000 Kilometers Apart



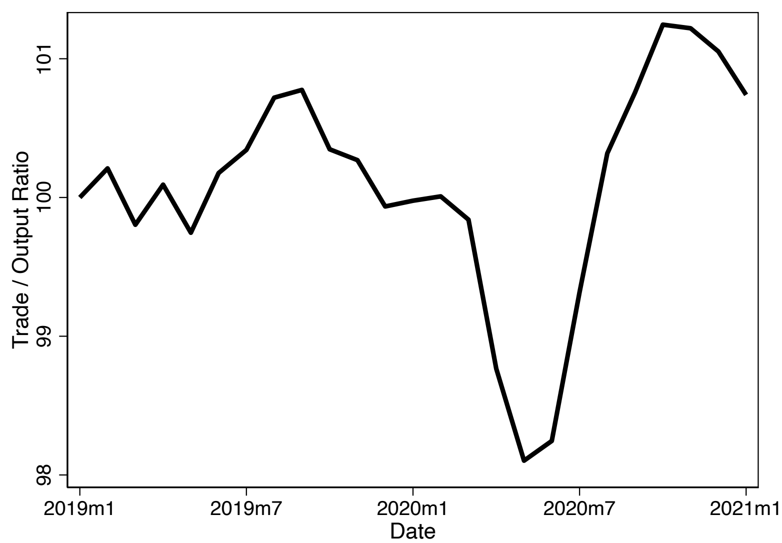
Note: Residual log air passengers and residual log geographical distance after controlling for origin country and destination country fixed effects; sample includes all origin-destination pairs more than 3,000 km apart; blue circles correspond to ventiles of the conditional relationship between the two residuals; red line shows the linear regression fit between the two residuals.

Evidence of Substitutability Our empirical evidence that the constant elasticity gravity equation provides a good approximation to observed travel flows, and hence that origin-destination pairs are substitutes for one another, is consistent with the existing empirical literature on travel flows. As discussed above, tourism can be interpreted in terms of our model as a form of business travel to consume non-traded services. Einav and Yair (2004) provide empirical evidence on substitutability across tourist destinations using data on bilateral tourism flows from 1985-1998. The paper estimates a multinomial logit model of tourism decisions, in which the price of a tourist destination is captured by the relative cost of living in the destination and origin countries. Consistent with our empirical evidence above, the paper finds that the multinomial logit model provides a good approximation to the observed tourism data, with a negative own price elasticity and a positive cross-price elasticity for each destination market. Therefore, an increase in the cost of living in a given foreign tourist destination leads to a reduction in tourism to that destination and an increase in tourism to all other destinations, including the own destination, consistent with our assumption that origin-destination pairs are substitutes for one another.

J Pandemics and the Trade to Output Ratio

In this section of the Online Appendix, we present a brief discussion on the role of global pandemics in shaping international trade flows relative to output. The literature on this feedback from pandemics to international trade is scant. There is a voluminous literature on the economic consequences of the Black Death (see Jedwab et al., 2019, for a review), but it is a challenge to measure the impact of this shock on trade integration given the paucity of the available data that far back in time.[31] For the more recent 2003 SARS pandemic, Fernandes and Tang (2020) finds that firms in Chinese regions with local transmission of SARS experienced lower import and export growth compared to those in the unaffected regions in China, but that this effect is relatively short lived, and disappears after about two years.

Figure J.1: World Trade Relative to Output and the Covid-19 Pandemic



Note: Data from the CPB (Netherlands Bureau for Economic Policy Analysis); ratio of the three-month moving average of the CPB series for world trade volume and production-weighted world industrial output. Both the trade and output moving averages are indexes that take the value 100 in January 2019. Therefore, the ratio of these two indexes multiplied by one hundred takes the value 100 in January 2019.

The current Covid-19 pandemic offers an additional valuable lens through which to assess this feedback from pandemics to international trade. Although the data we currently have at hand is still somewhat tentative in nature, Figure J.1 provides a preliminary diagnostic of the impact of the current global pandemic on the flows of goods across countries relative to global output. The figure uses data from the World Trade Monitor produced by the CPB Netherlands Bureau for Economic Policy Analysis. Relative to its level in August of 2019, the volume of world trade reached a bottom in May of 2020, when it had reached a cumulative decline of over 14 percent. In June, July, and August of that year, however, trade flows grew at a fast pace, and by the end of August 2020, the

[31] Anecdotal evidence suggests a substantial reduction in international trade, as remarked by Daniel Defoe in his *A Journal of the Plague Year*, 1665: "As to foreign trade, there needs little to be said. The trading nations of Europe were all afraid of us; no port . . . would admit our ships or correspond with us."

year-on-year decline in trade had been reduced to a much more moderate 4 percent. World trade continued to grow in the last few months of 2020 and early in 2021, reaching levels in late 2021 that are *higher* than those preceding the pandemic. Figure J.1 shows that, although the response of world industrial output to the current pandemic is qualitatively similar to that of world trade, the response of world trade was more pronounced leading to a decline of about 3 percent in the ratio of trade to GDP.

Figure J.1 thus indicates a disproportionate effect of the Covid-19 pandemic on international transactions relative to domestic ones. Furthermore, the figure is also suggestive of the recovery from a pandemic being relatively quick. Admittedly, at this point in time, the figure can only speak to the short-term impact of the pandemic on economic integration (see Antràs, 2021, for a longer-run perspective), and it also masks important composition effects related to the impact of the pandemic on merchandise versus service trade.

K Computational Appendix

In this section of the Online Appendix, we discuss our choice of parameter values and describe the algorithms that we use to do the numerical simulations in each section of the paper. In Subsection K.1, we discuss our choice of parameter values. In Subsection K.2, we discuss the solution algorithm for our baseline open economy SIR model from Section 4 of the paper. In Subsection K.3, we discuss the solution algorithm for our open economy SIR model with general equilibrium social distancing from Section 5 of the paper. In Subsection K.4, we discuss the solution algorithm for our open economy SIR model with behavioral responses from Section 6 of the paper.

K.1 Parameters

In this subsection, we discuss our choice of parameter values. The simulation presented in the main text are supposed to be illustrative rather than a detailed calibration for a specific circumstance. Nevertheless, the baseline calibration adopts the central values of the epidemiology parameters in Fernández-Villaverde and Jones (2022). For example, in Figure 1 we set the value of the exogenous component of the infection rate in the healthy country, $\alpha_1 = 0.04$, and we vary the value for the sick country between $\alpha_2 \in [0.04, 0.1]$. Using the equilibrium values of interactions, this leads to a value of $2n_{ii}\alpha_i + n_{ij}\alpha_j + n_{ji}\alpha_i$ (the actual infection rate in Country i if $I_i = I_j$) in the range $[0.15, 0.20]$ in Country 1 and $[0.15, 0.33]$ in Country 2, well in the range of values estimated in Fernández-Villaverde and Jones (2022). We also set $\gamma_i = 0.2$, which implies an infectious period of 5 days.

The economic model also involves a number of parameters. We set the elasticity of substitution $\sigma = 5$, a central value in the trade literature (Costinot and Rodríguez-Clare, 2014), and normalize productivity $Z_i = 1$ for all i. We also set Country size $L_i = 3$ when countries are symmetric. We choose values so that the choice of bilateral interactions n_{ij} is never constrained. We choose a baseline value for the elasticity of the cost of consuming more varieties in a location of $\phi = 2$.

Hence, the second-order conditions discussed in the text are satisfied since $\phi > 1/(\sigma - 1)$. Note that we also require $\phi > 1$. We eliminate all man-made frictions in the baseline, so $t_{ij} = \mu_{ij} = 1$ for all i, j, and let $d_{ij} = 1.1$ for $i \neq j$ and 1 otherwise. We set to one the elasticity of trade costs with respect to distance, so $\delta = 1$. Finally we set the level of the cost of creating contacts, $c = 0.15$, which guarantees that equilibrium interactions are always in an interior solution. Of course, in the main text we show a number of exercises in which we change these parameter values, and in particular introduce trade and mobility frictions. Whenever we depart from the parameter values mentioned above, we state that in the discussion of the relevant graph below.

K.2 Trade, Travel and Disease Diffusion

In this subsection, we discuss the solution algorithm for our baseline open economy SIR model from Section 4 of the paper.

Solution Algorithm

1. Compute the value of n_{ii}, n_{ij}, n_{ij}, and n_{jj} as the outcome of the equilibrium that solves

$$n_{ij} = (c(\sigma-1)\mu_{ij})^{-1/(\phi-1)} (d_{ij})^{-\frac{\rho+(\sigma-1)\delta}{\phi-1}} \left(\frac{t_{ij}w_j}{Z_j P_i}\right)^{-\frac{\sigma-1}{(\phi-1)}} \left(\frac{w_i}{P_i}\right)^{1/(\phi-1)}$$

$$\pi_{ii} w_i L_i + \pi_{ji} w_j L_j = w_i L_i,$$

where π_{ij} is given by

$$\pi_{ij} = \frac{X_{ij}}{\sum_{\ell \in \mathcal{J}} X_{i\ell}} = \frac{(w_j/Z_j)^{-\frac{\phi(\sigma-1)}{\phi-1}} (\mu_{ij})^{-\frac{1}{\phi-1}} (d_{ij})^{-\frac{\rho+\phi(\sigma-1)\delta}{\phi-1}} (t_{ij})^{-\frac{\phi(\sigma-1)}{\phi-1}}}{\sum_{\ell \in \mathcal{J}} (\mu_{i\ell})^{-\frac{1}{\phi-1}} (d_{i\ell})^{-\frac{\rho+\phi(\sigma-1)\delta}{\phi-1}} (t_{i\ell} w_\ell / Z_\ell)^{-\frac{\phi(\sigma-1)}{\phi-1}}},$$

corresponding to equation (9) in the paper. Call them $\bar{n}_{ii}$, $\bar{n}_{ij}$, $\bar{n}_{ij}$, and $\bar{n}_{jj}$. Provided population, technology, and relative wages are time invariant, these quantities will be fixed.

2. Set $I_i(0) = 0.110^{-4}$, $S_i(0) = 1 - I_i(0)$, and $R_i(0) = 0$ for all i. For each $t \in [1, T]$ solve the following system of equations:

$$\begin{bmatrix} S_i(t+1) \\ I_i(t+1) \\ R_i(t+1) \\ S_j(t+1) \\ I_j(t+1) \\ R_j(t+1) \end{bmatrix} = \begin{bmatrix} -\Omega_i & \Omega_i & 0 & 0 & 0 & 0 \\ 0 & -\gamma_i & \gamma_i & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -\Omega_j & \Omega_j & 0 \\ 0 & 0 & 0 & 0 & -\gamma_j & \gamma_j \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} (1/step) \begin{bmatrix} S_i(t) \\ I_i(t) \\ R_i(t) \\ S_j(t) \\ I_j(t) \\ R_j(t) \end{bmatrix} + \begin{bmatrix} S_i(t) \\ I_i(t) \\ R_i(t) \\ S_j(t) \\ I_j(t) \\ R_j(t) \end{bmatrix},$$

where

$$\Omega_i = \alpha_i 2\bar{n}_{ii} I_i(t) + \alpha_j \bar{n}_{ij} I_j(t) + \alpha_i \bar{n}_{ji} I_j(t).$$

This system corresponds to equations (13) − (15) in the paper. The variable *step* marks the number of steps taken within each time period, in this section we use $step = 2$.

Associated Figures

Section 4 in the paper uses three sets of parameters. Figures 2 and 3 present a general specification in which international trade favors the onset of a pandemic, with standard parameters as listed in Table K.1 for Figure 2 and Table K.2 for Figure 3. Figure 4 looks at an example in which free trade prevents the onset of a pandemic, using parameters listed in Table K.3. Figure D.1 presents the possibility of second waves of infection, using parameters listed in Table K.4.

If no other mention is made, trade frictions are set at baseline values $\mu_{ij} = \mu_{ji} = 1$, $t_{ij} = t_{ji} = 1$, $d_{ij} = d_{ij} = 1.1$. Some of these figures study changes in trade frictions moving one of these parameters. All other parameters are kept at baseline value.

Table K.1: Baseline parameters - Figure 2

Parameter	Value
σ	5
ϕ	2
Z_1, Z_2	1
L_1, L_2	$3, 3$
$d_{12} = d_{21}$	1.1
$\mu_{12} = \mu_{21}$, $t_{12} = t_{21}$	1
δ	1
ρ	1
c	0.15
α_1	0.04
α_2	$\{0.04, 0.10\}$
γ_1, γ_2	$0.20, 0.20$
η_1, η_2	$0.0, 0.0$

In order to obtain the result described for the second set of parameters, $\phi = 1.5$ is crucial. The only other difference with respect to the general scenario is a decrease of c to 0.1. This is not necessary: the qualitative result also holds for $c = 0.15$ but it was originally changed so that n_{ii} would be approximately the same in both cases.

There are more parameters that will generate a second wave of infections. The ones presented here were picked to obtain *reasonable* values for R^{0i} and R^0. What is essential for this feature to occur is that both countries have different timings for their own pandemics in autarky. One (small) country has very fast contagion rates (α) and very short recovery periods (high γ), while in the other (big) country the disease must progress much slower so that when the cycle starts it will drag the first country with it once again. The difference in size ensures that when the small country goes through its first cycle, the big country will remain mostly unaffected.

Table K.2: Baseline parameters - Figure 3

Parameter	Value
σ	5
ϕ	2
Z_1, Z_2	1
L_1, L_2	$3, 3$
$d_{12} = d_{21}$	1.1
$\mu_{12} = \mu_{21},\ t_{12} = t_{21}$	1
δ	1
ρ	1
c	0.15
α_1, α_2	$0.04, 0.07$
γ_1, γ_2	$0.20, 0.20$
η_1, η_2	$0.0, 0.0$

Table K.3: "*Better trade*" parameters - Figure 4

Parameter	Value
σ	5
ϕ	1.5
Z_1, Z_2	1
L_1, L_2	$3, 3$
$d_{12} = d_{21}$	1.1
$\mu_{12} = \mu_{21},\ t_{12} = t_{21}$	1
δ	1
ρ	1
c	0.10
$\alpha_1,\ \alpha_2$	$0.04, 0.07$
γ_1, γ_2	$0.20, 0.20$
η_1, η_2	$0.0, 0.0$

K.3 General-Equilibrium Social Distancing

In this subsection, we discuss the solution algorithm for our open economy SIR model with general equilibrium social distancing from Section 5 of the paper.

Solution Algorithm

1. Compute the value of $n_{ii}(0)$, $n_{ij}(0)$, $n_{ij}(0)$, and $n_{jj}(0)$ as the outcome of the equilibrium that solves

$$n_{ij} = \left(c\left(\sigma-1\right)\mu_{ij}\right)^{-1/(\phi-1)}\left(d_{ij}\right)^{-\frac{\rho+(\sigma-1)\delta}{\phi-1}}\left(\frac{t_{ij}w_j}{Z_jP_i}\right)^{-\frac{\sigma-1}{(\phi-1)}}\left(\frac{w_i}{P_i}\right)^{1/(\phi-1)}$$

$$\pi_{ii}w_iL_i(1-D_i(t)) + \pi_{ji}w_jL_j(1-D_j(t)) = w_iL_i(1-D_i(t)),$$

Table K.4: Second-wave parameters - Figure D.1

Parameter	Value
σ	4.5
ϕ	2
Z_1, Z_2	1
L_1, L_2	$2, 20$
$d_{12} = d_{21}$	1
δ	1
ρ	1
c	0.12
α_1, α_2	$0.69, 0.09$
β_1, β_2	$2.29, 0.30$
γ_1, γ_2	$2.1, 0.18$

where π_{ij} is once again given by

$$\pi_{ij} = \frac{X_{ij}}{\sum_{\ell \in \mathcal{J}} X_{i\ell}} = \frac{(w_j/Z_j)^{-\frac{\phi(\sigma-1)}{\phi-1}} (\mu_{ij})^{-\frac{1}{\phi-1}} (d_{ij})^{-\frac{\rho+\phi(\sigma-1)\delta}{\phi-1}} (t_{ij})^{-\frac{\phi(\sigma-1)}{\phi-1}}}{\sum_{\ell \in \mathcal{J}} (\mu_{i\ell})^{-\frac{1}{\phi-1}} (d_{i\ell})^{-\frac{\rho+\phi(\sigma-1)\delta}{\phi-1}} (t_{i\ell} w_\ell/Z_\ell)^{-\frac{\phi(\sigma-1)}{\phi-1}}},$$

corresponding to equation (9) in the paper. These values are no longer fixed and will evolve as the pandemic progresses.

2. Set $I_i(0) = 0.110^{-4}$, $S_i(0) = 1 - I_i(0)$, and $R_i(0) = 0$ for all i. For each $t \in [1, T]$:

   (a) Solve the following system of equations:

$$\begin{bmatrix} S_i(t+1) \\ I_i(t+1) \\ R_i(t+1) \\ D_i(t+1) \\ S_j(t+1) \\ I_j(t+1) \\ R_j(t+1) \\ D_j(t+1) \end{bmatrix} = \begin{bmatrix} -\Omega_i & \Omega_i & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & -\kappa_i & \gamma_i & \eta_i & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -\Omega_j & \Omega_j & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & -\kappa_j & \gamma_j & \eta_j \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} (1/step) \begin{bmatrix} S_i(t) \\ I_i(t) \\ R_i(t) \\ D_i(t) \\ S_j(t) \\ I_j(t) \\ R_j(t) \\ D_j(t) \end{bmatrix} + \begin{bmatrix} S_i(t) \\ I_i(t) \\ R_i(t) \\ D_i(t) \\ S_j(t) \\ I_j(t) \\ R_j(t) \\ D_j(t) \end{bmatrix}$$

   where $\kappa_i = \gamma_i + \eta_i$ and

$$\Omega_i = \alpha_i 2 n_{ii}(t) I_i(t) + \alpha_j n_{ij}(t) I_j(t) + \alpha_i n_{ji}(t) I_j(t).$$

   This system corresponds to equations (20) – (23) in the paper. The variable *step* marks the number of steps taken within each time period, in this section we use $step = 2$.

(b) Update $n_{ij}(t+1)$ and $w_i(t+1)$ as the values that solve:

$$n_{ij}(t+1) = (c(\sigma-1)\mu_{ij})^{-1/(\phi-1)} (d_{ij})^{-\frac{\rho+(\sigma-1)\delta}{\phi-1}} \left(\frac{t_{ij}w_j(t+1)}{Z_j P_i}\right)^{-\frac{\sigma-1}{(\phi-1)}} \left(\frac{w_i(t+1)}{P_i}\right)^{1/(\phi-1)}$$

$$\pi_{ii}w_i(t+1)L_i(1-D_i(t+1)) + \pi_{ji}w_j(t+1)L_j(1-D_j(t+1)) = w_i(t+1)L_i(1-D_i(t+1)).$$

Associated Figures

Section 5 in the paper includes Figure 5, which uses the parameters described in Table K.5. These correspond to the first set of parameters in the previous section (associated with Figures 2 and 3). The duration of the disease remains the same, as the exit rate from the infected stage $(\gamma_i + \eta_i)$ is unchanged, but now both countries experience deaths, with one of them having a much higher death rate than the other (η_i marks the entry into the dead stage, so $\eta_i/(\gamma_i + \eta_i)$ marks how many of those that were infected will end up dying).

Table K.5: Section 4 parameters - Figures 5 and 6

Parameter	Value
σ	5
ϕ	2
Z_1, Z_2	1
L_1, L_2	3, 3
$d_{12} = d_{21}$	1.1
$\mu_{12} = \mu_{21}$, $t_{12} = t_{21}$	1
δ	1
ρ	1
c	0.15
α_1, α_2	0.04, 0.07
$(\gamma_i + \eta_i)$	0.20
$\eta_i/(\gamma_i + \eta_i)$	0.01, 0.50

Figure 6 in the paper, and Figures E.1 and E.2 in Section E.4 of this Online Appendix, use an identical algorithm, but in step 1 use the equilibrium condition discussed in Section 5.2. We use the parameter values in Table K.6 on top of the ones described in the label of the figure.

K.4 Behavioral Responses - Symmetric Case

In this subsection, we discuss the solution algorithm for our open economy SIR model with behavioral responses from Section 6 of the paper.

Solution Algorithm

1. Choose $T(\infty) = 500,000$ (some large number), and $T = 10,000$. Guess $D(\infty) = \mathcal{D}_i$.

2. Compute the value of $n_{ii}(\infty)$, $n_{ij}(\infty)$, $n_{ij}(\infty)$, and $n_{jj}(\infty)$ as the outcome of the equilibrium

Table K.6: Section 4 parameters - Figure E.1 and E.2

Parameter	Value
σ	5
ϕ	1.5
Z_1, Z_2	1
L_1, L_2	$10, 2$
$d_{12} = d_{21}$	1.1
$\mu_{12} = \mu_{21}$, $t_{12} = t_{21}$	1
δ	1
ρ	1
$c_{11} = c_{21}, c_{12} = c_{22}$	$0.1, 0.2$
α_1, α_2	$0.01, 0.35$

that solves

$$n_{ij} = \left(c\left(\sigma-1\right)\mu_{ij}\right)^{-1/(\phi-1)}\left(d_{ij}\right)^{-\frac{\rho+(\sigma-1)\delta}{\phi-1}}\left(\frac{t_{ij}w_j}{Z_jP_i}\right)^{-\frac{\sigma-1}{(\phi-1)}}\left(\frac{w_i}{P_i}\right)^{1/(\phi-1)}$$

$$\pi_{ii}w_iL_i(1-\mathcal{D}_i) + \pi_{ji}w_jL_j(1-\mathcal{D}_j) = w_iL_i(1-\mathcal{D}_i),$$

where π_{ij} is given by

$$\pi_{ij} = \frac{X_{ij}}{\sum_{\ell\in\mathcal{J}} X_{i\ell}} = \frac{(w_j/Z_j)^{-\frac{\phi(\sigma-1)}{\phi-1}}\left(\mu_{ij}\right)^{-\frac{1}{\phi-1}}\left(d_{ij}\right)^{-\frac{\rho+\phi(\sigma-1)\delta}{\phi-1}}\left(t_{ij}\right)^{-\frac{\phi(\sigma-1)}{\phi-1}}}{\sum_{\ell\in\mathcal{J}}\left(\mu_{i\ell}\right)^{-\frac{1}{\phi-1}}\left(d_{i\ell}\right)^{-\frac{\rho+\phi(\sigma-1)\delta}{\phi-1}}\left(t_{i\ell}w_\ell/Z_\ell\right)^{-\frac{\phi(\sigma-1)}{\phi-1}}}$$

corresponding to equation (9) in the paper.

3. Transversality conditions are satisfied if

$$\lim_{t\to\infty}\theta_i^k(t) = 0$$
$$\lim_{t\to\infty}\theta_i^i(t) = 0$$
$$\lim_{t\to\infty}\theta_i^s(t) = 0.$$

Set $\theta_i^k(\infty) = \theta_i^i(\infty) = \theta_i^s(\infty) = 0$ and let the economy run without infections between T and $T(\infty)$, that is, for each time period $t \in [T, T(\infty)]$ update the Lagrange multipliers as

$$\theta_i^k(t) = \theta_i^k(t+1) - \left[Q_i(n_{ii}(\infty), n_{ij}(\infty)) - C_i(n_{ii}(\infty), n_{ij}(\infty))\right]e^{-\xi t}\Delta t$$
$$\theta_i^i(t) = \frac{1}{1+(\gamma_i+\eta_i)\Delta t}[\eta_i\theta_i^k(t)\Delta t + \theta_i^i(t+1)],$$

where Δt is the step size (one over how many times you update within each day). Keep $\theta^k(T)$ and $\theta^i(T)$ as the terminal values of the Lagrange multipliers.

4. Set $I_i(T) = 10^{-6}$, $\theta_i^s(T) = 0$ and $S_i(T) = 1 - I_i(T) - \mathcal{D}_i/(\eta_i/(\gamma_i+\eta_i))$. Recompute $n_{i\cdot}(T)$ as

the values that solve

$$\left[\frac{\partial Q_i(n_{ii}(T), n_{ij}(T))}{\partial n_{ij}} - \frac{\partial C_i(n_{ii}(T), n_{ij}(T))}{\partial n_{ij}}\right](1-\mathcal{D}_i)e^{-\xi T} = [\theta_i^s(T) - \theta_i^i(T)]S_i(T)\alpha_j I_j(T),$$

corresponding to equation (25) in the paper. If countries are perfectly symmetric countries when infections are zero, we will have $w_i = 1$ for all i.

5. For each $t \in [T, 0]$ solve the following system of equations, where all values evaluated at $t+1$ are known, to obtain values at t:

$$\begin{aligned}
\theta_i^s(t+1) - \theta_i^s(t) &= [\theta_i^s(t) - \theta_i^i(t)][2\alpha_i n_{ii}(t)I_i(t) + (\alpha_j n_{ij}(t) + \alpha_i n_{ji}(t))I_j(t)]\Delta t \\
\theta_i^s(t+1) - \theta_i^i(t) &= (\gamma_i + \eta_i)\theta_i^i(t)\Delta t - \eta_i\theta_i^k(t)\Delta t \\
\theta_k^s(t+1) - \theta_i^k(t) &= [Q_i(n_{ii}(t), n_{ij}(t)) - C_i(n_{ii}(t), n_{ij}(t))]\, e^{-\xi t}\Delta t \\
I_i(t+1) - I_i(t) &= S_i(t)[2\alpha_i n_{ii}(t)I_i(t) + (\alpha_j n_{ij}(t) + \alpha_i n_{ji}(t))I_j(t)]\Delta t - (\gamma_i + \eta_i)I_i(t)\Delta t \\
S_i(t+1) - S_i(t) &= -S_i(t)[2\alpha_i n_{ii}(t)I_i(t) + (\alpha_j n_{ij}(t) + \alpha_i n_{ji}(t))I_j(t)]\Delta t \\
D_i(t+1) - D_i(t) &= \eta_i I_i(t)\Delta t
\end{aligned}$$

and where $n_{i\cdot}(t)$ is again obtained as the value that solves:

$$\left[\frac{\partial Q_i(n_{ii}(t), n_{ij}(t))}{\partial n_{ij}} - \frac{\partial C_i(n_{ii}(t), n_{ij}(t))}{\partial n_{ij}}\right](1-D_i(t))e^{-\xi t} = [\theta_i^s(t) - \theta_i^i(t)]S_i(t)\alpha_j I_j(t).$$

These correspond to equations (25)-(28) in the paper plus the equations determining the evolution of the epidemiological variables, once we have imposed equilibrium conditions.

6. Repeat for all periods until $I(t)$ reaches the desired initial condition, that is, $I(t) = 10^{-5}$. If at this t we have $|D(t)| < 10^{-5}$ stop. Otherwise, adjust guess $\mathcal{D}_i$.

Associated Figures

Section 6 in the paper includes Figures 7 and 8, which use the parameters described in Table K.7.

The initial guess used in the code for Figure 7 in the paper is $\mathcal{D}_i = 0.0022$, and the initial guess for Figure 8 in the paper is $\mathcal{D}_i = 0.004$.

K.5 Behavioral Responses - Asymmetric Case

Solution Algorithm

1. Choose $T(\infty) = 500,000$ (some large number), and $T =$ 10,000. Guess $D_1(\infty) = \mathcal{D}_1$. Fix $I_1(T) = 10^{-7}$.

2. Generate a grid for $D_2(\infty) = \mathcal{D}_2$ wide enough to contain the solution (use solution without behavioral responses as an upper bound for this guess). For each of the points in this grid

Table K.7: Behavioral response parameters - Figures 7 and 8

Parameter	Value
σ	5
ϕ	1.5
Z_1, Z_2	1
L_1, L_2	$3, 3$
$d_{12} = d_{21}$	1.1
$\mu_{12} = \mu_{21}$, $t_{12} = t_{21}$	1
δ	1
ρ	1
c	0.10
α_1, α_2	$0.1, 0.1$
$\gamma_i + \eta_i$	$0.20, 0.20$
$\eta_i/(\gamma_i + \eta_i)$	$0.0062, 0.0062$
Δt	$1/5$
ξ	$0.05/(365\Delta t)$

(a) Compute the value of $n_{ii}(\infty)$, $n_{ij}(\infty)$, $n_{ij}(\infty)$, and $n_{jj}(\infty)$ as the outcome of the equilibrium that solves

$$n_{ij} = (c(\sigma - 1)\mu_{ij})^{-1/(\phi-1)} (d_{ij})^{-\frac{\rho+(\sigma-1)\delta}{\phi-1}} \left(\frac{t_{ij}w_j}{Z_j P_i}\right)^{-\frac{\sigma-1}{(\phi-1)}} \left(\frac{w_i}{P_i}\right)^{1/(\phi-1)}$$

$$\pi_{ii} w_i L_i (1 - \mathcal{D}_i) + \pi_{ji} w_j L_j (1 - \mathcal{D}_j) = w_i L_i (1 - \mathcal{D}_i),$$

where π_{ij} is once again given by

$$\pi_{ij} = \frac{X_{ij}}{\sum_{\ell \in \mathcal{J}} X_{i\ell}} = \frac{(w_j/Z_j)^{-\frac{\phi(\sigma-1)}{\phi-1}} (\mu_{ij})^{-\frac{1}{\phi-1}} (d_{ij})^{-\frac{\rho+\phi(\sigma-1)\delta}{\phi-1}} (t_{ij})^{-\frac{\phi(\sigma-1)}{\phi-1}}}{\sum_{\ell \in \mathcal{J}} (\mu_{i\ell})^{-\frac{1}{\phi-1}} (d_{i\ell})^{-\frac{\rho+\phi(\sigma-1)\delta}{\phi-1}} (t_{i\ell} w_\ell / Z_\ell)^{-\frac{\phi(\sigma-1)}{\phi-1}}}.$$

(b) Transversality conditions are satisfied if

$$\lim_{t\to\infty} \theta_i^k(t) = 0$$

$$\lim_{t\to\infty} \theta_i^i(t) = 0$$

$$\lim_{t\to\infty} \theta_i^s(t) = 0.$$

Set $\theta_i^k(\infty) = \theta_i^i(\infty) = \theta_i^s(\infty) = 0$ and let the economy run without infections between T and $T(\infty)$, that is, for each time period $t \in [T, T(\infty)]$ update the multipliers as

$$\theta_i^k(t) = \theta_i^k(t+1) - [Q_i(n_{ii}(\infty), n_{ij}(\infty)) - C_i(n_{ii}(\infty), n_{ij}(\infty))]\, e^{-\xi t}\Delta t$$

$$\theta_i^i(t) = \frac{1}{1 + (\gamma_i + \eta_i)\Delta t}[\eta_i \theta_i^k(t)\Delta t + \theta_i^i(t+1)],$$

where Δt is the step size (one over how many times you update within each day). Keep $\theta^k(T)$ and $\theta^i(T)$ as the terminal values of the Lagrange multipliers.

(c) Guess a value for $I_2(T)$. Set $\theta_i^s(T) = 0$ and $S_i(T) = 1 - I_i(T) - \mathcal{D}_i/(\eta_i/(\gamma_i + \eta_i))$. Recompute $n_{i\cdot}(T)$ as the values that solve

$$\left[\frac{\partial Q_i(n_{ii}(T), n_{ij}(T))}{\partial n_{ij}} - \frac{\partial C_i(n_{ii}(T), n_{ij}(T))}{\partial n_{ij}}\right](1 - \mathcal{D}_i)e^{-\xi T} = [\theta_i^s(T) - \theta_i^i(T)]S_i(T)\alpha_j I_j(T),$$

corresponding to equation (25) in the paper. Given perfect symmetry between countries, we will have $w_i = 1$ for all i.

i. Given a value for $I_2(T)$, for each $t \in [T, 0]$ solve the following system of equations, where all values evaluated at $t+1$ are known, to obtain values at t:

$$\begin{aligned}
\theta_i^s(t+1) - \theta_i^s(t) &= [\theta_i^s(t) - \theta_i^i(t)][2\alpha_i n_{ii}(t)I_i(t) + (\alpha_j n_{ij}(t) + \alpha_i n_{ji}(t))I_j(t)]\Delta t \\
\theta_i^s(t+1) - \theta_i^i(t) &= (\gamma_i + \eta_i)\theta_i^i(t)\Delta t - \eta_i\theta_i^k(t)\Delta t \\
\theta_k^s(t+1) - \theta_i^k(t) &= [Q_i(n_{ii}(t), n_{ij}(t)) - C_i(n_{ii}(t), n_{ij}(t))]\, e^{-\xi t}\Delta t \\
I_i(t+1) - I_i(t) &= S_i(t)[2\alpha_i n_{ii}(t)I_i(t) + (\alpha_j n_{ij}(t) + \alpha_i n_{ji}(t))I_j(t)]\Delta t - (\gamma_i + \eta_i)I_i(t)\Delta t \\
S_i(t+1) - S_i(t) &= -S_i(t)[2\alpha_i n_{ii}(t)I_i(t) + (\alpha_j n_{ij}(t) + \alpha_i n_{ji}(t))I_j(t)]\Delta t \\
D_i(t+1) - D_i(t) &= \eta_i I_i(t)\Delta t
\end{aligned}$$

and where $n_{i\cdot}(t)$ is again obtained as the value that solves:

$$\left[\frac{\partial Q_i(n_{ii}(t), n_{ij}(t))}{\partial n_{ij}} - \frac{\partial C_i(n_{ii}(t), n_{ij}(t))}{\partial n_{ij}}\right](1 - D_i(t))e^{-\xi t} = [\theta_i^s(t) - \theta_i^i(t)]S_i(t)\alpha_j I_j(t).$$

These correspond to equations (25)-(28) in the paper plus the equations determining the evolution of the epidemiological variables, once we have imposed equilibrium conditions.

ii. Given a particular grid, two adjacent guesses of $\mathcal{D}_2$ may lead to diverging paths for I_i. If this is the case, pick the two guesses that split the paths between those diverging upwards and downwards and re-draw a finer grid for $\mathcal{D}_2$ within these bounds.

iii. Repeat for all periods until $I_i(t)$ reaches the desired initial condition, that is, $I(t) = 10^{-5}$ and $I_i(t) < I_i(t+1)$ in a flat line (meaning it does not diverge to plus or minus infinity). If at this t we have $D_1(t) = D_2(t)$ go back to outside layer of the loop. Otherwise, adjust guess $I_2(T)$.

3. If at this t we have $|D_i(t)| < 10^{-5}$ stop. Otherwise, adjust guess $\mathcal{D}_1$.

Associated Figures

Section 6 in the paper includes Figure 9, which uses the parameters described in Table K.8.

Table K.8: Behavioral response parameters - Figure 9

Parameter	Value
σ	5
ϕ	1.5
Z_1, Z_2	1
L_1, L_2	$3, 3$
$d_{12} = d_{21}$	1.1
$\mu_{12} = \mu_{21}$, $t_{12} = t_{21}$	1
δ	1
ρ	1
c	0.10
α_1, α_2	$0.1, 0.1$
$\gamma_i + \eta_i$	$0.20, 0.20$
$\eta_i/(\gamma_i + \eta_i)$	$0.003, 0.0062$
Δt	$1/3$
ξ	$0.05/(365\Delta t)$

The initial guesses used in the code for Figure 9 in the paper are $\mathcal{D}_i = 0.00227$ and $I_1(T) = 10^{-7}$ and 9.192^{-7}. This algorithm is not closed, as it still requires a mechanism that will automatically define which are the bounds for $\mathcal{D}_2$ in step 2(c)ii.

K.6 Adjustment Costs and the Risk of a Pandemic

Solution Algorithm

1. Choose $T(\infty) = 500,000$ (some large number), and $T =$ 10,000. Guess $D(\infty) = \mathcal{D}_i$.

2. Compute the value of $n_{ii}(\infty)$, $n_{ij}(\infty)$, $n_{ij}(\infty)$, and $n_{jj}(\infty)$ as the outcome of the equilibrium that solves

$$n_{ij} = \left(c\left(\sigma-1\right)\mu_{ij}\right)^{-1/(\phi-1)}\left(d_{ij}\right)^{-\frac{\rho+(\sigma-1)\delta}{\phi-1}}\left(\frac{t_{ij}w_j}{Z_jP_i}\right)^{-\frac{\sigma-1}{(\phi-1)}}\left(\frac{w_i}{P_i}\right)^{1/(\phi-1)}$$
$$\pi_{ii}w_iL_i(1-\mathcal{D}_i) + \pi_{ji}w_jL_j(1-\mathcal{D}_j) = w_iL_i(1-\mathcal{D}_i),$$

where π_{ij} is once again given by

$$\pi_{ij} = \frac{X_{ij}}{\sum_{\ell\in\mathcal{J}} X_{i\ell}} = \frac{\left(w_j/Z_j\right)^{-\frac{\phi(\sigma-1)}{\phi-1}}\left(\mu_{ij}\right)^{-\frac{1}{\phi-1}}\left(d_{ij}\right)^{-\frac{\rho+\phi(\sigma-1)\delta}{\phi-1}}\left(t_{ij}\right)^{-\frac{\phi(\sigma-1)}{\phi-1}}}{\sum_{\ell\in\mathcal{J}}\left(\mu_{i\ell}\right)^{-\frac{1}{\phi-1}}\left(d_{i\ell}\right)^{-\frac{\rho+\phi(\sigma-1)\delta}{\phi-1}}\left(t_{i\ell}w_\ell/Z_\ell\right)^{-\frac{\phi(\sigma-1)}{\phi-1}}}.$$

3. Transversality conditions are satisfied if

$$\lim_{t\to\infty} \theta_i^k(t) = 0$$
$$\lim_{t\to\infty} \theta_i^i(t) = 0$$
$$\lim_{t\to\infty} \theta_i^s(t) = 0$$

Set $\theta_i^k(\infty) = \theta_i^i(\infty) = 0$ and let the economy run without infections between T and $T(\infty)$, that is, for each time period $t \in [T, T(\infty)]$ update the multipliers as

$$\theta_i^k(t) = \theta_i^k(t+1) - [Q_i(n_{ii}(\infty), n_{ij}(\infty)) - C_i(n_{ii}(\infty), n_{ij}(\infty))]\, e^{-\xi t}\Delta t$$
$$\theta_i^i(t) = \frac{1}{1+(\gamma_i+\eta_i)\Delta t}[\eta_i \theta_i^k(t)\Delta t + \theta_i^i(t+1)]$$

where Δt is the step size (one over how many times you update within each day). Keep $\theta^k(T)$ and $\theta^i(T)$ as the terminal values of the Lagrange multipliers.

4. Set $I_i(T) = 10^{-7}$, $\theta_i^s(T) = 0$ and $S_i(T) = 1 - I_i(T) - \mathcal{D}_i/(\eta_i/(\gamma_i+\eta_i))$. Recompute $n_{i\cdot}(T)$ as the values that solve

$$\left[\frac{\partial Q_i(n_{ii}(T), n_{ij}(T))}{\partial n_{ij}} - \frac{\partial C_i(n_{ii}(T), n_{ij}(T))}{\partial n_{ij}}\right](1-\mathcal{D}_i)e^{-\xi T} = [\theta_i^s(T) - \theta_i^i(T)]S_i(T)\alpha_j I_j(T),$$

corresponding to equation (25) in the paper. Again, if absent a pandemic countries are symmetric, we will have $w_i = 1$ for all i.

5. For each $\tau - 1 \in [T, 0]$ solve the following system of equations, where all values evaluated at τ are known and we have imposed perfect symmetry between countries, to obtain values at t:

$$\theta^s(\tau) - \theta^s(\tau-1) = [\theta^s(\tau) - \theta^i(\tau)][2\alpha n_i(\tau)I(\tau) + 2\alpha n_j(\tau)I(\tau)]\Delta\tau$$
$$\theta^s(\tau) - \theta^s(\tau-1) = (\gamma+\eta)\theta^i(\tau)\Delta\tau - \eta\theta^k(\tau)\Delta\tau$$
$$\theta^k(\tau) - \theta^k(\tau-1) = \left[Q(n_j(\tau), n_j(\tau)) - C(n_i(\tau), n_j(\tau)) - \psi_1(|g_{ii}(t)|^{\psi_2} + |g_{ij}(t)|^{\psi_2})\right] e^{-\xi\tau}\Delta\tau$$
$$I(\tau) - I(\tau-1) = S(\tau)[2\alpha n_i(\tau)I(\tau) + 2\alpha n_j(\tau)I(\tau)]\Delta\tau - (\gamma+\eta)I(\tau)\Delta\tau$$
$$S(\tau) - S(\tau-1) = -S(\tau)[2\alpha n_i(\tau)I(\tau) + 2\alpha n_j(\tau))I(\tau)]\Delta\tau$$
$$D(\tau) - D(\tau-1) = \eta I(\tau)\Delta\tau$$

and where $n_{i\cdot}(\tau)$ is obtained as $n_{i\cdot}(\tau+1) - g_{i\cdot}(\tau)\Delta t$ for the value of $g_{i\cdot}(\tau)$ that solves:

$$\begin{aligned}
&e^{-\xi\tau}\left[\frac{\partial Q_i}{\partial n_{ij}}(n_{ij}(\tau)) - \frac{\partial C_i}{\partial n_{ij}}(n_{ij}(\tau))\right](1-D(\tau)) \\
&+ \sum_{t=\tau+1}^{\infty} e^{-\xi t}\left[\frac{\partial Q_i}{\partial n_{ij}}(n_{ij}(t)) - \frac{\partial C_i}{\partial n_{ij}}(n_{ij}(t))\right](1-D(t)) \\
&- (\theta^s(\tau) - \theta^i(\tau))S(\tau)\alpha I(\tau) - \sum_{t=\tau+1}^{\infty}(\theta^s(t) - \theta^i(t))S(t)\alpha I(t) \\
&- \psi_1\psi_2 \left|\frac{n_{ij}(\tau+1) - n_{ij}(\tau)}{\Delta\tau}\right|^{\psi_2 - 1}(1-D(\tau))e^{-\xi\tau} \\
&= 0.
\end{aligned}$$

Note that, in contrast to the other cases above, we compute changes as happening between τ and $\tau-1$, rather $\tau+1$ and τ. This makes the system easier to solve backwards, although the difference in solutions is negligible for small enough step size.

6. Repeat for all periods until $I(\tau)$ reaches the desired initial condition, that is, $I(\tau) = 10^{-5}$. If at this τ we have $D(\tau) = 0$ stop. Otherwise, adjust guess $\mathcal{D}_i$.

Associated Figures

Section 6 in the paper includes Figure F.1, which uses the parameters described in Table K.9.

Table K.9: Behavioral response parameters - Figure F.1

Parameter	Value
σ	5
ϕ	1.5
Z_1, Z_2	1
L_1, L_2	$3, 3$
$d_{12} = d_{21}$	1.1
$\mu_{12} = \mu_{21}$, $t_{12} = t_{21}$	1
δ	1
ρ	1
c	0.10
α_1, α_2	$0.1, 0.1$
$\gamma_i + \eta_i$	$0.20, 0.20$
$\eta_i/(\gamma_i + \eta_i)$	$0.0062, 0.0062$
ξ	$0.05/(365\Delta t)$
ψ_1	1
ψ_2	4
Δt	$1/10$

L Data Appendix

L.1 Black Death

Our main data source on the Black Death is the "Digitizing Historical Plague" data from Büntgen and Ginzler (2019): https://www.envidat.ch/#/metadata/digitizing-historical-plague. We use data on plague outbreaks in European cities and towns from 1347-1760. The data report the name of the location (town or city), its latitude and longitude coordinate, and the year of the plague outbreak. The first plague outbreak in Europe is in 1347 in Messina, Italy. We construct the plague arrival time for each location as the year of its first outbreak minus 1347. We compute the geographical distance between each location and Messina in Italy.

We also use data on Old World trade routes from http://www.ciolek.com/owtrad.html. We obtain ArcGIS shapefiles on the following Old World trade routes in Europe: (i) The Silk Road from the Adriatic to the Pacific 1200-1400 CE; (ii) Chief trade routes in Europe, Levant and North Africa 1300-1500 CE; (iii) North African pilgrimage routes 1300-1900 CE; (iv) Main trade routes in the Holy Roman Empire and nearby countries, c. 1500 CE; (v) Courier routes connecting banking places in Western Europe 1370-1430 CE; (vi) Venetian galley-operated trade routes 1400-1530 CE; (vii) Trade routes in SE Poland and Ukraine 1200-1700 CE; (viii) Major trade roads in Poland and adjacent border regions 1200-1450 CE; (ix) Major trade roads in Poland and adjacent border regions in 1370 CE; (x) Major major roads in Poland and adjacent regions c. 1150 CE; (xi) South German trade routes before 1500 CE; (xii) Central European pilgrimage routes to Rome c. 1500 CE; (xiii) Woolen cloth trade routes in North-Western Europe 1100-1500 CE; (xiv) Spanish pilgrimage routes 900-2000 CE; (xv) NW African trade routes 500-1900 CE; (xvi) Moroccan and Trans-Saharan trade routes 200-1930 CE; (xvii) Silk Road routes 1-1400 CE; (xviii) Trade routes in the Ottoman Empire 1300-1600 CE; (xix) The Anatolian Silk Road 1200-1400 CE; (xx) Islamic trade and pilgrimage routes 1300-1600 CE; (xxi) Silk Road routes between the Mediterranean, Iran and China 200 BCE-1400 CE; (xxii) French pilgrimage routes 1000-1500 CE. We construct our trade access variable as the inverse of the geographical distance of each location from the nearest Old World trade route.

L.2 1957-8 Influenza

We construct newly-digitized data on the global diffusion of the 1957-8 Influenza Pandemic from the Weekly Epidemiological Reports of the World Health Organization (1957, 1958). For each country, we record the date of the first outbreak of this disease. We define the influenza arrival time for each country as the difference in days between the first outbreak in that country and the first outbreak worldwide in China in February 1957. We measure the bilateral geographical distance between the cities in which the first outbreak of 1957-8 Influenza occurred in each country. We measure bilateral trade between countries in 1956 using the Historical Bilateral Trade and Gravity Dataset (TRADHIST) from CEPII (Fouquin and Hugot, 2016).

L.3 COVID-19

Our main data source on the Covid-19 pandemic is the Center for Systems Science and Engineering (CSSE) at Johns Hopkins University (JHU). For each country, the data report new cases, new deaths, cumulative cases, and cumulative deaths by day, month and year. We define the Covid-19 arrival time for each country as the difference in days between the first outbreak in that country and the first outbreak worldwide in China in December 2019. We measure the bilateral distance between countries as the geographical distance between their capital cities. We examine the role of international trade and other international linkages in the spread of Covid-19 using data on bilateral trade for the year 2019 before the pandemic from the United Nations COMTRADE database; bilateral migrant stocks in 2017 from the World Bank; total arrivals and departures of people in China (including migrants, business travelers and tourists) from China's Census and Population Sampling Survey Database for 2010; bond security flows with China (inflows + outflows) and equity and mutual fund security flows with China (inflows + outflows) for 2015-7 from the Global Capital Allocation Project; outward Foreign Direct Investment (FDI) from China for 2010-2 from UNCTAD; and the total value of debt and equity assets held by a country in China for 2018-9 from the International Monetary Fund (IMF).

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