Divided We Fall: International Health and Trade Coordination During a Pandemic*

Viral V. Acharya† Zhengyang Jiang‡ Robert J. Richmond§
Ernst-Ludwig von Thadden¶

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Abstract

We analyze the role of international trade and health coordination during a pandemic by developing a two-economy, two-good trade model integrated into a micro-founded SIR model of infection dynamics. Governments can adopt containment policies to suppress infection spread domestically, and levy import tariffs to prevent infection coming from abroad. The efficient, i.e., coordinated, risk-sharing arrangement dynamically adjusts both policy instruments to share infection and economic risks internationally. However, in the Nash equilibrium of uncoordinated governments with national mandates, trade policies robustly feature inefficiently high tariffs that peak with the pandemic in the foreign economy. This distorts terms-of-trade dynamics and magnifies the welfare costs during a pandemic, featuring lower levels of consumption and production, as well as smaller gains via diversification of infection curves across economies.

Keywords: International Trade, Terms of Trade, SIR Model, COVID-19, Containment Policies, International Coordination, Nash Equilibrium

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†NYU Stern School of Business, CEPR, ECGI and NBER. Email: vva1@stern.nyu.edu

‡Kellogg School of Management, Northwestern University and NBER. Email: zhengyang.jiang@kellogg.northwestern.edu.

§NYU Stern School of Business. Email: rrichmon@stern.nyu.edu

¶Department of Economics, Universitat Mannheim, CEPR, and ECGI. Email: vthadden@uni-mannheim.de.

The Covid-19 pandemic of 2020–22 has been truly international, spreading globally through health and economic linkages between countries and regions. Given that the policy response to the pandemic has been mostly along national lines, the role and value of international coordination in combating pandemics has emerged as potentially of great importance. To analyze and understand how coordination in international economic and health policies can determine the impact of pandemics on the global economy, we develop and study an epidemiological model of disease dynamics embedded in a model of international trade. Our model builds on the observation that the pandemic can be transmitted between countries by trade (goods and/or services), and illustrates how national containment measures and trade policies impact this transmission, as well as economic well-being of the countries.

By way of motivation, consider the stylized facts for China and the United States presented in Figure 1 for the first wave of the pandemic from January 2020 to October 2020: the evolution of the pandemic (top panel); the US-China terms of trade measured as the relative price index of US exports and imports with China (second panel); and the year-on-year (y-o-y) and growth in industrial production in the two countries (third panel). The pandemic peaked in China, in terms of new infections, around late February 2020, while the first wave in the US began soon afterwards, peaking in early April. Unsurprisingly, the y-o-y change in industrial production evolved in each country in sync with the pandemic, dipping as the pandemic took grip and recovering (in the case of China) as the pandemic subsided. In contrast, and significantly from an international trade perspective, the price of US exports to China relative to the price of imports from China sharply deteriorated between the infection peak in China and the peak in the US. This observation suggests that terms of trade appear to have varied during the pandemic in a manner that they deteriorated over time for the country nearing the peak of infection.

Clearly, these observations are rather noisy given the global political and economic turmoil during the period. That said, this all the more raises the conceptual question as to whether this observation – wherein the terms of trade deteriorate for the country experiencing the pandemic – is consistent with global health dynamics and policy decisions of national governments. In particular, are the observed terms-of-trade dynamics efficient from an interenational risk-sharing standpoint? More basically, how do health and trade policies affect each other during a pandemic, and in turn, the attendant health and trade outcomes? And, how should national governments coordinate their health and trade policies? We provide a framework to answer these important questions by introducing epidemiological SIR-dynamics along the lines of Kermack and McKendrick (1932) into a dynamic model of international trade. Using this framework, we analyze the lack of international cooperation explicitly by modeling national policy-making as a non-cooperative game and studying its Nash equilibria. We characterize and numerically simulate the resulting high-dimensional dynamic macroeconomic equilibrium, which involves a significant – and as far as we know hitherto unaddressed – degree of analytical and computational complexity.

The recent economic literature (Brotherhood et al., 2020; Garibaldi, Moen and Pissarides, 2020; Eichenbaum, Rebelo and Trabandt, 2021, and others) has emphasized that if a pandemic hits an economy, local consumption and production adjust, but health externalities still justify domestic containment policies. One of our model's key insights is that, if the pandemic peaks asynchronously in different countries, then externalities also arise across borders; in such a setting, international trade offers a dynamic risk-sharing mechanism in *both* health and economic terms. Risk is shared through trade policies that help pandemic-affected economies support their economic activity while minimizing the unavoidable health externalities arising from it. In particular, a globally efficient coordinated trade policy softens the economic impact on an infected country by boosting its consumption of foreign goods and services, which makes it possible to use national containment policies more efficiently. This mechanism requires the less-infected country to make a short-term sacrifice in terms of both economic and health welfare, in exchange for receiving the same type of help when it eventually also experiences the pandemic.

However, if the countries act non-cooperatively, the result is not only a trade war with lower economic welfare, but importantly, also worse health consequences. Specifically, the trade war forces households to overweight domestic consumption and production, exacerbating negative externalities both on the health and on the economic fronts. We investigate how these externalities are optimally addressed with and without international coordination. In both settings, governments impose domestic containment policies during the course of the domestic infection (which we model as a "dissipative tax" on domestic consumption similar to Eichenbaum, Rebelo and Trabandt (2021)). This policy discourages households from consuming goods and thus internalizes the health externalities. As a result, the levels of consumption and production in each country largely track the evolution of infected cases in each country.

In addition to the domestic containment policies, governments can levy import tariffs as an instrument to address the international dimension of the problem. In the absence of a pandemic, our model features a trade war, which as in the literature on international trade wars and negotiations (Brander and Spencer (1985), Bagwell and Staiger (1999) or Ossa (2014)), leads to high tariffs and to poor consumption choices between domestic and foreign goods. However, in a pandemic tariffs can play a beneficial role, as they can alter the temporal structure of the terms of trade, inducing variation that is linked to the *relative* state of the pandemic in the two countries.

Figure 2 illustrates this key insight about equilibrium terms of trade in our model. The underlying model features pandemic waves that peak asynchronously in two countries, A and B. The dashed vertical lines signify the peak of the pandemic in each country (by assumption, country A peaks first, then country B). Consider the uncoordinated (Nash) case first, which is depicted with the blue curve. When the pandemic first hits country A, it seeks to limit the spread of the disease domestically by imposing strong containment measures on domestic consumption. These containment measures put downward pressure on its domestic price level, resulting in a decline in the terms of trade. Furthermore, the lower price level in country A incentivizes imports from A in B and leads to an increase in the risk of infection in B. In response, country B *raises* its import tariffs beyond the case without a pandemic. Other things equal, the infected country has to consume more of its own goods which generates more infection. In equilibrium, the infected country therefore *lowers* import tariffs drastically, in order to encourage its domestic households to consume more foreign goods which are less conducive to infection. As a result, uncoordinated policies modulate the tariff structure in a manner that skews the terms of trade *against* the infected country's production, aggravating economic risk-sharing possibilities in the midst of a pandemic.

Next, consider the case of optimal international coordination, which is depicted by the dashed red curve in Figure 2. As the graph shows, also in this case the structure of tariffs is modulated, but in a manner that is exactly the *opposite* of the uncoordinated case. As domestic containment measures required to reduce domestic infections aggravate production and consumption in the infected country, the planner lowers the import tariffs in the foreign country and raises the import tariffs in the infected one. The structure of these tariffs might seem strange because it encourages both countries to consume more goods produced by the more infected country, raising the likelihood of infection. However, the terms of trade are now skewed in favor of the infected country's goods in order to ameliorate its economic situation. Furthermore, the effect is counteracted by an increase in production in the less affected country.

This intertemporal economic risk-sharing under coordinated policies also helps to share health risk. In particular, the less infected country imports a part of the infections by facilitating trade with the infected country and increasing production of its own good. This encourages the infected country to shift consumption towards foreign goods (even as it reduces overall consumption in order to prevent its domestic infection rates from rising more strongly). In this sense, "*trade is essential to save both lives and livelihoods*" (OECD (2020)), i.e., there need be no tradeoff between economic and health performance in the international context. This normative conclusion of our model mirrors the argument by Antràs, Redding and Rossi-Hansberg (2020) who argue, using comparative statics around exogenous policy choices, that for countries with similar disease fundamentals, reducing trade frictions can increase the international spread of a pandemic, but that this effect is reversed if countries have sufficiently different health conditions. This latter situation arises endogenously in our model, as the disease spreads asymmetrically between countries. In fact, while the Nash equilibrium tariff policies reduce international disease transmission compared to laissez-faire policies, they still produce worse health outcomes in each country than socially optimal coordinated policies.[1]

Since it is well known that there are large economic benefits from eliminating trade war

[1] In Section 4.5, we show that this crucially depends on the availability of multiple policy instruments; we do so by restricting our model to only one policy instrument per country, viz., domestic containment policies.

inefficiencies that are also present in static models, it is natural to ask how much of the benefits from cooperation identified in our analysis is due to the intertemporal nature of risk-sharing of health between countries. To answer this question, we consider a variant of the model in which the pandemic breaks out in both countries simultaneously. The model then becomes completely symmetric. It turns out that most of the welfare gain from cooperation relative to uncoordinated policies is indeed due to the economic benefit from eliminating trade wars. But about one half of the gain in terms of lives saved is due to intertemporal risk-sharing of health between countries (which is possible only when their infection waves are asynchronous).[2]

While our model is relatively stylized, it nevertheless provides a useful framework for studying different important factors that have influenced the Covid-19 pandemic. We consider three such variations of our benchmark analysis, which also serve as robustness checks for our simulations and show that our findings are remarkably robust. First, we show that the gains from international risk sharing decline with the intensity of international transmission (which is greater from more contact-intensive travel and tourism services relative to the trade of merchandise goods). In contrast, the gains from international risk-sharing increase when containment policies become more harmful for productivity (such as during the generalized lockdowns of 2020). Finally, we show that the gains from international risk-sharing increase as healthcare congestion in pandemic-induced mortality becomes more important (as in countries with poorly developed healthcare infrastructure).

From a technical point of view, our analysis is, as far as we are aware, the first to study Nash equilibrium with fully dynamic economic and health policies. This is computationally demanding because strategies are high-dimensional and each iteration of the best-response algorithm requires solving a dynamic macroeconomic equilibrium model. For the sake of computational feasability, we therefore model economic, health, and policy interactions as parsimoniously as possible. In particular, we restrict attention to open-loop Nash equilibria (see Fudenberg and Tirole (1991) or Dockner et al. (2000)) and thus assume that governments can commit to policy paths at the beginning of the interaction. However, even solving for open-loop equilibria by using modifications of standard best-response algorithms can test the limits of large computing power.[3]

From a positive standpoint, our model helps to explain why, in the real-world scenario of

[2] An interesting observation in this respect is the case of India, when it faced the outbreak of the highly infectious Delta variant of COVID-19 during April-May 2021. This was a time when the pandemic, e.g., in the U.S. had largely subsided, also because of the start of the vaccination program. In fact, at the peak of the Indian wave in early May, the number of reported daily infections in the U.S. had fallen below 40,000 from the peak of 250,000 in early January. After a deliberate decision of the Indian government of classifying exports as "essential services", India managed to achieve a smaller lockdown-related contraction than the one experienced during the generalized lockdown of March-May 2020 (when it in fact faced a lower infection rate).

[3] Each government must choose a two-dimensional policy in each of the 156 weeks of the pandemic and once more for the ensuing steady state. Under this assumption, the strategy spaces in the game between the two governments are 314-dimensional, where the outcome generated by any strategy profile is an infinite trajectory of consumption and production decisions by different agents and of aggregate health states in both economies.

uncoordinated decision-making by countries, terms of trade and economic outcomes may end up being excessively dire for the infected countries. As a consequence, an important normative insight of our model is that the purely epidemiological consideration of "closing the borders" for trade and travel to limit the spread of infections should be weighed against its implications for loss of economic risk-sharing; indeed, our model suggests that even health outcomes end up being superior with some coordination on trade.

Related Literature. Our paper is related to a growing literature that studies the nexus between economics and disease[4]. In one of the few papers on the economics of disease dynamics before 2020, Greenwood et al. (2019) analyzed the dynamics of HIV in Africa and its economic consequences. Building on this work, Brotherhood et al. (2020) analyze a rich set of behavioral patterns and show the importance of heterogeneous lockdown policies for the Covid-19 environment. At a single country level, Eichenbaum, Rebelo and Trabandt (2021) embed SIR disease dynamics into a macroeconomic model and study the tradeoffs resulting from simple suppression policies. Alvarez, Argente and Lippi (2021) study the optimal lockdown policy in a single country as a planning problem in a macroeconomic disease model. Health externalities arising from Covid-19 are discussed in Garibaldi, Moen and Pissarides (2020) and Assenza et al. (2020). Just like our paper, these early papers are mostly concerned with delaying or flattening the infection curve; modelling dynamics with several infection waves as observed in the first 18 months of the global pandemic of 2020/21 requires additional model ingredients, as discussed by Atkeson (2021).[5]

Our paper also relates to other recent contributions studying hetereogeneity in macroeconomic SIR dynamics, such as Acemoglu et al. (2021) who develop an SIR model with heterogeneous groups and lockdown policies, and Kaplan, Moll and Violante (2020) who integrate the SIR disease dynamics in a heterogeneous agent new-Keynesian model to study the distributional consequences of different containment strategies, with a focus similar to Glover et al. (2020). Fernandez-Villaverde and Jones (2020) estimate and simulate an SIR model by using disaggregated data from various locations, including international evolution of such data. In a similar vein, McKibbin and Roshen (2020) and Liu, Moon and Schorfheide (2021) estimate respectively a DSGE model and a Bayesian panel VAR in order to make global forecasts of different health-economics scenarios.

Similar to our paper, Antràs, Redding and Rossi-Hansberg (2020) study the economics of international trade and disease transmission conceptually. The authors develop a two-country

[4]This literature has grown impressively during the last year, and we cannot do justice to it here. See Brodeur et al. (2020) and references therein for an early overview.

[5]A number of papers have investigated different containment policies, such as Berger, Herkenhoff and Mongey (2021) on the role of testing and case-dependent quarantine, Alon et al. (2020) on age-specific lockdown policies among sets of developing and advanced economies, and Jones, Philippon and Venkateswaran (2021) on work-from-home-policies. There is also a large body of work on national fiscal and macroeconomic stabilization policies in response to the pandemic, but that is too large to review here.

model of household interaction in equilibrium with spatial frictions that jointly addresses the international spread of a disease and the gravity structure of international trade. While both our paper and their paper develop microfoundations of international SIR dynamics, the papers differ substantially otherwise. Our key focus is on governments, strategic national policies, and international coordination. In fact, unlike us, Antràs, Redding and Rossi-Hansberg (2020) treat the key policy frictions as exogenous parameters on which they perform comparative statics.[6] In this sense, our paper is closer to Beck and Wagner (2020) who also study cooperation across countries in containment policies in a simple two-stage model. However, their stylized model leaves aside the macroeconomic dynamics at the core of our model.[7]

Our paper owes much to the literature on trade wars and negotiations in international trade (Brander and Spencer, 1985; Perroni and Whalley, 2000; Broda, Limao and Weinstein, 2008; Ossa, 2011). Most closely related are Bagwell and Staiger (1999), which analyses a tractable static general equilibrium model with governments that non-cooperatively set tariffs to maximize different forms of national welfare in Nash equilibrium, and Ossa (2014), which quantitatively studies optimal tariffs that arise during a trade war and quantifies the costs of failures of coordination on trade policy. We add a temporal dimension to this work and study how international trade policy interacts with the global propagation of a pandemic. Our model generates many of the features present in these models of trade wars, while highlighting the novel interaction between trade wars, health outcomes, and international coordination of policies.[8]

1 The Model

We develop and study a two-country international trade model which embeds an epidemiological model of disease dynamics. The model has three key ingredients. First, households in each country have preferences for the consumption of goods (more generally, goods and

[6]Our paper models all individual behavioral responses as privately optimal throughout, which as Antràs, Redding and Rossi-Hansberg (2020) note is "challenging"; they mostly focus on the case where the disease either has no health or productivity effects or households are not aware of them in their decisions.

[7]In related more specialized work, Leibovici and Santacreu (2020) studies the role of international trade in essential goods during a pandemic with a multi-country, multi-sector model. Bonadio et al. (2021) and Yildirim et al. (2021) examine the role of global supply chains' impact on GDP growth across countries, while Meier and Pinto (2020) study the specific disruption of China-US supply chains and its impact on US production in March/April 2020 in detail. Subsequent to us, Xie, Wang and Liu (2021) have used a two-country model similar to ours in order to study tourism and travel restrictions. They restrict attention to partial equilibrium analysis, ignore the terms-of-trade effects that are central to our theory, and focus on specific policies such as border closures and travel bubbles. Early empirical work comparing pandemic policies internationally includes Ullah and Ajala (2020), who analyze effects of testing and lockdown in 69 countries, and Noy et al. (2020) who estimate measures of exposure, vulnerability and resilience to Covid-19 across countries.

[8]At a conceptual level, our paper connects to a recent and growing literature on the broader theme of international coordination in open economies. For example, Auray, Devereux and Eyquem (2019) study the strategic interaction of governments in trade and monetary policy, while Egorov, Mukhin et al. (2019) study the coordination of monetary policies in a world with international trade and sticky prices.

services) produced in both countries. Second, consumption of foreign goods potentially leads to the transmission of disease across countries. Third, governments in each country can impose containment policies in the form of dissipative taxes on total consumption and separately tariffs or subsidies on international consumption.

Specifically, we consider a global economy with two countries, $k = A, B$. Each country has households, identical competitive firms, and a government. Time is discrete, $t = 0, 1, 2, ...$

For all variables we use the following notational convention. Variables describing consumption, production, or government activity in country $k \in \{A, B\}$ have the superscript k. When discussing a single country, the superscript $-k$ denotes the other country. To simplify the presentation, superscripts in equations referring to a single country are dropped whereever possible without ambiguity.

The households in each country are defined over a continuum of unit mass. Let S_t, I_t, R_t, and D_t denote the mass of susceptible, infected, recovered and deceased people in any of the two countries. The total population of the country at any date t then is $N_t = S_t + I_t + R_t$. Individuals are infinitely lived except for deaths from the disease. We do not distinguish between individuals and households. Households within each of the three living categories are identical. S_t^{-k}, I_t^{-k}, R_t^{-k}, and D_t^{-k} are the masses of the respective groups in the other country, if we discuss activity in one country k. $h \in \{s, i, r\}$ indicates the three health types.

1.1 Firms and Households

There are two goods $j \in \{A, B\}$, which are denoted by subscripts throughout the paper. Each period, good j is produced in country j only, by using country j labor according to the linear technology

$$y_t = z_t \left(\ell_t(s) + \phi \ell_t(i) + \ell_t(r)\right) \tag{1}$$

where $\ell_t(h) = \ell_t^k(h)$ is the amount of labor provided by employees of health status h, and $z_t = z_t^k$ is country k's productivity. In our baseline model, we assume constant productivity, i.e., $z_t^k = \bar{z}$. Infected individuals ($h = i$) have a lower productivity, as given by $\phi < 1$. Firms act competitively, maximizing profits and taking prices as given.

The prices of the goods in both countries are p_j, $j = A, B$. When discussing a single country k, p_{-k} denotes the price of good $j \neq k$. There are no transport costs or other exogenous physical trade frictions between countries.

Households in each country provide labor and consume a basket of the two goods A and B. Suppressing the time index for simplicity, denote the per household consumption of good j by households in country k by $c_j^k = c_j^k(h)$. Households in country k consume the goods as a basket composed by the standard constant-elasticity-of-substitution (CES) aggregator

$$q(c_k^k, c_{-k}^k) = \left(\alpha (c_k^k)^{\frac{\sigma-1}{\sigma}} + (1-\alpha)(c_{-k}^k)^{\frac{\sigma-1}{\sigma}}\right)^{\frac{\sigma}{\sigma-1}} \tag{2}$$

where c_k^k denotes consumption of the domestic good, c_{-k}^k of the foreign good, $\alpha \in (0.5, 1)$ is the home bias for domestic consumption goods, and $\sigma > 1$ the substitution elasticity between the domestic and the foreign good. These two parameters are identical in both countries in order to focus on the pure effects of disease transmission in international trade.[9]

At each time t, the representative households in any of the two countries have the following objective function, where we suppress notation for the household's health status to simplify the presentation:

$$U_t = \mathbb{E}_t \sum_{\tau=t}^{\infty} \beta^{\tau-t} \left[v(x_\tau) - \frac{1}{2}\kappa \ell_\tau^2 \right], \tag{3}$$

where $0 < \beta < 1$ is the discount rate, $\ell_\tau = \ell_\tau^k(h)$ is labor supplied, and

$$x_\tau = x_\tau^k(h) = q(c_{k,\tau}^k(h), c_{-k,\tau}^k(h)) \tag{4}$$

is the composite consumption basket. We assume for computational simplicity that the utility of consumption is of the constant-relative-risk-aversion type (with $\rho = 1$ corresponding to the log-utility case):

$$v'(x) = x^{-\rho}, \, \rho > 0. \tag{5}$$

In each country k, we denote aggregate consumption of the home good by

$$H_t^k = S_t^k c_{k,t}^k(s) + I_t^k c_{k,t}^k(i) + R_t^k c_{k,t}^k(r), \tag{6}$$

and that of the foreign good (“imports") by

$$M_t^k = S_t^k c_{-k,t}^k(s) + I_t^k c_{-k,t}^k(i) + R_t^k c_{-k,t}^k(r). \tag{7}$$

Hence, the exports of country k are M_t^{-k}.

1.2 Microfoundations of Disease Dynamics

Like Eichenbaum, Rebelo and Trabandt (2021), Brotherhood et al. (2020) and other recent contributions, we augment the classic SIR model by economic activity. Different from these contributions, we include not only domestic economic interactions, but also interactions due to international trade. In the basic SIR model following Kermack and McKendrick (1932), an infectious individual in any given area can spread the virus at the rate ηS_t (so-called “mass action incidence"), where S_t is the number of susceptibles in that area. Hence, the mass of newly infected people in that area at time t is given by $T_t = \eta S_t I_t$. Eichenbaum, Rebelo and

[9] The symmetry assumption can be dispensed with. The most interesting feature of the asymmetric model is the possibility of multiple infection waves along the logic described by Antràs, Redding and Rossi-Hansberg (2020): if the wave in country A is naturally short and weak and that of country B strong, then this may lead to a second wave in country A.

Trabandt (2021) generalize this to transmission through consumption and work activities in a single country by splitting the individual's transmission rate ηS_t into three components to obtain

$$T_t = [\pi_1 c_t(s) c_t(i) + \pi_2 \ell_t(s)\ell_t(i) + \pi_3]\, S_t I_t \tag{8}$$

where $c_t(h)$ and $\ell_t(h)$ are respectively the representative consumer's consumption and labor. We add a simple international economic channel to this transmission mechanism, taking into account that the consumption of imports leads to cross-border contacts that are potentially contagious. Typical examples of such imports of country k would be the delivery and installation of goods and equipment in k by producers from country $j \neq k$, tourists from country k in j, or services provided by j-firms in k.

This channel builds on the following generalization of the original SIR-type models, which we describe in more detail in Section A.2 in the Appendix. Dropping the time index for convenience, suppose individuals of country k and health status h spend a fraction $\ell^k(h)$ of their time at work, a fraction $\gamma c_k^k(h)$ of their time consuming the domestic good, a fraction $\gamma c_{-k}^k(h)$ consuming the foreign good, and a fraction f out of their home for other reasons, neither consuming nor working. The assumption is that the time spent consuming is proportional to the quantity consumed. Let η denote the probability of infection through contacts per unit of time spent on a given activity.[10] When "shopping", an individual is exposed to domestic residents and foreigners. Suppose there are I^k infected domestic individuals and I^{-k} infected foreigners. Since the contact intensity for foreign and domestic consumption is likely to differ, let η^f and η^d denote the corresponding infection probabilities, respectively. Then the probability of getting infected by domestic residents, per unit of time, from consuming domestic goods is $\eta^d \gamma c_k^k(i) I^k$ and that from consuming foreign goods $\eta^d \gamma c_{-k}^k(i) I^k$. Similarly, the probability of getting infected by foreigners, per unit of time, from consuming domestic goods (which are the foreigners' foreign goods) is $\eta^f \gamma c_k^{-k}(i) I^{-k}$ and that from consuming foreign goods (which are the foreigners' domestic goods) $\eta^f \gamma c_{-k}^{-k}(i) I^{-k}$. Hence, when consuming the bundle $(c_k^k(s), c_{-k}^k(s))$, the representative susceptible consumer in country k faces the probability of infection

$$\gamma c_k^k(s)\eta^d \gamma c_k^k(i) I^k + \gamma c_{-k}^k(s)\eta^d \gamma c_{-k}^k(i) I^k = \left(c_k^k(s) c_k^k(i) + c_{-k}^k(s) c_{-k}^k(i)\right)\gamma^2 \eta^d I^k$$

from domestic residents, and

$$\gamma c_k^k(s)\eta^f \gamma c_k^{-k}(i) I^{-k} + \gamma c_{-k}^k(s)\eta^f \gamma c_{-k}^{-k}(i) I^{-k} = \left(c_k^k(s) c_k^{-k}(i) + c_{-k}^k(s) c_{-k}^{-k}(i)\right)\gamma^2 \eta^f I^{-k}$$

[10] This is approximately equal to the contact rate (say φ) times the transmission probability per unit of time (say θ). Both these parameters depend on individual behavior and policy, but for tractability we take both as given. What matters for transmission is $\varphi\theta t_c$, where t_c is the duration of contacts. We model policy as influencing t_c.

from foreigners.[11]

We assume for simplicity that there are no international encounters in non-work-non-consumption situations, and we also ignore those at the workplace. In particular, the infection risk from working $\ell^k(s)$ hours is $\eta^d \ell^k(s)\ell^k(i)I^k$, and the background risk from non-work-non-consumption activity is $\eta^d f^2 I^k$, both independent of foreign infections.

Hence, a susceptible individual in country k who chooses $\ell^k(s)$, $c_k^k(s)$, and $c_{-k}^k(s)$ transits to the infectious state with probability

$$\begin{aligned} & \tau(c_k^k(s), c_{-k}^k(s), \ell^k(s)) \\ = & \left[\gamma^2 \left(c_k^k(s)c_k^k(i) + c_{-k}^k(s)c_{-k}^k(i)\right) + \ell^k(s)\ell^k(i) + f^2\right]\eta^d I^k \\ + & \left[c_k^k(s)c_k^{-k}(i) + c_{-k}^k(s)c_{-k}^{-k}(i)\right]\gamma^2\eta^f I^{-k}. \end{aligned} \tag{9}$$

By the Law of Large Numbers, this yields the following number of new infections in country k at date $t+1$:

$$\begin{aligned} T_t^k = & \left[\pi_1 \left(c_{k,t}^k(s)c_{k,t}^k(i) + c_{-k,t}^k(s)c_{-k,t}^k(i)\right) + \pi_2 \ell_t^k(s)\ell_t^k(i) + \pi_3\right] I_t^k S_t^k \\ + & \pi_4 \left[c_{k,t}^k(s)c_{k,t}^{-k}(i) + c_{-k,t}^k(s)c_{-k,t}^{-k}(i)\right] I_t^{-k} S_t^k, \end{aligned} \tag{10}$$

where

$$\pi_1 = \gamma^2\eta^d, \tag{11}$$

$$\pi_2 = \eta^d, \tag{12}$$

$$\pi_3 = f^2\eta^d, \tag{13}$$

$$\pi_4 = \gamma^2\eta^f. \tag{14}$$

As in (8), the first three terms of (10) capture infections from domestic contacts arising during consumption, work, and all other local activity, respectively. The fourth term describes infections arising from contacts with foreigners while importing or exporting.[12] This is the international disease transmission mechanism at the heart of our analysis, of which the single country case (8) is a special case obtained by setting $c_{-k}^k = 0$, for $k = A, B$.

[11] The difference between these two expressions is mostly due to the difference in contact intensities between domestic residents and foreigners. These are related to, but different from, the difference between contact intensities of goods and services. Importantly, consumption includes tourism, which is a large component of international trade in several countries (see, e.g., Culiuc (2014)). In standard foreign trade statistics holidays abroad therefore count as the domestic purchase of a foreign consumption good. This type of import is particularly foreign contact intensive. On the other hand, imports of so-called *mode-3-services* (commercial presence) involve hardly any additional contacts with foreigners. In Section 5.2, we vary the foreign contact intensity as a comparative static to derive some conclusions on how our results and their implications apply to merchandise versus services trade.

[12] In order to simplify the model and the calibration, we do not include an international spillover-term from labor, as in π_2, which would be particularly relevant for the import and export of services. We have experimented with such a model, and our results become stronger. Details are available upon request.

As in standard epidemiological models, the evolution of the transmission in any country is now given by

$$
\begin{aligned}
S_{t+1} &= S_t - T_t, && (15)\\
I_{t+1} &= I_t + T_t - (p_r + p_d) I_t, && (16)\\
R_{t+1} &= R_t + p_r I_t, && (17)\\
D_{t+1} &= D_t + p_d(I_t) I_t, && (18)
\end{aligned}
$$

where p_r and p_d are the fractions of infected individuals that recover or die, respectively, during the period. To capture the potential crowding out of medical resources, we allow the transition probability p_d to be a function of the population currently infected I_t.[13] In order to keep the computational complexity as low as possible, we assume that the death rate is a linear (affine) function of the infection rate: $p_d(I_t) = p_d(0) + \zeta I_t$, where $\zeta \geq 0$ measures the fragility of the national health system under intensive care pressure.

Note that the system (15)–(18) is deterministic, and the overall population, $N_t = S_t + I_t + R_t$, decreases by $p_d I_t$ each period. We normalize the initial population in each country to $N_1^k = 1$. As is commonly assumed in much of the applied epidemiological literature at the moment, we assume that recovered individuals remain in that category for sure (i.e., acquire at least temporary immunity). Importantly, by (10), the epidemiological evolution in each country depends on that of the other. Finally, we denote the current state of the disease by

$$\Theta_t = \left(S_t^A, I_t^A, R_t^A, S_t^B, I_t^B, R_t^B\right) \quad (19)$$

and consider a situation in which initially,

$$
\begin{aligned}
S_1^A &= 1 - \varepsilon, I_1^A = \varepsilon, R_1^A = 0, && (20)\\
S_1^B &= 1, I_1^B = R_1^B = 0, && (21)
\end{aligned}
$$

where $\varepsilon > 0$ is a small number. Hence, the pandemic begins with a small number of infections in country A and then spreads endogenously to country B.

1.3 The Role of Government

In each country, the government can impose measures to contain the spread of the pandemic. We follow the approach taken by Eichenbaum, Rebelo and Trabandt (2021) and assume that these measures act like ad valorem "containment taxes" $\mu^k = \mu_t^k \geq 0$. This means that

[13] The role of such "congestion externalities" has been emphasized and modelled in the work on optimal containment policies, e.g. by Brotherhood et al. (2020), Kaplan, Moll and Violante (2020), Favero (2020), and Assenza et al. (2020).

households in country k have to pay an extra $\mu^k p_j$ per unit of consumption of good j, $j = A, B$. These additional costs include the costs of safety measures, new regulatory product features, waiting times, and all other additional costs induced by policies restricting contact and economic activity, mostly deadweight costs of consumption. Let δ_μ^k be the exogenous fraction of these costs actually received by the government as revenue. So while μ is a policy parameter, δ_μ^k is not. The fraction $(1 - \delta_\mu^k)$ is pure waste from a public finance perspective and represents frictions to reduce consumption activity or make it safer in health terms.[14]

As witnessed in the lockdowns of 2020, the government's domestic containment measures can also affect productivity. In a model extension in Section 5.1 we therefore model productivity as $z_t^k = \bar{z}(1 - \mu_t^k)$. In our baseline case, however, we abstract away from this friction and assume constant productivity, i.e., $z_t^k = \bar{z}$.

In addition, governments can intervene in the market for foreign goods. This happens through import tariffs $\nu^k \in \mathbb{R}$, incurred over and above the general domestic frictions generated by μ^k. If $\nu^k < 0$ this intervention is an import subsidy. In any of the two countries $k = A, B$, households then have to pay $(1 + \mu^k)p_k$ per unit of consumption of the domestic good and $(1 + \mu^k + \nu^k)p_{-k}$ per unit of consumption of the foreign good. For each country k, we can thus simplify notation by defining the "consumer prices" as

$$\widehat{p}_k = \widehat{p}_k^k = (1 + \mu^k)p_k, \tag{22}$$

$$\widehat{p}_{-k} = \widehat{p}_{-k}^k = (1 + \mu^k + \nu^k)p_{-k}, \tag{23}$$

for the domestic and foreign goods, respectively.

The government's budget in either country therefore is

$$G_t^k = \delta_\mu^k \mu^k p_{k,t} H_t^k + (\delta_\mu^k \mu^k + \nu^k) p_{-k,t} M_t^k \ . \tag{24}$$

In order to simplify the dynamics, we again follow Eichenbaum, Rebelo and Trabandt (2021), Brotherhood et al. (2020) and others, by assuming that households do not save or borrow. Hence, the only intertemporal link of household decisions is given by health concerns, and the budget constraint of a household of type h in country k at time t is static and given by

$$\widehat{p}_{k,t} c_{k,t}(h) + \widehat{p}_{-k,t} c_{-k,t}(h) = w_t(h)\ell_t(h) + g_t + v_t, \tag{25}$$

where we have again dropped the superscript k for notational convenience, and $w_t(h)$ is the domestic wage, g_t the per household government transfer to households, and v_t the per household

[14] Like most of the literature, Kaplan, Moll and Violante (2020) recognize that, factually, containment measures mostly generate costs rather than revenue, but propose, in a normative sense, to replace pure frictions by equivalent Pigouvian taxes, i.e. to make δ_μ^k a policy instrument and set it as large as possible.

profit of the corporate sector in the country.[15] The government's budget constraint therefore is

$$G_t^k = (1 - D_t^k) g_t^k \tag{26}$$

where $(1 - D_t^k)$ is the size of the population at time t, determined by the disease dynamics.

Government policy therefore consists in setting the domestic containment policy μ_t^k that controls overall consumption and the tariffs ν_t^k that control imports. Once these are fixed, government spending g_t is given by the government budget constraint (24) and (26). The tariff can be used to achieve the following partially conflicting goals of trade and health policy. First, of course, tariffs raise money that can be distributed directly to households. Second, as usual, positive (negative) tariffs manipulate the terms of trade in favor of (against) domestic goods and thus higher domestic labor income. Third, positive tariffs (or related frictions) reduce infections resulting from foreign contacts. And fourth, tariffs can be used to influence the infection dynamics by attempting to shift production internationally to where infection rates are lower.

Since the international infection dynamic (10) is deterministic, the interaction between the two governments is an infinite-horizon, deterministic, multi-stage game with observed actions (see Fudenberg and Tirole, 1991). In a single-agent framework, conditioning on the state of nature (here: the aggregate infection state) would therefore not be necessary, and every open-loop optimal path can be implemented by closed-loop strategies (i.e., strategies that depend on time t and the state) and vice versa. In a multi-agent framework, on the other hand, conditioning on the state of nature (i.e., considering Markov Nash equilibria) usually increases the set of equilibria. Here, for computational reasons, we restrict attention to open-loop strategies, i.e., strategies that only depend on time t and not on the state. Hence, governments set their policy path initially once and for all.[16] To further simplify the computation, we assume that a vaccine or other cure is known to exist in a fixed, finite time T in the future. Hence, after date T there are no more infections and the economies operate without any SIR-dynamics.

As discussed, households maximize their expected discounted utility, given government policy and the evolution of the disease. Let

$$u_t^k(h_t) = v(x_t^k(h_t)) - \frac{1}{2}\kappa \ell_t^k(h_t)^2 \tag{27}$$

denote the flow utility of households of health status h_t in country k at the household's optimum, and

$$V_t^k(h_t) = \mathbb{E}_t \sum_{\tau=t}^{\infty} \beta^{\tau-t} u_\tau^k(h_\tau) \tag{28}$$

[15] To keep the model simple, we ignore health-dependent redistributive policies $g_t(h)$ and simply assume public transfers to be independent of health status.

[16] Uniqueness of equilibrium is, of course, difficult to prove. We have conducted extensive computational searches for other equilibria from different starting values, but always found the single Nash equilibrium reported in Section 4.

the corresponding value functions. By symmetry, we assume that the government of country k maximizes the utilitarian welfare function

$$V^k = S_1^k V_1^k(s) + I_1^k V_1^k(i) \ . \tag{29}$$

Uncoordinated Policy: Without coordination, we assume that the two governments play a non-cooperative game, where each chooses open-loop policy paths as described, such as to

$$\max_{\{\mu_t^k, \nu_t^k\}_t} V^k$$

taking the other government's policy path $\{\mu_t^{-k}, \nu_t^{-k}\}_t$ as given. A Nash equilibrium consists of two policy paths that is each a best response to the other.

Coordinated Policy: Alternatively, we consider the benchmark of a single social planner who makes the containment and tariff decisions for both countries in order to maximize the sum of the two countries' welfare:

$$\max_{\{\mu_t^A, \nu_t^A, \mu_t^B, \nu_t^B\}_t} V^A + V^B \tag{30}$$

We next turn to the equilibrium analysis. Our focus is on understanding how international risk-sharing of health and economic well-being is affected by uncoordinated versus coordinature nature of government policy.[17]

2 Equilibrium Analysis

Given government policy μ_t^k, ν_t^k, and g_t^k in each country, firms maximize profits and households expected utility taking prices and the economic and epidemiological constraints as given.

2.1 Firm behavior

Because of the constant-returns-to-scale structure (1), firms make zero profits in equilibrium and hire as much labor as is supplied by households. Hence, in equilibrium, dropping the country superscript k, aggregate output in each country is

$$Y_t = z_t \left(S_t \ell_t(s) + \phi I_t \ell_t(i) + R_t \ell_t(r) \right) \tag{31}$$

[17] It is worth noting that risk-sharing in this context refers to individual risk. Once national policies are determined, the disease in our model runs its course deterministically, with aggregate transmissions determined by the Law of Large Numbers. Government policies, however, influence the laws of motion of the domestic transmissions and can shift aggregate infection rates internationally. This results in changing infection risks for the individuals in each country.

wages are

$$w_t(h) = \begin{cases} \overline{w}_t & \text{for } h = s, r \\ \phi\overline{w}_t & \text{for } h = i \end{cases} \quad (32)$$

$$\overline{w}_t = p_t z_t \quad (33)$$

and firm profits are $v_t = 0$.

2.2 Household behavior

Households of each country at each date t maximize expected utility U_t given by (3) subject to the budget constraint (25). Again dropping the country superscript k, they choose their levels of domestic consumption $c_{k,t} = c_{k,t}(h)$, foreign consumption $c_{-k,t} = c_{-k,t}(h)$, and labor $\ell_t = \ell_t(h)$. They know their own health status h,[18] and the current state of the disease Θ_t, given by (19). Using (28), in recursive terms, households thus choose current labor and consumption to maximize

$$v(x_t) - \frac{1}{2}\kappa\ell_t^2 + \beta\mathbb{E}_t V_{t+1}(h_{t+1}; \Theta_{t+1}) \quad (34)$$

where the expectation operator refers to the distribution of personal health h_{t+1} next period.

Susceptible Households. For a susceptible individual there are two possible future health states - either she remains in s or she gets infected and transits to i. Given (10), there are four possibilities to get infected. First, she may get infected from local contacts while consuming (shopping, eating out, etc.). This probability is increasing with her own time spent on that activity and the total time infected domestic or foreign individuals do the same. This corresponds to the first part of the π_1-term and of the π_4-term in (10), respectively. Second, she may get infected at work with a similar logic, which corresponds to the π_2-term. Third, she may get infected in general encounters with infected people locally, not related to consumption or work, summarized by the π_3-term. Fourth, she may get infected during the consumption of goods and services abroad or coming from abroad, which is summarized by the second part of the π_1- and of the π_4-term. While the first three possibilities refer to infections from domestic households, the fourth explicitly highlights the consumption risk from imports and exports and the associated interaction with foreigners.

As discussed in Section 1.2, when choosing $(c_k^k(s), c_{-k}^k(s), \ell^k(s)) \geq 0$, and thus the consumption basket $x^k(s)$ at time t, a susceptible household will transit to the infectious state with probability $\tau(c_k^k(s), c_{-k}^k(s), \ell^k(s))$ given by (9), where $c_k^k(i), c_{-k}^k(i), c_k^{-k}(i), c_{-k}^{-k}(i), \ell^k(i)$ are

[18] Hence, we ignore the problem of asymptomatic or presymptomatic infections. See, for example, von Thadden (2020) for a detailed discussion.

the equilibrium decisions by domestic and foreign infected households. We assume that susceptible households take this probability into account when making their decision.

Bringing back the time index, at time t the value function of s-households therefore is

$$
\begin{aligned}
V_t^k(s) \quad = \quad & \max_{c_{k,t}^k(s), c_{-k,t}^k(s), \ell_t^k(s)} v(x_t^k(s)) - \frac{1}{2}\kappa \left(\ell_t^k(s)\right)^2 + \beta \left[\tau_t^k(s) V_{t+1}^k(i) + (1-\tau_t^k(s)) V_{t+1}^k(s)\right] \\
& \text{subject to} \\
& x_t^k(s) = q(c_{k,t}^k(s), c_{-k,t}^k(s)) \qquad (35) \\
& \widehat{p}_{k,t}^k c_{k,t}^k(s) + \widehat{p}_{-k,t}^k c_{-k,t}^k(s) = \overline{w}_t^k \ell_t^k(s) + g_t^k \qquad (36)
\end{aligned}
$$

where $\tau_t^k(s) = \tau(c_{k,t}^k(s), c_{-k,t}^k(s), \ell_t^k(s))$. Here, (35) describes the household's consumption basket according to (2), and (36) is its budget constraint.

If λ_t^{ks} is the Lagrange multiplier of the budget contraint (36), the first-order conditions for the consumption of the domestic good, the consumption of the imported good, and labor are respectively given as:

$$
\begin{aligned}
x_t^k(s)^{-\rho} \frac{\partial x_t^k(s)}{\partial c_{k,t}^k(s)} + \beta \left(\pi_1 c_{k,t}^k(i) I_t^k + \pi_4 c_{k,t}^{-k}(i) I_t^{-k}\right) \left(V_{t+1}^k(i) - V_{t+1}^k(s)\right) &= \lambda_t^{ks} \widehat{p}_{k,t}^k \\
x_t^k(s)^{-\rho} \frac{\partial x_t^k(s)}{\partial c_{-k,t}^k(s)} + \beta \left(\pi_1 c_{-k,t}^k(i) I_t^k + \pi_4 c_{-k,t}^{-k}(i) I_t^{-k}\right) \left(V_{t+1}^k(i) - V_{t+1}^k(s)\right) &= \lambda_t^{ks} \widehat{p}_{-k,t}^k \\
\kappa \ell_t^k(s) - \beta \pi_2 \ell_t^k(i) I_t^k \left(V_{t+1}^k(i) - V_{t+1}^k(s)\right) &= \lambda_t^{ks} \overline{w}_t^k
\end{aligned}
$$

where the second terms in each equation reflect the fact that consuming foreign goods and services increases the chances of getting infected through contacts with foreigners. Eliminating λ_t^{ks} and simplifying yields the following two first-order conditions for the optimal choices of susceptible individuals:

$$
\begin{aligned}
& \overline{w}_t^k \left[\alpha x_t^k(s)^{\frac{1}{\sigma}-\rho} c_{k,t}^k(s)^{-\frac{1}{\sigma}} + \beta \left(\pi_1 c_{k,t}^k(i) I_t^k + \pi_4 c_{k,t}^{-k}(i) I_t^{-k}\right) \left(V_{t+1}^k(i) - V_{t+1}^k(s)\right)\right] \\
= \; & \left[\kappa \ell_t^k(s) - \beta \pi_2 \ell_t^k(i) I_t^k \left(V_{t+1}^k(i) - V_{t+1}^k(s)\right)\right] \widehat{p}_{k,t}^k \qquad (37) \\
& \overline{w}_t^k \left[(1-\alpha) x_t^k(s)^{\frac{1}{\sigma}-\rho} c_{-k,t}^k(s)^{-\frac{1}{\sigma}} + \beta \left(\pi_1 c_{-k,t}^k(i) I_t^k + \pi_4 c_{-k,t}^{-k}(i) I_t^{-k}\right) \left(V_{t+1}^k(i) - V_{t+1}^k(s)\right)\right] \\
= \; & \left[\kappa \ell_t^k(s) - \beta \pi_2 \ell_t^k(i) I_t^k \left(V_{t+1}^k(i) - V_{t+1}^k(s)\right)\right] \widehat{p}_{-k,t}^k \qquad (38)
\end{aligned}
$$

Together with the aggregation condition (35) and the budget constraint (36), (37)–(38) determine the behavior of s-individuals as a function of current prices, the state of the pandemic, the current choices of infected agents, and the policy parameters g_t^k and μ_t^k, ν_t^k (which are inherent in the consumer prices $\widehat{p}_{k,t}^k, \widehat{p}_{-k,t}^k$).

Infected Households. The behavior of infected households is simpler. Their behavior has no consequences for their future health, which is exogenously given by either recovery, with probability p_r, or death, with probability p_d. A type i household at time t therefore chooses $(c^k_{k,t}(i), c^k_{-k,t}(i), \ell^k_t(i)) \geq 0$ such as to optimize the static decision problem

$$
\begin{aligned}
V^k_t(i) &= \max v(x^k_t(i)) - \frac{1}{2}\kappa\left(\ell^k_t(i)\right)^2 + \beta\left[(1-p_r-p_d)V^k_{t+1}(i) + p_r V^k_{t+1}(r) + p_d V^k_{t+1}(d)\right] \\
&\quad \text{subject to} \\
&\quad x^k_t(i) = q(c^k_{k,t}(i), c^k_{-k,t}(i)) \qquad (39) \\
&\quad \widehat{p}^k_{k,t} c^k_{k,t}(i) + \widehat{p}^k_{-k,t} c^k_{-k,t}(i) = \phi \overline{w}^k_t \ell^k_t(i) + g^k_t \qquad (40)
\end{aligned}
$$

Note that via p_d, $V^k_t(i)$ depends on the aggregate domestic pandemic state. Letting λ^{ki}_t denote the multiplier of the budget constraint, the problem yields the following three first-order conditions

$$
\begin{aligned}
x^k_t(i)^{-\rho}\frac{\partial x^k_t(i)}{\partial c^k_{k,t}(i)} &= \lambda^{ki}_t \widehat{p}^k_{k,t} \\
x^k_t(i)^{-\rho}\frac{\partial x^k_t(i)}{\partial c^k_{-k,t}(i)} &= \lambda^{ki}_t \widehat{p}^k_{-k,t} \\
\kappa \ell^k_t(i) &= \lambda^{ki}_t \phi \overline{w}^k_t
\end{aligned}
$$

These conditions can be further simplified and even solved explicitly for $\rho = 1$, which we do in Appendix Section A.1. Together with the aggregation condition (39) and the budget constraint (40), they determine the behavior of i-individuals as a function of current prices and the policy parameters g^k_t, μ^k_t, and ν^k_t, as well as I^k_t.

Recovered Households. Similarly, when recovered, a type r household at time t chooses $(c^k_{k,t}(r), c^k_{-k,t}(r), \ell^k_t(r)) \geq 0$ such as to optimize the static decision problem

$$
\begin{aligned}
V^k_t(r) = &\max v(x^k_t(r)) - \frac{1}{2}\kappa\left(\ell^k_t(r)\right)^2 + \beta V^k_{t+1}(r) \\
&\quad \text{subject to} \\
&\quad x^k_t(r) = q(c^k_{k,t}(r), c^k_{-k,t}(r)) \qquad (41) \\
&\quad \widehat{p}^k_{k,t} c^k_{k,t}(r) + \widehat{p}^k_{-k,t} c^k_{-k,t}(r) = \overline{w}^k_t \ell^k_t(r) + g^k_t(r) \qquad (42)
\end{aligned}
$$

Letting λ_t^{kr} denote the multiplier of the budget constraint, the first-order conditions are

$$\begin{aligned} x_t^k(r)^{-\rho} \frac{\partial x_t^k(r)}{\partial c_{k,t}^k(r)} &= \lambda_t^{kr} \widehat{p}_{k,t}^k \\ x_t^k(r)^{-\rho} \frac{\partial x_t^k(r)}{\partial c_{-k,t}^k(r)} &= \lambda_t^{kr} \widehat{p}_{-k,t}^k \\ \kappa \ell_t^k(r) &= \lambda_t^{kr} \overline{w}_t^k \end{aligned}$$

As before, these conditions can be further simplified and even solved explicitly for $\rho = 1$, which we do in Appendix Section A.1. Together with the aggregation condition (41) and the budget constraint (42), they determine the behavior of r-individuals as a function of current prices and the policy parameters.

2.3 The macroeconomic synthesis

Each period, the following endogenous economic variables are determined in equilibrium:

- Households: 18 variables $c_{k,t}^k(h), c_{-k,t}^k(h), \ell_t^k(h)$, for $h = s, i, r$ and $k = A, B$.
- Markets: 4 variables $p_{k,t}$, $\overline{w}_t^k$ for $k = A, B$, where prices, consumer prices, and government policy are linked by (22)–(23).
- Government expenditures: 2 variables g_t^k, $k = A, B$. In the absence of health dependent transfers $g_t(h)$, fiscal policy is reduced to the balanced-budget rule (26).

As argued above, given the linear production technologies, the firm variables follow automatically from the household decisions.

The governments or the common social planner set the epidemiological and trade policy consisting of the 4 variables μ_t^k, ν_t^k, $k = A, B$, which are exogenous from the point of view of market participants. These variables are implicit in the consumer prices $\widehat{p}_{k,t}^k, \widehat{p}_{-k,t}^k$.

Counting equations, we have

- Labor markets: 2 equations in (33)
- Households: in each country 9 equations
  - for s: (36)–(38),
  - for i: (A.9), (A.10), and (A.6), with $w = \phi \overline{w}_t^k$, appropriately indexed.
  - for r: (A.9), (A.10), and (A.6), with $w = \overline{w}_t^k$, appropriately indexed.
- Goods markets: 2 equations for market-clearing

$$Y_t^k = \left(1 + (1 - \delta_\mu)\mu_t^k\right) H_t^k + \left(1 + (1 - \delta_\mu)\mu_t^{-k}\right) M_t^{-k} \tag{43}$$

for $k = A, B$, where output Y_t^k is given by (31), domestic consumption H_t^k by (6) and exports M_t^{-k} by (7). The right-hand side of (43) reflects the fact that the containment measures μ^k destroy real value, as measured by δ_μ.

There are 6 value functions to be solved, $V_t^k(s), V_t^k(i), V_t^k(r)$, for $k = A, B$. As usual, we normalize the value function $V_t^k(d) = 0$, assuming that the cost of death is the lost utility of life. To help interpret the results, we define the terms of trade as the relative price of the output of country A to that of country B, before taxes and tariffs:

$$e = \frac{p^A}{p^B} \ . \tag{44}$$

Finally, we define the aggregate consumption in each country as the population-weighted sum of the consumption baskets of all health groups

$$X_t^k = S_t^k x^k(s) + I_t^k x^k(i) + R_t^k x^k(r) \ . \tag{45}$$

3 Parameterization

Our parameterization builds on Eichenbaum, Rebelo and Trabandt (2021). Table 1 provides a summary of the our calibration choices. Each period in the model is a week. To make computation feasible in our high-dimensional environment, we assume log utility from consumption, i.e., we set $\rho = 1$, because this yields simple closed-form solutions to some expressions (see Appendix Section A.1).[19] We set $\beta = .96^{(1/52)}$ such that the value of life in autarky is approximately \$10 million.[20] Furthermore, for the sake of comparability we follow Eichenbaum, Rebelo and Trabandt (2021) and set $\phi = .8$, such that the average productivity loss for infected individuals is 20%.[21] We set productivity $z_t = \bar{z} = 39.835$ and $\kappa = 0.001275$ so that in the pre-pandemic steady state each person works 28 hours per week and earns $58,000$ per year, consistent with average data from the U.S. Bureau of Economic Analysis and the Bureau of

[19] Noting that ρ is also the inverse of the marginal rate of intertemporal substitution, Kaplan, Moll and Violante (2020) argue that also empirically $\rho = 1$ is a reasonable assumption.

[20] See, e.g., Hall, Jones and Klenow (2020) for a discussion.

[21] ϕ probably is the most difficult parameter to calibrate, and the choice by Eichenbaum, Rebelo and Trabandt (2021), which is based on early data about asymptomatic infections from China, likely too high. This is aggravated by various factors ranging from testing over mandatory quarantine policies to post-Covid conditions. See von Thadden (2020) for references and a detailed early discussion.

It therefore is important to note that with lower values of ϕ our findings are remarkably robust and some of the results are even stronger. If the economic cost of the disease, as expressed by the loss of individual productivity, increases (i.e., ϕ decreases), individuals have a greater private incentive to restrain their activity. This reduces infections and fatalities and makes it possible for governments to weaken domestic containment measures (i.e., reduce the μ^k). This is true under coordinated planning and in Nash Equilibrium. Interestingly, an increased productivity loss makes the tariff reactions to the infection waves stronger under coordinated planning (and thus strengthens the terms-of-trade effect), while it dampens the tariff reactions by Nash governments. Results are available on request.

Labor Statistics in 2018. Initial populations are normalized to 1. In the pre-pandemic steady state the countries are symmetric. For the elasticity of substitution between home and foreign goods, we follow Costinot and Rodríguez-Clare (2014) and set $\sigma = 6$. The home bias parameter $\alpha = 0.53$ is chosen such that the pre-pandemic steady-state domestic consumption share is 66%.

To fix ideas, we assume that the infection originates in country A with an initial infected population of $I_1^A = \epsilon = 0.001(0.1\%)$.[22] It then spreads to country B via international trade, at a speed that is endogenous to each country's policy. To parameterize our disease transmission, we again follow Eichenbaum, Rebelo and Trabandt (2021), who carefully derive values of π_1, π_2, and π_3 that make the model's pre-pandemic time-use and occupational predictions good matches for data from the Bureau of Labor Statistics 2018 American Time Use Survey and other statistics. With these choices, in a closed economy 1/6 of transmission would occur through consumption, 1/6 of transmission through production, and the remaining 2/3 of transmission through other activities. This prominent role of exogenous, behavioral transmission, which cannot be influenced by the economic policies discussed in the present model, implies that infections indeed develop into pandemics in our model.[23] We then choose π_4 such that, without government intervention, the peak of the infection in country B occurs approximately 6 months after the peak of the infection in country A. Our theory of intertemporal risk-sharing through trade requires some degree of asynchronicity of infection dynamics, which is driven by π_4 (we document and discuss our conclusions for the case of synchronous waves in Section 4.6). We have experimented extensively with different values of π_4 and show in Section 5.2 that the results are remarkably robust as long as infections waves are at least some months apart.

Moreover, we calibrate the benchmark transition probability p_r and $p_d(0)$ so that, when the infection rate approaches 0, the baseline mortality rate is 0.5% for the infected and it takes an average of 18 days to either recover or die from infection.[24] We consider a linear specification for the death rate as a function of the infection rate: $p_d(I_t) = p_d(0) + \zeta I_t$ where $\zeta = 0.05$ in the benchmark case. This means that the mortality rate increases approximately 2.6-fold when the infection rate I_t is 10%. Again, we provide extensive comparative statics in Section

[22] This is a relatively large number to start out with, but in the build-up phase for small early infection levels there is no noticeable behavioral reaction by agents and governments.

[23] A policy that makes sweeping use of curfews, quarantines, and other direct non-pharmaceutical interventions would provide a different and largely orthogonal channel to our analysis (with unmodeled dramatic economic consequences) and can potentially suppress early outbreaks by cutting these direct contacts. Given our interest in the transmission of infection waves as observed in 2020/21, such radical alternatives are not very informative (except perhaps at the very early stage of the pandemic), and the current model seems more appropriate. However, since some containment measures adopted in 2020/21 clearly also had direct effects on productivity, we generalize the model to such a scenario in Section 5.1 and find our results qualitatively unchanged.

[24] Our calibration of the case fatality rate is at the lower end of the early estimates that we are aware of (see, for example, Fernandez-Villaverde and Jones (2020) or Verity et al. (2020)). These early estimates reflect high uncertainty, but also lack of experience with the treatment of severe cases.

5.3 where we vary ζ. As noted earlier, for computational reasons we cut the disease off by assuming that a vaccine becomes available after T years. In calibrations, we use $T = 3$.[25]

Finally, we differ from Eichenbaum, Rebelo and Trabandt (2021) by letting $\delta_{\mu}^{k} = .5$ in our baseline simulations. Clearly, containment "taxes" are not meant to raise money for the government and in reality they don't. Our parameter choice means that half of the containment taxes are collected by the government as revenues and the rest is pure frictions, i.e. financially wasted. Hence, letting $\delta_{\mu}^{k} = .5$ is a pragmatic choice that provides for some scope of government expenditure and public insurance in a model that abstracts from taxation in the first place, and therefore makes containment measures sufficiently attractive. In our baseline scenario with uncoordinated policies, this choice predicts a level of peak infections of around 3.75% in both countries (see Table 3). This matches the observed values in the U.S. pretty well: at the peak of the pandemic in the U.S. in early January 2021, the weekly infection rate in the U.S population above the age of 5 was approximately 3.5–4.0% (remember that public data refer to reported new infections, which are estimated to underreport the true values by 40 to 60%).

Finally, we provide technical details about our computation algorithm in Appendix Section A.3.[26]

4 Numerical Results and Interpretation

Figures 3 to 5 in this section contain the main numerical results of our simulations of the laws of motion derived analytically in Sections 2.2 and A.1 in the appendix. In this section, we discuss the key qualitative insights from the simulations by first presenting the case with no policy, second the coordinated case, and third the Nash case. Section 4.4 compares the three cases to highlight the structure of optimal health and trade coordination during a pandemic. Sections 4.5 and 4.6 consider alternative scenarios without tariffs and with synchronous waves, respectively.

4.1 Health and Economic Outcomes with No Government Policy

As a benchmark, Figure 3 illustrates the SIR dynamics and economic outcomes when there are no containment policies or tariffs. The top 4 panels present the disease dynamics in both countries. As summarized in Table 3, starting with an initial infection rate of $I_0 = 0.001$ in country A, the pandemic takes off in country A and slowly spreads to country B, where it

[25] If in our simulations we take 2 years instead of 3, the results are qualitatively unchanged. In fact, as shown below, countries reach herd immunity and all our simulated time-series endogenously reach steady-state behavior well before the end of 3 years, so that the restriction is not binding.

[26] We have conducted extensive sensitivity tests studying how the numerical solutions vary for perturbations of all key parameters and found them to be remarkably robust.

begins to take off after week 25. The share of infected households in country A peaks at 4.6% in week 33 and declines thereafter. Around week 50, infections in country B overtake those in A and peak at 4.6% in week 60. After week 97 the disease has run its course in country A, and after week 122 in country B, when almost 50% of the population in each country has become infected and around 0.45% of the population in each country has died.

The economic outcomes track local infection rates closely. When the infection wave hits country A, its labor and therefore output decline by more than 15%, while the values for country B stay constant (third row, third panel). Similarly for country B, when the pandemic hits there. In both countries during their peaks, when the domestic infection rates are much higher than the foreign ones, households increase the share of foreign consumption to reduce the exposure to domestic infection (third row, second panel). These shifts in consumption shares have a small impact on the terms of trade expressed by the relative prices of both goods (which, as shown in panel 4 of the second row, change by at most 2%), but they do not impact production (as illustrated by the use of foreign labor). Interestingly, consumers of country B pick up some of the lost consumption of country A when the latter collapses during the peak of the crisis in A and the price of A's good falls. This even yields a decline of the domestic share in total consumption in country B, indicating that country B's households view the health risk from imports from country$A$ as less important than the economic benefit from the improved exchange rate.

4.2 Fully Coordinated Government Policies

Next, we consider the optimal policy of a coordinated planner who maximizes the sum of the welfare of both countries' households as given by (30). At time 0, this planner determines both countries' domestic containment policies and tariffs from week 1 to 156 until the pandemic is over. Figure 4 reports these internationally optimal outcomes for the respective health and economic variables. As in the no-policy case, the first 4 panels show that the pandemic quickly takes off in country A and slowly spreads to country B, where it begins to take off after around week 25. The infection in country A peaks in week 33, the same time as in the unfettered outbreak, and declines thereafter. But the peak is more than 20% lower and the disease lasts 10 weeks longer (see Table 3). Hence, the planner "flattens the curve".

The picture is almost identical in country B. The infection peak in B is slightly higher than in country A, and the disease again lasts 10 weeks longer than under laissez-faire. Around 47% of the population becomes infected eventually in both countries, and total death rates are almost the same at 0.39% in both countries, around 13% lower than under laissez-faire.

The economic outcomes react both to the infection rates and the domestic containment and tariff policies. When the wave of infection hits country A, its labor and therefore output decline by 22% (third row, third panel), significantly more than under laissez-faire. Also differently from the laissez-faire case, labor and production in B increase during the peak in A, by more than 5%. This makes up for some of the lost output in country A, by shifting the consumption baskets consumed in both countries towards good B. Interestingly, consumption in country B, as defined in (45), first recovers together with consumption in A and only collapses when the pandemic hits country B. In fact, when the wave of infection hits country B, its consumption and labor decline significantly. Mirroring the wave of infection for country A, it is now country A's turn to make up for some of the lost production in B.

The decline in both consumption and labor is much more drastic than in the laissez-faire case, because the planner internalizes the infection externalities within and between the two countries. The planner achieves these health and economic outcomes with a combination of domestic containment measures and tariffs (second row). The severity of domestic containment measures in each country roughly tracks the level of infection rates in the country, with some front-running due to rational expectations and prevention. In contrast, tariffs have a pattern across time that is inversely symmetric between the two countries and very different from the one under laissez-faire. When the infection peaks in country A, the planner responds by *raising* tariffs drastically, to more than 60%, in country A, while imposing a *negative* tariff in country B, i.e., an import subsidy.

These tariffs are intriguing at a first pass because, in the wave of infection for country A, they encourage both countries to consume more of country A's goods, which transmits the pandemic via consumption- and labor-induced interactions in country A and via imports to country B. However, these health costs are dominated by the economic benefits, which ultimately make it possible to tighten health standards without losing too much on the consumption side; in other words, tariffs raise the terms of trade for country A during the peak of the infection and its households earn higher wages by (33). Given the higher wages, households can even reduce infectious labor contacts without sacrificing total income, and can thus enjoy a higher level of consumption, for a given level of containment measures.

Similarly, when the wave of infection hits country B, the planner reverses the tariffs in both countries, leading to more favorable terms of trade for country B and supporting its households' consumption. The tariffs act as a lever to change the terms of trade. Note that the planner raises the terms of trade by more than 40% in favor of country A during the peak of its pandemic, while they actually decrease under laissez-faire. Interestingly, this reversal of the terms of trade brought about by boosting tariffs allows for overall production to be maintained at higher and more efficient levels: there is further risk-sharing between the two countries by shifting production at the margin to the less infected country (third row, third panel). Since work becomes riskier (from a health standpoint) in country A during its infection wave, households reduce labor supply there and production increases in country B, implying that the planner uses the asynchronous feature of the pandemic to not only shift consumption, but also production, between countries.

4.3 Government Policy in Nash Equilibrium

We next consider the case where each country's government determines its own domestic containment and tariff policies in order to maximize the welfare of their domestic households, defined as the weighted average of their lifetime utilities (29). We consider open-loop strategies, which is tantamount to assuming commitment and perfect foresight. This creates room for intertemporal tradeoffs of the *do-ut-des* sort: governments can agree in advance on future actions to smooth health shocks. However, this also creates the potential to create the "Prisonners'-Dilemma" type blockades found in traditional theories of trade wars.

Figure 5 reports the outcomes and Table 3 summarizes the basic health statistics. To interpret the results, it is helpful to begin at the end. Once the pandemic is over (week 107 in country A, week 132 in country B), both governments impose a tariff of 23%, due to the standard Nash logic that each country wants to boost its domestic employment and wages, given that the other country does so (second row, second panel). This logic interferes with the objective of smoothing intertemporal shocks during the pandemic. Still, the health outcome is better than that under laissez-faire discussed above. In particular, Nash governments manage to flatten the curve and reduce total deaths by about 10% compared to laissez-faire. But compared to optimal coordination, total deaths are 3.6% higher in country A and 5.4% in B.

The logic behind this coordination failure can again best be understood when looking at the peak of infection in country A. During this wave, country B raises its tariff by more than one third, because this way it seeks to boost its own production and at the same time keep infections from country A out. As a reaction country A slashes its tariffs to levels even below 0, i.e., it provides import subsidies in order to encourage its domestic households to consume more foreign goods which are less conducive to infection. Both actions in the end tilt the terms of trade against the infected country, dramatically amplifying the terms-of-trade problem (a deterioration by almost 17%) compared to that under no policy. Given this defensive policy by country A, country B's aggressive behavior is rational. On average, over the course of the pandemic, A's tariffs are below the stationary trade-war level, but their timing is inefficient.

The trade-war logic is particularly visible in the period around week 50 when the pandemic is equally bad in both countries (first row, second panel). At that time tariffs in both countries are relatively low, as each country tries to balance its beggar-thy-neighbor policies between tariff predation and health protection. Around that time, both countries display the lowest level of consumption distortion, with a domestic consumption share of below 75% (third row, second panel). This level of consumption distortion is still much higher than what would be optimal (Figure 4), and also higher than what households would choose to self-insure under laissez-faire (Figure 3). Note that the compounding of trade-war and health motives prevents the trade-based risk-sharing observed in the coordinated case, in which imports are clearly counter-cyclical to health (as shown in the third row in Figure 4, where week 50 marks an inflection point, not an extremum of import shares of country A).

4.4 Comparing Nash and Coordinated Policies

Figure 6 compares the equilibrium government policies and pandemic dynamics in the three cases discussed above. Both the Nash case and the Planner case feature similar paths of domestic containment policies, with high values during the peak of the infection waves and no action outside this period. As noted above, qualitatively the major difference is the dynamics of the other policy instrument, viz., tariffs.

During both peaks, the coordinated planner can get away with less domestic containment in the affected country than under Nash. This less aggressive containment is possible because the dynamics of the pandemic make it possible to modulate tariffs intertemporally, thus reducing the home bias and improving the terms of trade when the more-infected country needs this most. As the first row of Figure 6 shows, this positive spiral also reduces A's infections and ultimately its death toll. As the first and the third panel of row 2 show, the planner's advantage over Nash is the greatest during country A's wave, because Nash governments do not take the positive international externality into account that their domestic policies have with respect to future spillovers of infections.

This observation highlights the contrast between health and economic externalities. Negative health externalities arise from the possibility that a country does too little to restrain its production and consumption activities, thus spreading the pandemic. That said, as the preceding argument shows, there are also positive health externalities. Negative economic externalities arise from the possibility that a country reduces its consumption of foreign goods in order to promote the interests of its own production sector. The coordinated planner fully internalizes this economic externality and uses tariffs to control the pandemic and smooth out its impact on both countries' economies. This way, international trade can lead to better risk-sharing and facilitate global health diversification. Importantly, the two externalities interact. When the disease hits one country, the demand for its good collapses for health reasons, leading to a collapse of its price. This, however, triggers a demand effect in the less-infected country and thus provides a countervailing stimulus that is absent in the more-infected country. Under Nash, the government in the less-infected country reacts by increasing tariffs to contain that stimulus and, at the same time, benefit financially from tariff revenues. This leads to the apparently paradoxical situation that in Nash equilibrium imports in one country can be high when its tariffs on foreign goods are high, an effect that reverses the standard price logic, but is due to an interaction of economic forces with the pandemic.

We disentangle these forces in the decomposition of the overall welfare effect in Table 2. Panel (b) reminds us that without a pandemic, laissez-faire (*no policy*) is optimal, and Nash behavior leads to a utility loss of 25.23 in each country. Panel (a) first reports, as a benchmark, the welfare loss of laissez-faire in a pandemic (discussed above) compared to the no-pandemic case. The next two lines compare the different policies relative to the laissez-faire case during a pandemic. We decompose the households' utility loss or gain (negative or positive value, respectively) in each country relative to laissez-faire into two components: the welfare loss due to economic recession, and the welfare loss due to death. The former is the present value of the utility change in the consumption and labor of living households, from period 1 to the infinite future; the latter is the present value of the foregone utility due to death. Their sum is the total utility loss relative to laissez-faire.

The fourth line compares the gains from optimal international coordination to those from uncoordinated Nash policies. We observe that in both countries the coordinated outcome alleviates both economic and death-related welfare losses relative to the Nash equilibrium. Not surprisingly, Nash governments create an enormous economic loss in each country (28.1 utils in A and 27.5 utils in B) by using too strict domestic measures and ill-timed tariff policies. But these generate a gain on the health front of 3.4 and 3.0, respectively. This is “too much of a good thing"; the results of the planner’s policy show that coordination achieves a much lower economic loss and still a higher health gain in both countries. In particular, these numbers show that there is no consumption-health tradeoff, and remarkably, not only in the aggregate, but in each country.

Figures 4 and 5 also show how optimal international coordination achieves this Pareto improvement. The manipulation of the terms of trade by the central planner does not only change the marginal rates of substitution between domestic and foreign consumption and thus shifts consumption between countries, it also shifts the marginal rates of substitution between consumption and leisure and thus affects labor supply and production. In turn, this shifts production internationally to where the labor transmission channel in (10) is the least harmful.

4.5 Containment Without Tariffs: The Case $\nu \equiv 0$

An interesting variant of our model obtains if we rule out tariffs, i.e., set $\nu \equiv 0$. This case certainly is realistic in some cases, as tariffs and other trade barriers are internationally regulated by trade agreements and cannot be changed flexibly in crises. Furthermore, in many parts of the world, most notably the European Union, tariffs and non-tariff barriers have been abolished altogether among the member countries.

We report the health and economic dynamics in this case in Figure 7, which mirrors Figure 6 of the full model and again compares laissez-faire, Nash equilibrium, and optimal coordination. Table 5 reports the corresponding statistics in greater detail. In this case, and different from the case with tariffs, the domestic containment policies adopted under coordinated planning and in Nash equilibrium are qualitatively and quantitatively quite similar, and so are the outcomes. In particular, governments in Nash equilibrium cannot use tariffs to counteract the risk-sharing policies that are optimal under coordination. Therefore, key variables such as the terms of trade now move much alike under coordination and non-coordination, and furthermore, they move little. Thus, in terms of the observed dynamics in this world with only domestic containment measures, “Nash broadly gets it right".

This, however, masks an important difference between the two settings that is brought to light in Table 5. As the third line shows, Nash governments do almost exactly as well as the social planner in each country.[27] But they achieve this optimum for rather different reasons. In each country, optimal coordination yields significantly higher economic benefits than the Nash outcome, but loses almost exactly as much aggregate utility in terms of health (a difference that is invisible in the first row of Figure 7, but shows up in Table 5). Hence, the social planner implements a quite different health-consumption tradeoff from Nash, relative to the laissez-faire case. In fact, as noted before, Nash governments ignore the positive international health externality of their aggressive economic policies. The social planner takes this externality into account and thus implements slightly weaker containment measures. This creates a real trade-off, which is different from the case when governments have both instruments at their disposal – domestic containment and tariffs – as in that case international coordination improves upon the Nash outcome in terms of health *and* consumption.

4.6 Synchronous Waves

In order to understand the role of the asynchronous spread of the pandemic in our model, we now consider a variant of our baseline model with synchronous waves. In this variant we assume that 0.1% of the population is infected in both countries in period 0. We report the health and economic dynamics in this case in Figure 8. Table 7 reports the corresponding statistics in greater detail.

As expected, the SIR dynamics and the government policies are exactly symmetric between countries A and B. There is a single peak of infection that occurs around week 33. Both the Nash governments and the social planner impose their highest containment tax around the peak of infection, and at all times Nash governments follow the standard trade war logic and impose much higher higher import tariffs than the coordinated planner. However, in both scenarios, all through the pandemic tariffs are lower than before the pandemic. This is because during the pandemic, governments want to shift production abroad to reduce infection at work. In terms of time-series variation, the governments impose higher tariffs around the peak of infection relative to other parts of the wave because at that point it is most urgent to discourage the consumption of any good, including the foreign good, so as to limit the spread of disease.

These policies result in similar levels of overall infection and death when we compare the outcomes of coordinated and uncoordinated policies. Table 6 reports the welfare comparison under different policies: the welfare gain of the planner relative to Nash governments due to life saving is only 0.5 utils in either country, compared to about 1.1 utils in the baseline model with asymmetric waves. This difference suggests that over half of the improvement in the health outcome gained by the planner relative to the uncoordinated outcome in the baseline

[27] The total expected utility difference for country B is positive at the third decimal position and thus disappears in the table due to rounding.

model is attributable to the fact that the two waves in countries A and B are asynchronous. Furthermore, and importantly for the comparison of the two models, international coordination reduces the average number of deaths in the synchronous model over the full course of the pandemic from 4.08 to 3.99 per 1,000 households in each country, i.e., by 2.2 percent, relative to governments acting non-cooperatively. In the asynchronous baseline model, coordination reduces the average number of deaths per 1,000 from 4.10 to 3.92 per country, i.e., by 4.4 percent, a decrease that is twice as much as that with synchronous waves. Hence, much of the health gain from international cooperation in our model is due to the intertemporal nature of health risk that can be shared internationally.

5 Generalized Lockdown, International Transmission Intensity, and Health Sector Overload

In this section, we discuss three variations of our model that broaden the perspective on its interpretation. First, we present results for containment policies which suppress productivity along with consumption; such policies can be interpreted as "generalized lockdowns" wherein not just consumption, but production too is impaired by the containment measures. Second, we vary the cross-border contact intensity parameter π_4, which allows us to explore the implications of our model for different types of trade, in particular, merchandise vs services trade. Third, we consider variation in the sensitivity of fatality rate to the number of infections, which can be interpreted as an indicator of the congestion externality from a health-sector overload. Tables and Figures corresponding to these extensions are contained in the online appendix.

5.1 Generalized Lockdown through Productivity Suppression

At the onset of the pandemic in March 2020, most countries adopted lockdowns that restricted both consumption and production, barring the most essential services such as health and food delivery. Such generalized lockdowns appeared to have dramatic consequences on consumption and production of affected countries, even if there was global demand for some of the production in foreign countries. In contrast, in later waves (in 2020 or 2021), lockdowns were less generalized and more targeted. In particular, exports emerged as a potential way to keep the domestic economy stronger by benefiting from demand in less- or non-infected parts of the world. Recognizing this, exports were included in many countries (such as India) as "essential' services" during the second waves.

To study generalized lockdowns, we now assume that the domestic containment measures also affect productivity: $z_t^k = \bar{z}(1-\mu_t^k)$. Figure B.1 in the appendix compares the coordinated outcome between our baseline model and the model with productivity suppression; Figure B.2 compares the Nash outcome. In this new scenario, the government is more reluctant to impose stringent domestic containment measures and both the Nash governments and the planner use more aggressive tariff policies, which in turn exacerbates the intertemporal misalignment of the terms of trade.

Not surprisingly, the attendant welfare and health statistics show that, as with our benchmark model, the planner improves outcomes relative to Nash on both the economic and health fronts. And again as expected, relative to our benchmark model, health outcomes under generalized lockdowns are worse in both the Nash and the coordinated outcomes, leading to more deaths in both countries. But somewhat unexpectedly, and importantly for the theme of this paper, the misalignment of the terms of trade between Nash behavior and optimal coordination becomes worse, which increases the value of international coordination of trade policies.

5.2 Varying Degrees of Contact Intensity

While our modeling of trade so far carried the semantics of merchandise goods, in practice – depending on the country pairs – trade often is in services. Especially in the context of the pandemic, services trade relating to tourism, travel, transport, etc., is particularly important as it has much greater contact intensity than trade in other services (such as technology services) and merchandise goods. Consistent with this view, travel and transport have been among the most adversely affected sectors during the pandemic, and overall services trade in March 2021 remained below its pre-pandemic levels, unlike merchandise trade that had recovered more fully (World Bank, "Trade Watch", June 2021). At the political level, the ongoing restrictions of travel, tourism, and entertainment have been among the most controversial questions with respect to the direct intervention of governments in consumption choices.

While modeling the full richness of merchandise versus services trade is beyond the scope of this paper, we can offer some insights by varying π_4, which measures the intensity in the transmission of disease between households in different countries due to the consumption of foreign goods. Increasing π_4 can be considered as shifting focus towards more contact-intensive trade such as services versus merchandise, or within services, tourism versus technology services.

In our simulations (reported in Figures B.3 and B.4 in the online appendix), we have varied π_4 from the benchmark case to a scenario in which π_4 is five times higher, and then to one in which π_4 is ten times higher. A higher π_4 implies that the pandemic is transmitted faster across countries for a given level of international trade. International transmission in the benchmark case has been calibrated to be approximately 100 times weaker than domestic transmission. So, when we raise the π_4 by a factor of 10, international transmission is about 1/10 as strong as the domestic transmission.

In both the coordinated planning equilibrium and the Nash equilibrium, faster transmission means that the infection peaks in the two countries are temporally closer. If we raise the international transmission coefficient ten fold, the two infection peaks in the absence of government policies are 12 weeks apart instead of 27. As π_4 is varied, the results remain qualitatively similar. In the coordinated planning equilibrium, each government imposes domestic containment taxes during the peak of its local infection. It also raises its import tariffs during the peak of its local infection, and lowers its import tariffs during the peak of the other country's local infection to provide intertemporal risk-sharing. And, just as in the baseline case, in Nash equilibrium, this latter pattern is reversed, leading to an unfavorable intertemporal modulation of the terms of trade

When comparing the welfare effects of increasing π_4, we are interested in whether a stronger international transmission limits the scope of international coordination by governments. To measure this scope, we compare the difference between the welfare obtained under coordinated and Nash policies. Iin the baseline case, the welfare gain in terms of health under coordinated policies relative to Nash policies is 0.90 for country A and 1.34 for country B. When we raise the international transmission coefficient ten-fold, this welfare gain goes down to 0.76 for country A and to 0.88 for country B. To understand this difference, note that, since the pandemic starts in country A, a stronger international transmission is always bad news for country B, as it allows less time for country B to flatten the curve. As a result, country B suffers more deaths and there is less its government can do, even under coordinated policies. Conversely, since the pandemic also spreads back from country B to country A, a higher international transmission intensity is also bad news for country A. These results suggest, quite expectedly, that more contact-intensive trade leads to a faster spread of the pandemic, but also, less obviously, that the misalignment of terms of trade brought about by non-cooperation continues to be a central problem in the international spread of the the pandemic.

5.3 Varying Degrees of Healthcare Congestion

It is interesting to apply our model to the issue of trade between advanced economies (AEs) versus emerging markets (EMs). While at the onset of the pandemic, EMs were thought to be less exposed due to younger and less obese populations, in many cases the fallout of the pandemic has been worse in the EMs, notably due to their limited capacity in health infrastructure. For instance, in terms of hospital beds per 1,000 people, a recent World Bank statistic shows that India has 0.5, the Philippines 1, the United States 2.9, China 4.3, and Japan 13.4 hospital beds, the statistics being even more dispersed in case of Intensive Care Unit (ICU) beds.

The lack of limited healthcare capacity has been found to extend beyond just hospital and ICU beds to availability of medical equipment and oxygen supply, implying that the realized infection fatality rate in EMs can be country-specific due to "congestion externalities" from healthcare overload, rather than being just disease-specific. While there are several other differences in EMs relative to AEs, due to the former's greater population density, higher contact-intensity nature of low-paying jobs, and higher imports' component in the consumption basket, our model allows us to focus on varying the congestion externality to compare these two types of countries.[28]

Recall that we model the death rate as a linear function of the infection rate: $p_d(I_t) = p_d(0) + \zeta I_t$, where ζ can be interpreted as a measure of the healthcare congestion externality. In our simulations, we either raise the congestion parameter from the benchmark of 0.05 to 0.075, or lower the congestion parameter from the benchmark to 0.025. Naturally, we find that a higher congestion parameter leads to more death, and governments impose more stringent domestic containment measures as a response in both the coordinated and the Nash equilibria. Importantly, the governments' tariff policies remain modulated in a similar fashion as in the benchmark case. Table B.5 in the online appendix reports these statistics in the same format as the table for the benchmark specification.

However, quantitatively the welfare differences do change. Comparing the welfare differences of these cases illustrates clearly that the welfare gain due to fewer deaths in the coordinated policies relative to the Nash policies increases strongly as the congestion parameter rises. In other words, a higher congestion parameter (as would typify countries with underdeveloped healthcare systems) makes it more important to contain the pandemic, and increases the welfare gains from the international coordination of health and trade policies.

6 Conclusion

In this paper, we have developed a model of epidemiology and international trade to study how international coordination, and the lack thereof, influences the impact of government policies on health and economic outcomes during a pandemic. A major insight from our work is that the interplay between domestic health policies and international trade policies makes it possible to share economic and health risks better across countries. This can be achieved by intertemporally modulating the terms of trade to shift consumption, production, and infection patterns internationally as a function of the global state of the pandemic. When policies are introduced in a coordinated manner between countries, this makes it possible to influence the terms of trade such as to favor countries experiencing infection waves when they need it most. In contrast, uncoordinated policies aggravate overall outcomes by achieving exactly the opposite, highlighting the importance of international cooperation in dealing with the health and economic fallout from a pandemic. Tariffs and trade frictions are thus a two-sided sword: when used wisely they provide valuable international risk-sharing, when used non-cooperatively, they destroy valuable trading opportunities.

There are several fruitful avenues to extend our model. For instance, the model can be generalized to study the role of non-tariff barriers during a pandemic in affecting international

[28] Our analysis and simulations become inordinately more complex than the present formulation if we introduce too much heterogeneity among the two countries; hence, we limit our present comparison to simply varying the congestion externality for both countries.

supply chains, which seem disrupted far more than originally envisaged at the time of outbreak of the COVID-19 pandemic. Traded goods can be intermediary inputs into domestic production functions that produce the final good consumed in each country. As supply chains get disrupted, agents may switch consumption not just from foreign to domestic goods, but also to those that involve less contact-intensive services (such as e-commerce), creating secular shifts in labor and production allocation. We believe our analysis can be extended to ultimately be able to shed light on implications for such allocation shifts arising from a coordination of local health and economic policies, be it between different sovereign governments, between states in a federation, or within economic unions such as the European Union.

Finally, it seems equally fruitful to extend SIR-model dynamics with micro-founded international transmission (as we did in this paper) to entertain the possibility of "variants" due to pathogen evolution. Such modeling advances can help better understand the empirical patterns observed in international terms-of-trade during the pandemic. Our model can be a useful foundation for this significant next step.

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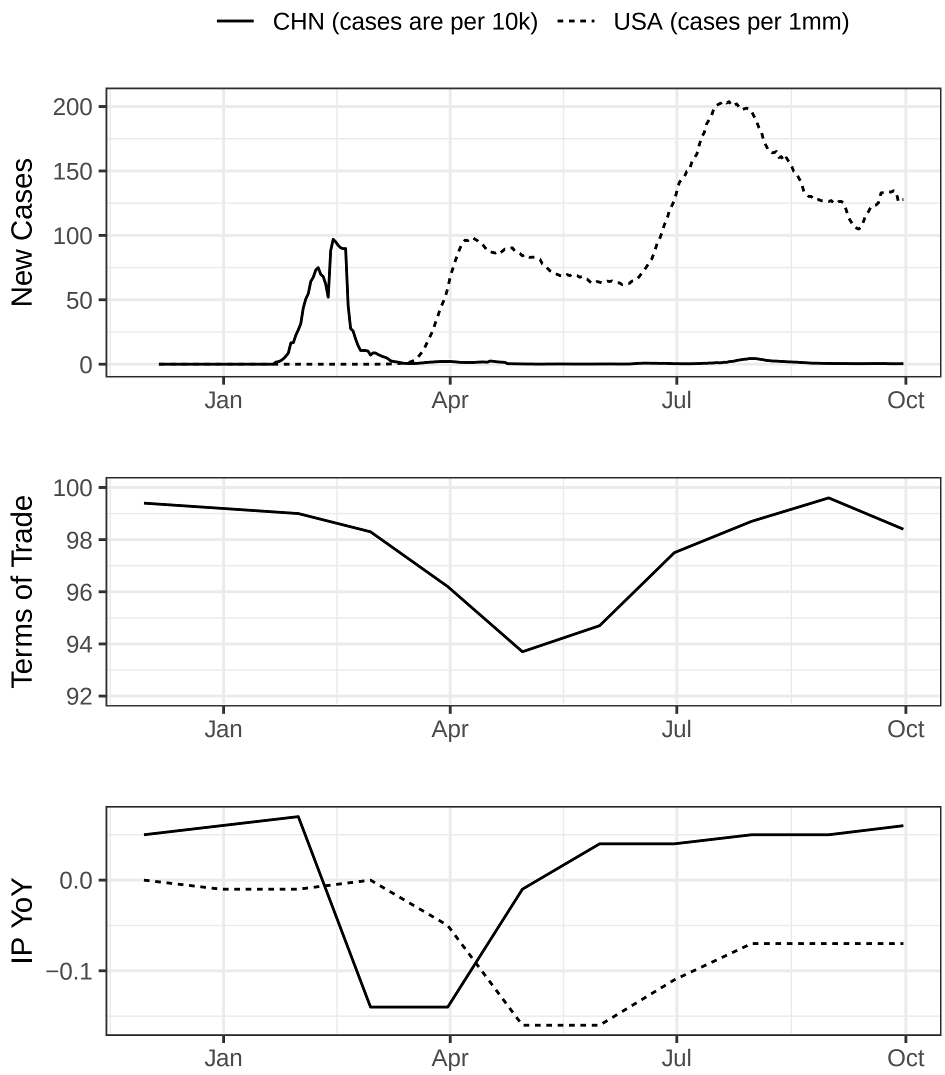
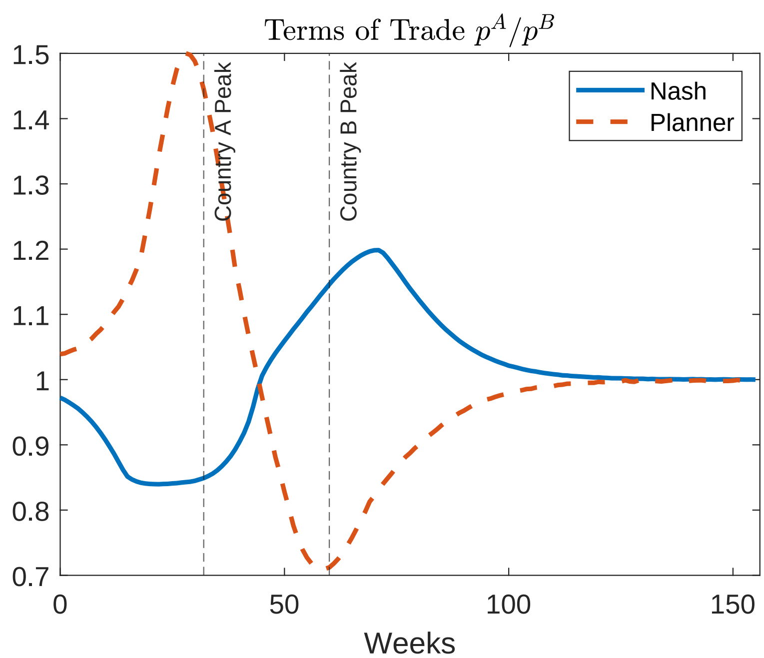
Figure 1: Pandemic and Economic Outcomes in China and the U.S.



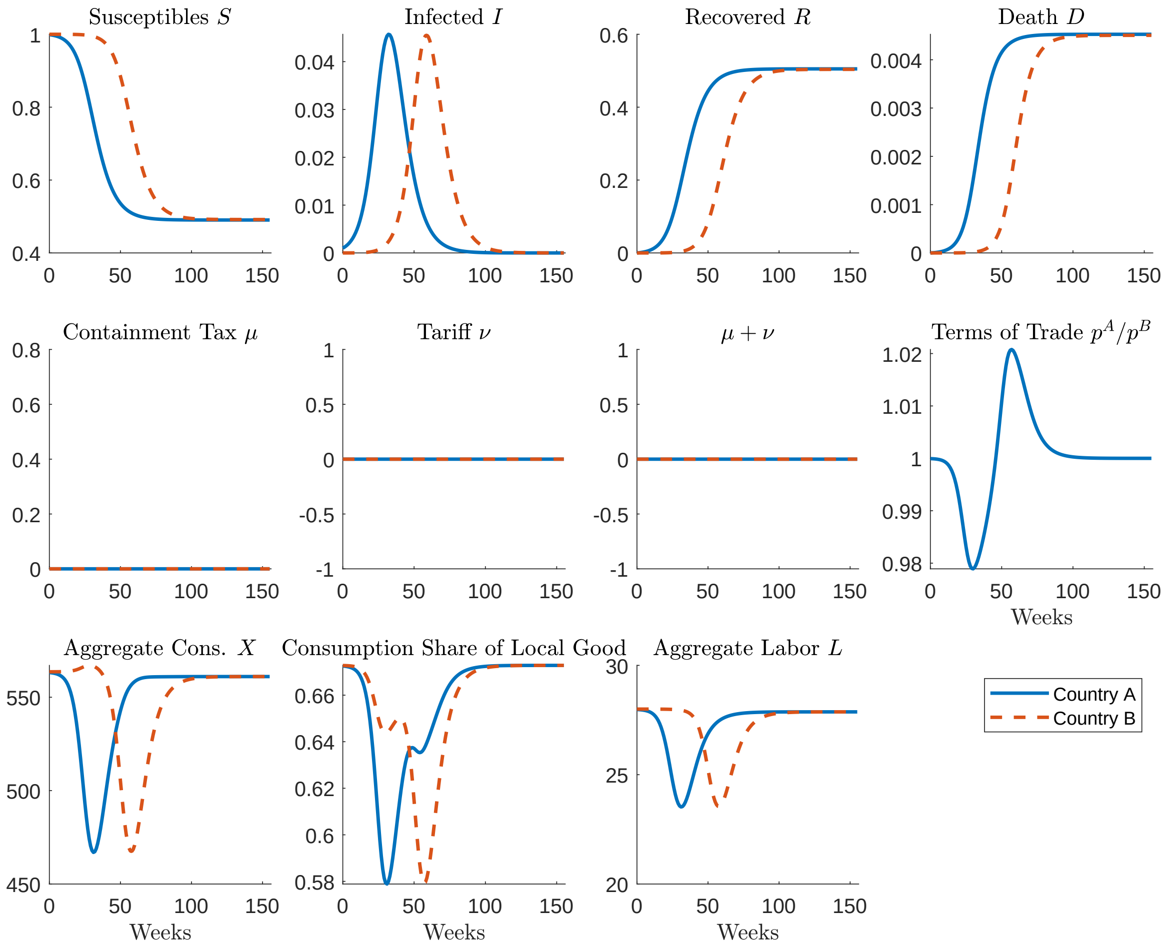
Note: Health and economic outcomes in China and the United States during the 2020 pandemic. Daily new cases for China are per 10,000 people and per 1,000,000 for the United States. Terms of trade is the price index of US exports to China divided by the price index of imports by the US from China. Industrial production is measured year-over-year.

Figure 2: Terms of Trade With and Without Coordination



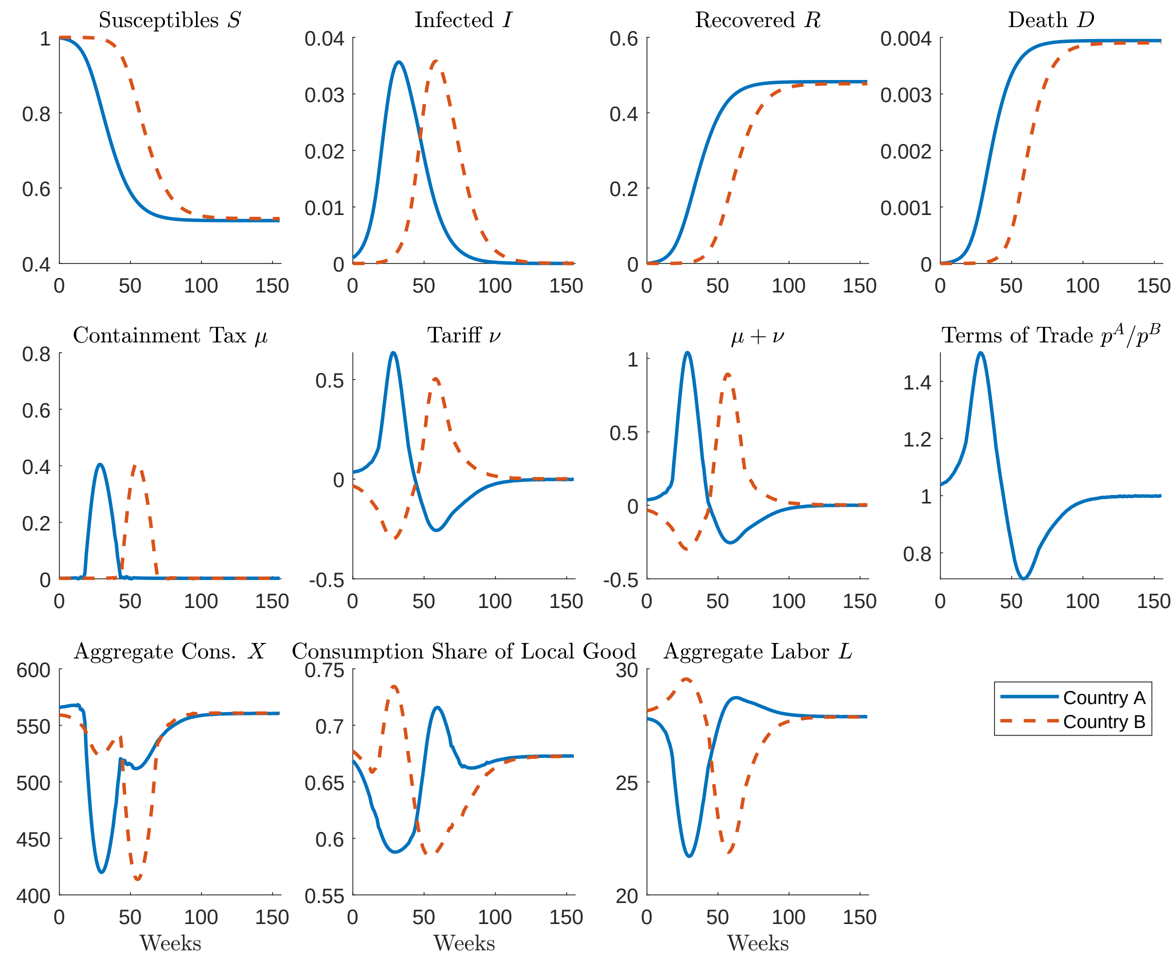
Note: Terms of Trade in uncoordinated (Nash) and coordinated (Planner) equilibrium. The dashed lines specify the approximate peak of maximum infections in country A and country B.

Figure 3: Benchmark SIR Dynamics



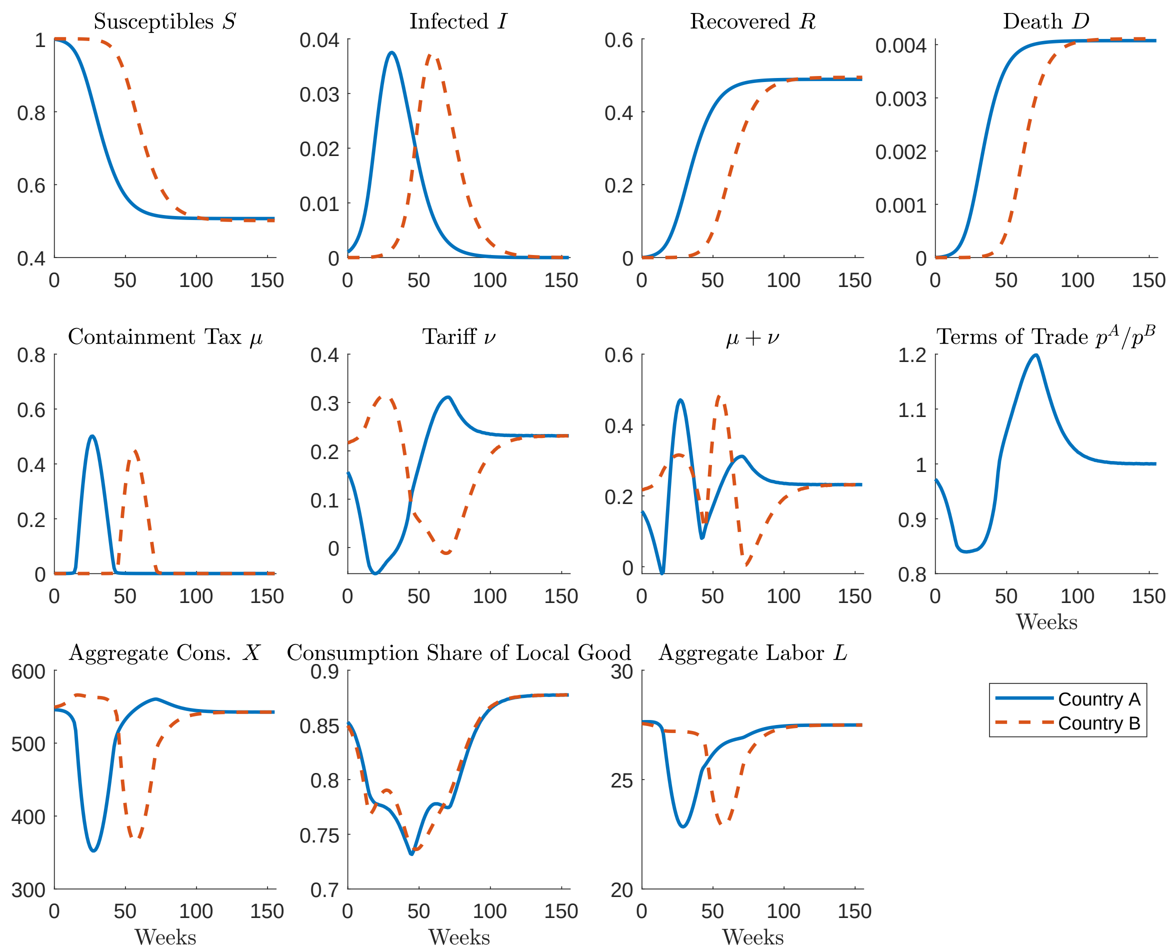
Note: Benchmark model with international transmission of pandemic. No government domestic containment policies or tariffs.

Figure 4: Coordinated Planning Equilibrium Outcomes



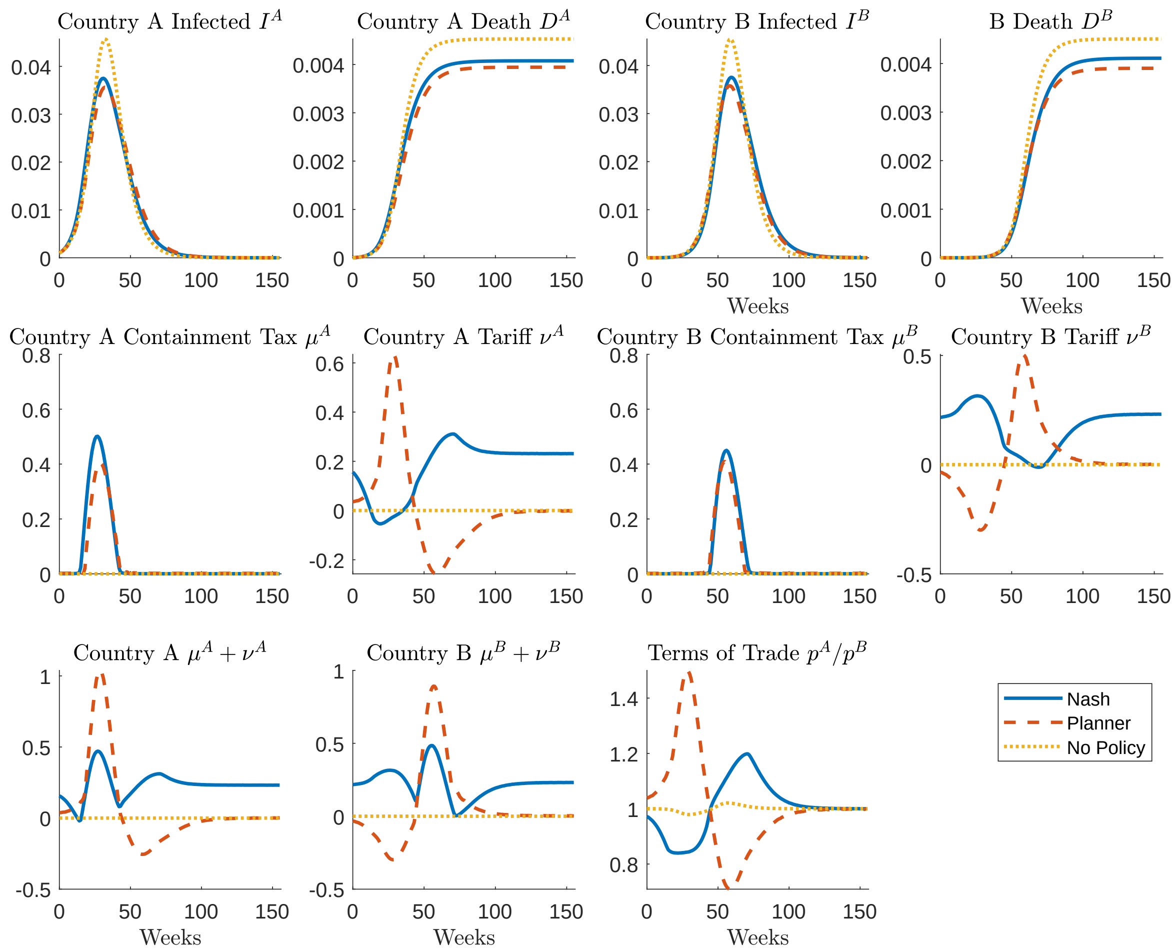
Note: Benchmark model with international transmission of pandemic. Equilibrium domestic containment policies and tariffs are determined by a global social planner that maximizes the sum of both countries' welfare.

Figure 5: Nash Equilibrium Outcomes



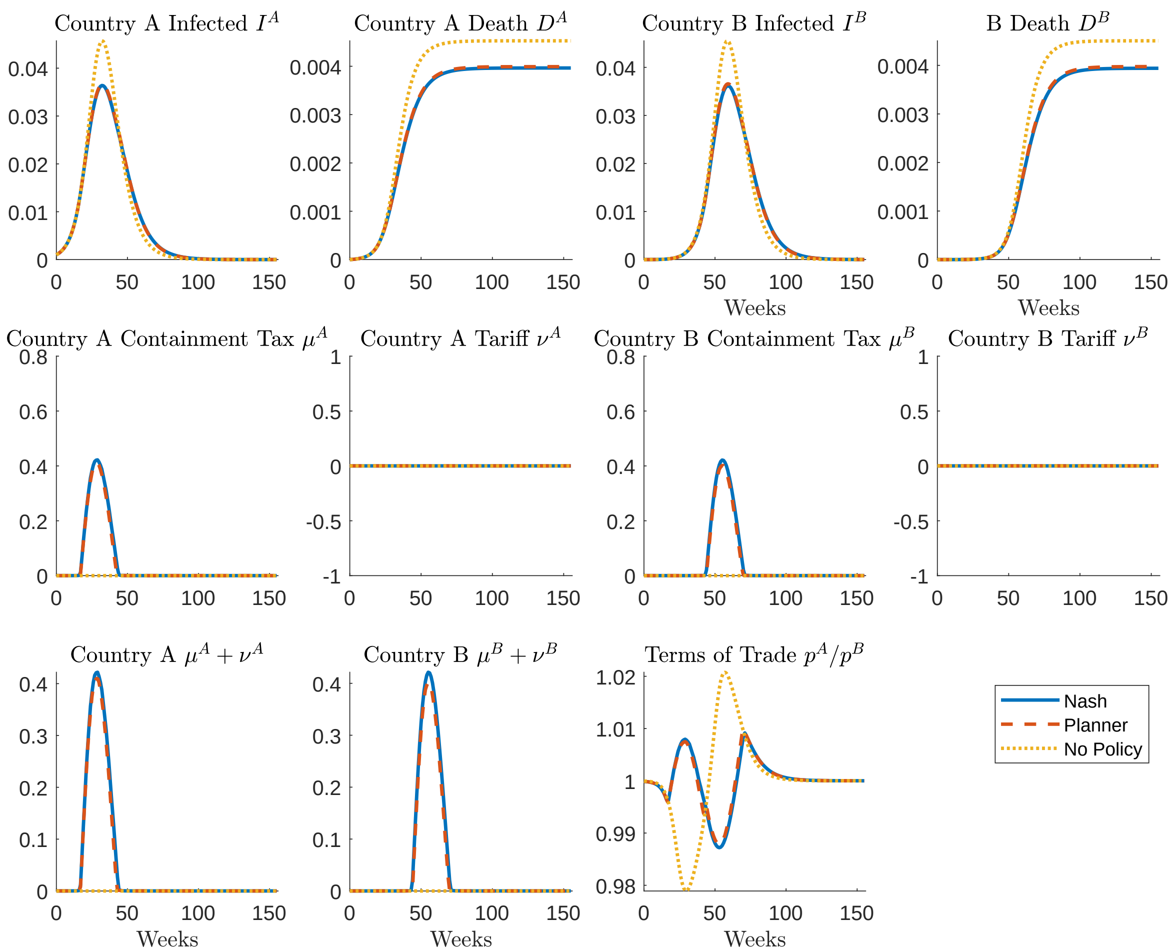
Note: Benchmark model with international transmission of pandemic. Equilibrium domestic containment policies and tariffs are the outcome of a Nash game between the two countries.

Figure 6: Comparing Equilibrium Policies and Outcomes



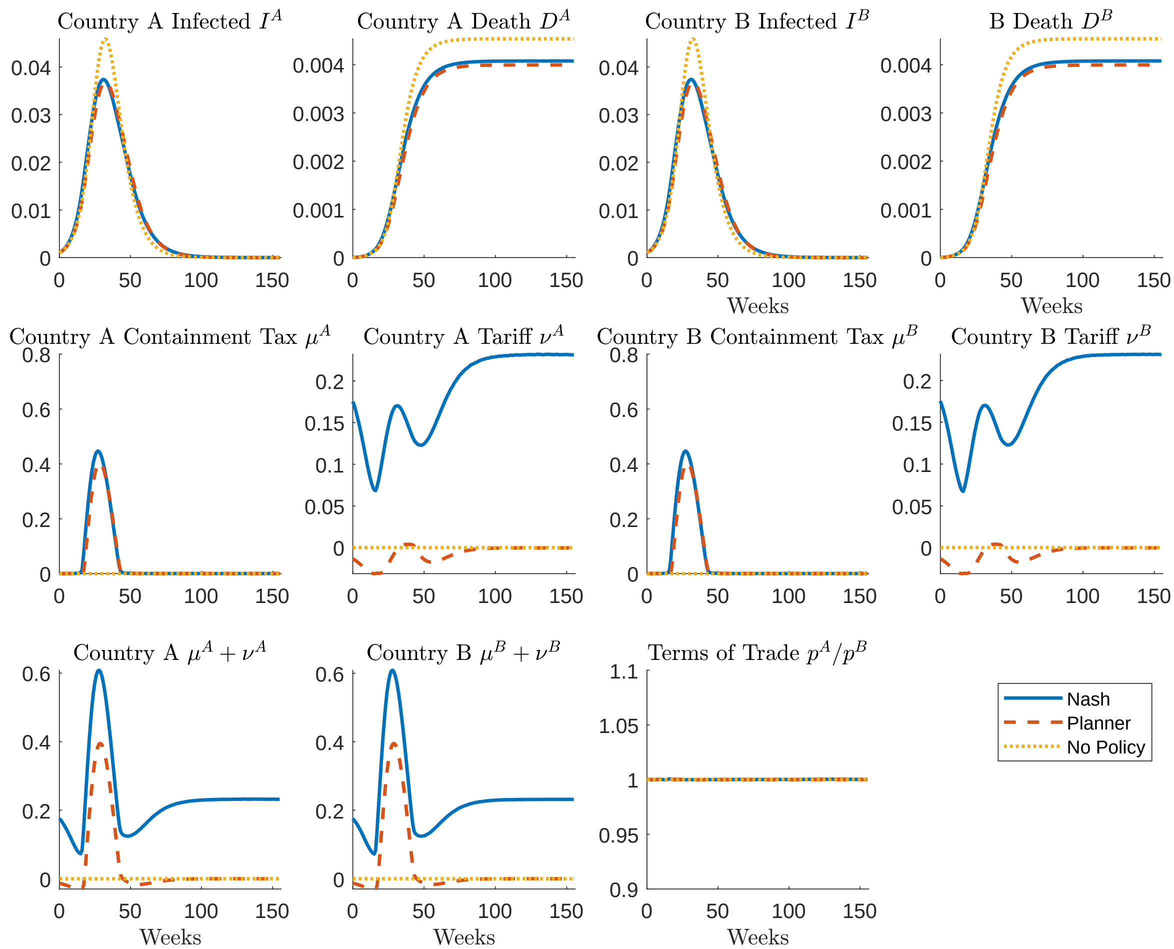
Note: Comparison of SIR dynamics, government policies, and economic outcomes in three cases: benchmark, Nash, and Planner. In the no policy case there are no domestic containment policies. In the Nash case, equilbirium domestic containment policies and tariffs are the outcome of a Nash game between the two countries. In the planner case, equilbirium domestic containment policies and tariffs are determined by a global social planner that maximizes the sum of both countries welfare.

Figure 7: Comparing Equilibrium Policies and Outcomes, No Tariff



Note: Comparison of SIR dynamics, government policies, and economic outcomes in three cases: benchmark, Nash, and Planner. We study the case in which no tariff can be imposed.

Figure 8: Comparing Equilibrium Policies and Outcomes, Synchronous Waves



Note: Comparison of SIR dynamics, government policies, and economic outcomes in three cases: benchmark, Nash, and Planner. We study the case in which the pandemic starts synchronously in the two countries.

Table 1: Parameter Choices

This table reports the values of calibrated parameters and our calibration targets. Our model is calibrated at the weekly frequency.

Symbol	Interpretation	Value	Calibration Target
β	discount factor	$0.96^{1/52}$	Value of life (Hall, Jones and Klenow, 2020)
p_d	probability of dying	$7 \times 0.5\%/18$	Fatality rate (Eichenbaum, Rebelo and Trabandt, 2021)
p_r	probability of recovering	$7 \times 1/18$	Recovery rate (Eichenbaum, Rebelo and Trabandt, 2021)
σ	Elasticity of substitution	6	CES Elasticity Costinot and Rodríguez-Clare (2014)
α	Home bias	0.53	Home consumption share (Costinot and Rodríguez-Clare, 2014)
κ	Labor disutility	0.13%	Bureau of Labor Statistics (Eichenbaum, Rebelo and Trabandt, 2021)
z	Productivity	39.84	Bureau of Labor Statistics (Eichenbaum, Rebelo and Trabandt, 2021)
ϕ	Productivity level of the infected	80%	Share of asymptomatic infected (Eichenbaum, Rebelo and Trabandt, 2021)
π_1	Consumption-based pandemic transmission	1.4×10^{-7}	Share of infection through consumption (Eichenbaum, Rebelo and Trabandt, 2021)
π_2	Labor-based pandemic transmission	1.2×10^{-4}	Share of infection through labor (Eichenbaum, Rebelo and Trabandt, 2021)
π_3	Unconditional pandemic transmission	0.39	Share of residual infection (Eichenbaum, Rebelo and Trabandt, 2021)
π_4	Interntional pandemic transmission	1.4×10^{-9}	6-month distance between wave peaks
δ_μ	Share of containment tax retained	0.5	Peak level of infections

Table 2: Welfare Decomposition

We report the welfare change relative to the steady-state level without pandemic and policy. We decompose the welfare change in each country into two components. The *economic* component is the present value of the utility change of living households due to changes in consumption and labor during the pandemic episode, and the *death* component is the present value of the foregone utility due to death.

Panel (a): With Pandemic						
	Country A			Country B		
	Total	Economic	Death	Total	Economic	Death
No Policy - No Pandemic	-33.62	-0.88	-32.74	-32.79	-0.87	-31.92
Nash - No Policy	-24.73	-28.10	3.37	-24.55	-27.51	2.96
Planner - No Policy	1.02	-3.25	4.27	1.27	-3.04	4.31
Planner - Nash	25.75	24.85	0.90	25.82	24.47	1.34

Panel (b): No Pandemic						
	Country A			Country B		
	Total	Economic	Death	Total	Economic	Death
Nash - No Policy	-25.23	-25.23	0.00	-25.23	-25.23	0.00
Planner - No Policy	0.00	0.00	0.00	0.00	0.00	0.00
Planner - Nash	25.23	25.23	0.00	25.23	25.23	0.00

Table 3: Health Dynamics

We report some statistics about infection and death rates in both countries.

Benchmark Case			
	No Policy	Nash	Planner
Week of infection peak A	33.00	32.00	33.00
Week of infection peak B	60.00	60.00	59.00
Level of peak infection A (per 1000 households)	45.72	37.51	35.64
Level of peak infection B (per 1000 households)	45.52	37.54	35.80
Last week of pandemic A (over 0.01% infected)	97.00	106.00	107.00
Last week of pandemic B (over 0.01% infected)	122.00	135.00	132.00
Overall deaths A (per 1000 households)	4.53	4.08	3.94
Overall deaths B (per 1000 households)	4.51	4.11	3.90

Table 4: Welfare Decomposition, No Tariff

We report the welfare change relative to the steady-state level without pandemic and policy. We decompose the welfare change in each country into two components. The *economic* component is the present value of the utility change of living households due to changes in consumption and labor during the pandemic episode, and the *death* component is the present value of the foregone utility due to death.

No Tariff						
	Country A			Country B		
	Total	Economic	Death	Total	Economic	Death
Nash - No Policy	0.91	-3.19	4.11	0.95	-3.11	4.05
Planner - No Policy	0.92	-2.99	3.91	0.95	-2.86	3.81
Planner - Nash	0.01	0.21	-0.20	0.00	0.25	-0.25

Table 5: Health Dynamics, No Tariff

We report some statistics about infection and death rates in both countries.

No Tariff			
	No Policy	Nash	Planner
Week of infection peak A	33.00	33.00	33.00
Week of infection peak B	60.00	60.00	60.00
Level of peak infection A (per 1000 households)	45.72	36.38	36.59
Level of peak infection B (per 1000 households)	45.52	36.17	36.59
Last week of pandemic A (over 0.01% infected)	97.00	106.00	106.00
Last week of pandemic B (over 0.01% infected)	122.00	132.00	131.00
Overall deaths A (per 1000 households)	4.53	3.96	3.99
Overall deaths B (per 1000 households)	4.51	3.94	3.97

Table 6: Welfare Decomposition, Synchronous Waves

We report the welfare change relative to the steady-state level without pandemic and policy. We decompose the welfare change in each country into two components. The *economic* component is the present value of the utility change of living households due to changes in consumption and labor during the pandemic episode, and the *death* component is the present value of the foregone utility due to death.

Synchronous Waves						
	Country A			Country B		
	Total	Economic	Death	Total	Economic	Death
Nash - No Policy	-25.70	-29.14	3.44	-25.70	-29.14	3.44
Planner - No Policy	0.98	-2.98	3.96	0.98	-2.98	3.96
Planner - Nash	26.68	26.16	0.52	26.68	26.16	0.52

Table 7: Health Dynamics, Synchronous Waves

We report some statistics about infection and death rates in both countries.

Synchronous Waves			
	No Policy	Nash	Planner
Week of infection peak A	33.00	32.00	33.00
Week of infection peak B	33.00	32.00	33.00
Level of peak infection A (per 1000 households)	45.90	37.39	36.83
Level of peak infection B (per 1000 households)	45.90	37.40	36.83
Last week of pandemic A (over 0.01% infected)	95.00	107.00	104.00
Last week of pandemic B (over 0.01% infected)	95.00	107.00	104.00
Overall deaths A (per 1000 households)	4.54	4.08	3.99
Overall deaths B (per 1000 households)	4.54	4.08	3.99

A Model Appendix (For Online Publication)

A.1 The Static Model

Without pandemics, the model boils down to an essentially static two-country macro model. This is because, in order to focus on the epidemiological dynamics, in (25) we have ruled out economic dynamics. As a benchmark we now provide the basic properties of this simple static model. This analysis is also useful because it directly applies to the choice problems of the infected and the recovered households in the full model, who structurally solve the same static decision problems. The only truly dynamic decisions are made by susceptible households, whose choices influence their future health status.

To simplify notation, we drop country superscripts and time subscripts for the static analysis of households of country k. Denote the wage by w.

The representative consumer of country k (who is not concerned with health) chooses per-period consumption and labor $(c_k, c_{-k}, \ell) \geq 0$ in order to

$$\max v(x) - \frac{1}{2}\kappa\ell^2$$

$$\text{subject to} \quad x = q(c_k, c_{-k}) \tag{A.1}$$

$$\widehat{p}_k c_k + \widehat{p}_{-k} c_{-k} = w\ell + g \tag{A.2}$$

where $\widehat{p}_j$ are consumer prices and g is the public transfer. Let λ denote the Lagrange multiplier of the budget constraint. Importantly, λ measures the pre-epidemic willingness to pay for utility, i.e. the “exchange rate between utils and dollars", which is needed to calibrate the model. As noted in Section 2, the solution is characterized by the following first-order constraints:

$$x^{-\rho}\frac{\partial x}{\partial c_k} = \lambda\widehat{p}_k \tag{A.3}$$

$$x^{-\rho}\frac{\partial x}{\partial c_{-k}} = \lambda\widehat{p}_{-k} \tag{A.4}$$

$$\kappa\ell = \lambda w \tag{A.5}$$

Dividing (A.3) by (A.4) yields

$$c_{-k} = \left(\frac{1-\alpha}{\alpha}\right)^{\sigma}\left(\frac{\widehat{p}_k}{\widehat{p}_{-k}}\right)^{\sigma} c_k \tag{A.6}$$

Hence, unsurprisingly, c_k and c_{-k} are linear functions of each other.

Inserting (A.6) into (A.1) yields

$$x = \psi^{\frac{\sigma}{\sigma-1}}\left(\alpha\widehat{p}_{-k}\right)^{-\sigma} c_k \tag{A.7}$$

where

$$\psi = \alpha^{\sigma}\widehat{p}_{-k}^{\sigma-1} + (1-\alpha)^{\sigma}\widehat{p}_{k}^{\sigma-1}$$

Inserting (A.7) into (A.3), using (A.5), yields

$$w\psi^{-\frac{\sigma\rho-1}{\sigma-1}}\left(\alpha\widehat{p}_{-k}\right)^{\sigma\rho}c_k^{-\rho} = \kappa\widehat{p}_k\widehat{p}_{-k}\ell \tag{A.8}$$

By straightforward calculations, the three equations (A.2), (A.6), and (A.8) yield the following solutions for the three unknowns (c_k, c_{-k}, ℓ). Labor ℓ is given by

$$\ell\left(w\ell + g\right)^{\rho} = \frac{w}{\kappa}\psi^{\frac{1-\rho}{\sigma-1}}\left(\widehat{p}_k\widehat{p}_{-k}\right)^{\rho-1} \tag{A.9}$$

home consumption c_k by

$$\psi\left(\widehat{p}_k\widehat{p}_{-k}\right)^2 c_k^{\rho+1} - \widehat{p}_k\widehat{p}_{-k}\left(\alpha\widehat{p}_{-k}\right)^{\sigma} g c_k^{\rho} = \frac{w^2}{\kappa}\psi^{-\frac{\sigma\rho-1}{\sigma-1}}\left(\alpha\widehat{p}_{-k}\right)^{\sigma(\rho+1)} \tag{A.10}$$

and foreign consumption by (A.6). It is easy to see that (A.9) and (A.10) each have a unique positive root. Hence, the household problem has a unique solution.

For the case $\rho = 1$, which we use in the numerical calibration, things are particular simple, as both equations are quadratic. In particular, we have

$$\ell = -\frac{g}{2w} + \frac{1}{2w}\sqrt{g^2 + \frac{4w^2}{\kappa}} \tag{A.11}$$

which yields the multiplier λ, the "price of utility", by (A.5), as $\lambda = \frac{\kappa}{w}\ell$.

Optimal domestic consumption is

$$c_k = \frac{g\left(\alpha\widehat{p}_{-k}\right)^{\sigma}}{2\psi\widehat{p}_k\widehat{p}_{-k}} + \frac{\left(\alpha\widehat{p}_{-k}\right)^{\sigma}}{2\psi\widehat{p}_k\widehat{p}_{-k}}\sqrt{g^2 + \frac{4w^2}{\kappa}} \tag{A.12}$$

and foreign consumption correspondingly.

The above analysis describes the demand side of each of the two economies in the absence of health concerns.

A.1.1 No-Pandemic Equilibria

We re-introduce country superscripts to describe market clearing in economies with no health concerns, be it pre-pandemic or after the arrival of a vaccine. The conditions are

$$w^k = p_k z^k \tag{A.13}$$

$$z^k\ell^k = c_k^k + c_k^{-k} \tag{A.14}$$

$k = A, B$, for labor market and product market clearing, respectively.

Social Planner Under a benevolent social planner, government policy in each country will be $(\mu^k, \nu^k) = (0, 0)$: levying taxes on domestic or foreign goods is welfare reducing. Hence, the government collects no taxes, and by the budget constraint (26) transfers are $g = 0$. Consumer prices are undistorted,

$$\widehat{p}_k^k = p_k, \widehat{p}_{-k}^k = p_{-k}$$

and the 4 equations (A.13) and (A.14) to are sufficient to determine the 4 prices w^k, p_k, $k = A, B$, by using the solutions of (A.9), (A.10), and (A.6) obtained above. Of course, prices are determined only up to one degree of freedom, and by Walras' Law one of the above equilibrium relations is redundant.

Nash In Nash Equilibrium, $\mu^k = 0$ in each country. Yet, tariffs can be positive, for the standard economic reasons of trade wars discussed more broadly in the main text. Hence, consumer prices are

$$\begin{aligned} \widehat{p}_k^k &= p_k \\ \widehat{p}_{-k}^k &= (1 + v^k) p_{-k} \end{aligned}$$

Public transfers are therefore endogenous even in the static setting,

$$g^k = \nu^k p_{-k} c_{-k}^k \tag{A.15}$$

Now, for given government policies (ν^A, ν^B), we have the 6 equations (A.13), (A.14), and (A.15) to determine the 6 endogenous variables w^k, p_k, g^k, $k = A, B$.

A.1.2 Demand by Infected or Recovered Households

As noted above, the demand of infected and of recovered households in the full model in Section 2 derives from an essentially static optimization problem. Hence, by letting $w = \phi \overline{w}_t^k$ for the infected households of country k at date t, the household optimization conditions of the full model yield the conditions (A.9), (A.10), and (A.6), appropriately indexed for the i households. Similarly, by letting $w = \overline{w}_t^k$ for the recovered households, the household optimization conditions of the full model lead to (A.9), (A.10), and (A.6), appropriately indexed for the r households.

A.2 Disease Transmission

This subsection provides a more detailed microfoundation for the disease transmission dynamics (10) in Section 1.2.

In the basic SIR model (without economic choices) transmission occurs according to

$$T_t = \eta S_t I_t \tag{A.16}$$

This has the following logic. Let N be size of a given population. Let $N = S + I + R$, where I is the number of infectious, and S that of susceptibles. Let φN be the rate of contacts of a single individual during which the disease can potentially be transmitted.[29] The assumption is that individuals spend a fixed proportion of their time (normalized to 1) outside the home, where they can transmit or contract the virus. Letting θ denote the probability that a contact leads to an infection, equation (A.16) can now be derived as follows.[30] One susceptible individual outside his home, per unit of time, on average has φN contacts. This leads to $\varphi N(I/N) = \varphi I$ contacts with infectious individuals. The probability of getting infected in these $k = \varphi I$ contacts is

$$\overline{\tau} = 1 - (1-\theta)^k = \theta \sum_{m=0}^{k-1} \binom{k}{m+1} (-\theta)^m \tag{A.17}$$

for $k > 0$, and the expected total number of transmissions per unit of time is $\overline{\tau} S$. $\overline{\tau}$ as a function of θ is a polynomial of degree k and strictly concave for $k > 1$. Hence, for small θ and large k, $\overline{\tau}$ is smaller than, but approximately equal to $k\theta$. In this case, letting $\eta = \theta\varphi$, the average rate of transmission is approximately equal to

$$\theta k S = \theta \varphi I S = \eta I S$$

as stated in (A.16).

A.2.1 The Macro-SIR Model

Eichenbaum et al. (2020) have incorporated economic activity into the above model, by distinguishing transmissions while consuming, at work, and during other activities outside the home. This model does not distinguish between foreign and domestic consumption goods.

To make that precise, dropping the time index for convenience, suppose that individuals spend a fixed fraction $f < 1$ of their time outside neither at work nor consuming. All durations are in terms of the unit of time chosen (which is scaled by φ).[31] To simplify, and different from Eichenbaum, Rebelo and Trabandt (2021); Brotherhood et al. (2020), we do not distinguish

[29] This is the so-called "mass incidence" model which is relevant for Covid-19 (differently from, say, HIV, as analyzed in Greenwood et al. (2019)): one infectious individual can infect a whole (sub-)group, no need for bilateral interaction.

[30] This is the perspective of susceptibles, which is most relevant for economic incentives. Usually, the derivation takes the perspective of infectious. See standard textbooks such as Brauer (2008).

[31] If this unit is a week and a day has 16 useful hours (e.g. McGrattan, Rogerson et al., 2004), then the individual has $112f$ hours of non-shopping leisure per week outside the home.

between utility from different types of leisure. Hence, individuals do not derive specific utility from leisure outside the home, and we therefore assume this fraction to be constant.[32] Suppose that individuals of health status h spend a fraction $\ell(h) < 1$ of their time at work, and a fraction $\gamma c(h) < 1$ consuming (shopping, dining, ...), the assumption being that the time spent on consumption is proportional to the quantity bought. We assume that $f + \ell(h) + \gamma c(h) < 1$, the remaining time being leisure alone at home.[33] Then, using the linear approximation of the infection probability $\overline{\tau}$, we have the following infection probabilities for susceptibles and aggregate average transmission rates:

1. During non-work-non-consumption time outside the home,
   - individual proba of becoming infected: $f^2\eta I$
   - expected total number of transmissions: $f^2\eta IS$
2. During work,
   - average rate of susceptible contacts with infected per unit of time: $\varphi\ell(i)I$
   - individual proba of becoming infected when working: $\ell(s)\eta\ell(i)I$
   - expected total number of transmissions at work: $\eta\ell(s)\ell(i)IS$
3. During consumption,
   - average rate of contacts with infected per unit of time: $\varphi\gamma c(i)I$
   - individual proba of becoming infected when consuming $c(s)$: $\gamma c(s)\eta\gamma c(i)I$
   - expected total number of transmissions from consumption: $\eta\gamma^2 c(s)c(i)IS$

Hence, an s individual faces the following transition probability to the infected state, if she chooses individual consumption $c(s)$ and labor supply $\ell(s)$:

$$\tau(c(s), \ell(s)) = f^2\eta I + \ell(s)\eta\ell(i)I + c(s)\eta\gamma^2 c(i)I \tag{A.18}$$

$$= \eta\left[\gamma^2 c(s)c(i) + \ell(s)\ell(i) + f\right] I \tag{A.19}$$

This yields the expected total number of transmissions from all activities, now with time indices:

$$T_t = \eta\left(\gamma^2 c_t(s)c_t(i) + \ell_t(s)\ell_t(i) + f\right) I_t S_t \tag{A.20}$$

A.2.2 International transmission

Again dropping the time index for convenience, suppose individuals of country k and health status h spend a fraction $\ell^k(h)$ of their time at work, a fraction $\gamma c_k^k(h)$ of their time consuming

[32] See Garibaldi, Moen and Pissarides (2020) for work that endogenizes f in a model of occupational choice, abstracting from the work-consumption choice considered here.

[33] We calibrate the parameter values such that the individual time constraints are satisfied in our simulations. Hence, we can ignore the time constraint in the household's optimization problem of (34).

the domestic good, a fraction $\gamma c_{-k}^k(h)$ consuming the foreign good, and a fraction f out of their home for other reasons. When “shopping", an individual is directly exposed to home residents and foreigners. Since the contact intensity for foreign and domestic consumption is likely to differ we assume that the consumer has a contact rate $\varphi^d\gamma(C_k^k + C_{-k}^k)$ with domestic residents and a contact rate $\varphi^f\gamma(C_k^{-k} + C_{-k}^{-k})$ with foreigners. In fact, when consuming the domestic good, an individual in country k meets foreign consumers who consume her domestic good, which leads to a number of contacts per unit of time of $\varphi^f\gamma C_k^{-k}$. And when consuming the foreign good, she meets foreign consumers who consume this good, i.e. their domestic good, which leads to a number of contacts per unit of time of $\varphi^f\gamma C_{-k}^{-k}$. Since the consumption of foreign goods is often intermediated by specialized import/export agents and thus likely to involve fewer direct contacts, we expect $\varphi^f < \varphi^d$.

We ignore international encounters at work and in non-work-non-consumption situations. Hence, the transmission dynamics is unchanged from the previous subsection as regards these two types of encounters. With respect to consumption related transmissions, a susceptible consuming the bundle $(c_k^k(s), c_{-k}^k(s))$ has an average rate of contacts with infected per unit of time of

$$\gamma\varphi^d(c_k^k(i) + c_{-k}^k(i))I^k + \gamma\varphi^f(c_k^{-k}(i) + c_{-k}^{-k}(i))I^{-k}$$

where $\gamma\varphi^d c_x^k(i)I^k$ are the contacts with domestic infected and $\gamma\varphi^f c_x^{-k}(i)I^{-k}$ those with foreign infected individuals.

Hence, her individual proba of becoming infected through consumption is approximately

$$c_k^k(s)\theta\gamma^2\left[\varphi^d c_k^k(i)I^k + \varphi^f c_k^{-k}(i)I^{-k}\right] + c_{-k}^k(s)\theta\gamma^2\left[\varphi^d c_{-k}^k(i)I^k + \varphi^f c_{-k}^{-k}(i)I^{-k}\right]$$

Adding the infection probabilities yields the formulas (9) and (10) in the main text. These transmission dynamics are the simplest possible generalization of those of the single good case (A.20). The new terms reflect the transmissions through consumption interactions in exports ($c_{kt}^{-k}(i)$) and imports ($c_{-kt}^k(i)$) and therefore also involve foreign consumption abroad, $c_{-kt}^{-k}(i)$. More complicated interaction models (interactions at work or between consumption and leisure) do not change the results significantly.

A.3 Computation Details

The numerical algorithm for solving our model proceeds in a number of steps. We first detail the solution to the model for fixed containment policies and then detail the solution for the optimal coordinated and uncoordinated policies.

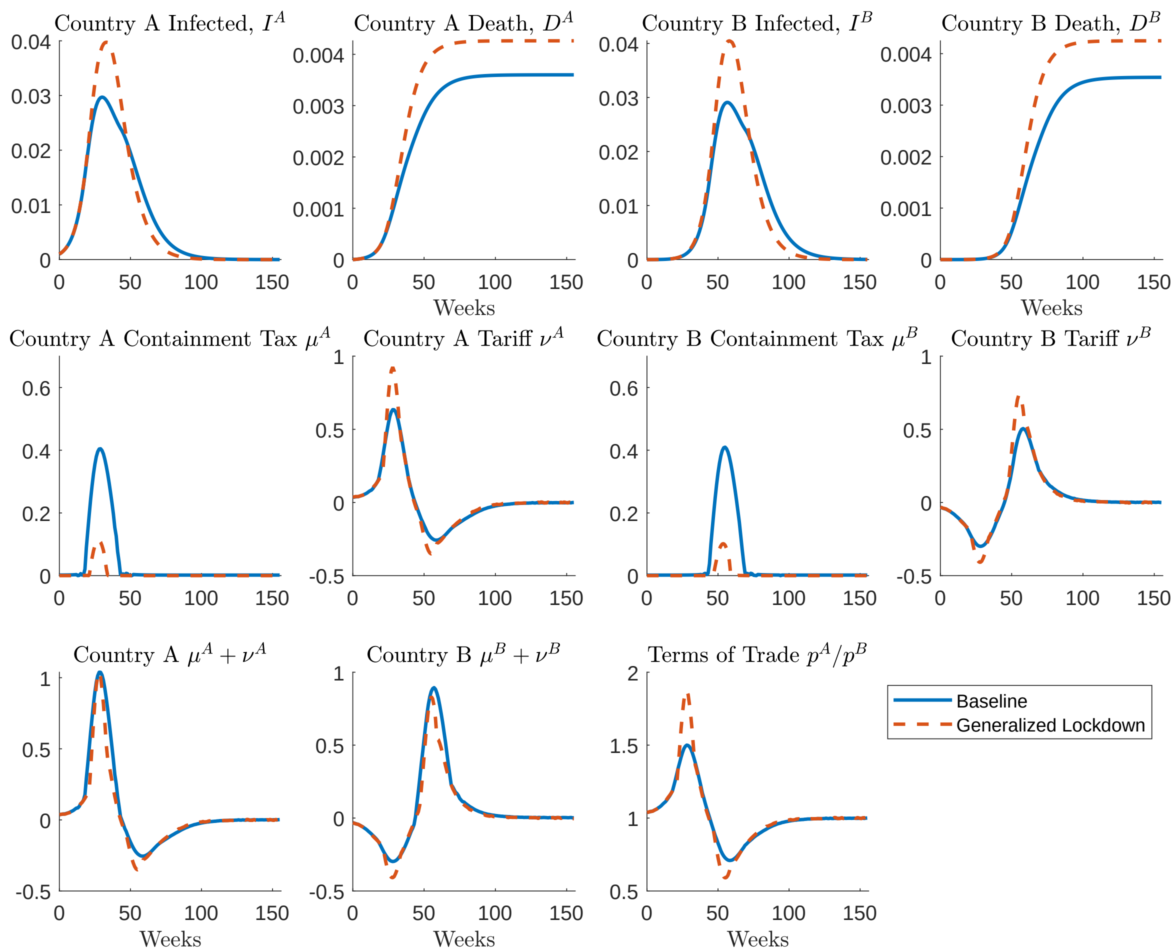
Solution for fixed policies. To solve the model for a fixed set of containment taxes, we begin with guesses for the susceptible households' labor and consumption choices in each country and period as well as the relative price of country B's good in each period. Note that we normalize country A prices to 1. Given these guesses, we calculate the implied government tax as well as the labor and consumption of all other household types. We then iterate forward on the SIR equations until the final period of the model, at which point consumption and labor return to their steady state values due to the vaccine's arrival. Next, we iterate backward to derive the present value of lifetime utility for each agent. We then use gradient-based methods to adjust our initial guesses until the susceptible agents' first-order conditions, market clearing conditions, and government budget constraints hold. In this way, we confirm all equilibrium conditions are satisfied.

Social planner solution. To solve for optimal containment policies from the perspective of a social planner, we nest the solution for fixed policies within another gradient-based optimizer. In this outer loop, we solve for containment policies and tariffs which maximize the present value of total time-0 utility, equally weighted across both countries.

Nash equilibrium solution. To solve for the Nash Equilibrium containment policies we begin with a guess for containment policies and tariffs across both countries. Given a fixed policy for a given country, we use a gradient-based optimizer to find the optimal policy response of the other country that maximizes the welfare of its own households. We then take this policy as fixed and find the optimal policy response of the other country. We iterate on this procedure until both countries' policies are the best responses to each other. We experiment with many different starting values but do not find any differences in the final result, which makes us believe that the identified Nash equilibrium is unique.

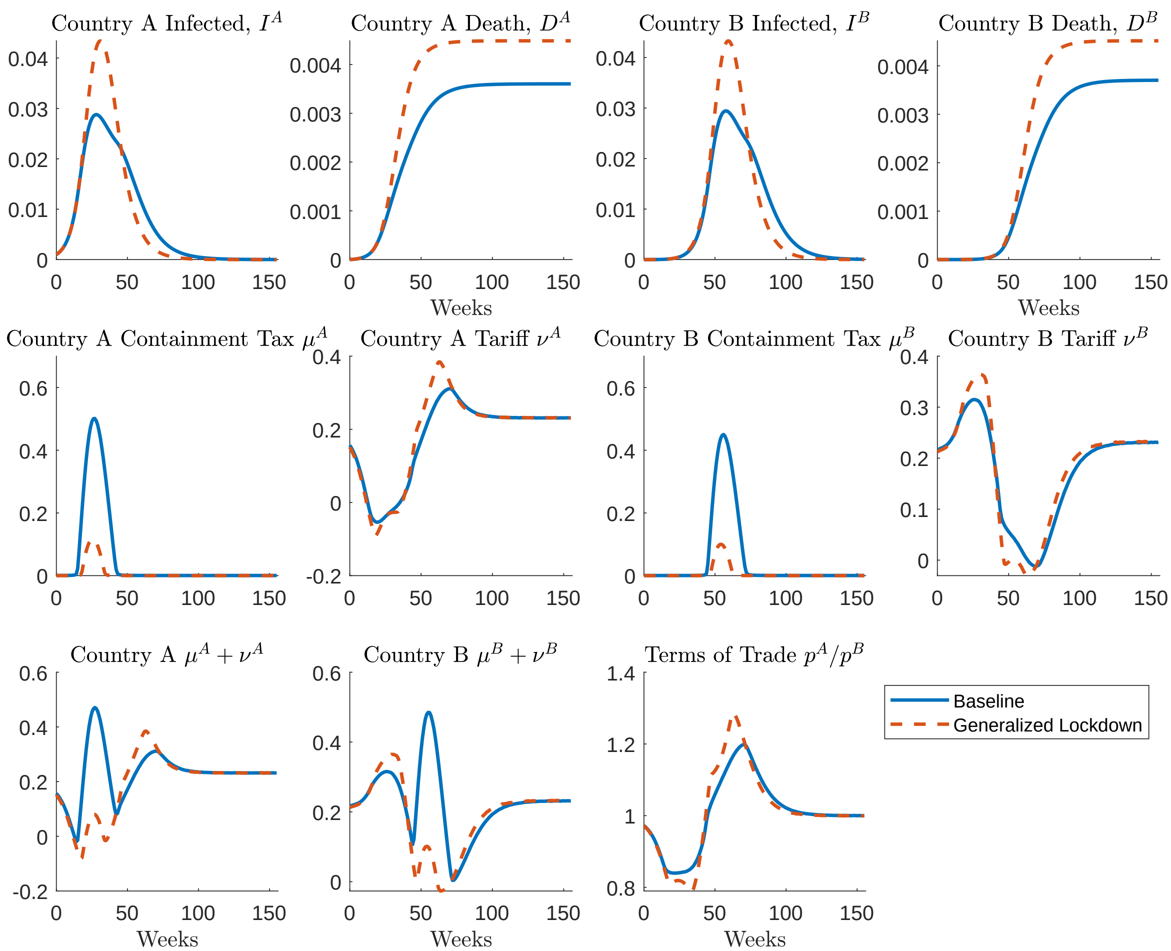
B Result Appendix (For Online Publication)

Figure B.1: Production Supression, Coordinated Planning Equilibrium



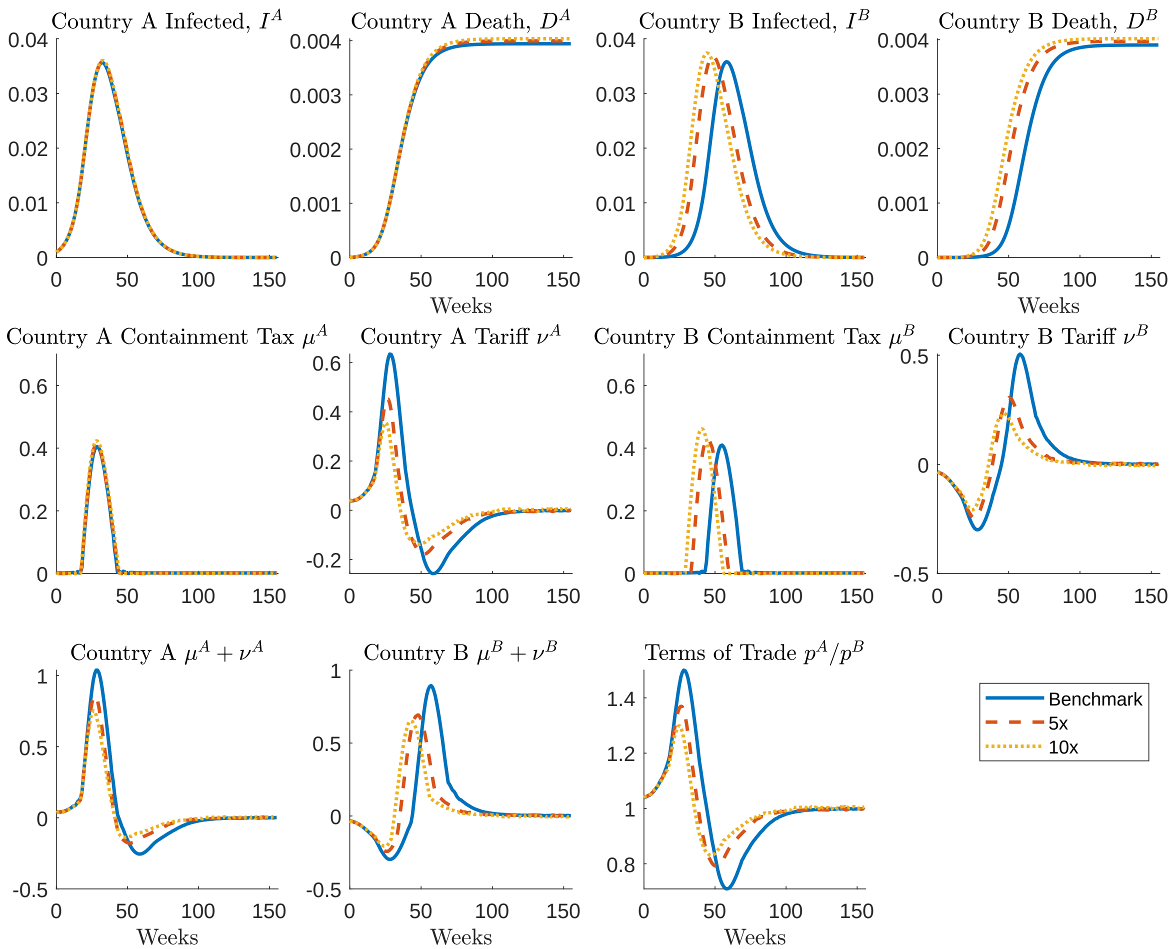
Note: Comparison of SIR dynamics, government policies, and economic outcomes in coordinated planning equilibria. In this variation, we allow the government containment policy to affect local productivity level.

Figure B.2: Production Supression, Nash Equilibrium



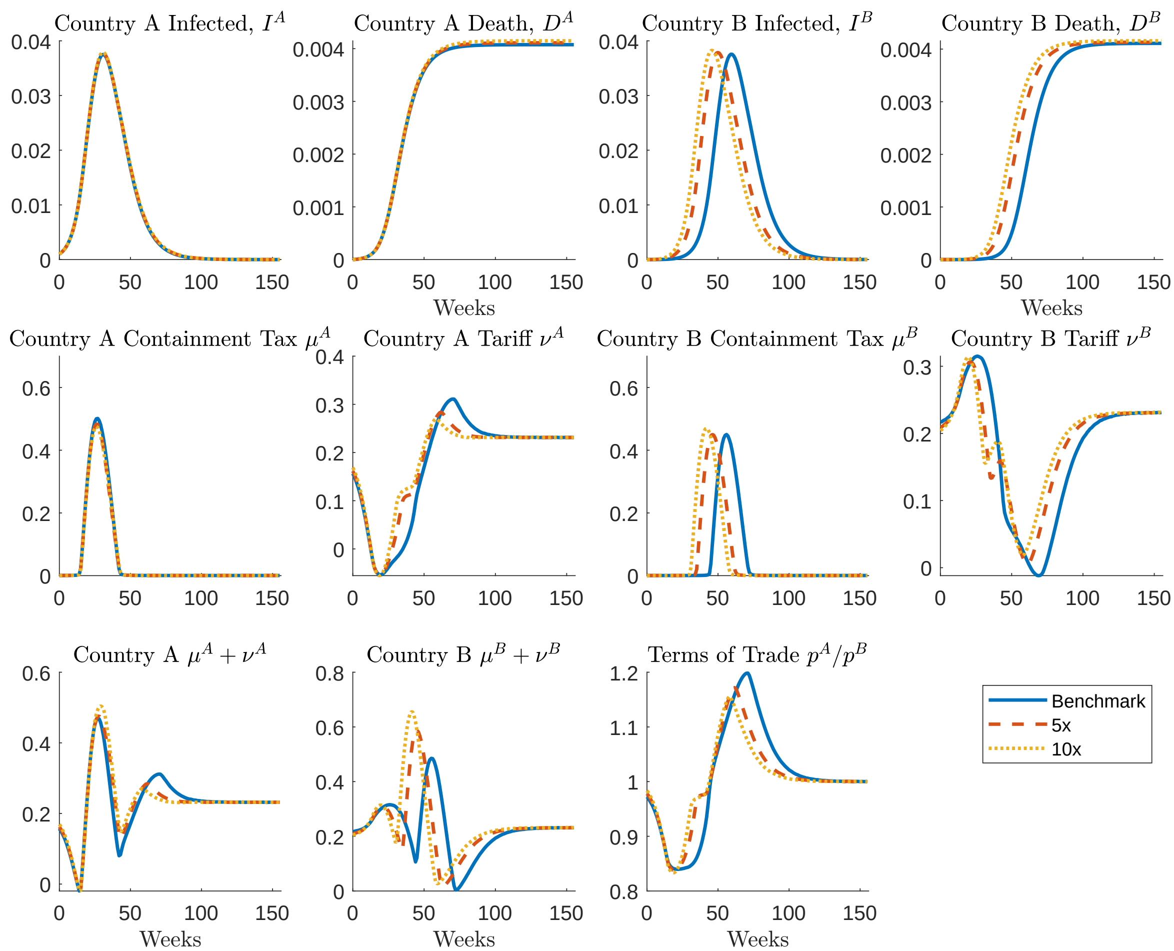
Note: Comparison of SIR dynamics, government policies, and economic outcomes in Nash equilibria. In this variation, we allow the government containment policy to affect local productivity level.

Figure B.3: Varying International Transmission π_4, Coordinated Planning Equilibrium



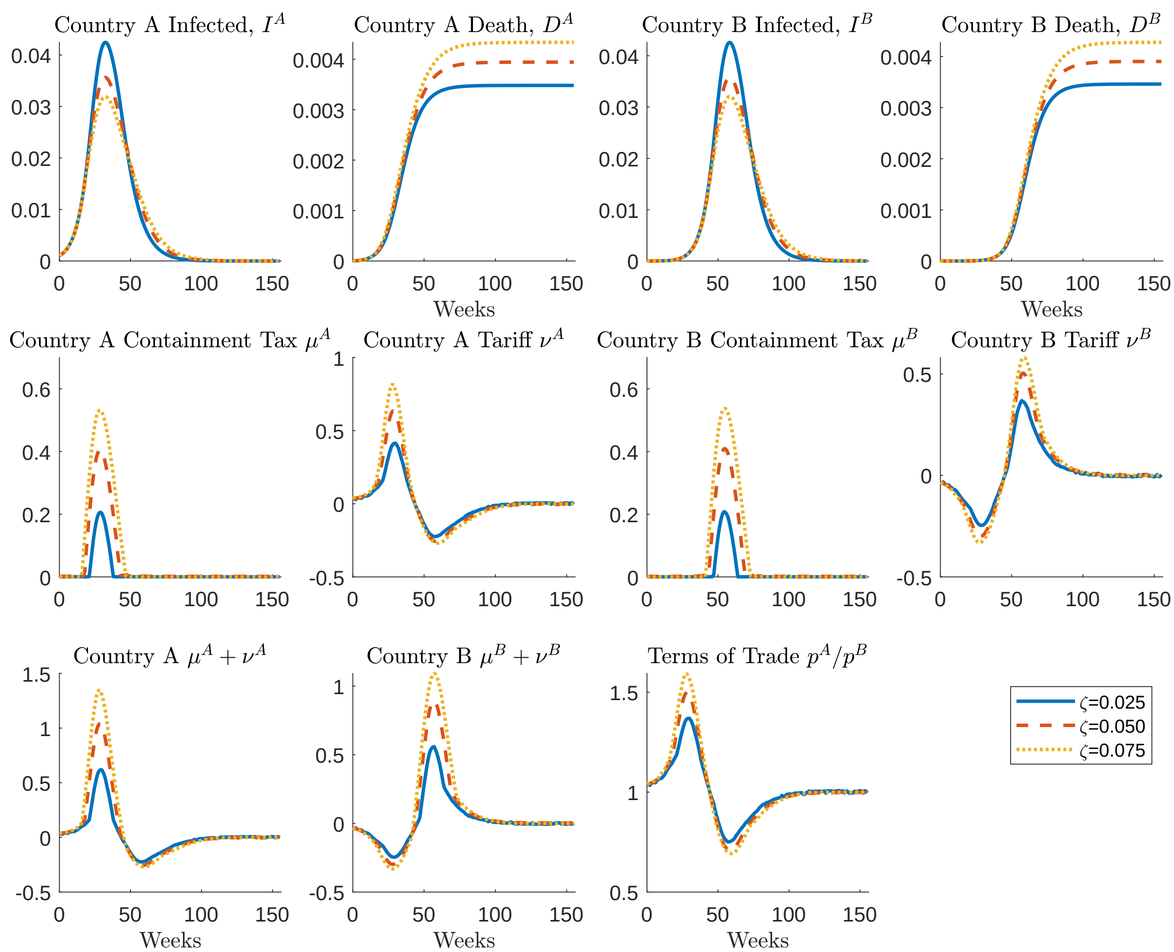
Note: Comparison of SIR dynamics, government policies, and economic outcomes in coordinated planning equilibria. We vary the parameter π_4 that governs the intensity of international transmission of disease.

Figure B.4: Varying International Transmission π_4, Nash Equilibrium



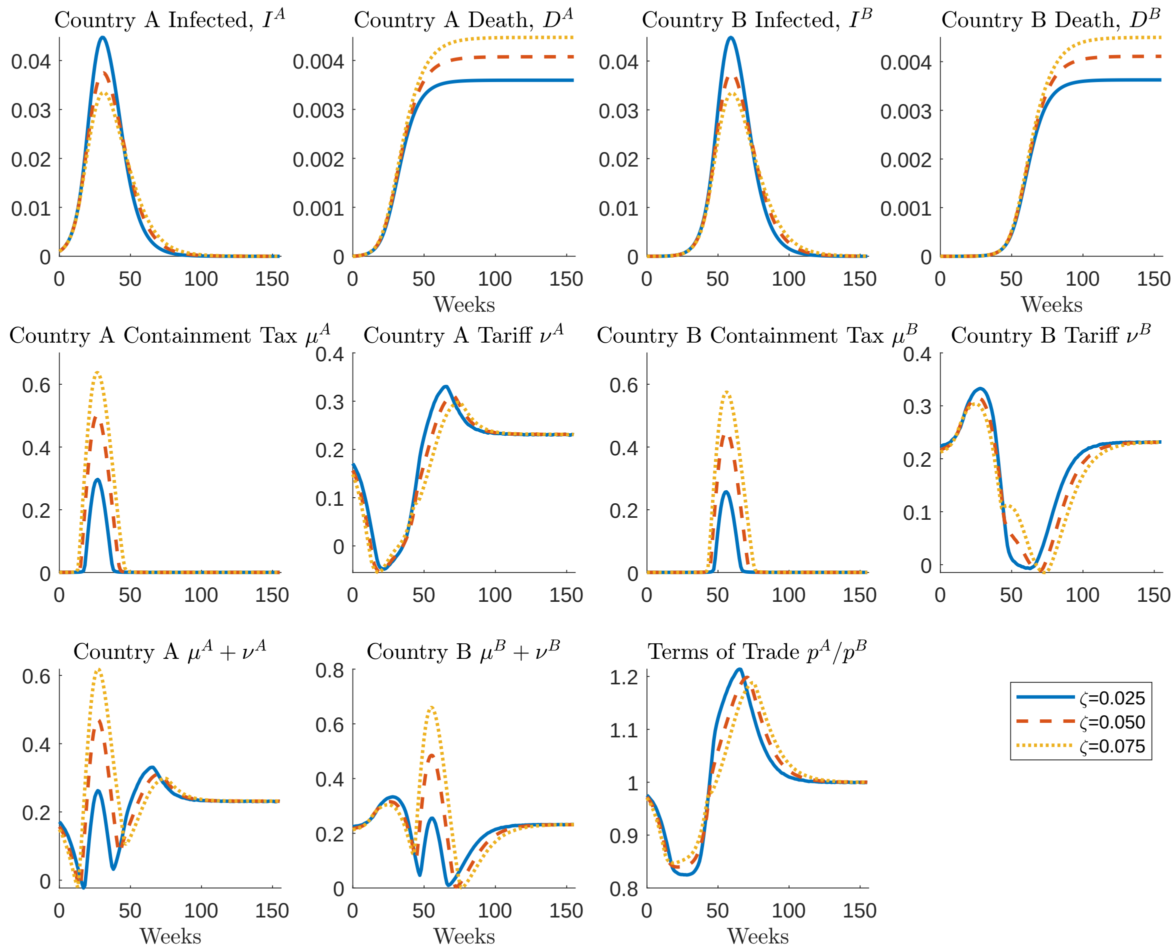
Note: Comparison of SIR dynamics, government policies, and economic outcomes in Nash equilibria. We vary the parameter π_4 that governs the intensity of international transmission of disease.

Figure B.5: Varying Congestion Rate ζ, Coordinated Planning Equilibrium



Note: Comparison of SIR dynamics, government policies, and economic outcomes in coordinated planning equilibria. We vary the parameter ζ that governs the increase in death rate due to congestion in hospital. The benchmark is $\zeta = 0.050$.

Figure B.6: Varying Congestion Rate ζ, Nash Equilibrium



Note: Comparison of SIR dynamics, government policies, and economic outcomes in Nash equilibria. We vary the parameter ζ that governs the increase in death rate due to congestion in hospital. The benchmark is $\zeta = 0.050$.

Table B.1: Welfare Decomposition, Generalized Lockdown

We report the welfare change relative to the steady-state level without pandemic and policy. We decompose the welfare change in each country into two components. The *economic* component is the present value of the utility change of living households due to changes in consumption and labor during the pandemic episode, and the *death* component is the present value of the foregone utility due to death.

Generalized Lockdown						
	Country A			Country B		
	Total	Economic	Death	Total	Economic	Death
Nash - No Policy	-25.86	-26.23	0.37	-25.69	-25.75	0.06
Planner - No Policy	0.37	-1.56	1.93	0.68	-1.13	1.81
Planner - Nash	26.23	24.67	1.57	26.37	24.62	1.76

Table B.2: Health Dynamics, Generalized Lockdown

We report some statistics about infection and death rates in both countries.

Generalized Lockdown			
	No Policy	Nash	Planner
Week of infection peak A	33.00	32.00	34.00
Week of infection peak B	60.00	60.00	59.00
Level of peak infection A (per 1000 households)	45.72	43.42	39.74
Level of peak infection B (per 1000 households)	45.52	43.31	40.48
Last week of pandemic A (over 0.01% infected)	97.00	98.00	101.00
Last week of pandemic B (over 0.01% infected)	122.00	127.00	125.00
Overall deaths A (per 1000 households)	4.53	4.49	4.26
Overall deaths B (per 1000 households)	4.51	4.52	4.25

Table B.3: Health Dynamics, Varying International Transmission π_4

We report some statistics about infection and death rates in both countries.

Panel (a): 1 times π_4, Baseline			
	No Policy	Nash	Planner
Week of infection peak A	33.00	32.00	33.00
Week of infection peak B	60.00	60.00	59.00
Level of peak infection A (per 1000 households)	45.72	37.51	35.64
Level of peak infection B (per 1000 households)	45.52	37.54	35.80
Last week of pandemic A (over 0.01% infected)	97.00	106.00	107.00
Last week of pandemic B (over 0.01% infected)	122.00	135.00	132.00
Overall deaths A (per 1000 households)	4.53	4.08	3.94
Overall deaths B (per 1000 households)	4.51	4.11	3.90
Panel (b): 5 times π_4			
	No Policy	Nash	Planner
Week of infection peak A	33.00	32.00	33.00
Week of infection peak B	50.00	51.00	50.00
Level of peak infection A (per 1000 households)	45.86	37.71	35.77
Level of peak infection B (per 1000 households)	46.83	37.87	36.78
Last week of pandemic A (over 0.01% infected)	97.00	108.00	107.00
Last week of pandemic B (over 0.01% infected)	111.00	125.00	122.00
Overall deaths A (per 1000 households)	4.57	4.11	4.00
Overall deaths B (per 1000 households)	4.59	4.13	3.97
Panel (c): 10 times π_4			
	No Policy	Nash	Planner
Week of infection peak A	33.00	32.00	34.00
Week of infection peak B	45.00	47.00	45.00
Level of peak infection A (per 1000 households)	46.20	37.90	36.03
Level of peak infection B (per 1000 households)	48.32	38.25	37.37
Last week of pandemic A (over 0.01% infected)	97.00	108.00	108.00
Last week of pandemic B (over 0.01% infected)	106.00	121.00	117.00
Overall deaths A (per 1000 households)	4.63	4.15	4.04
Overall deaths B (per 1000 households)	4.69	4.16	4.02

Table B.4: Welfare Decomposition, Varying International Transmission π_4

We report the welfare change relative to the steady-state level without pandemic and policy. We decompose the welfare change in each country into two components. The *economic* component is the present value of the utility change of living households due to changes in consumption and labor during the pandemic episode, and the *death* component is the present value of the foregone utility due to death.

Panel (a): 1 times π_4, Baseline						
	Country A			Country B		
	Total	Economic	Death	Total	Economic	Death
Nash - No Policy	-24.73	-28.10	3.37	-24.55	-27.51	2.96
Planner - No Policy	1.02	-3.25	4.27	1.27	-3.04	4.31
Planner - Nash	25.75	24.85	0.90	25.82	24.47	1.34
Panel (b): 5 times π_4						
	Country A			Country B		
	Total	Economic	Death	Total	Economic	Death
Nash - No Policy	-24.63	-28.05	3.42	-24.10	-27.58	3.48
Planner - No Policy	0.96	-3.23	4.20	1.30	-3.19	4.49
Planner - Nash	25.60	24.82	0.78	25.40	24.39	1.01
Panel (c): 10 times π_4						
	Country A			Country B		
	Total	Economic	Death	Total	Economic	Death
Nash - No Policy	-24.59	-28.18	3.59	-23.75	-27.75	4.00
Planner - No Policy	1.14	-3.21	4.36	1.41	-3.47	4.88
Planner - Nash	25.73	24.97	0.76	25.15	24.28	0.88

Table B.5: Health Dynamics, Varying Congestion Intensity ζ

We report some statistics about infection and death rates in both countries.

Panel (a): $\zeta = 0.025$, Low Congestion			
	No Policy	Nash	Planner
Week of infection peak A	34.00	31.00	33.00
Week of infection peak B	60.00	60.00	59.00
Level of peak infection A (per 1000 households)	48.50	44.74	42.45
Level of peak infection B (per 1000 households)	48.34	44.84	42.61
Last week of pandemic A (over 0.01% infected)	94.00	97.00	99.00
Last week of pandemic B (over 0.01% infected)	119.00	125.00	123.00
Overall deaths A (per 1000 households)	3.68	3.60	3.48
Overall deaths B (per 1000 households)	3.67	3.63	3.46
Panel (b): $\zeta = 0.050$, Baseline			
	No Policy	Nash	Planner
Week of infection peak A	33.00	32.00	33.00
Week of infection peak B	60.00	60.00	59.00
Level of peak infection A (per 1000 households)	45.72	37.51	35.64
Level of peak infection B (per 1000 households)	45.52	37.54	35.80
Last week of pandemic A (over 0.01% infected)	97.00	106.00	107.00
Last week of pandemic B (over 0.01% infected)	122.00	135.00	132.00
Overall deaths A (per 1000 households)	4.53	4.08	3.94
Overall deaths B (per 1000 households)	4.51	4.11	3.90
Panel (c): $\zeta = 0.075$, High Congestion			
	No Policy	Nash	Planner
Week of infection peak A	33.00	32.00	33.00
Week of infection peak B	60.00	61.00	59.00
Level of peak infection A (per 1000 households)	43.46	33.49	31.89
Level of peak infection B (per 1000 households)	43.23	33.47	32.08
Last week of pandemic A (over 0.01% infected)	99.00	114.00	114.00
Last week of pandemic B (over 0.01% infected)	124.00	143.00	139.00
Overall deaths A (per 1000 households)	5.27	4.47	4.33
Overall deaths B (per 1000 households)	5.24	4.50	4.28

Table B.6: Welfare Decomposition, Varying Congestion Intensity ζ

We report the welfare change relative to the steady-state level without pandemic and policy. We decompose the welfare change in each country into two components. The *economic* component is the present value of the utility change of living households due to changes in consumption and labor during the pandemic episode, and the *death* component is the present value of the foregone utility due to death.

Panel (a): $\zeta = 0.025$, Low Congestion						
	Country A			Country B		
	Total	Economic	Death	Total	Economic	Death
Nash - No Policy	-25.50	-26.17	0.68	-25.33	-25.73	0.40
Planner - No Policy	0.28	-1.18	1.46	0.38	-1.09	1.47
Planner - Nash	25.78	24.99	0.79	25.71	24.64	1.07
Panel (b): $\zeta = 0.050$, Baseline						
	Country A			Country B		
	Total	Economic	Death	Total	Economic	Death
	total	economy	death	total	economy	death
Nash - No Policy	-24.73	-28.10	3.37	-24.55	-27.51	2.96
Planner - No Policy	1.02	-3.25	4.27	1.27	-3.04	4.31
Planner - Nash	25.75	24.85	0.90	25.82	24.47	1.34
Panel (c): $\zeta = 0.075$, High Congestion						
	Country A			Country B		
	Total	Economic	Death	Total	Economic	Death
Nash - No Policy	-23.78	-29.66	5.88	-23.57	-28.99	5.43
Planner - No Policy	2.24	-4.56	6.80	2.32	-4.55	6.87
Planner - Nash	26.02	25.10	0.92	25.88	24.44	1.44