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

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

First Version: November 2020
This version: December 2021

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 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 of tariff wars during a pandemic, featuring lower levels of consumption and production, as well as smaller gains via diversification of infection curves across economies. Gains from international coordination decline with the intensity of international transmission but increase in productivity-dampening effects of containment policies and congestion effects in pandemic-induced mortality.

Keywords: International Trade, Tariffs, Terms of Trade, SIR Model, COVID-19, Coronavirus, Containment Policies, Lockdown

*We thank Harald Fadinger, George Mailath, Volker Nocke, Raghu Sundaram, Michèle Tertilt, and Mathias Trabandt for comments. Steven Zheng and Cody Wan provided excellent research assistance. Von Thadden thanks the German Science Foundation for support through grant CRC TR 224, C03.

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

‡Kellogg School of Management, Northwestern University. 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.

1 Introduction

The Covid-19 pandemic has been truly international, spreading globally through health and economic linkages between countries and regions. Given that the policy response to the pandemic of 2020 has been mostly along national lines, the role and the value of international coordination in combatting 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 outbreak of a pandemic in one country can be transmitted to other countries by trade, and illustrates how national containment measures and trade (tariff) policies impact the spread of the pandemic in other countries.

By way of motivation, consider the stylized facts for China and the United States presented in Figure 1 for the period December 2019 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 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. Significant from an international trade perspective is the observation that the terms of trade deteriorated for the country experiencing the pandemic, with the price of US exports to China sharply deteriorating relative to the price of imports around the peak of the first wave in the US.

Is this outcome – wherein the terms of trade deteriorate for the country experiencing the pandemic – consistent with optimal health and policy decisions of national governments? What is the role of demand and supply effects in the observed changes? How do health and tariff policies affect each other, and in turn, the attendant health and trade outcomes, during a pandemic? What would the outcomes be if national governments were to coordinate their health and tariff policies? To answer these important questions, we provide a theoretical framework by introducing into a model of international trade SIR-dynamics along the lines of Kermack and McKendrick (1932) for international disease transmission. 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 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.

It has been widely noted in the recent economic literature (Eichenbaum, Rebelo and Trabandt, 2020; Brotherhood et al., 2020, and others) that if a pandemic hits an economy, local consumption and production create health externalities among its individuals, therefore justifying domestic containment policies. One of our model's key insights is that, if the pandemic peaks asynchronously in different countries, then cross-border externalities arise; 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 sustain their consumption without aggravating the unavoidable health externalities from consumption and production. In particular, a globally efficient trade policy softens the economic impact on an infected country by boosting the foreign consumption of its goods and 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 experiences a pandemic outbreak.

However, if the countries address their pandemic and trade issues in a non-cooperative manner, the resulting trade war leads to both lower economic welfare, and importantly, also worse health consequences. Specifically, non-cooperation produces a misguided intertemporal pattern of import tariffs, which exacerbates negative externalities, both on the health and on the economic front. What is crucial to understanding the economic and health losses from international non-coordination is the interplay between domestic containment policies and international frictions relating to distortionary tariffs. A globally efficient trade policy makes it possible to use national containment policies more efficiently compared to Nash equilibrium behavior.

Our dynamic two-country model with SIR dynamics has three key ingredients. First, households in each country have preferences for the consumption of goods produced in both countries. Second, consumption of goods, both foreign and domestic, leads to disease transmission. SIR dynamics are derived from a micro-founded model of international transmission through consumption. Third, in order to manage the pandemic, countries can implement policy instruments for domestic containment and international tariffs. Policies can be uncoordinated or coordinated. Uncoordinated international activity takes the form of an infinite-horizon Nash equilibrium game between governments choosing their policies driven by national mandates, while coordinated policies are those chosen by a utilitarian global social planner.

The pandemic induces households to endogenously adjust their consumption and labor provision in order to reduce the probability of getting infected. Hence, unlike agents in classic (mechanical) epidemiological models, households understand that they are in a pandemic and react rationally. However, households do not internalize health externalities on other agents. Our model features what are likely the two most important such externalities (see, e.g., Garibaldi, Moen and Pissarides (2020) for a fuller discussion) and extends them to the international context. First, self-interested infected individuals ignore the health impact of their activity on others. Second, even healthy individuals can pose a risk to others as they risk getting infected and thus posing a risk to others in the future, but ignore this dynamic externality on other not yet infected individuals.

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 as in Eichenbaum, Rebelo and Trabandt (2020)). This policy contains the spread of the pandemic, as it further discourages households from consuming goods and internalizes the health externalities. Both uncoordinated governments and optimal coordination reduce the amount of infection during the pandemic, at the expense of substantially lower consumption and production in both countries. As a result, the levels of consumption and production in each country largely track the evolution of infected cases in each country, due to both the government's containment policies and the households' endogenous responses.

In addition to the domestic containment policies, governments can levy import tariffs as a second instrument for addressing the international dimension of the problem. Even in the absence of a pandemic, our model features a trade war. As in the literature on international trade wars and negotiations (Brander and Spencer (1985), Bagwell and Staiger (1999) or Ossa (2014)), when countries take uncoordinated Nash policy decisions, they impose import tariffs that are too high relative to the coordinated social planner case. Such tariffs lead to poor consumption levels and choices between domestic and foreign goods, resulting in a significant loss of welfare. The pandemic fundamentally alters the temporal structure of tariffs, inducing variation that is linked to the *relative* state of the pandemic in the two countries. Our model predicts novel tariff patterns, resulting in important welfare consequences, depending on whether they are coordinated or uncoordinated.

Consider the uncoordinated (Nash) case first. Our model features pandemic waves that peak asynchronously in the two countries. When the pandemic hits the first country, it seeks to limit transmission 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 the first country incentivizes imports from this country and leads to an increase in the risk of infection to the foreign country. In response, the foreign country *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 below the case without a pandemic, 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.

Figure 2 illustrates this key insight about equilibrium terms of trade in our model. The solid blue curve displays the terms of trade with uncoordinated policies. The dashed vertical lines signify the peak of the panedemic in each country (by assumption, country A peaks first, then country B). The terms of trade from the perspective of country A are at their worst exactly when the pandemic peaks in that country. These dynamics of terms of trade lead to a substantial loss of risk-sharing, which manifests itself in the form of a high domestic consumption bias in the infected country and an insufficient shift of production across countries. As the pandemic recedes and peaks in the foreign country, their roles are reversed in this loss of risk-sharing.

Consider now the case where the two countries coordinate on a jointly optimal outcome. The pandemic leads to a modulation of the structure of tariffs in this case, too (dashed red curve in Figure 2), 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 seems strange because it encourages both countries to consume more goods produced by the more infected country and therefore raise the likelihood of infection. However, terms of trade are now skewed in favor of the infected country's goods to ameliorate its economic situation. In particular, the terms of trade dynamics in the coordinated case are exactly the opposite of those in the uncoordinated equilibrium. This leads to better economic risk-sharing and manifests itself in the form of more efficient home bias in each country, in particular, a home bias far lower than in the uncoordinated case.[1] Such economic risk-sharing allows the infected country to impose a stricter domestic containment measures while sustaining economic welfare.

This analysis implies that the intertemporal economic risk-sharing under coordinated policies also leads to a sharing of health risk. In particular, the foreign country imports a part of the infections by facilitating trade with the infected country. This encourages the infected country to shift consumption towards foreign goods and therefore prevents its domestic infection rates from rising more strongly. In turn, this risk-sharing then benefits the foreign country at the peak of its own infection. 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 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

[1] 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.

coordinated policies.[2]

We consider three important variations of our benchmark analysis, which also serve as useful robustness checks for our simulations. First, we allow containment policies to have a direct dampening effect on domestic economy productivity (not just affecting infected but all workers, as has probably been the case in the generalized lockdowns of 2020). Second, we vary the intensity of international transmission to reflect heterogeneity in the nature of trade between different countries: some countries specialize in more contact-intensive trade, for example, in travel and tourism services, whereas others trade predominantly in merchandise goods and information technology services which are less contact-intensive. Third, to capture the variation across countries in the development of their healthcare infrastructure, we vary the dependence of pandemic-induced mortality on the domestic infection rate; an increase in such dependence proxies for greater congestion effects due to limited availability of medical equipment, oxygen supply, and hospital or intensive-care unit (ICU) beds. We show that the gains from international coordination decline with the intensity of international transmission, but increase in direct productivity-dampening effects of containment policies and health care congestion in pandemic-induced mortality.

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 can help to explain why, in the real-world scenario of 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"

[2]In Section 5.5, we show that this crucially depends on the availability of multiple policy instruments, by restricting our model to only one policy instrument per country, viz., their domestic containment policies. In the restricted model, Nash equilibrium outcomes are, of course, overall inferior to the coordinated outcome, but can result in fewer infections and deaths. In fact, the lack of coordination in Nash Equilibrium leads to excessive domestic containment, because an instrument to address the positive international health externality is missing. With the additional instrument of import tariffs or subsidies, governments can relax domestic containment measures and thus share health losses more efficiently.

[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.

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 (2020) embed SIR disease dynamics into a macroeconomic model and study the tradeoffs resulting from simple suppression policies. Alvarez, Argente and Lippi (2021) is another early paper studying the optimal lockdown policy in a single country as a planning problem in a macroeconomic disease model. Foundational work on the health externalities arising from Covid-19 is, among others, 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 studies multiple countries and international trade in multiple goods, with associated domestic and trade policies to manage the pandemic. It thus 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 and 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 disaggregate data from various locations, providing also an overview of the international evolution of the disease on their website. In a similar vein, McKibbin and Roshen (2020) and Liu, Moon and Schorfheide (2021) estimate a DSGE model and a Bayesian panel VAR, respectively in order to make global forecasts of different health-economics scenarios.

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

[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.

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, they 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. 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.[6]

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 which are present in these standard models of trade wars, while highlighting the novel interaction between trade wars, health outcomes, and international coordination of policies.[7]

2 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 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 dissipative taxes on total consumption and separately tariffs or subsidies on international consumption.

[6] In related 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. 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.

[7] In addition to the large literature on trade wars, our paper therefore 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 on 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.

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.

2.1 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.[8]

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

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

the composite consumption basket. We assume for computational simplicity that the utility of consumption is of the constant-relative-risk-aversion type:

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

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 by

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

that of the foreign good ("imports"). Hence, the exports of country k are M_t^{-k}.

2.2 The Disease

Like Eichenbaum, Rebelo and Trabandt (2020), Brotherhood et al. (2020) and other recent economic contributions, we augment the classic SIR model by economic activity. Different from these contributions, we do not only include 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 Trabandt (2020) generalize this to transmission through consumption and work activities in a single country by splitting the individual transmission rate ηS_t into three components to obtain

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

[8] 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.

where $c_t(h)$ and $\ell_t(h)$ are consumption and labor, respectively, by the representative consumers.

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.[9] 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 consumer 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

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

[9] 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. Later, we model policy as influencing t_c.

from foreigners.[10]

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 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.[11] 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 $k = A, B$.

[10]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 6.2, 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.

[11]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.

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.[12] 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 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.

We denote the current state of the disease by

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

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.

2.3 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 (2020) and assume that

[12] 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).

these measures act like ad valorem "containment taxes" $\mu^k = \mu_t^k \geq 0$. This means that 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. The μ^k are material or immaterial and mostly deadweight costs of consumption. Let δ_μ^k be the exogenous fraction of these costs actually received by the government. 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.[13] The fraction δ_μ^k is collected as revenue by the government.

As witnessed in the lockdowns of 2020, the government's domestic containment measures can also affect productivity. In a model extension in Section 6.1 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. We consider explicit 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 produces 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"

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

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

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 (2020), 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

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

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

[13]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.

household profit of the corporate sector in the country. 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.

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. 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, tariffs manipulate the terms of trade in favor of domestic goods and thus higher domestic labor income. Third, high 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.[14] 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

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

[14] 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 equilibria reported in Section 5 below.

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 are each optimal responses to each 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:

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

3 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.

3.1 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

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

wages are

$$\begin{aligned} w_t(h) &= \begin{cases} \overline{w}_t & \text{for } h = s, r \\ \phi \overline{w}_t & \text{for } h = i \end{cases} \qquad (32) \\ \overline{w}_t &= p_t z_t \qquad (33) \end{aligned}$$

and firm profits are $v_t = 0$.

3.2 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,[15] 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

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

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 2.2, 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 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

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

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

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 $(c_{k,t}^k(i), c_{-k,t}^k(i), \ell_t^k(i)) \geq 0$ such as to optimize the static decision problem

$$
\begin{aligned}
V_t^k(i) \quad = \quad & \max v(x_t^k(i)) - \frac{1}{2}\kappa\left(\ell_t^k(i)\right)^2 + \beta\left[(1-p_r-p_d)V_{t+1}^k(i) + p_r V_{t+1}^k(r) + p_d V_{t+1}^k(d)\right] \\
& \text{subject to} \\
& x_t^k(i) = q(c_{k,t}^k(i), c_{-k,t}^k(i)) \qquad (39) \\
& \widehat{p}_{k,t}^k c_{k,t}^k(i) + \widehat{p}_{-k,t}^k c_{-k,t}^k(i) = \phi\overline{w}_t^k\ell_t^k(i) + g_t^k \qquad (40)
\end{aligned}
$$

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

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

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_t^k, μ_t^k, and ν_t^k, as well as I_t^k.

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

$$V_t^k(r) = \quad \max v(x_t^k(r)) - \frac{1}{2}\kappa\left(\ell_t^k(r)\right)^2 + \beta V_{t+1}^k(r)$$

subject to

$$x_t^k(r) = q(c_{k,t}^k(r), c_{-k,t}^k(r)) \tag{41}$$

$$\widehat{p}_{k,t}^k c_{k,t}^k(r) + \widehat{p}_{-k,t}^k c_{-k,t}^k(r) = \overline{w}_t^k\ell_t^k(r) + g_t^k(r) \tag{42}$$

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.

3.3 The macroeconomic synthesis

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

- Households: 18 variables $c^k_{k,t}(h), c^k_{-k,t}(h), \ell^k_t(h)$, for $h = s, i, r$ and $k = A, B$
- Markets: 4 variables $p_{k,t}$, $\overline{w}^k_t$ for $k = A, B$, where prices, consumer prices, and government policy are linked by (22)–(23).
- Government expenditures: 2 variables g^k_t, $k = A, B$. 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^k_t, ν^k_t, $k = A, B$, which are exogenous from the point of view of market participants. These variables are implicit in the consumer prices $\widehat{p}^k_{k,t}, \widehat{p}^k_{-k,t}$.

Counting equations, we have

- Labor markets: 2 equations in (33)
- Households: in each country 9 equations
  - for s: (36)–(38),
  - for i: (54), (55), and (51), with $w = \phi\overline{w}^k_t$, appropriately indexed.
  - for r: (54), (55), and (51), with $w = \overline{w}^k_t$, appropriately indexed.
- Goods markets: 2 equations

$$Y^k_t = \left(1 + (1 - \delta_\mu)\mu^k_t\right) H^k_t + \left(1 + (1 - \delta_\mu)\mu^{-k}_t\right) M^{-k}_t \tag{43}$$

  for $k = A, B$, where output Y^k_t is given by (31), domestic consumption H^k_t by (6) and exports M^{-k}_t 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, $V^k_t(s), V^k_t(i), V^k_t(r)$, for $k = A, B$. As usual, we normalize the value function $V^k_t(d) = 0$, 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

$$X^k_t = S^k_t x^k(s) + I^k_t x^k(i) + R^k_t x^k(r) \tag{45}$$

4 Parameterization

Our parameterization builds on Eichenbaum, Rebelo and Trabandt (2020). 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).[16] We set $\beta = .96^{(1/52)}$ such that the value of life in autarky is approximately \$10 million.[17] Furthermore, we let $\phi = .8$, such that the productivity loss for infected individuals is 20%, and 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 Labor Statistics in 2018. Initial populations are normalized to 1. In the pre-pandemic steady state the countries are symmetric.

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 $I_1^A = \epsilon = 0.001(0.1\%)$. 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 choose π_1, π_2, and π_3 such that 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.[18] 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. We have experimented extensively with different values of π_4 and show the results, which are remarkably similar, in Section 6.2.

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.[19] We consider a linear specification

[16] 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.

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

[18] 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, 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 6.1 and find our results qualitatively unchanged.

[19] 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.

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 6.2 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 $T = 3$.[20]

Finally, since we have no other taxes in our model, we let $\delta_\mu^k = .5$ in most of our simulations in order to have some scope for government expenditure and public insurance. This means half of the containment taxes are collected by the government as revenues and the rest is wasted. We provide further details about the computation algorithm in Appendix Section A.3.

5 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 3.2 and A.1 in the appendix.[21] 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. Subsection 5.4 compares the three cases to highlight the structure of optimal health and trade coordination during a pandemic.[22]

5.1 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 2, 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 begins to take off after around 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 first wave of infection hits country A, its labor and therefore output decline by more than 15%, while the values for

[20] 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 calibration is not binding.

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

[22] As discussed by Atkeson (2021), in SIR models without exogenous shocks and delays, optimal policies generally do not generate multiple waves in the propagation of the pandemic. Our results are therefore best interpreted in terms of a prototypical sequence of two waves spreading from one country to the next.

country B stay constant (third row, third panel). Similarly for country B, when the pandemic hits there. In both countries during their peaks, i.e., 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 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.

5.2 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 2). 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 become 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 first 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 second wave of infection hits country B, its consumption and labor decline significantly. As in the first wave, 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. On the other hand, 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 first wave, 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 — as the tariffs raise the terms of trade for country A during the peak of the infection, 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 second 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 the first wave, households reduce labor supply there and production increases in country B, as the planner uses the asynchronous feature of the pandemic to not only shift consumption, but also production, between countries.

5.3 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 2 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 first peak, in country A. During this wave, country B raises its tariff by more than one third, because this way it can 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 wrong.

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 distorition 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).

5.4 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 their infection waves and no action outside this period. As noted above, qualitatively the major difference is the dynamics of the other policy instrument, tariffs.

During both peaks, the 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 abandon the trade-war logic and modulate tariffs intertemporally, thus reducing the home bias and improving the terms of trade when the affected 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 greatest during the first 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. 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 facilitates 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 affected country, where the risk of infection is overall lower, and thus provides a countervailing stimulus that is absent in the affected country. Under Nash, the government in the unaffected 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 tariffs are high.

We disentangle these forces in the decomposition of the overall welfare effect in Table 1. 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 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 gain 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, as the results of the planner's policy show, who 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 the labor supply and therefore production. In turn, this shifts production internationally to where the labor transmission channel in (10) is the least harmful.

5.5 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.

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 4 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 very 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 very much alike under coordination and non-coordination, and furthermore, they move very little. Thus, in terms of the observed dynamics in this world with only domestic containment measures, "Nash broadly gets it right".

This, however, masks some important differences between the two settings that are brought to light in Table 4. As the third line shows, Nash governments do almost exactly as well as the social planner in each country.[23] But they achieve this optimum for very different reasons. In each country, optimal coordination yields significantly higher economic benefits than the Nash

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

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 4). 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 the Nash outcome in terms of health *and* consumption.

6 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 on merchandise vs services trade. Third, we consider variation in the death (fatality) rate sensitivity to infections that can be interpreted as varying the congestion externality from a health-sector overload; this allows us to understand the implications of the model for countries with varying degrees of development in terms of healthcare infrastructure.

6.1 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, by second 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 as "essential" services during the second waves.[24]

[24] A striking case of such classification was in India when it faced the outbreak of the highly infectious Delta variant of COVID-19 during April-June 2021. On the back of exports it 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).

To study generalized lockdowns, we allow the domestic containment tax to also suppress productivity: $z_t^k = \bar{z}(1-\mu_t^k)$. Figure 8 compares the coordinated outcome between our baseline model and the model with productivity suppression; Figure 9 compares the Nash outcome. When the government containment policy negatively affects productivity, the government is more reluctant to impose a stringent containment policy. As a result, the infection curve rises more drastically and the death toll is higher, both in the coordinated outcome and in the Nash outcome. Furthermore, since using containment taxes is rather costly, both the Nash and the planner outcomes use more aggressive tariff policies.

Table 5 compares the welfare differences of these cases. As with our benchmark model, the planner improves outcomes relative to Nash on both the economic and health fronts. Table 6 reports statistics about the pandemic in the same format as the table for the benchmark specification. Relative to our benchmark model without productivity suppression, health outcomes are worse in both the Nash and the coordinated outcomes, leading to more deaths in both countries. This suggests that, to the extent that it is feasible to limit lockdown restrictions, using more targeted lockdowns rather than generalized lockdowns which suppress productivity and consumption, can lead to better global outcomes.

6.2 Policy with 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., carries a particular importance 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 the most adversely affected services sector 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).

This distinction between merchandise and services trade is also germane from the standpoint of governments having adjusted "tariffs" during the pandemic. Within merchandise trade, an important trade restriction has been in the form of port shutdowns. Infections at docks are a relevant concern given the high contact intensity involved in the jobs there. As a result of countries adopting port shutdowns, notably in China but also elsewhere, container throughput capacity collapsed to 70% during the pandemic. Additionally, benchmark costs of shipping a container between China and the United States tripled during the pandemic in some cases,[25] and rose to 10 times higher than the pre-pandemic level in other cases. Nevertheless, it has been noted that direct restrictions due to government interventions have been limited in the

[25] See, for example, China's Port Shutdown Raises Fears of Closures Worldwide, Bloomberg Economics, August 12, 2021: https://www.bloomberg.com/news/articles/2021-08-12/massive-china-port-shutdown-raises-fears-of-closures-worldwide.

context of merchandise goods. This, however, is certainly not the case in services trade, notably in travel. Border controls and restrictions to tourism have been ramped up dramatically, for example in the form of border shutdowns, even within otherwise integrated regions such as states of the United States and member countries of the Eurozone.

While modeling the full richness of merchandise versus services trade is beyond the scope of this paper, we derive some conclusions implied by their difference. To do so, we vary π_4, which measures the intensity in the transmission of disease between households in different countries due to the consumption of foreign goods. In particular, varying π_4 to higher levels can be considered as shifting focus towards countries engaged in more contact-intensive trade such as services versus merchandise, or within services, tourism versus technology services.

This is done in Figures 10 and 11, where we vary π_4 and report the equilibrium outcomes with coordinated and non-cooperative governments, respectively. We consider the benchmark case, the case in which π_4 is five times higher, and the case in which π_4 is ten times higher. A higher π_4 means 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 1/100 as strong as 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, the 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. Table 7 reports these statistics in the same format as the table for the benchmark specification. 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. As we discussed above, these coordinated tariff policies allow the country that is experiencing the pandemic at the moment to benefit from stronger terms of trade and therefore achieve higher welfare, acting as a risk-sharing scheme. And, in Nash equilibrium, each government imposes domestic containment taxes during the peak of its local infection. Its import tariff is unconditionally high, except during the peak of its local infection. This pattern is also qualitatively consistent with our finding in the benchmark specification.

Table 8 compares the welfare differences of these cases. 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. We find that 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 in the baseline case. 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, we note that, given the pandemic starts in country A, a stronger international transmission is always a bad news for country B, as it allows less time for country B to flatten the curve. As a result, country B suffers higher death and there is less its government can do, even under coordinated policies. Conversely, to the extent that the pandemic also spreads back from country A to country B, a stronger international transmission is also bad news for country A.

6.3 Policy with Varying Degrees of Healthcare Congestion

Another interesting application of our international model of the pandemic is to consider 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, World Bank's most recently available statistics show that India has 0.5, Philippines 1, United States 2.9, China 4.3 and Japan 13.4, 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 density of population, 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 extent of congestion externality to compare these two types of countries.[26]

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 Figures 12 and 13, we either raise the congestion parameter from the benchmark of 0.05 to 0.075, or lower the congestion parameter from the benchmark of 0.05 to 0.025. Naturally, we find that a higher congestion parameter leads to more death, and governments impose more stringent domestic containment tax 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 9 reports these statistics in the same format as the table for the benchmark specification.

However, quantitatively the welfare differences do change. Table 10 compares the welfare differences of these cases and illustrates clearly that the welfare gain due to less death in the coordinated policies relative to the Nash policies increases strongly as the congestion parameter

[26]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.

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.

7 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. A major insight from our work is that the interplay between domestic health policies and international trade policies makes it possible to dynamically modulate the terms of trade and thus shift consumption, production, and infection patterns internationally as a function of the global state of the pandemic. When policies are modulated in a coordinated manner between countries, dynamics are efficient at generating variation in terms of trade that favor the country experiencing peaks of their infections waves; uncoordinated policies aggravate overall outcomes by achieving exactly the opposite, highlighting the importance of standing united as countries in dealing with the health and economic fallout from a pandemic.

In ongoing work, we are generalizing the model to study the role of non-tariff barriers during a pandemic in affecting international supply chains, which seem disrupted far more than originally envisaged at the time of outbreak of the COVID-19 pandemic. An important generalization is that 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 hope that our analysis will 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.

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 and its analysis could be a useful foundation for this significant next step.

References

Acemoglu, Daron, Victor Chernozhukov, Iván Werning, and Michael D Whinston. 2021. "Optimal Targeted Lockdowns in a Multi-Group SIR Model." *American Economic Review: Insights forthcoming*.

Alon, Titan, Minki Kim, David Lagakos, and Mitchell VanVuren. 2020. "How should policy responses to the Covid-19 pandemic differ in the developing world?" *Covid Economics*, 22: 1–46.

Alvarez, Fernando E, David Argente, and Francesco Lippi. 2021. "A Simple Planning Problem for COVID-19 Lockdown." *American Economic Journal, Insights forthcoming*.

Antràs, Pol, Stephen J Redding, and Esteban Rossi-Hansberg. 2020. "Globalization and Pandemics." *Covid Economics*, 49: 1–84.

Assenza, Tiziana, Fabrice Collard, Martial Dupaigne, Patrick Fieve, Christian Hellwig, Sumudu Kankanamge, and Nicolas Wequin. 2020. "The Hammer and the Dance: Equilibrium and Optimal Policy during a Pandemic Crisis." University of Chicago Working Paper.

Atkeson, Andrew. 2021. "A Parsimonious Behavioral SEIR Model of the 2020 Covid Epidemic in the United States and the United Kingdom." National Bureau of Economic Research Working Paper 28434.

Auray, Stéphane, Michael B Devereux, and Aurélien Eyquem. 2019. "Endogenous Trade Protection and Exchange Rate Adjustment." National Bureau of Economic Research.

Bagwell, Kyle, and Robert W. Staiger. 1999. "An Economic Theory of GATT." *American Economic Review*, 89(1): 215–248.

Beck, Thorsten, and Wolf Wagner. 2020. "National containment policies and international cooperation." *Covid Economics*, 8: 134–148.

Berger, David W, Kyle F Herkenhoff, and Simon Mongey. 2021. "Testing and Reopening in an SEIR Model." *Review of Economic Dynamics forthcoming*.

Bonadio, Barthélémy, Zhen Huo, Andrei A Levchenko, and Nitya Pandalai-Nayar. 2021. "Global Supply Chains in the Pandemic." *Journal of International Economics forthcoming*.

Brander, James A, and Barbara J Spencer. 1985. "Export subsidies and international market share rivalry." *Journal of International Economicsl*, 18(1-2): 83–100.

Brauer, Fred. 2008. "Compartmental models in epidemiology." In *Mathematical epidemiology*. 19–79. Springer.

Broda, Christian, Nuno Limao, and David E Weinstein. 2008. "Optimal tariffs and market power: the evidence." *American Economic Review*, 98(5): 2032–65.

Brodeur, Abel, David Gray, Anik Islam, and Suraiya Bhuiyan. 2020. "A literature review of the economics of COVID-19." *Journal of Economic Surveys*.

Brotherhood, Luis, Philipp Kircher, Cezar Snatos, and Michele Tertilt. 2020. "An economic model of the Covid-19 epidemic: The importance of testing and age-specific policies." Working Paper.

Costinot, Arnaud, and Andrés Rodríguez-Clare. 2014. "Trade theory with numbers: Quantifying the consequences of globalization." In *Handbook of international economics*. Vol. 4, 197–261. Elsevier.

Dockner, Engelbert, Steffen Jorgensen, Ngo Van Long, and Gerhard Sorger. 2000. *Differential games in economics and management science.* Cambridge University Press.

Egorov, Konstantin, Dmitry Mukhin, et al. 2019. "Optimal monetary policy under dollar pricing." Vol. 1510.

Eichenbaum, Martin S, Sergio Rebelo, and Mathias Trabandt. 2020. "The Macroeconomics of Epidemics." *Review of Financial Studies*.

Favero, Carlo. 2020. "Why is Mortality in Lombardy so High?" *Covid Economics*, 4: 47–61.

Fernandez-Villaverde, Jesus, and Charles I Jones. 2020. "Estimating and Simulating a SIRD Model of COVID-19 for Many Countries, States, and Cities." Working Paper.

Fudenberg, Drew, and Jean Tirole. 1991. *Game theory.* MIT Press.

Garibaldi, Pietro, Espen R. Moen, and Christopher A. Pissarides. 2020. "Modelling contacts and transitions in the SIR epidemics model." *Covid Economics*, 5: 1–20.

Glover, Andrew, Dirk Krueger, Jonathan Heathcote, and Jose-Victor Rios-Rull. 2020. "Health versus Wealth: On the Distributional Effects of Controlling a Pandemic." *Covid Economics*, 6: 22–64.

Greenwood, Jeremy, Philipp Kircher, Cezar Santos, and Michele Tertilt. 2019. "An equilibrium model of the African HIV/AIDS epidemic." *Econometrica*, 87(4): 1081–1113.

Hall, Robert E, Charles I Jones, and Peter J Klenow. June 2020. "Trading Off Consumption and COVID-19 Deaths." *Minneapolis Fed Quarterly Review*.

Jones, Callum J, Thomas Philippon, and Venky Venkateswaran. 2021. “Optimal Mitigation Policies in a Pandemic: Social Distancing and Working from Home.” *Review of Financial Studies forthcoming*.

Kaplan, Greg, Ben Moll, and Gianluca Violante. 2020. “The Great Lockdown and the Big Stimulus: Tracing the Pandemic Possibility Frontier for the U.S.” University of Chicago.

Kermack, William Ogilvy, and Anderson G McKendrick. 1932. “Contributions to the mathematical theory of epidemics. II.—The problem of endemicity.” *Proceedings of the Royal Society of London. Series A, containing papers of a mathematical and physical character*, 138(834): 55–83.

Leibovici, Fernando, and Ana Maria Santacreu. 2020. “International trade of essential goods during a pandemic.” *Covid Economics*, 21: 59–99.

Liu, Laura, Hyungsik Roger Moon, and Frank Schorfheide. 2021. “Panel forecasts of country-level Covid-19 infections.” *Journal of econometrics*, 220(1): 2–22.

McGrattan, Ellen R, Richard Rogerson, et al. 2004. “Changes in hours worked, 1950-2000.” *Federal Reserve Bank of Minneapolis Quarterly Review*, 28(1): 14–33.

McKibbin, Warren, and Fernando Roshen. 2020. “The global macroeconomic impacts of covid-19: seven scenarios.” *Covid Economics*, 10: 116–156.

Meier, Matthias, and Eugenio Pinto. 2020. “Covid-19 Supply Chain Disruptions.” *Covid Economics*, 48: 139–170.

Noy, Ilan, Nguyen Doan, Benno Ferrarini, and Donghyun Park. 2020. “Measuring the economic risk of Covid-19.” *Covid Economics*, 3: 103–118.

OECD. 2020. “COVID 19 and International Trade: Issues and Action.”

Ossa, Ralph. 2011. “A “new trade” theory of GATT/WTO negotiations.” *Journal of Political Economy*, 119(1): 122–152.

Ossa, Ralph. 2014. “Trade wars and trade talks with data.” *American Economic Review*, 104(12): 4104–46.

Perroni, Carlo, and John Whalley. 2000. “The new regionalism: trade liberalization or insurance?” *Canadian Journal of Economics/Revue canadienne d’économique*, 33(1): 1–24.

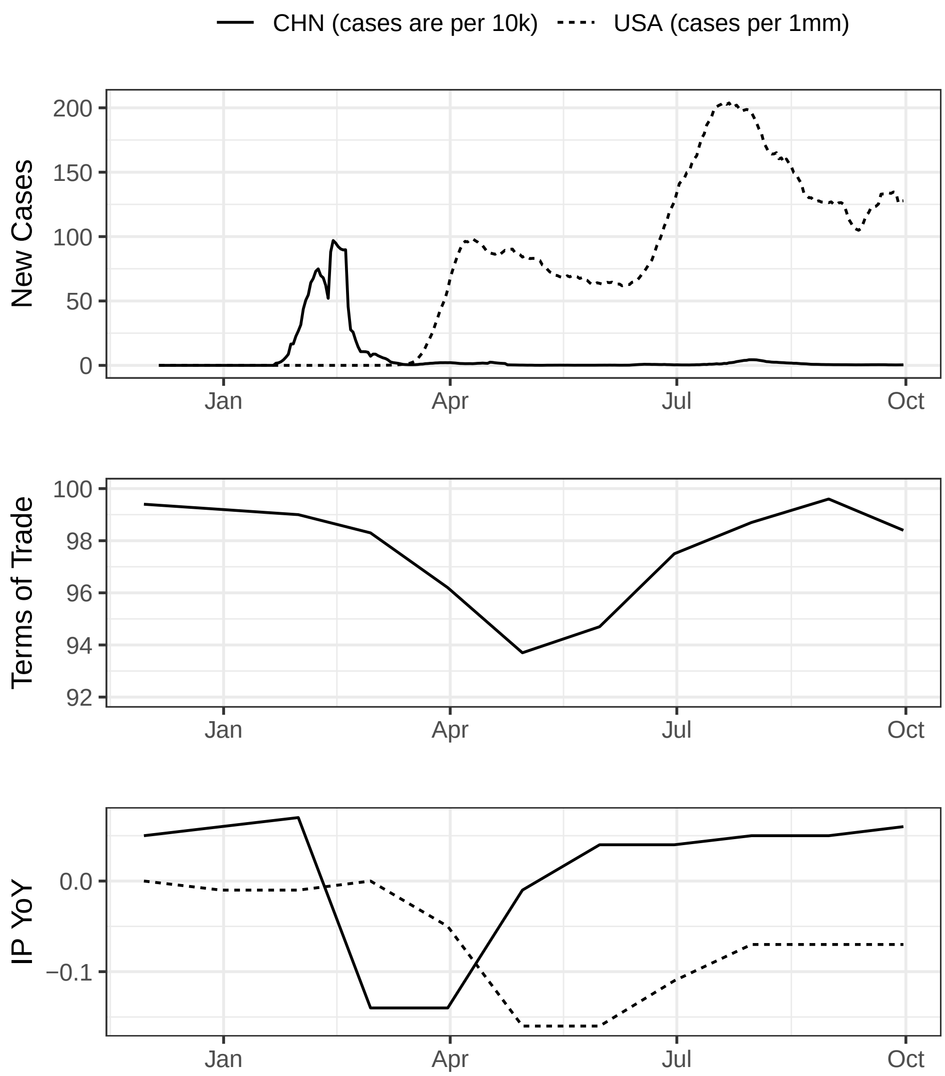
Ullah, Akbar, and Olubunmi Agift Ajala. 2020. “Do lockdown and testing help in curbing Covid-19 transmission?” *Covid Economics*, 13: 137–155.

Verity, Robert, Lucy C Okell, Ilaria Dorigatti, Peter Winskill, Charles Whittaker, Natsuko Imai, Gina Cuomo-Dannenburg, Hayley Thompson, Patrick GT Walker, Han Fu, et al. 2020. "Estimates of the severity of coronavirus disease 2019: a model-based analysis." *The Lancet infectious diseases*.

von Thadden, Ernst-Ludwig. 2020. "A generalized SEIR-model of Covid-19 with applications to health policy." *Covid Economics*, 10: 24–48.

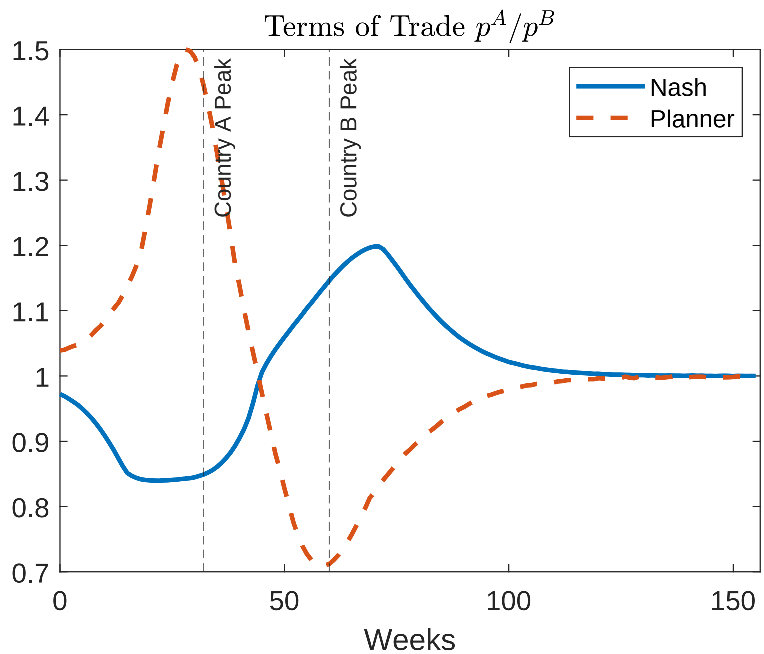
Yildirim, Muhammed A, Cem Cakmakli, Selva Demiralp, Sebnem Kalemli-Ozcan, Sevcan Yesiltas, et al. 2021. "The Economic Case for Global Vaccinations: An Epidemiological Model with International Production Networks." Center for International Development at Harvard University.

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



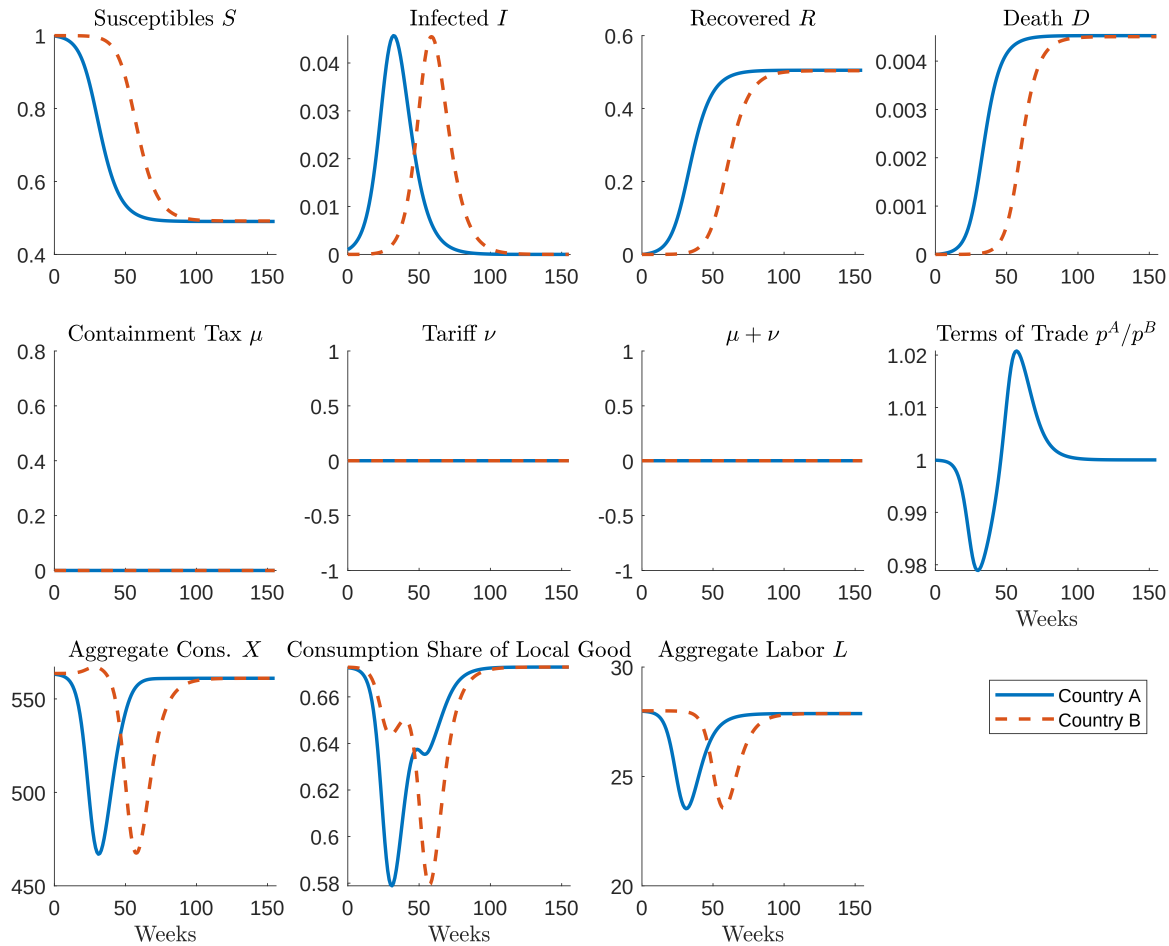
Note: Health and economic outcomes in China and the United States during the 2020 pandemic. Daily new cases for China are per 10,000 people and per 1,000,000 for the United States. Terms of trade is the price index of US exports to China divided by the price index of imports by the US from China. Industrial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

Figure 2: Terms of Trade With and Without Coordination



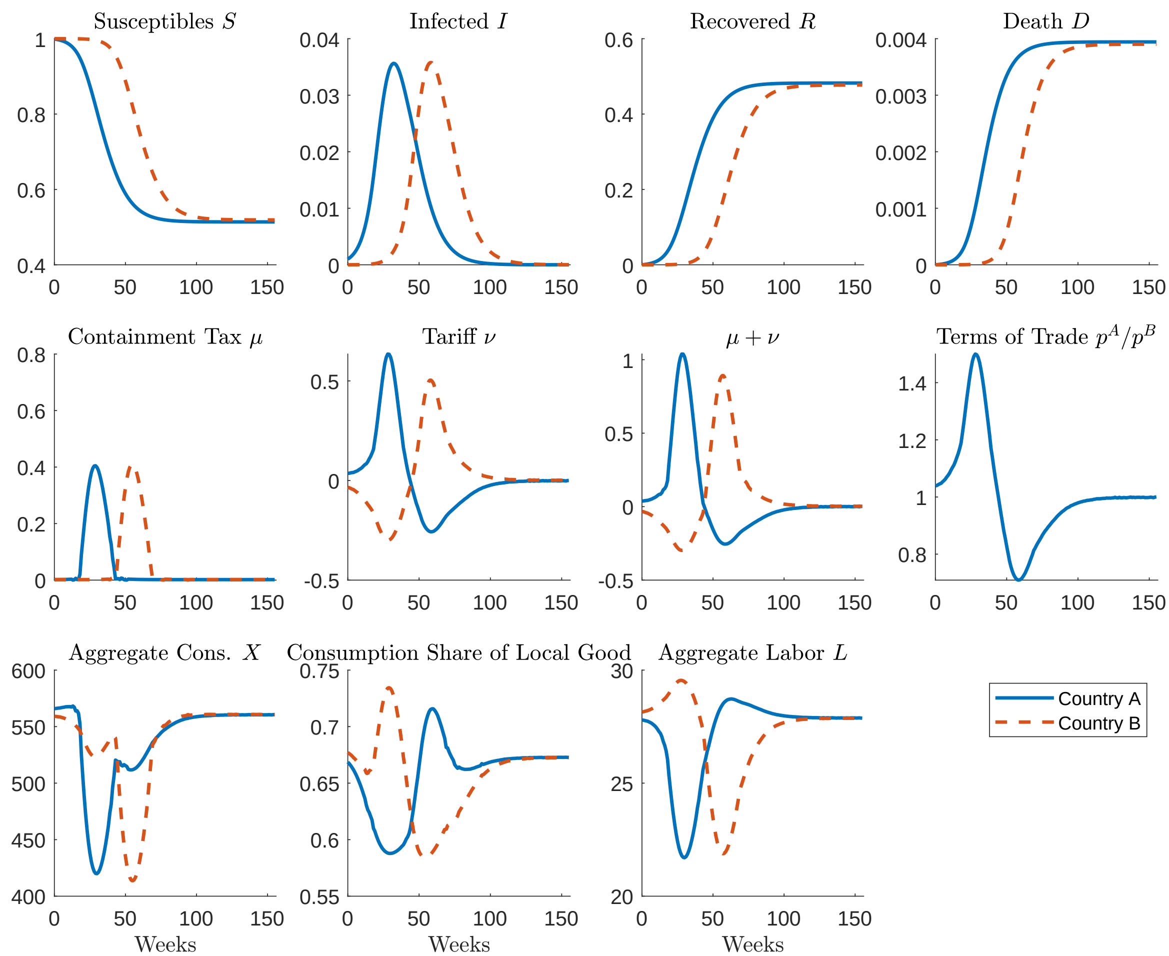
Note: Terms of Trade in uncoordinated (Nash) and coordinated (Planner) equilibrium. The dashed lines specify the approximate peak of maximum infections in country A and country B.

Figure 3: Benchmark SIR Dynamics



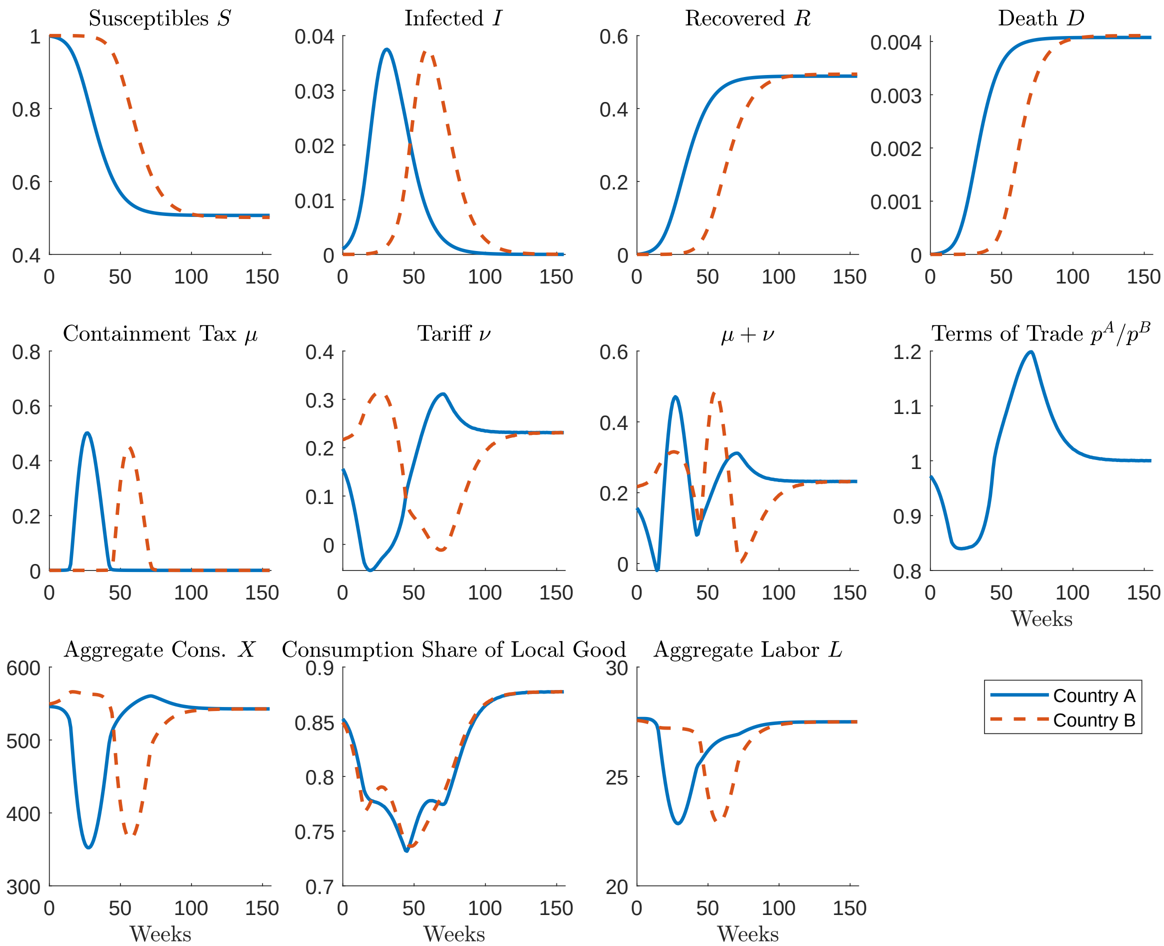
Note: Benchmark model with international transmission of pandemic. No government domestic containment policies or tariffs.

Figure 4: Coordinated Planning Equilibrium Outcomes



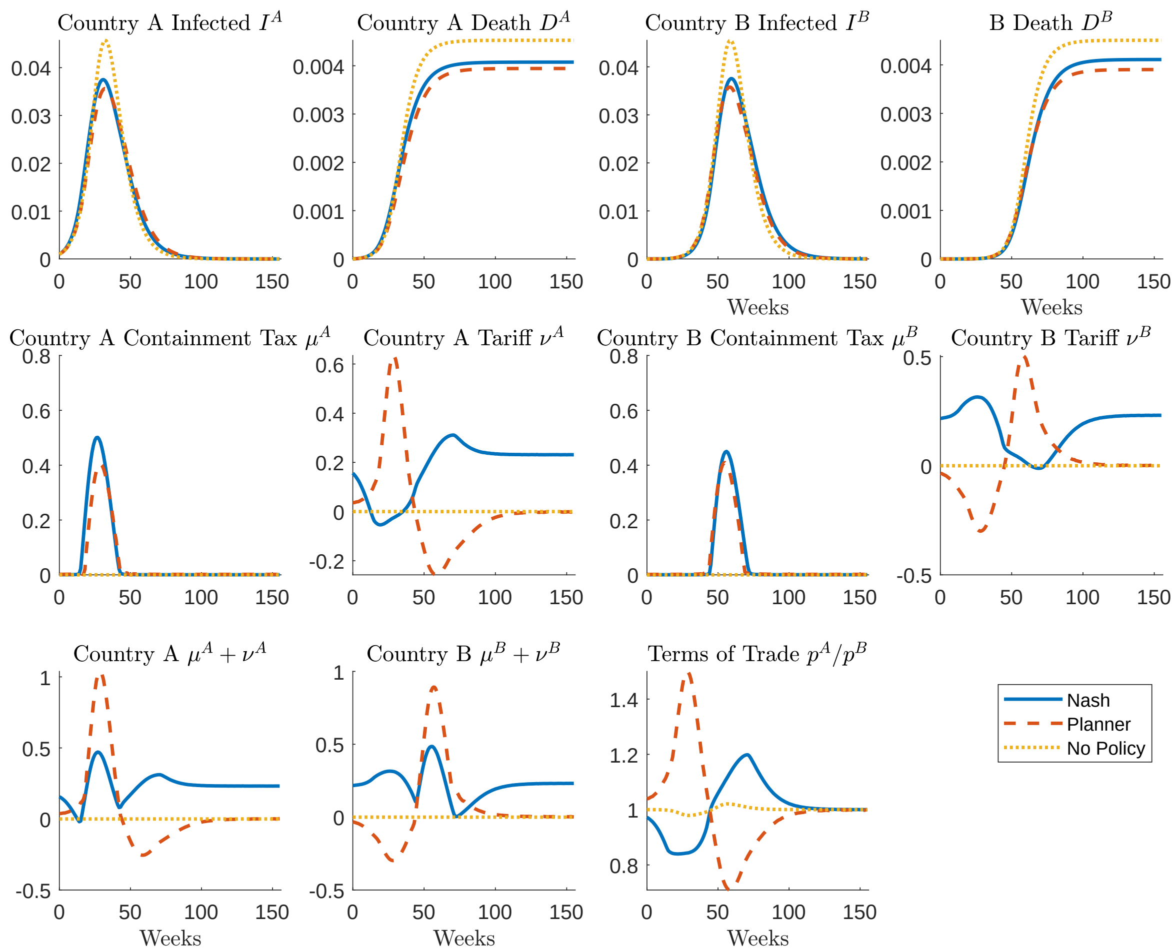
Note: Benchmark model with international transmission of pandemic. Equilibrium domestic containment policies and tariffs are determined by a global social planner that maximizes the sum of both countries' welfare.

Figure 5: Nash Equilibrium Outcomes



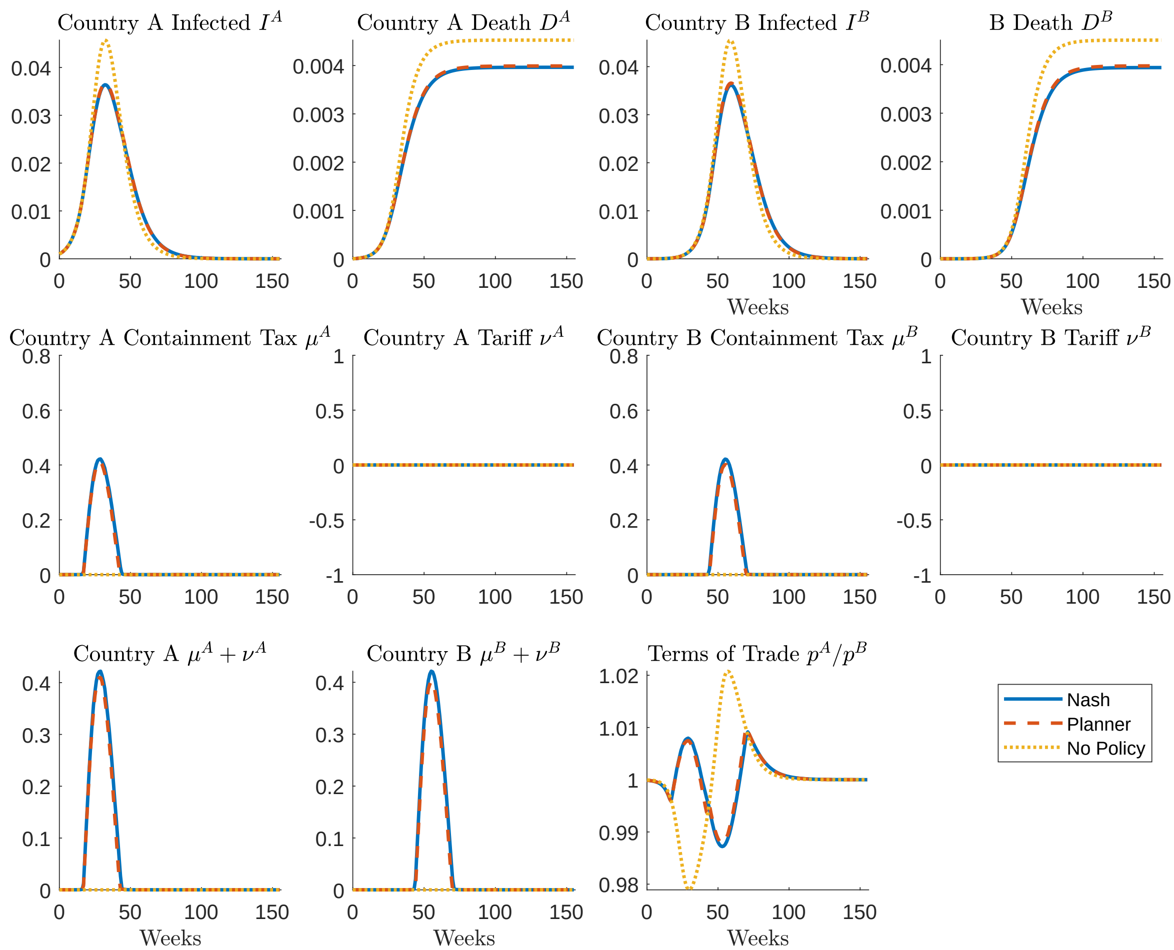
Note: Benchmark model with international transmission of pandemic. Equilibrium domestic containment policies and tariffs are the outcome of a Nash game between the two countries.

Figure 6: Comparing Equilibrium Policies and Outcomes



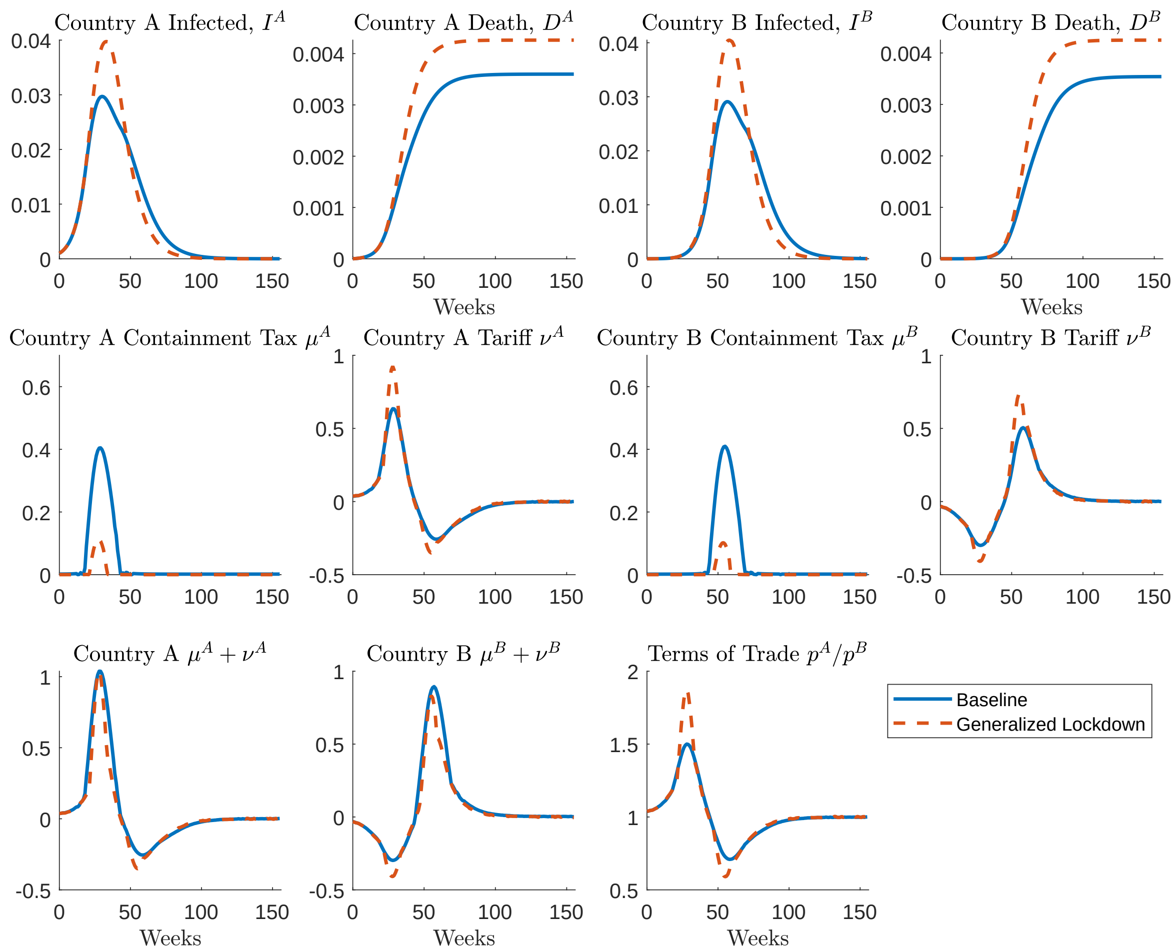
Note: Comparison of SIR dynamics, government policies, and economic outcomes in three cases: benchmark, Nash, and Planner. In the no policy case there are no domestic containment policies. In the Nash case, equilbirium domestic containment policies and tariffs are the outcome of a Nash game between the 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



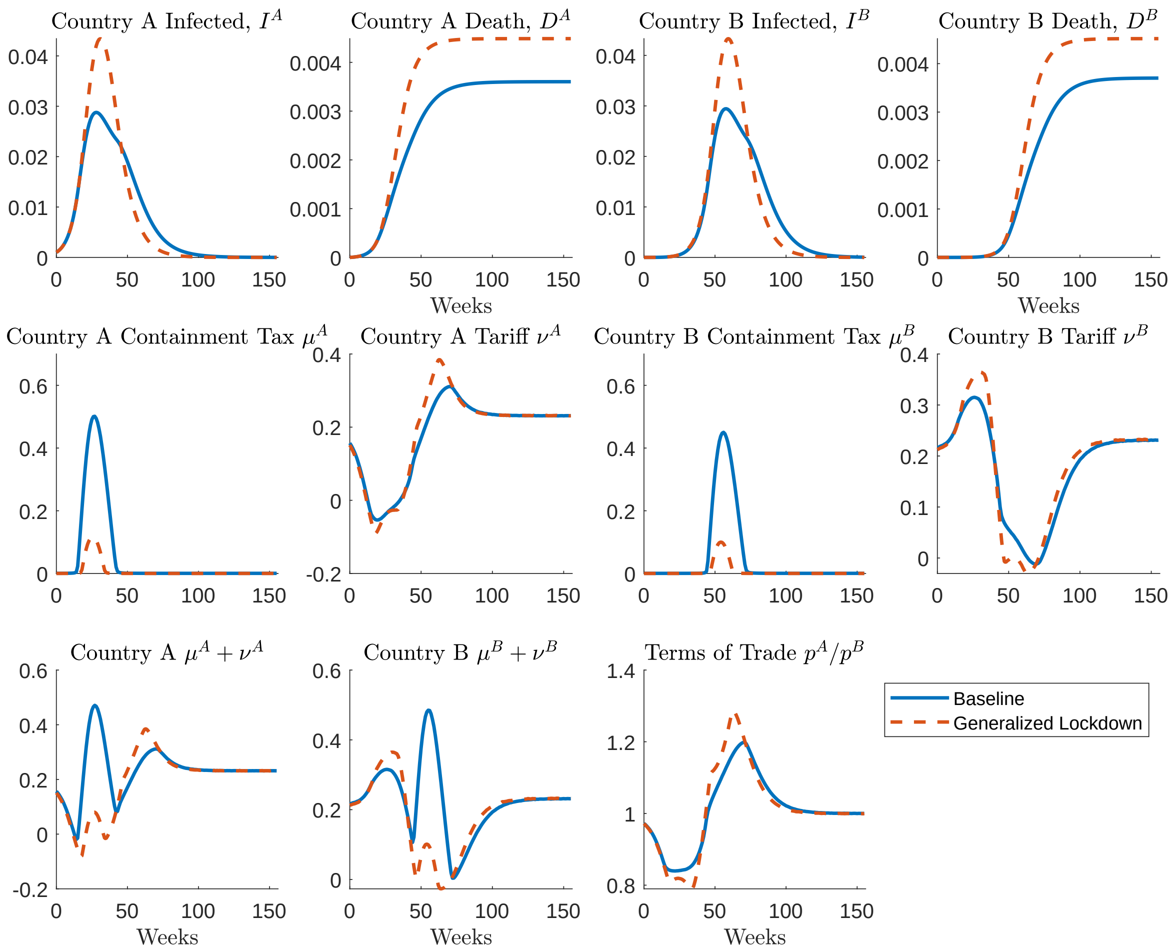
Note: Comparison of SIR dynamics, government policies, and economic outcomes in three cases: benchmark, Nash, and Planner. We study the case in which no tariff can be imposed.

Figure 8: Production Supression, Coordinated Planning Equilibrium



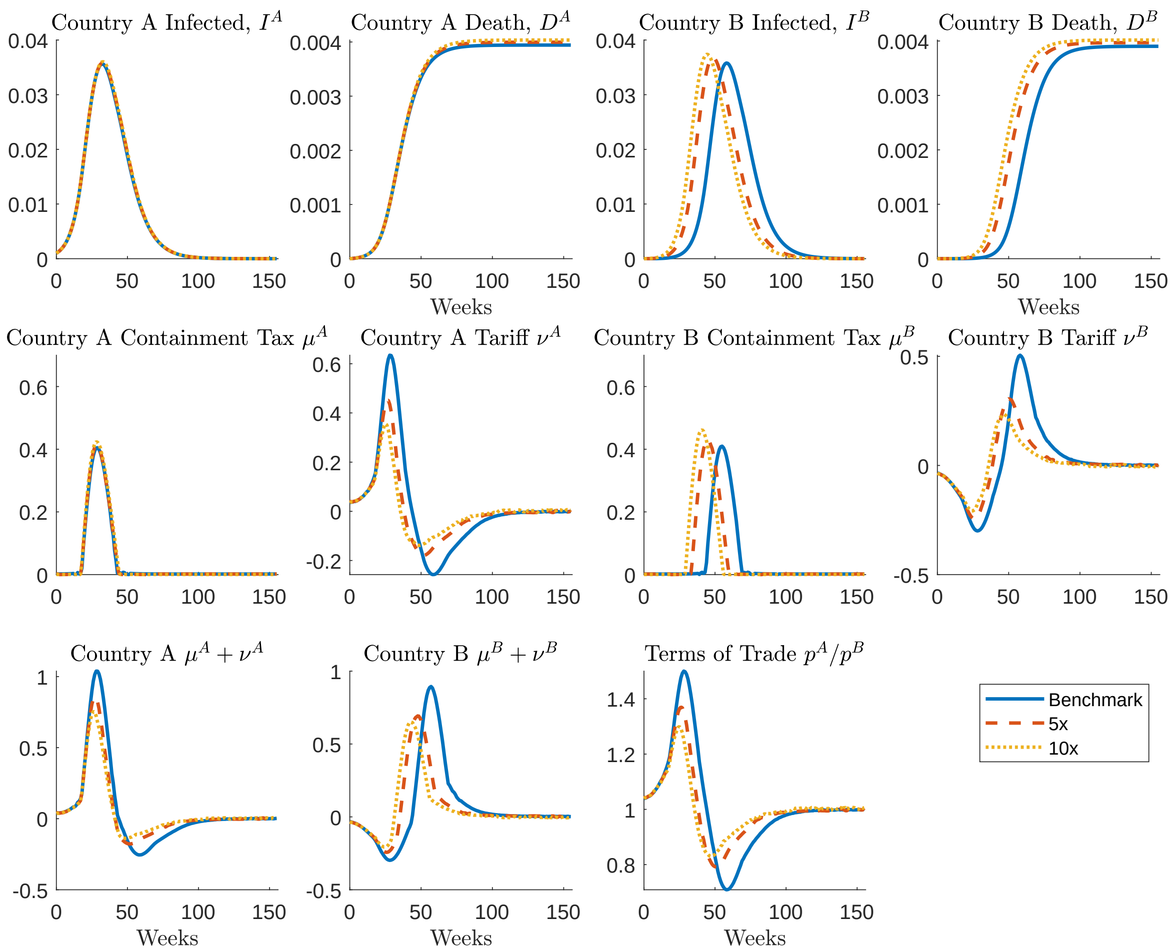
Note: Comparison of SIR dynamics, government policies, and economic outcomes in coordinated planning equilibria. In this variation, we allow the government containment policy to affect local productivity level.

Figure 9: Production Supression, Nash Equilibrium



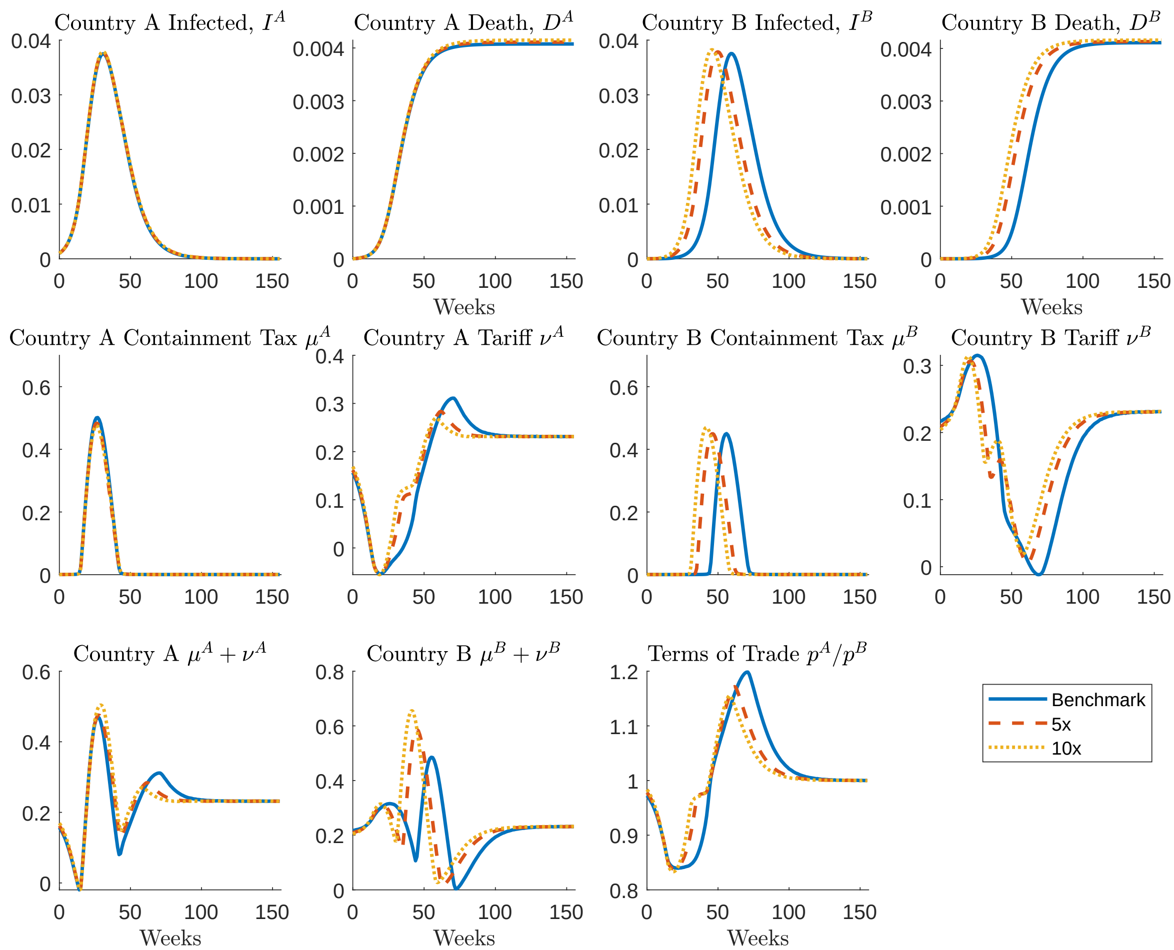
Note: Comparison of SIR dynamics, government policies, and economic outcomes in Nash equilibria. In this variation, we allow the government containment policy to affect local productivity level.

Figure 10: Varying International Transmission π_4, Coordinated Planning Equilibrium



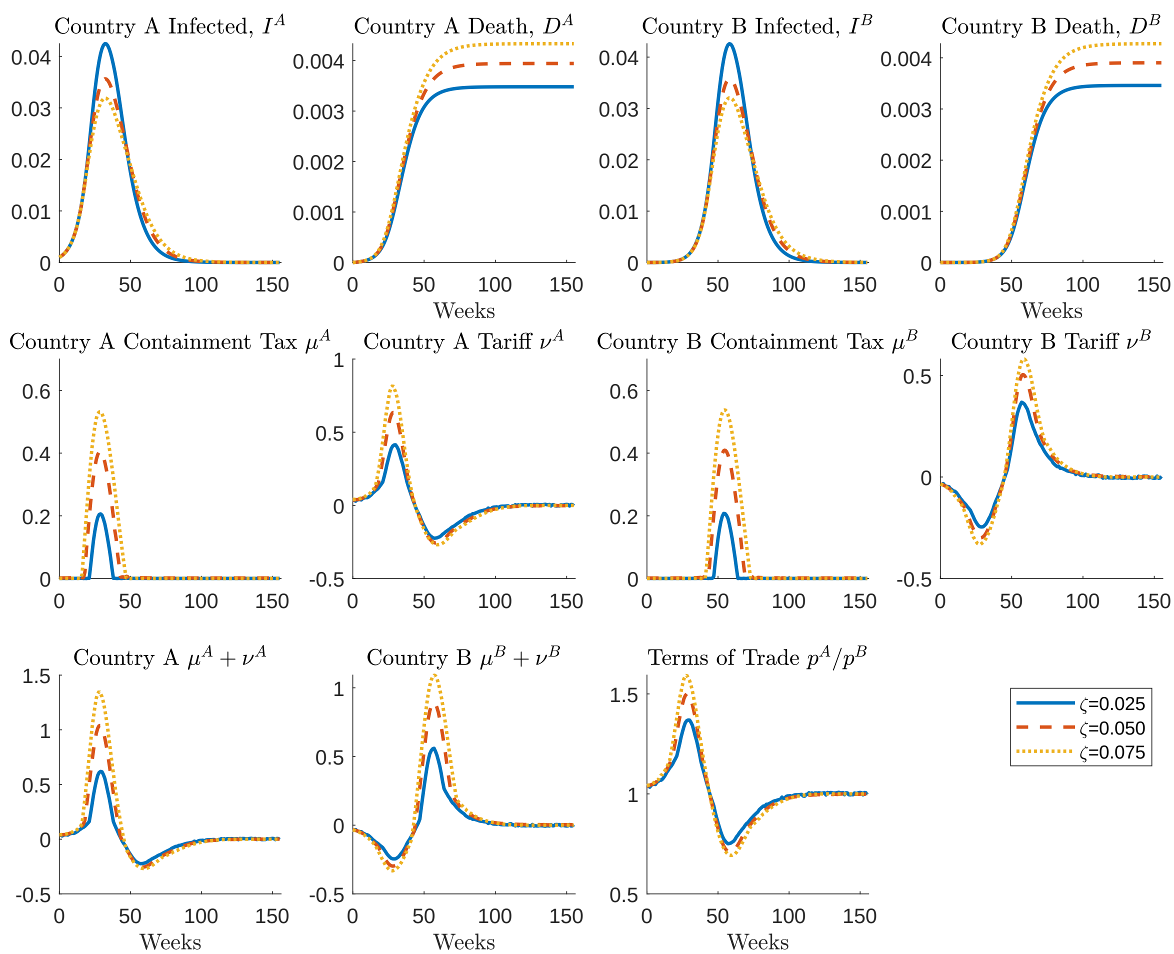
Note: Comparison of SIR dynamics, government policies, and economic outcomes in coordinated planning equilibria. We vary the parameter π_4 that governs the intensity of international transmission of disease.

Figure 11: Varying International Transmission π_4, Nash Equilibrium



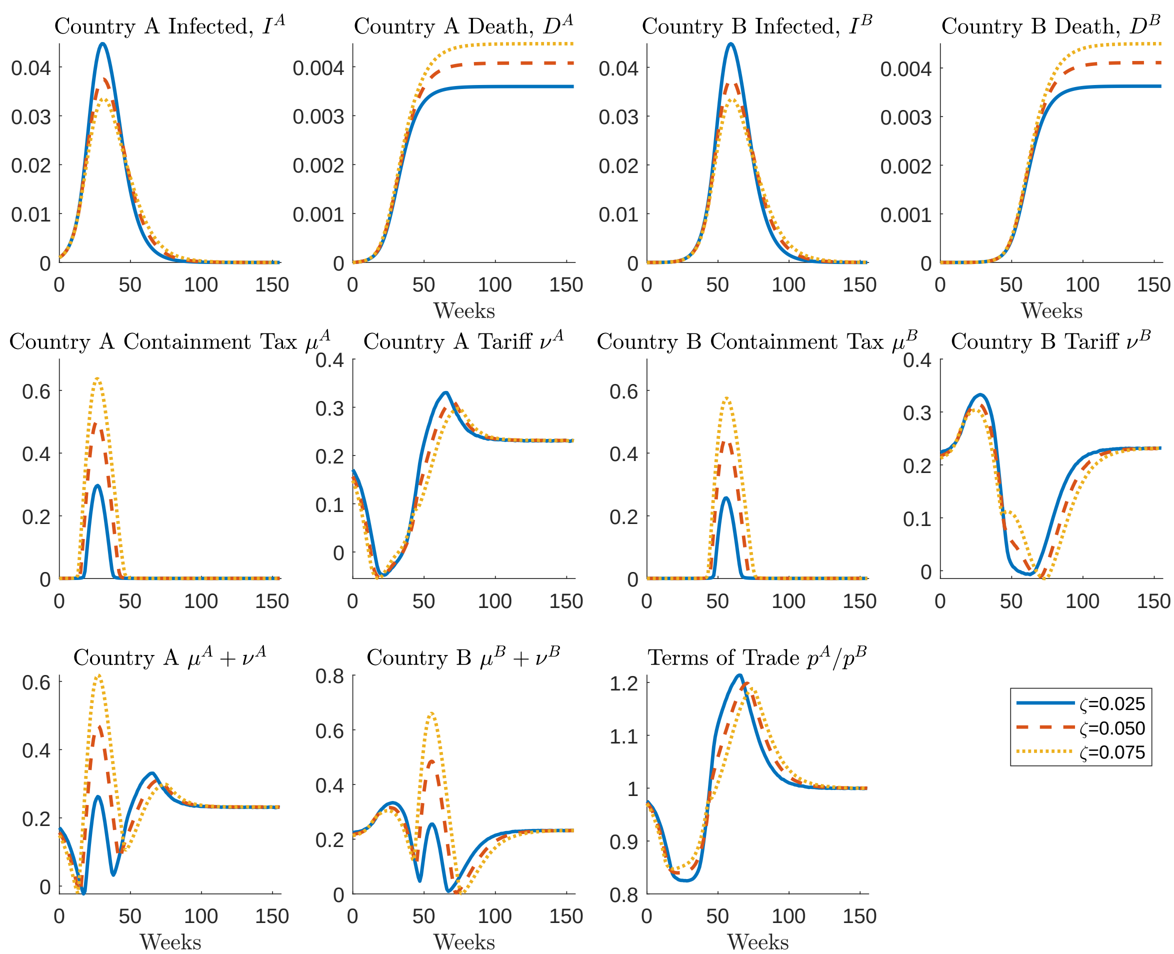
Note: Comparison of SIR dynamics, government policies, and economic outcomes in Nash equilibria. We vary the parameter π_4 that governs the intensity of international transmission of disease.

Figure 12: 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 13: 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 1: 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 2: 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 3: 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 4: 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 5: 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 6: 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 7: 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 8: 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.

	Country A			Country B		
	Total	Economic	Death	Total	Economic	Death
Panel (a): 1 times π_4, Baseline						
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						
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						
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 9: 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 10: 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

A Model Appendix

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

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

$$\text{subject to} \quad x = q(c_k, c_{-k}) \tag{46}$$

$$\widehat{p}_k c_k + \widehat{p}_{-k} c_{-k} = w\ell + g \tag{47}$$

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 3, the solution is characterized by the following first-order constraints:

$$x^{-\rho}\frac{\partial x}{\partial c_k} = \lambda\widehat{p}_k \tag{48}$$

$$x^{-\rho}\frac{\partial x}{\partial c_{-k}} = \lambda\widehat{p}_{-k} \tag{49}$$

$$\kappa\ell = \lambda w \tag{50}$$

Dividing (48) by (49) yields

$$c_{-k} = \left(\frac{1-\alpha}{\alpha}\right)^{\sigma}\left(\frac{\widehat{p}_k}{\widehat{p}_{-k}}\right)^{\sigma} c_k \tag{51}$$

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

Inserting (51) into (46) yields

$$x = \psi^{\frac{\sigma}{\sigma-1}}\left(\alpha\widehat{p}_{-k}\right)^{-\sigma} c_k \tag{52}$$

where

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

Inserting (52) into (48), using (50), yields

$$w\psi^{-\frac{\sigma\rho-1}{\sigma-1}} \left(\alpha \widehat{p}_{-k}\right)^{\sigma\rho} c_k^{-\rho} = \kappa \widehat{p}_k \widehat{p}_{-k} \ell \tag{53}$$

By straightworward calculations, the three equations (47), (51), and (53) yield the following solutions for the three unknowns (c_k, c_{-k}, ℓ). Labor ℓ is given by

$$\ell \left(w\ell + g\right)^{\rho} = \frac{w}{\kappa} \psi^{\frac{1-\rho}{\sigma-1}} \left(\widehat{p}_k \widehat{p}_{-k}\right)^{\rho-1} \tag{54}$$

home consumption c_k by

$$\psi \left(\widehat{p}_k \widehat{p}_{-k}\right)^2 c_k^{\rho+1} - \widehat{p}_k \widehat{p}_{-k} \left(\alpha \widehat{p}_{-k}\right)^{\sigma} g c_k^{\rho} = \frac{w^2}{\kappa} \psi^{-\frac{\sigma\rho-1}{\sigma-1}} \left(\alpha \widehat{p}_{-k}\right)^{\sigma(\rho+1)} \tag{55}$$

and foreign consumption by (51). It is easy to see that (54) and (55) 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

$$\ell = -\frac{g}{2w} + \frac{1}{2w}\sqrt{g^2 + \frac{4w^2}{\kappa}} \tag{56}$$

which yields the multiplier λ, the "price of utility", by (50), as $\lambda = \frac{\kappa}{w}\ell$.

Optimal domestic consumption is

$$c_k = \frac{g\left(\alpha \widehat{p}_{-k}\right)^{\sigma}}{2\psi \widehat{p}_k \widehat{p}_{-k}} + \frac{\left(\alpha \widehat{p}_{-k}\right)^{\sigma}}{2\psi \widehat{p}_k \widehat{p}_{-k}} \sqrt{g^2 + \frac{4w^2}{\kappa}} \tag{57}$$

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

$$w^k = p_k z^k \tag{58}$$

$$z^k \ell^k = c_k^k + c_k^{-k} \tag{59}$$

$k = A, B$, 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 (58) and (59) to are sufficient to determine the 4 prices w^k, p_k, $k = A, B$, by using the solutions of (54), (55), and (51) 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,

$$g^k = \nu^k p_{-k} c_{-k}^k \tag{60}$$

Now, for given government policies (ν^A, ν^B), we have the 6 equations (58), (59), and (60) 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 3 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 (54), (55), and (51), 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 (54), (55), and (51), 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 2.2.

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

$$T_t = \eta S_t I_t \tag{61}$$

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.[27] 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 (61) can now be derived as follows.[28] 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

$$\overline{\tau} = 1 - (1-\theta)^k = \theta \sum_{m=0}^{k-1} \binom{k}{m+1} (-\theta)^m \tag{62}$$

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 (61).

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).[29] To simplify, and different from Eichenbaum, Rebelo and Trabandt (2020); Brotherhood et al. (2020), we do not distinguish 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.[30] Suppose that individuals of health status h spend a fraction $\ell(h) < 1$ of their time at work, and a fraction

[27] 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.

[28] 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).

[29] 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.

[30] 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.

$\gamma c(h) < 1$ 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.[31] 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 $\ell(s)$:

$$\tau(c(s), \ell(s)) = f^2\eta I + \ell(s)\eta\ell(i)I + c(s)\eta\gamma^2 c(i)I \tag{63}$$
$$= \eta\left[\gamma^2 c(s)c(i) + \ell(s)\ell(i) + f\right] I \tag{64}$$

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

$$T_t = \eta\left(\gamma^2 c_t(s)c_t(i) + \ell_t(s)\ell_t(i) + f\right) I_t S_t \tag{65}$$

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 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

[31] 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).

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 (65). 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.